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RAW & UNEDITED

Effective Modern C++

42 SPECIFIC WAYS TO IMPROVE YOUR USE OF C++11 AND C++14

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Contents

Introduction

If you're an experienced C++ programmer and are anything like me, you initially approached C++11 thinking, "Yes, yes, I get it. It's C++, only more so." But as your knowledge of the revised language increased, you were surprised by the scale of the changes. `auto` objects, range-based `for` loops, lambda expressions, and rvalue references change the very face of C++, to say nothing of the new concurrency features. And then there are the idiomatic changes! `0` and `typedef`s are out, `nullptr` and alias declarations are in. Enums should now be scoped. Smart pointers are now preferable to built-in ones. Moving objects is normally better than copying them. There's a lot to learn about C++11.

The adoption of C++14 hardly made things easier.

So...a lot to learn. More importantly, a lot to learn about making *effective* use of the new capabilities. If you need information on the basic syntax or semantics of features in "modern" C++, resources abound, but if you're looking for guidance on how to employ the features to create software that's correct, efficient, maintainable, and portable, the search is more challenging. That's where this book comes in. It's devoted not to describing the features of C++11 and C++14, but rather to their effective application.

The information in the book is broken into guidelines called *Items*. Want to understand the various forms of type deduction? Or to know when (and when not) to declare objects using `auto`? Are you interested in why `const` member functions should be thread-safe, how to implement the Pimpl Idiom using `std::unique_ptr`, why you should avoid default capture modes in lambda expressions, or the differences between (and proper uses of) `std::atomic` and `volatile`? The answers are all here. Furthermore, they're platform-independent, Standards-conformant answers. This is a book about *portable* C++.

Items comprise guidelines, not rules, because guidelines have exceptions. The most important part of each Item is not the advice it offers, but the rationale behind the advice. Once you've read that, you'll be in a position to determine whether the circumstances of your project justify disregarding the Item's guidance. The true goal of this book isn't to tell you what to do or what to avoid doing, but to convey a deeper understanding of how things work in C++11 and C++14.

Terminology and Conventions

To make sure we understand one another, it's important to agree on some terminology, beginning, ironically, with "C++." There have been four standardized versions of C++, each named after the year in which the corresponding ISO Standard was adopted: *C++98*, *C++03*, *C++11*, and *C++14*. C++98 and C++03 differ only in subtle technical details, so in this book, I refer to both as C++98.

When I mention C++98, I mean only that version of the language. Where I refer to C++11, I mean both C++11 and C++14, because C++14 is effectively a superset of C++11. When I write C++14, I mean specifically C++14. And if I simply mention C++, I'm making a broad statement that pertains to all language versions. As a result, I might say that C++ places a premium on efficiency (true for all versions), that C++98 lacks support for concurrency (true for C++98 only), that C++11 supports lambda expressions (true for C++11 and C++14), and that C++14 offers generalized function return type deduction (true for C++14 only).

C++11's most pervasive feature is probably move semantics, and the foundation of move semantics is distinguishing expressions that are *rvalues* from those that are *lvalues*. That's because rvalues indicate objects eligible for move operations, while lvalues generally don't. In concept (though not always in practice), rvalues correspond to anonymous temporary objects returned from functions, while lvalues correspond to objects you can refer to, either by name or by following a pointer or reference.

A useful heuristic to determine whether an expression is an lvalue is to ask if you can take its address. If you can, it typically is. If you can't, it's usually an rvalue. A nice feature of this heuristic is that it helps you remember that the type of an expression is independent of whether the expression is an lvalue or an rvalue. That is, given a type `T`, you can have both lvalues of type `T` and rvalues of type `T`. It's especially important to remember this when dealing with a parameter of rvalue reference type, because the parameter itself is an lvalue:

```
class Widget {
public:
  Widget(Widget&& rhs);     // rhs is an lvalue, though it has
  …                         // an rvalue reference type
};
```

Here, it'd be perfectly valid to take rhs's address inside Widget's move constructor, so rhs is an lvalue, even though its type is an rvalue reference. (By similar reasoning, all parameters are lvalues.)

This code example demonstrates several conventions I typically follow:

- The class name is Widget. I use Widget whenever I want to refer to an arbitrary user-defined type. Unless I need to show specific details of the class, I use Widget without declaring it.

- I use the parameter name *rhs*, which stands for "right-hand side." It's my preferred parameter name for the *move operations* (i.e., move constructor and move assignment operator) and the *copy operations* (i.e., copy constructor and copy assignment operator), though I also employ it for the right-hand parameter of binary operators:

  ```
  Matrix operator+(const Matrix& lhs, const Matrix& rhs);
  ```

  It's no surprise, I hope, that *lhs* stands for "left-hand side."

- I highlight parts of code or parts of comments to draw your attention to them. In the code above, I've highlighted the declaration of rhs and the part of the comment noting that rhs is an lvalue.

- I use "…" to indicate "other code could go here." This narrow ellipses is different from the wide ellipsis ("...") that's used in the source code for C++11's variadic templates. That sounds confusing, but it's not. For example:

  ```
  template<typename... Ts>                // these are C++
  void processVals(const Ts&... params)   // source code
  {                                       // ellipses

    …                                     // this means "some
                                          // code goes here"

  }
  ```

> The declaration of `processVals` shows that I use `typename` when declaring type parameters in templates, but that's merely a personal preference; the keyword `class` would work just as well. On those few occasions where I show code excerpts from a C++ Standard, I declare type parameters using `class`, because that's what the Standards do.

When an object is initialized with another object of the same type, the new object is said to be a *copy* of the initializing object, even if the copy was created via the move constructor. Regrettably, there's no terminology in C++ that distinguishes between an object that's a copy-constructed copy and one that's a move-constructed copy:

```
void someFunc(Widget w);         // someFunc's parameter w
                                 // is passed by value

Widget wid;                      // wid is some Widget

someFunc(wid);                   // in this call to someFunc,
                                 // w is a copy of wid that's
                                 // created via copy construction

someFunc(std::move(wid));        // in this call to SomeFunc,
                                 // w is a copy of wid that's
                                 // created via move construction
```

Copies of rvalues are generally move-constructed, while copies of lvalues are typically copy-constructed. An implication is that if you know only that an object is a copy of another object, it's not possible to say how expensive it was to construct the copy. In the code above, for example, there's no way to say how expensive it is to create the parameter `w` without knowing whether rvalues or lvalues are passed to `someFunc`. (You'd also have to know the cost of moving and copying `Widget`s.)

In a function call, the expressions passed at the call site are the function's *arguments*. The arguments are used to initialize the function's *parameters*. In the first call to `someFunc` above, the argument is `wid`. In the second call, the argument is `std::move(wid)`. In both calls, the parameter is `w`. The distinction between arguments and parameters is important, because parameters are lvalues, but the arguments with which they are initialized may be rvalues or lvalues. This is especially relevant during the process of *perfect forwarding*, whereby an argument passed to a function is passed to a second function such that the original argument's rvalueness or lvalueness is preserved. (Perfect forwarding is discussed in more detail in Item 32.)

Well-designed functions are *exception-safe*, meaning they offer at least the basic exception safely guarantee (i.e., the *basic guarantee*). Such functions assure callers that even if an exception is emitted, program invariants remain intact (i.e., no data structures are corrupted) and no resources are leaked. Functions offering the strong exception safety guarantee (i.e., the *strong guarantee*) assure callers that if an exception is emitted, the state of the program remains as it was prior to the call. As Item 16 explains, C++98 Standard Library functions offering the strong guarantee constrain the applicability of move semantics in the C++11 Standard Library.

I use the term *callable entity* to refer to anything that can be called using the syntax of a call to a non-member function, i.e., the syntax "`functionName(arguments)`". Functions, function pointers, and function objects are all callable entities. Function objects created through lambda expressions are known as *closures*. It's seldom necessary to distinguish between lambda expressions and the closures they create, so I often refer to both as *lambdas*.

In the same vein, I rarely distinguish between *function templates* (i.e., templates that generate functions) and *template functions* (i.e., the functions generated from function templates). Ditto for *class templates* and *template classes*.

Many things in C++ can be both declared and defined. *Declarations* introduce names without giving details, such as where storage is located or how the entity is implemented:

```
extern int x;                     // object declaration

class Widget;                     // class declaration

int func(const Widget& w);        // function declaration

enum class Color;                 // scoped enum declaration
                                  // (see Item 10)
```

Definitions provide the storage location or implementation details:

```
int x;                            // object definition
```

```
class Widget {                    // class definition
  …
};

int func(const Widget& w)
{ return w.size(); }              // function definition

enum class Color
{ Yellow, Red, Blue };            // scoped enum definition
```

A definition also qualifies as a declaration, so unless it's really important that something is a definition, I tend to refer to declarations.

New C++ Standards generally preserve the validity of code written under older ones, but occasionally the Standardization Committee *deprecates* features. That's a warning that the features may be removed from future Standards. You should avoid deprecated features. (The reason for deprecation is usually that newer features offer the same functionality, but with fewer restrictions or drawbacks. `std::auto_ptr` is deprecated in C++11, for example, because `std::unique_ptr` does the same job, only better.)

Sometimes the Standard says that the result of an operation is *undefined behavior*. That means that runtime behavior is unpredictable, and it should go without saying that you want to steer clear of such uncertainty. Examples of actions with undefined behavior include using square brackets ("`[]`") to index beyond the bounds of a `std::vector`, dereferencing an uninitialized iterator, or engaging in a data race (i.e., having two or more threads, at least one of which is a writer, simultaneously access the same memory location).

In source code comments, I sometimes abbreviate "constructor" as *`ctor`* and "destructor" as *`dtor`*.

Reporting Bugs and Suggesting Improvements

I've done my best to fill this book with clear, accurate, useful information, but surely there are ways to make it better. If you find errors of any kind (technical, expository, grammatical, typographical, etc.), or if you have suggestions for how the book could otherwise be improved, please email me at emc++@aristeia.com. New printings give me the opportunity to revise *Effective Modern C++*, and I can't address issues I don't know about!

To view the list of the issues I do know about, consult the book's errata page, `http://www.aristeia.com/BookErrata/emc++-errata.html`.

Chapter 1 Deducing Types

C++98 had a single set of rules for type deduction: the one for function templates. C++11 modifies those rules a bit and adds two more, one for `auto` and one for `decltype`. C++14 then extends the usage contexts in which `auto` and `decltype` may be employed. The increasingly widespread application of type deduction frees programmers from the tyranny of spelling out types that are obvious or redundant. It makes C++ software more adaptable, because changing a type at one point in the source code automatically propagates through type deduction to other locations. However, it can render code more difficult to reason about, because the types deduced by compilers may not be as apparent as we'd like.

Effective programming in modern C++ isn't possible without a solid understanding of how type deduction operates. There are just too many contexts where it takes place: in calls to function templates, in most situations where `auto` appears, in `decltype` expressions, and, as of C++14, where the enigmatic `decltype(auto)` construct is employed.

This chapter provides the foundational information about type deduction that every C++ developer requires. It explains how template type deduction works, how `auto` builds on that, and how `decltype` goes its own way. It even explains how you can force compilers to make the results of their type deductions visible, thus enabling you to ensure that compilers are deducing the types you want them to.

Item 1: Understand template type deduction.

It's said that imitation is the sincerest form of flattery, but blissful ignorance can be an equally heartfelt accolade. When users of a complex system are ignorant of how it works, yet happy with what it does, that says a lot about the design of that system. By this measure, template type deduction in C++ is a tremendous success. Millions of programmers have passed arguments to template functions with completely satisfactory results, even though many of those programmers would be hard-pressed to give more than the haziest description of how the types used by those functions were deduced.

If that group includes you, I have good news and bad news. The good news is that the type deduction process for `auto`-declared variables is essentially the same as for templates (see Item 2), so when it comes to `auto`, you're on familiar ground. The bad news is that when the template type deduction rules are employed by `auto`, you're more likely to be surprised by what happens. If you want to use `auto` (and you certainly should—see Item 5), you'll need a reasonable understanding of the rules that drive template type deduction. They're generally straightforward, so this poses little challenge. It's just that they worked so naturally in C++98, you probably never had to think much about them.

If you're willing to overlook a pinch of pseudocode, we can think of a function template as looking like this:

```
template<typename T>
void f(ParamType param);
```

A call can look like this:

```
f(expr);                    // call f with some expression
```

During compilation, compilers use *`expr`* to deduce two types: one for `T` and one for *`ParamType`*. These types are frequently different, because *`ParamType`* often contains adornments, e.g., `const`- or reference qualifiers. For example, if the template is declared like this,

```
template<typename T>
void f(const T& param);     // ParamType is const T&
```

and we have this call,

```
int x = 0;

f(x);                       // call f with an int
```

`T` is deduced to be `int`, but *`ParamType`* is deduced to be `const int&`.

It's natural to expect that the type deduced for `T` is the same as the type of the argument passed to the function, i.e., that `T` is the type of *`expr`*. In the above example, that's the case: `x` is an `int`, and `T` is deduced to be `int`. But it doesn't always work that way. The type deduced for `T` is dependent not just of the type of *`expr`*, but also on the form of *`ParamType`*. There are three cases:

- *ParamType* is a pointer or reference type, but not a universal reference. (Universal references are described in Item 26. At this point, all you need to know is that they exist.)

- *ParamType* is a universal reference.

- *ParamType* is neither a pointer nor a reference.

We therefore have three type deduction scenarios to examine. Each will be based on our general form for templates and calls to it:

```
template<typename T>
void f(ParamType param);

f(expr);                   // deduce T and ParamType from expr
```

Case 1: *ParamType* is a Pointer or Reference, but not a Universal Reference

The simplest situation is when *ParamType* is a pointer type or a reference type, but not a universal reference. In that case, type deduction works like this:

- If *expr*'s type is a reference, ignore the reference part.

- Pattern-match *expr*'s type against *ParamType* to determine `T`.

For example, if this is our template,

```
template<typename T>
void f(T& param);          // param is a reference
```

and we have these variable declarations,

```
int x = 27;                // x is an int
const int cx = x;          // cx is a const int
const int& rx = x;         // rx is a read-only view of x
```

the deduced types for `param` and `T` in various calls are as follows:

```
f(x);                      // T is int, param's type is int&

f(cx);                     // T is const int,
                           // param's type is const int&

f(rx);                     // T is const int,
                           // param's type is const int&
```

In the second and third calls, notice that because `cx` and `rx` designate `const` values, `T` is deduced to be `const int`, thus yielding a parameter type of `const int&`. That's important to callers. When they pass a `const` object to a reference parameter, they expect that object to remain unmodifiable, i.e., for the parameter to be a reference-to-`const`. That's why passing a `const` object to a template taking a `T&` parameter is safe: the `const`ness of the object becomes part of the type deduced for `T`.

In the third example, note that even though `rx`'s type is a reference, `T` is deduced to be a non-reference. That's because `rx`'s reference-ness is ignored during type deduction. If this were not the case (i.e., if `T` were deduced to be `const int&`), `param`'s type would be `const int& &`, i.e., a reference to a reference. References to references aren't permitted in C++, and one way they're avoided is by ignoring the reference-ness of expressions during type deduction.

These example all show lvalue reference parameters, but type deduction works exactly the same way for rvalue reference parameters. Of course, only rvalue arguments may be passed to rvalue reference parameters, but that restriction has nothing to do with type deduction.

If we change the type of `f`'s parameter from `T&` to `const T&`, things change a little, but not in any really surprising ways. The constness of `cx` and `rx` continues to be respected, but because we're now assuming that `param` is a reference-to-`const`, there's no longer a need for `const` to be deduced as part of `T`:

```
template<typename T>
void f(const T& param);   // param is now a ref-to-const

int x = 27;               // as before
const int cx = x;         // as before
const int& rx = x;        // as before

f(x);                     // T is int, param's type is const int&

f(cx);                    // T is int, param's type is const int&

f(rx);                    // T is int, param's type is const int&
```

As before, `rx`'s reference-ness is ignored during type deduction.

If `param` were a pointer (or a pointer to `const`) instead of a reference, things would work essentially the same way:

```
template<typename T>
void f(T* param);          // param is now a pointer

int x = 27;                // as before
const int *px = &x;        // px is a ptr to a read-only view of x

f(&x);                     // T is int, param's type is int*

f(px);                     // T is const int,
                           // param's type is const int*,
```

At this point, you may find yourself yawning and nodding off, because C++'s type deduction rules work so naturally for reference and pointer parameters, seeing them in written form is really dull. Everything's just obvious! Which is exactly what you want in a type deduction system.

Case 2: *ParamType* is a Universal Reference

Things are less obvious for templates taking universal reference parameters (i.e., "`T&&`" parameters), because lvalue arguments get special treatment. The complete story is told in Item 26, but here's the headline version:

- If *expr* is an lvalue, both `T` and *ParamType* are deduced to be lvalue references.
- If *expr* is an rvalue, the usual type deduction rules apply.

For example:

```
template<typename T>
void f(T&& param);         // param is now a universal reference

int x = 27;                // as before
const int cx = x;          // as before
const int& rx = x;         // as before

f(x);                      // x is lvalue, so T is int&,
                           // param's type is also int&

f(cx);                     // cx is lvalue, so T is const int&,
                           // param's type is also const int&
```

```
f(rx);                    // rx is lvalue, so T is const int&,
                          // param's type is also const int&

f(27);                    // 27 is rvalue, so T is int,
                          // param's type is therefore int&&
```

Item 26 explains exactly why these examples play out the way they do, but the key point is that the type deduction rules for parameters that are universal references are different from those for parameters that are lvalue references or rvalue references. In particular, when universal references are in use, type deduction distinguishes between lvalue arguments and rvalue arguments. That never happens for non-universal (i.e., “normal”) references.

Case 3: *ParamType* is Neither a Pointer nor a Reference

When *ParamType* is neither a pointer nor a reference, we’re dealing with pass-by-value:

```
template<typename T>
void f(T param);          // param is now passed by value
```

That means that `param` will be a copy of whatever is passed in—a completely new object. The fact that `param` will be a new object motivates the rules that govern how `T` is deduced from *expr*:

- As before, if *expr*’s type is a reference, ignore the reference part.
- If, after ignoring *expr*’s reference-ness, *expr* is `const`, ignore that, too. If it’s `volatile`, also ignore that. (`volatile` objects are uncommon. They’re generally used only for implementing device drivers. For details, see Item 42.)

Hence:

```
int x = 27;               // as before
const int cx = x;         // as before
const int& rx = x;        // as before

f(x);                     // T and param are both int

f(cx);                    // T and param are again both int

f(rx);                    // T and param are still both int
```

Note that even though `cx` and `rx` represent `const` values, `param` isn't const. That makes sense. `param` is an object that's completely independent of `cx` and `rx`—a *copy* of `cx` or `rx`. The fact that `cx` and `rx` can't be modified says nothing about whether `param` can be. That's why *`expr`*'s `const`ness (if any) is ignored when deducing a type for `param`: just because *`expr`* can't be modified doesn't mean that a copy of it can't be.

It's important to recognize that `const` is ignored only for by-value parameters. As we've seen, for parameters that are references-to- or pointers-to-`const`, the `const`ness of *`expr`* is preserved during type deduction. But consider the case where *`expr`* is a `const` pointer to a `const` object, and *`expr`* is passed to a by-value `param`:

```
template<typename T>
void f(T param);          // param is still passed by value

const char* const ptr =   // ptr is const pointer to const object
  "Fun with pointers";

f(ptr);                   // pass arg of type const char * const
```

Here, the `const` to the right of the asterisk declares `ptr` to be `const`: `ptr` can't be made to point to a different location, nor can it be set to null. (The `const` to the left of the asterisk says that what `ptr` points to—the character string—is `const`, hence can't be modified.) When `ptr` is passed to `f`, the bits making up the pointer are copied into `param`. As such, *the pointer itself (`ptr`) will be passed by value*. In accord with the type deduction rule for by-value parameters, the `const`ness of `ptr` will be ignored, and the type deduced for `param` will be `const char*`, i.e., a modifiable pointer to a `const` character string. The `const`ness of what `ptr` points to is preserved during type deduction, but the `const`ness of `ptr` itself is ignored when copying it to create the new pointer, `param`.

Array Arguments

That pretty much covers it for mainstream template type deduction, but there's a sidestream case that is worth knowing about. It's that array types are different from pointer types, even though they sometimes seem to be interchangeable. A primary contributor to this illusion is that, in many contexts, an array *decays* into a pointer to its first element. This decay is what permits code like this to compile:

```
const char name[] = "J. P. Briggs";  // name's type is
                                     // const char[13]

const char * ptrToName = name;       // array decays to pointer
```

Here, the `const char*` pointer `ptrToName` is being initialized with `name`, which is a `const char[13]`, i.e., a 13-element array of `const char`. These types (`const char*` and `const char[13]`) are not the same, but because of the array-to-pointer decay rule, the code compiles.

But what if an array is passed to a template taking a by-value parameter? What happens then?

```
template<typename T>
void f(T param);      // template with by-value parameter

f(name);              // what types are deduced for T and param?
```

We begin with the observation that there is no such thing as a function parameter that's an array. Yes, yes, the syntax is legal,

```
void myFunc(int param[]);
```

but the array declaration is treated as a pointer declaration, meaning that `myFunc` could be equivalently declared like this:

```
void myFunc(int* param);         // same function as above
```

This equivalence of array and pointer parameters is a bit of foliage springing from the C roots at the base of C++, and it fosters the illusion that array and pointer types are the same.

Because array parameter declarations are treated as if they were pointer parameter declarations, the type of an array that's passed to a template function by value is deduced to be a pointer type. That means that in the call to the template `f`, its type parameter `T` is deduced to be `const char*`:

```
f(name);          // name is array, but T deduced as const char*
```

But now comes a curve ball. Although functions can't declare parameters that are truly arrays, they *can* declare parameters that are truly *references* to arrays! So if we modify the template `f` to take its argument by reference,

```
template<typename T>
void f(T& param);       // template with by-reference parameter
```

and we pass an array to it,

```
f(name);                // pass array to f
```

the type deduced for `T` is the actual type of the array! That type includes the size of the array, so in this example, `T` is deduced to be `const char [13]`, and the type of `f`'s parameter (a reference to this array) is `const char (&)[13]`. Yes, the syntax looks toxic, but on the plus side, knowing it will score you mondo points with those rare souls who care.

Interestingly, the ability to declare references to arrays enables creation of a template to deduce the number of elements that an array contains:

```
template<typename T, std::size_t N>        // return size of
constexpr std::size_t arraySize(T (&)[N])  // an array as a
{                                          // compile-time
  return N;                                // constant
}
```

Note the use of `constexpr` (see Item 14) to make the result of this function available during compilation. That makes it possible to declare, say, an array with the same number of elements as a second array whose size is computed from list of initializers:

```
int keyVals[] = { 1, 3, 7, 9, 11, 22, 35 };      // keyVals has
                                                 // 7 elements

int mappedVals[arraySize(keyVals)];              // so does
                                                 // mappedVals
```

Of course, as a modern C++ developer, you'd naturally prefer a `std::array` to a built-in array:

```
std::array<int, arraySize(keyVals)> mappedVals;  // mappedVals'
                                                 // size is 7
```

Function Arguments

Arrays aren't the only entities in C++ that can decay into pointers. Function types can decay into function pointers, too, and everything we've discussed regarding type deduction and arrays applies to type deduction for functions and their decay into function pointers. As a result:

```
void someFunc(int, double);    // someFunc is a function;
                               // type is void(int, double)

template<typename T>
void f1(T param);              // in f1, param passed by value

template<typename T>
void f2(T& param);             // in f2, param passed by ref

f1(someFunc);                  // param deduced as ptr-to-func;
                               // type is void (*)(int, double)

f2(someFunc);                  // param deduced as ref-to-func;
                               // type is void (&)(int, double)
```

This rarely makes any difference in practice, but if you're going to know about array-to-pointer decay, you might as well know about function-to-pointer decay, too.

So there you have it: the rules for template type deduction. I remarked at the outset that they're pretty straightforward, and for the most part, they are. The special treatment accorded lvalues when deducing types for universal references muddies the water a bit, however, and the decay-to-pointer rules for arrays and functions stirs up even greater turbidity. Sometimes you simply want to grab your compilers and demand, "Tell me what type you're deducing!" When that happens, turn to Item 4, because it's devoted to coaxing compilers into doing just that.

Things to Remember

- When deducing types for parameters that are pointers and non-universal references, whether the initializing expression is a reference is ignored.
- When deducing types for parameters that are universal references, lvalue arguments yield lvalue references, and rvalue arguments yield rvalue references.
- When deducing types for by-value parameters, whether the initializing expression is a reference or is `const` is ignored.
- During type deduction, arguments that are array or function names decay to pointers, unless they're used to initialize references.

Item 2: Understand auto type deduction.

If you've read Item 1 on template type deduction, you already know almost everything you need to know about `auto` type deduction, because, with only one curious exception, `auto` type deduction *is* template type deduction. But how can that be? Template type deduction involves templates and functions and parameters, but `auto` deals with none of those things.

That's true, but it doesn't matter. There's a direct mapping between template type deduction and `auto` type deduction. There is literally an algorithmic transformation from one to the other.

In Item 1, template type deduction is explained using this general function template

```
template<typename T>
void f(ParamType param);
```

and this general call:

```
f(expr);                    // call f with some expression
```

In the call to `f`, compilers use *`expr`* to deduce types for `T` and *`ParamType`*.

When a variable is declared using `auto`, `auto` plays the role of `T` in the template, and the type specifier for the variable acts as *`ParamType`*. This is easier to show than to describe, so consider this example:

```
auto x = 27;
```

Here, the type specifier for `x` is simply `auto` by itself. On the other hand, in this declaration,

```
const auto cx = x;
```

the type specifier is `const auto`. And here,

```
const auto& rx = x;
```

the type specifier is `const auto&`. To deduce types for `x`, `cx`, and `rx` in these examples, compilers act as if there were a template for each declaration as well as a call to that template with the corresponding initializing expression:

```
template<typename T>             // conceptual template for
void func_for_x(T param);        // deducing x's type

func_for_x(27);                  // conceptual call: param's
                                 // deduced type is x's type

template<typename T>             // conceptual template for
void func_for_cx(const T param); // deducing cx's type

func_for_cx(x);                  // conceptual call: param's
                                 // deduced type is cx's type

template<typename T>             // conceptual template for
void func_for_rx(const T& param); // deducing rx's type

func_for_rx(x);                  // conceptual call: param's
                                 // deduced type is rx's type
```

As I said, deducing types for `auto` is the same as deducing types for templates.

Item 1 divides template type deduction into three cases, based on the characteristics of *`ParamType`*, the type specifier for `param` in the general function template. In a variable declaration using `auto`, the type specifier takes the place of *`ParamType`*, so there are three cases for that, too:

- Case 1: The type specifier is a pointer or reference, but not a universal reference.
- Case 2: The type specifier is a universal reference.
- Case 3: The type specifier is neither a pointer nor a reference.

We've already seen examples of cases 1 and 3:

```
auto x = 27;          // case 3 (x is neither ptr nor reference)

const auto cx = x;    // case 3 (cx isn't either)

const auto& rx = x;   // case 1 (rx is a non-universal ref.)
```

Case 2 works as you'd expect:

```
auto&& uref1 = x;     // x is int and lvalue,
                      // so uref1's type is int&

auto&& uref2 = cx;    // cx is const int and lvalue,
                      // so uref2's type is const int&
```

```
auto&& uref3 = 27;     // 27 is int and rvalue,
                       // so uref3's type is int&&
```

Item 1 concludes with a discussion of how array and function names decay into pointers for non-reference type specifiers. That happens in `auto` type deduction, too, of course:

```
const char name[] =             // name's type is const char[13]
  "R. N. Briggs";

auto arr1 = name;               // arr1's type is const char*

auto& arr2 = name;              // arr2's type is
                                // const char (&)[13]

void someFunc(int, double);     // someFunc is a function;
                                // type is void(int, double)

auto func1 = someFunc;          // func1's type is
                                // void (*)(int, double)

auto& func2 = someFunc;         // func2's type is
                                // void (&)(int, double)
```

As you can see, `auto` type deduction really is template type deduction. They're just two sides of the same coin.

Except for the one way they differ. We'll start with the observation that if you want to declare an `int` with an initial value of 27, C++98 gives you two syntactic choices:

```
int x1 = 27;
int x2(27);
```

C++11, through its support for uniform initialization, adds these:

```
int x3 = {27};
int x4{27};
```

All in all, four syntaxes, but only one result: a variable with value 27.

But as Item 5 explains, there are advantages to declaring variables using `auto` instead of fixed types, so it'd be nice to replace `int` with `auto` in the above variable declarations. Straightforward textual substitution yields this code:

```
auto x1 = 27;
auto x2(27);
auto x3 = {27};
auto x4{27};
```

These declarations all compile, but they don't have the same meaning as the ones they replace. The first two statements do, indeed, declare a variable of type `int` with value 27. The second two, however, declare a variable of type `std::initializer_list<int>` containing a single element with value 27!

```
auto x1 = 27;             // type is int, value is 27

auto x2(27);              // ditto

auto x3 = {27};           // type is std::initializer_list<int>,
                          // value is {27}

auto x4{27};              // ditto
```

This is due to a special type deduction rule for `auto`. When the initializer for an `auto`-declared variable is enclosed in braces, the deduced type is a `std::initializer_list`. If such a type can't be deduced (e.g., because the values in the braced initializer are of different types), the code will be rejected:

```
auto x5 = {1, 2, 3.0};    // error! can't deduce T for
                          // std::initializer_list<T>
```

As the comment indicates, type deduction will fail in this case, but it's important to recognize that there are actually two kinds of type deduction taking place. One kind stems from the use of `auto`: `x5`'s type has to be deduced. Because `x5`'s initializer is in braces, `x5` must be deduced to be a `std::initializer_list`. But `std::initializer_list` is a template. Instantiations are `std::initizalizer_list<T>` for some type `T`, and that means that `T`'s type must be deduced. Such deduction falls under the purview of the second kind of type deduction occurring here: template type deduction. In this example, that deduction fails, because the values in the braced initializer don't have a single type.

The treatment of braced initializers is the only way in which `auto` type deduction and template type deduction differ. When an `auto` variable is initialized with a braced initializer, the deduced type is some instantiation of `std::initializer_list`. If a template is faced with deducing the type for a braced initializer, however, the code is rejected. (This has consequences for perfect forwarding, as Item 32 explains.)

You might wonder why `auto` type deduction has a special rule for braced initializers, but template type deduction does not. I wonder this, myself. Unfortunately, I have not been able to find a compelling explanation. But the rule is the rule, and this means that you must bear in mind that if you declare a variable using `auto` and you initialize it with a braced initializer, the deduced type will always be `std::initializer_list`. It's especially important to bear this in mind if you embrace the philosophy of uniform initialization—of enclosing initializing values in braces as a matter of course. One of the most classic mistakes in C++11 programming is accidently declaring a `std::initializer_list` variable when you mean to declare something else. To reiterate:

```
auto x1 = 27;             // x1 and x2 are ints
auto x2(27);

auto x3 = {27};           // x3 and x4 are
auto x4{27};              // std::initializer_list<int>s
```

This pitfall is one of the reasons some developers put braces around their initializers only when they have to. (When you have to is discussed in Item 7.)

For C++11, this is the full story, but for C++14, the tale continues. C++14 permits `auto` to indicate that a function's return type should be deduced (see Item 3), and C++14 lambda expressions may use `auto` in parameter declarations. However, these uses of `auto` employ *template type deduction*, not `auto` type deduction. That means that braced initializers in these contexts cause type deduction to fail. So a function with an `auto` return type that returns a braced initializer won't compile:

```
auto createInitList()
{
  return { 1, 2, 3 };          // error: can't deduce type
}                              // for { 1, 2, 3 }
```

The same is true when `auto` is used in a parameter type specification in a C++14 lambda (thus yielding a generic lambda):

```
std::vector v;
…
```

```
auto resetV =
  [&v](const auto& newValue) { v = newValue; };  // C++14 only

…

resetV( { 1, 2, 3 } );          // error! can't deduce type
                                // for { 1, 2, 3 }
```

The net result is that `auto` type deduction is identical to template type deduction unless (1) a variable is being declared and (2) its initializer is inside braces. In that case only, `auto` deduces a `std::initializer_list`, but template type deduction fails.

Things to Remember

- `auto` type deduction is normally identical to template type deduction.
- The sole exception is that in variable declarations using `auto` and braced initializers, `auto` deduces `std::initializer_list`s.
- Template type deduction fails for braced initializers.

Item 3: Understand `decltype`.

`decltype` is a funny beast. Given a name or an expression, `decltype` tells you the name's or the expression's type. Typically, what it tells you is exactly what you'd predict. Occasionally however, it provides results that leave you scratching your head and turning to reference works or online Q&A sites for revelation.

We'll begin with the typical cases—the ones harboring no surprises. In contrast to what happens during type deduction for templates and `auto` (see Items 1 and 2), `decltype` almost always parrots back the type of the name or expression you give it without any modification:

```
const int i = 0;           // decltype(i) is const int

bool f(const Widget& w);   // decltype(w) is const Widget&
                           // decltype(f) is bool(const Widget&)

struct Point {
  int x, y;                // decltype(Point::x) is int
};                         // decltype(Point::y) is int

Widget w;                  // decltype(w) is Widget
```

```
if (f(w)) …                 // decltype(f(w)) is bool

template<typename T>        // simplified version of std::vector
class vector {
public:
  …
  T& operator[](std::size_t index);
  …
};

vector<int> v;              // decltype(v) is vector<int>
…
if (v[0] == 0) …            // decltype(v[i]) is int&
```

See? No surprises.

In C++11, the primary use for `decltype` is declaring function templates where the function's return type depends on its parameter types. For example, suppose we'd like to write a function that takes a container that supports indexing via square brackets (i.e., the use of "`[]`") plus an index, then authenticates the user before returning the result of the indexing operation. The return type of the function should be the same as the type returned by the indexing operation.

`operator[]` on a container of objects of type `T` typically returns a `T&`. This is the case for `std::deque`, for example, and it's almost always the case for `std::vector`. For `std::vector<bool>`, however, `operator[]` does not return a `bool&`. Instead, it returns a brand new object. The whys and hows of this situation are explored in Item 6, but what's important here is that the type returned by a container's `operator[]` depends on the container.

`decltype` makes it easy to express that. Here's a first cut at the template we'd like to write, showing the use of `decltype` to compute the return type. The template needs a bit of refinement, but we'll defer that for now:

```
template<typename Container, typename Index>    // works, but
auto authAndAccess(Container& c, Index i)       // requires
  -> decltype(c[i])                             // refinement
{
  authenticateUser();
  return c[i];
}
```

The use of auto before the function name has nothing to do with type deduction. Rather, it indicates that C++11's *trailing return type* syntax is being used, i.e., that the function's return type will be declared following the parameter list (after the "->"). A trailing return type has the advantage that the function's parameters can be used in the specification of its return type. In authAndAccess, for example, we specify the return type using c and i. If we were to have the return type precede the function name in the conventional fashion, c and i would be unavailable, because they would not have been declared yet.

With this declaration, authAndAccess returns whatever type operator[] returns when applied to the passed-in container, exactly as we desire.

C++11 permits return types for single-statement lambdas to be deduced, and C++14 extends this to both all lambdas and all functions (including those with multiple statements). In the case of authAndAccess, that means that in C++14 we can omit the trailing return type, leaving just the leading auto. With that form of declaration, auto *does* mean that type deduction will take place. In particular, it means that compilers will deduce the function's return type from the function's implementation:

```
template<typename Container, typename Index>   // C++14 only, and
auto authAndAccess(Container& c, Index i)      // not quite
{                                              // correct
  authenticateUser();
  return c[i];                      // return type deduced from c[i]
}
```

But which of C++'s type deduction rules will be used to infer authAndAccess's return type: those for templates, those for auto, or those for decltype?

Perhaps surprisingly, functions with an auto return type perform type deduction using the template type deduction rules. It might seem that use of the auto type deduction rules would better correspond to the declaration syntax, but remember that template type deduction and auto type deduction are nearly identical. The only difference is that template type deduction deduces no type for a braced initializer.

In this case, deducing authAndAccess's return type using template type deduction is problematic, but auto's type deduction rules would fare no better. The difficulty stems from something these forms of type deduction have in common: their treatment of expressions that are references.

As we've discussed, operator[] for most containers-of-T returns a T&, but Item 1 explains that during template type deduction, the reference-ness of an initializing expression is ignored. Consider what that would mean for this client code using the declaration for authAndAccess with an auto return type (i.e., using template type deduction for its return type):

```
std::deque<int> d;
…
authAndAccess(d, 5) = 10;  // authenticate user, return d[5],
                           // then assign 10 to it;
                           // this won't compile!
```

Here, d[5] returns an int&, but auto return type deduction for authAndAccess will strip off the reference, thus yielding a return type of int. That int, being the return value of a function, is an rvalue, and the code above thus attempts to assign 10 to an rvalue int. That's forbidden in C++, so the code won't compile.

The problem is that we're using template type deduction, which discards reference qualifiers from its initializing expression. What we want in this case is decltype type deduction. Such type deduction would permit us to say that authAndAccess should return exactly the same type that the expression c[i] returns.

The guardians of C++, anticipating the need to use decltype type deduction rules in some cases where types are inferred, make this possible in C++14 through the decltype(auto) specifier. What may initially seem contradictory (decltype *and* auto?) actually makes perfect sense: auto specifies that the type is to be deduced, and decltype says that decltype rules should be used during the deduction. We can thus write authAndAccess like this:

```
template<typename Container, typename Index>   // C++14 only;
decltype(auto)                                 // works, but
authAndAccess(Container& c, Index i)           // still requires
{                                              // refinement
  authenticateUser();
```

```
  return c[i];
}
```

Now `authAndAccess` will truly return whatever `c[i]` returns. In particular, for the common case where `c[i]` returns a `T&`, `authAndAccess` will also return a `T&`, and in the uncommon case where `c[i]` returns an object, `authAndAccess` will return an object, too.

The use of `decltype(auto)` is not limited to function return types. It can also be convenient for declaring variables when you want to apply the `decltype` type deduction rules to the initializing expression:

```
Widget w;

const Widget& cw = w;

auto myWidget1 = cw;              // auto type deduction:
                                  // myWidget1's type is Widget

decltype(auto) myWidget2 = cw;    // decltype type deduction:
                                  // myWidget2's type is
                                  //   const Widget&
```

But two things are bothering you, I know. One is the refinement to `authAndAccess` I mentioned, but have not yet described. Let's address that now.

Look again at the declaration for the C++14 version of `authAndAccess`:

```
template<typename Container, typename Index>
decltype(auto) authAndAccess(Container& c, Index i);
```

The container is passed by lvalue-reference-to-non-`const`, because returning a reference to an element of the container permits clients to modify that container. But this means it's not possible to pass rvalue containers to this function. Rvalues can't bind to lvalue references (unless they're lvalue-references-to-`const`, which is not the case here).

Admittedly, passing an rvalue container to `authAndAccess` is an edge case. An rvalue container, being a temporary object, would typically be destroyed at the end of the statement containing the call to `authAndAccess`, and that means that a reference to an element in that container (which is typically what `authAndAccess` would return) would dangle at the end of the statement that created it. Still, it could make sense to pass a temporary object to `authAndAccess`. A client might simply want to make a copy of an element in the temporary container, for example:

```
std::deque<std::string> makeStringDeque();   // factory function

// make copy of 5th element of deque returned
// from makeStringDeque
auto s = authAndAccess(makeStringDeque(), 5);
```

Supporting such use means we need to revise the declaration for `c` to accept both lvalues and rvalues, and that means that `c` needs to be a universal reference (see Item 26):

```
template<typename Container, typename Index>
decltype(auto) authAndAccess(Container&& c, Index i);
```

In this template, we don't know what type of container we're operating on, and that means we're equally ignorant of the type of index objects it uses. Employing pass-by-value for objects of an unknown type generally risks the performance hit of unnecessary copying, the behavioral problems of object slicing (see Item 17), and the sting of our coworkers' derision, but in the case of container indices, following the example of the Standard Library (e.g., `std::string`, `std::vector`, and `std::deque`) seems reasonable, so we'll stick with pass-by-value for them.

All that remains is to update the template's implementation to bring it into accord with Item 27's admonition to apply `std::forward` to universal references:

```
template<typename Container, typename Index>       // final
decltype(auto)                                     // C++14
authAndAccess(Container&& c, Index i)              // version
{
  authenticateUser();
  return std::forward<Container>(c)[i];
}
```

This should do everything we want, but it requires a C++14 compiler. If you don't have one, you'll need to use the C++11 version of the template. It's the same as its C++14 counterpart, except that you have to specify the return type yourself:

```
template<typename Container, typename Index>       // final
auto                                               // C++11
authAndAccess(Container&& c, Index i)              // version
```

```
-> decltype(std::forward<Container>(c)[i])
{
  authenticateUser();
  return std::forward<Container>(c)[i];
}
```

The other issue that's likely to be nagging at you is my remark at the beginning of this Item that decltype *almost* always produces the type you expect, that it *rarely* surprises. Truth be told, you're unlikely to encounter these exceptions to the rule unless you're a heavy-duty library implementer.

To *fully* understand `decltype`'s behavior, you'll have to familiarize yourself with a few special cases. Most of these are too obscure to warrant discussion in a book like this, but looking at one lends insight into `decltype` as well as its use.

Applying `decltype` to a name yields the declared type for that name, just as I said. Names are lvalue expressions, but that doesn't affect `decltype`'s behavior. For lvalue expressions more complicated than names, however, `decltype` ensures that the type reported is always an lvalue reference. That is, if an lvalue expression other than a name has type `T`, `decltype` reports that type as `T&`. This rarely has any impact, because the type of most lvalue expressions inherently includes an lvalue reference qualifier. Functions returning lvalues, for example, always return lvalue references.

There is an implication of this behavior that is worth being aware of, however. In

```
int x = 0;
```

`x` is the name of a variable, so `decltype(x)` is int. But wrapping the name `x` in parentheses—"`(x)`"—yields an expression more complicated than a name. Being a name, `x` is an lvalue, and C++ defines `(x)` to be an lvalue, too. `decltype(`**`(x)`**`)` is therefore `int&`. Putting parentheses around a name can change the type that `decltype` reports for it!

In C++11, this is little more than a curiosity, but in conjunction with C++14's support for `decltype(auto)`, it means that a seemingly trivial change in the way you write a `return` statement can affect the deduced type for a function:

```
decltype(auto) f1()
{
  int x = 0;
  …
  return x;        // decltype(x) is int, so f1 returns int
}

decltype(auto) f2()
{
  int x = 0;
  …
  return (x);      // decltype((x)) is int&, so f2 returns int&
}
```

Note that not only does `f2` have a different return type from `f1`, but it's also returning a reference to a local variable! That's the kind of code that puts you on the express train to undefined behavior—a train you most assuredly don't want to be on.

The primary lesson here is to pay very close attention when using `decltype(auto)`. Seemingly insignificant details in the expression whose type is being deduced can affect the type that `decltype(auto)` reports. To ensure that the type being deduced is the type you expect, use the techniques described in Item 4.

At the same time, don't lose sight of the bigger picture. Sure, `decltype` (both alone and in conjunction with `auto`) may occasionally yield type-deduction surprises, but that's not the normal situation. Normally, `decltype` produces the type you expect. This is especially true when `decltype` is applied to names, because in that case, `decltype` does just what it sounds like: it reports that name's declared type.

Things to Remember

- `decltype` almost always yields the type of a variable or expression without any modifications.
- For lvalue expressions of type `T` other than names, `decltype` always reports a type of `T&`.
- C++14 supports `decltype(auto)`, which, like `auto`, deduces a type from its initializer, but it performs the type deduction using the `decltype` rules.

Item 4: Know how to view deduced types.

People who want to see the types that compilers deduce usually fall into one of two camps. The first are the pragmatists. They're typically motivated by a behavioral problem in their software (i.e., they're debugging), and they're looking for insights into compilation that can help them identify the source of the problem. The second are the experimentalists. They're exploring the type deduction rules described in Items 1-3. Often, they want to confirm their predictions about the results of various type deduction scenarios ("For this code, I think compilers will deduce *this* type..."), but sometimes they simply want to answer "what if" questions. "How," they might wonder, "do the results of template type deduction change if I replace a universal reference (see Item 26) with an lvalue-reference-to-`const` parameter (i.e., replace `T&&` with `const T&` in a function template parameter list)?"

Regardless of the camp you fall into (both are legitimate), the tools you have at your disposal depend on the phase of the software development process where you'd like to see the types your compilers have inferred. We'll explore three possibilities: getting type deduction information as you edit your code, getting it during compilation, and getting it at runtime.

IDE Editors

Code editors in IDEs often show the types of program entities (e.g., variables, parameters, functions, etc.) when you do something like hover your cursor over the entity. For example, given this code,

```
const int theAnswer = 42;

auto x = theAnswer;
auto y = &theAnswer;
```

an IDE editor would likely show that `x`'s deduced type was `int` and `y`'s was `const int*`.

For this to work, your code must be in a more or less compilable state, because what makes it possible for the IDE to offer this kind of information is a C++ compiler running inside the IDE. If that compiler can't make enough sense of your code to parse it and perform type deduction, it can't show you what types it deduced.

Compiler Diagnostics

An effective way to get a compiler to show a type it has deduced is to use that type in a way that leads to compilation problems. The error message reporting the problem is virtually sure to mention the type that's causing it.

Suppose, for example, we'd like to see the types that were deduced for `x` and `y` in the previous example. We first declare a class template that we *don't define*. Something like this does nicely:

```
template<typename T>        // declaration only for TD;
class TD;                   // TD == "Type Displayer"
```

Attempts to instantiate this template will elicit an error message, because there's no template definition to instantiate. To see the types for `x` and `y`, just try to instantiate TD with their types:

```
TD<decltype(x)> xType;      // elicit errors containing
TD<decltype(y)> yType;      // x's and y's types;
                            // see Item 3 for decltype info
```

I use variable names of the form *`variableName`*`Type`, because they tend to yield quite informative error messages. For the code above, one of my compilers issues diagnositics reading, in part, as follows. (I've highlighted the type information we're looking for.)

```
error: aggregate 'TD<int> xType' has incomplete type and
    cannot be defined
error: aggregate 'TD<const int *> yType' has incomplete type
    and cannot be defined
```

A different compiler provides the same information, but in a different form:

```
error: 'xType' uses undefined class 'TD<int>'
error: 'yType' uses undefined class 'TD<const int *>'
```

Formatting differences aside, all the compilers I've tested produce error messages with useful type information when this technique is employed.

Runtime Output

The `printf` approach to displaying type information (not that I'm recommending you use `printf`) can't be employed until runtime, but it offers full control over the formatting of the output. The challenge is to create a textual representation of the type you care about that is suitable for display. "No sweat," you're thinking, "it's `typeid` and `std::type_info::name` to the rescue." In our continuing quest to see the types deduced for `x` and `y`, you figure, we can write this:

```
std::cout << typeid(x).name() << '\n';    // display types for
std::cout << typeid(y).name() << '\n';    // x and y
```

This approach relies on the fact that invoking `typeid` on an object such as `x` or `y` yields a `std::type_info` object, and `std::type_info` has a member function, `name`, that produces a C-style string (i.e., a `const char*`) representation of the name of the type.

Calls to `std::type_info::name` are not guaranteed to return anything sensible, but implementations try to be helpful. The level of helpfulness varies. The GNU and Clang compilers report that the type of `x` is "`i`", and the type of `y` is "`PKi`", for example. These results make more sense once you learn that, in output from these compilers, "`i`" means "`int`" and "`PK`" means "pointer to ~~`konst`~~ `const`." (Both compilers support a tool, c++filt, that decodes such "mangled" types.) Microsoft's compiler produces less cryptic output: "`int`" for `x` and "`int const *`" for `y`.

Because these results are correct for the types of `x` and `y`, you might be tempted to view the type-reporting problem as solved, but let's not be hasty. Consider a more complex example:

```
template<typename T>                // template function to
void f(const T& param);             // be called

std::vector<Widget> createVec();    // factory function

const auto vw = createVec();        // init vw w/factory return

if (!vw.empty()) {
  f(&vw[0]);                        // call f
  …
}
```

This code, which involves a user-defined type (`Widget`), an STL container (`std::vector`), and an `auto` variable (`vw`), is more representative of the situations where you might want some visibility into the types your compilers are deducing. For example, it'd be nice to know what types are inferred for the template type parameter `T` and the function parameter `param` in `f`.

Loosing `typeid` on the problem is straightforward. Just add some code to `f` to display the types you'd like to see:

```
template<typename T>
void f(const T& param)
{
  using std::cout;

  cout << "T =     " << typeid(T).name() << '\n';     // show T

  cout << "param = " << typeid(param).name() << '\n'; // show
  …                                                    // param's
}                                                      // type
```

Executables produced by the GNU and Clang compilers produce this output:

```
T =     PK6Widget
param = PK6Widget
```

We already know that for these compilers, `PK` means "pointer to `const`," so the only mystery is the number `6`. That's simply the number of characters in the class name that follows (`Widget`). So these compilers tell us that both `T` and `param` are of type `const Widget*`.

Microsoft's compiler concurs:

```
T =     class Widget const *
param = class Widget const *
```

Three independent compilers producing the same information suggests that the information is accurate. But look more closely. In the template `f`, `param`'s declared type is `const T&`. That being the case, doesn't it seem odd that `T` and `param` have the same type? If `T` were `int`, for example, `param`'s type should be `const int&`—not the same type at all.

Sadly, the results of `std::type_info::name` are not reliable. In this case, for example, the type that all three compilers report for `param` are incorrect. Furthermore, they're essentially *required* to be incorrect, because the specification for `std::type_info::name` mandates that the type being processed be treated as if it had been passed to a template function as a by-value parameter. As Item 1 explains, that means that if the type is a reference, its reference-ness is ignored, and if the type after reference removal is `const`, its `const`ness is also ignored. That's why `param`'s type—which is `const Widget * const &`—is reported as `const Widget*`. First the type's reference-ness is removed, and then the `const`ness of the result type is eliminated.

Equally sadly, the type information displayed by IDE editors is also not reliable—or at least not reliably useful. For this same example, one IDE editor I know reports `T`'s type as (I am not making this up):

```
const
std::_Simple_types<std::_Wrap_alloc<std::_Vec_base_types<Widget,
std::allocator<Widget> >::_Alloc>::value_type>::value_type *
```

The same IDE editor shows `param`'s type as:

```
const std::_Simple_types<...>::value_type *const &
```

That's less intimidating than the type for `T`, but the "`...`" in the middle is disturbing until you realize that it's the IDE editor's way of saying "I'm omitting all that stuff that's part of `T`'s type."

My understanding is that most of what's displayed here is `typedef` cruft and that once you push through the `typedef`s to get to the underlying type information, you get what you're looking for, but having to do that work pretty much eliminates any utility the display of the types in the IDE originally promised. With any luck, your IDE editor does a better job on code like this.

In my experience, compiler diagnostics are a more dependable source of information about the results of type deduction. Revising the template `f`'s implementation to instantiate the declared-but-not-defined template `TD` yields this:

```
template<typename T>
void f(const T& param)
{
  TD<T> TType;                       // elicit errors containing
  TD<decltype(param)> paramType;     // T's and param's types
  …
}
```

Each of GNU's, Clang's, and Microsoft's compilers produce error messages with the correct types for `T` and `param`. The exact message contents and formats vary, but as an example, this is what GNU's compiler issues (after minor reformatting):

```
error: 'TD<const Widget *> TType' has incomplete type
error: 'TD<const Widget * const &> paramType' has incomplete
       type
```

Beyond `typeid`

If you want accurate runtime information about deduced types, we've seen that `typeid` is not a reliable route to getting it. One way to work around that is to implement your own mechanism for mapping from a type to its displayable representation. In concept, it's not difficult: you just use type traits and template metaprogramming (see Item 9) to break a type into its various components (using type traits such as `std::is_const`, `std::is_pointer`, `std::is_lvalue_reference`, etc.), and you create a string representation of the type from textual representations of each of its parts. (You'd still be dependent on `typeid` and `std::type_info::name` to generate string representations of the names of user-defined classes, though.)

If you'd use such a facility often enough to justify the effort needed to write, debug, document, and maintain it, that's a reasonable approach. But if you're willing to live with a little platform-dependent code that's easy to implement and produces better results than those based on `typeid`, it's worth noting that many compilers support a language extension that yields a printable representation of the full signature for a function, including, for functions generated from templates, types for both template and function parameters.

For example, the GNU and Clang compilers support a construct called `__PRETTY_FUNCTION__`, and Microsoft's compiler offers `__FUNCSIG__`. These constructs represent a variable (for GNU and Clang) or a macro (for Microsoft) whose value is the signature of the containing function. If we reimplement our template `f` like this,

```
template<typename T>
void f(const T& param)
{
```

```
#if defined(__GNUC__)                              // For GNU and
  std::cout << __PRETTY_FUNCTION__ << '\n';        // Clang
#elif defined(_MSC_VER)
  std::cout << __FUNCSIG__ << '\n';                // For Microsoft
#endif

  …

}
```

and call `f` as we did before,

```
std::vector<Widget> createVec();      // factory function

const auto vw = createVec();          // init vw w/factory return

if (!vw.empty()) {
  f(&vw[0]);                          // call f
  …
}
```

we get the following result from GNU:

```
void f(const T&) [with T = const Widget*]
```

This tells us that `T` has been deduced to be `const Widget*` (the same thing we got via `typeid`, but without the "`PK`" encoding and the "`6`" in front of the class name), but it also tells us that `f`'s parameter has type `const T&`. If we expand `T` in that formulation, we get `const Widget * const &`. That's different from what `typeid` told us, though it's the same as the type in the error message provoked by use of the declared-but-not-defined `TD` template. It's also correct.

Use of Microsoft's `__FUNCSIG__` produces this output:

```
void __cdecl f<const classWidget*>(const class Widget *const &)
```

The type inside the angle brackets is the type deduced for `T`: `const Widget*`. This, too, is what we got via `typeid`. But the type inside parentheses is the type deduced for `param`: `const Widget * const&`. That's not what `typeid` told us, though, again, it's the same as the (correct) information we'd get during compilation from use of the `TD` template.

Clang's function-signature-reporting facility, despite using the same name as GNU's (__PRETTY_FUNCTION__), is not as forthcoming as GNU's or Microsoft's. It yields simply:

```
void f(const Widget *const &)
```

This shows `param`'s type directly, but it leaves it up to you to deduce that `T`'s type must have been `const Widget*` (or to rely on the information provided via `typeid`).

IDE editors, compiler error messages, `typeid`, and language extensions like `__PRETTY_FUNCTION__` and `__FUNCSIG__` are merely tools you can use to help you figure out what types your compilers are deducing for you. All can be helpful, but at the end of the day, there's no substitute for understanding the type deduction information in Items 1-3.

Things to Remember

- Deduced types can often be seen using IDE editors, compiler error messages, `typeid`, and language extensions such as `__PRETTY_FUNCTION__` and `__FUNCSIG__`.
- The results of such tools may be neither helpful nor accurate, so an understanding of C++'s type deduction rules remains essential.

Chapter 2 `auto`

It's been a wild ride for `auto`. In 1983, Bjarne Stroustrup took this lonely and largely superfluous keyword and gave it new purpose in his C++ compiler: to declare a variable whose type was deduced from its initializing expression. The move proved too bold for the C developers who were C++'s target audience, so `auto`'s revised semantics were rolled back, and the keyword retired to the home for trivia topics. ("What is `auto` used for?")

Nearly three decades later, it debuted a second time (with the same semantics Bjarne had instilled in it so many years before) and thereby became C++11's oldest new feature. It's also probably C++11's most frequently used one, because few acts are as common as declaring variables. In C++14, its utility gains new ground: lambda parameters may incorporate `auto`, and function return types may be `auto`-deduced. It took a long time for `auto` to make it into the limelight, but its tenure there now seems secure.

In concept, `auto` is as simple as simple can be, but it's more subtle than it looks. Using it saves typing, sure, but it also prevents correctness and performance issues that can bedevil manual type declarations. Furthermore, some of `auto`'s type deduction results, while dutifully conforming to the prescribed algorithm, are, from the perspective of a programmer, just plain wrong. When that's the case, it's important to know how to guide `auto` to the right answer, because falling back on manual type declarations is an alternative that's often best avoided.

This brief chapter covers all of `auto`'s ins and outs.

Item 5: Prefer auto to explicit type declarations.

Ah, the simple joy of

```
int x;
```

Wait. Damn. I forgot to initialize `x`, so its value is indeterminate. Maybe. It might actually be initialized to zero. Depends on the context. Sigh.

Never mind. Let's move on to the simple joy of declaring a local variable to be initialized with the value of an iterator:

```
template<typename It>     // algorithm to dwim ("do what I mean")
void dwim(It b, It e)     // for all elements in range from
{                         // b to e
  while (b != e) {
    typename std::iterator_traits<It>::value_type
      currValue = *b;
    …
  }
}
```

Ugh. "`typename std::iterator_traits<It>::value_type`" to express the type of the value pointed to by an iterator? Really? I must have blocked out the memory of how much fun that is. Damn. Wait—didn't I already say that?

Okay, simple joy (take three): the delight of declaring a local variable whose type is the same as that resulting from a lambda expression. Oh, right. The type of a lambda expression is known only to the compiler, hence can't be written out. Sigh. Damn.

Damn, damn, damn! Programming in C++ is not the joyous experience it should be!

Well, it didn't used to be. But as of C++11, all these issues go away, courtesy of `auto`. `auto` variables have their type deduced from their initializer, so they must be initialized. That means you can wave goodbye to a host of uninitialized variable problems as you speed by on the C++11 superhighway:

```
int x;          // valid in C++ 98/11/14, potentially uninitialized

auto x;         // error! initializer required

auto x = 0;     // fine, x's value is well-defined
```

Said highway also paves over the potholes associated with declaring a local variable whose value is determined by an iterator:

```
template<typename It>     // as before
void dwim(It b, It e)
{
  while (b != e) {
    auto currValue = *b;
    …
```

```
  }
}
```

And because `auto` is based on type deduction, it can represent types known only to compilers:

```
auto derefUPLess =                          // comparison func.
  [](const std::unique_ptr<Widget>& p1,     // for Widgets
     const std::unique_ptr<Widget>& p2)     // pointed to by
  { return *p1 < *p2; };                    // std::unique_ptrs
```

Very cool. In C++14, the coolness chills further, because in C++14, parameters to lambda expressions may involve `auto`:

```
auto derefLess =                            // comparison func.
  [](const auto& p1,                        // for values pointed
     const auto& p2)                        // to by anything
  { return *p1 < *p2; };                    // pointer-like
```

Coolness notwithstanding, perhaps you're thinking that we don't really need `auto` to declare a variable that holds a closure, because we can use a `std::function` object:

```
std::function<bool(const std::unique_ptr<Widget>&,
                   const std::unique_ptr<Widget>&)>
  derefUPLess = [](const std::unique_ptr<Widget>& p1,
                   const std::unique_ptr<Widget>& p2)
                 { return *p1 < *p2; };
```

You're right, but it's important to recognize that—even setting aside the syntactic verbosity and the need to repeat the parameter types—using `std::function` is not the same thing as using `auto`. An `auto`-declared variable holding the result of a lambda expression has the same type as the lambda expression. The type of a `std::function`-declared variable holding the result of a lambda expression is some instantiation of the `std::function` template. The constructor for such instantiations may allocate heap memory. (Whether it does depends on how much data is captured by the lambda and on how `std::function` is implemented). `auto` never allocates heap memory. The `std::function` object uses more memory than the `auto`-declared object. And, thanks to implementation details that restrict inlining and yield indirect function calls, invoking a lambda's closure via a `std::function` object is almost certain to be slower than calling it via an `auto`-declared object. In other words, the `std::function` approach is generally bigger and slower than the auto approach, and it may yield out-of-memory exceptions, too. Plus, as you can see in the examples above, writing "auto" is a whole lot less work than writing the type of the std::function instantiation. In the competition between auto and std::function for holding the result of a lambda expression, it's pretty much game, set, and match for auto. (A similar argument can be made for auto over std::function for holding the result of calls to std::bind, though in Item 36, I do my best to convince you to use lambdas instead of std::bind, anyway.)

The advantages of auto extend beyond the avoidance of uninitialized variables, verbose variable declarations, and the ability to directly hold the result of lambda expressions. One is the ability to avoid what I call problems related to "type shortcuts." Here's something you've probably seen—possibly even written:

```
std::vector<int> v;
…
unsigned sz = v.size();
```

The official return type of v.size() is std::vector<int>::size_type, but few developers are aware of that. std::vector<int>::size_type is specified to be an unsigned integral type, so a lot of programmers figure that unsigned is good enough and write code such as the above. This can have some interesting consequences. On 32-bit Windows, for example, both unsigned and std::vector<int>::size_type are the same size, but on 64-bit Windows, unsigned is 32 bits, while std::vector<int>::size_type is 64 bits. This means that code that works under 32-bit Windows may behave incorrectly under 64-bit Windows, and when porting your application from 32 to 64 bits, who wants to spend time on issues like that?

Using auto ensures that you don't have to:

```
auto sz = v.size();  // sz's type is std::vector<int>::size_type
```

Still unsure about the wisdom of using auto? Then consider this code:

```
std::unordered_map<std::string, int> m;
…
```

```
for (const std::pair<std::string, int>& p : m)
{
  …                      // do something with p
}
```

This looks perfectly reasonable, but there's a problem. Do you see it?

Recognizing what's amiss requires remembering that the key part of a `std::unordered_map` is `const`, so the type of `std::pair` in the hash table (which is what a `std::unordered_map` is) isn't `std::pair<std::string, int>`, it's `std::pair<`*`const`*` std::string, int>`. But that's not the type declared for the variable `p` in the loop above. As a result, compilers will strive to find a way to convert `std::pair<const std::string, int>` objects (i.e., what's in the hash table) to `std::pair<std::string, int>` objects (the declared type for `p`). They'll succeed by creating a temporary object of the type that `p` wants to bind to by copying each object in `m`, then binding the reference `p` to that temporary object. At the end of each loop iteration, the temporary object will be destroyed. If you wrote this loop, you'd likely be surprised by this behavior, because you'd almost certainly intend to simply bind the reference `p` to each element in `m`.

Such unintentional type mismatches can be `auto`ed away:

```
for (const auto& p : m)
{
 …                               // as before
}
```

This is not only more efficient, it's also easier to type. Furthermore, this code has the very attractive characteristic that if you take `p`'s address, you're sure to get a pointer to an element within `m`. In the code not using `auto`, you'd get a pointer to a temporary object—an object that would be destroyed at the end of the loop iteration.

The last two examples—writing `unsigned` when you should have written `std::vector<int>::size_type` and writing `std::pair<std::string, int>` when you should have written `std::pair<const std::string, int>`—demonstrate how explicitly specifying types can lead to implicit conversions that you neither want nor expect. Such conversions arise whenever the type of the initializing expression is different from the type you specify for the target variable, but an implicit conversion exists from one to the other. It generally arises because your expectations about the type of the initializing expression are incorrect, e.g., you believe that `std::vector<int>::size_type` is the same as `unsigned`, or you forget that the first component of the `std::pairs` in a `std::unordered_map` is `const`. If you use `auto` as the type of the target variable, you need not worry about mismatches between the type of variable you're declaring and the type of the expression used to initialize it.

There are thus several reasons to prefer `auto` over explicit type declarations. Yet `auto` isn't perfect. The type for each `auto` variable is deduced from its initializing expression, and some initializing expressions have types that are neither anticipated nor desired. The conditions under which such cases arise, and what you can do about them, are discussed in Items 2 and 6, so I won't address them here. Instead, I'll turn my attention to a different concern you may have about using `auto` in place of traditional type declarations: the readability of the resulting source code.

First, take a deep breath and relax. `auto` is an option, not a mandate. If, in your professional judgment, your code will be clearer or more maintainable or in some other way better by using explicit type declarations, you're free to continue using them. But bear in mind that C++ is far from breaking new ground in adopting what is generally known in the programming languages world as *type inference*. Other statically typed procedural languages (e.g., C#, D, Scala, Visual Basic) have a more or less equivalent feature, to say nothing of a variety of statically typed functional languages (e.g., ML, Haskell, OCaml, F#, etc.). In part, this is due to the success of dynamically typed languages such as Perl, Python, and Ruby, where variables are essentially never explicitly typed. The software development community has extensive experience with type inference, and it has demonstrated that there is nothing contradictory about such technology and the creation and maintenance of industrial-strength, industrial-sized code bases.

Some developers are disturbed by the fact that using `auto` eliminates the ability to determine an object's type by a quick glance at the source code. However, IDEs' ability to show object types often mitigates this problem (even taking into account the IDE type-display issues mentioned in Item 4), and, in many cases, a somewhat abstract view of an object's type is just as useful as the exact type. It often suffices, for example, to know that an object is a container or a counter or a smart pointer, without knowing exactly what kind of container, counter, or smart pointer it is. Assuming well-chosen variable names, such abstract type information should almost always be at hand.

The fact of the matter is that writing out types explicitly often does little more than introduce opportunities for subtle errors, either in correctness or efficiency or both. Furthermore, `auto` types automatically change if the type of their initializing expression changes, and that means that some refactorings are facilitated by the use of `auto`. For example, if a function is declared to return an `int`, but you later decide that a `long` would be better, the calling code automatically updates itself the next time you compile if the results of calling the function are stored in an `auto` variable. If the results are stored in a variable explicitly declared to be an `int`, you'll need to find all the call sites so that you can revise them.

By all means, consider the impact on your source code's readability when choosing between declaring `auto` types and explicit types. But before you reject `auto`, be sure you're doing it for a solid technical reason, not simply because you're used to writing out types by hand.

Things to Remember:

- `auto` variables must be initialized, are generally immune to type mismatches that can lead to portability or efficiency problems, can ease the process of refactoring, and typically require less typing than variables with explicitly specified types.
- `auto`-typed variables are subject to the pitfalls described in Items 2 and 6.

Item 6: Be aware of the typed initializer idiom.

Item 5 explains that using `auto` to declare variables offers a number of technical advantages over explicitly specifying types, but sometimes `auto`'s type deduction zigs when you want it to zag. For example, suppose I have a function that takes a `Widget` and returns a `std::vector<bool>`, where each `bool` indicates whether the `Widget` offers a particular feature:

```
std::vector<bool> features(const Widget& w);
```

Further suppose that bit 5 indicates whether the `Widget` has high priority. We can thus write code like this:

```
Widget w;
…
bool highPriority = features(w)[5];  // is w high priority?
…
processWidget(w, highPriority);      // process w in accord
                                     // with its priority
```

There's nothing wrong with this code. It'll work fine. But if we make the seemingly innocuous change of replacing the explicit type for `highPriority` with `auto`,

```
auto highPriority = features(w)[5];  // is w high priority?
```

the situation changes. All the code will continue to compile, but its behavior is no longer predictable:

```
processWidget(w, highPriority);      // undefined behavior!
```

As the comment indicates, the call to `processWidget` now has undefined behavior. But why? The answer is likely to be surprising. In the code using `auto`, the type of `highPriority` is no longer `bool`. Though `std::vector<bool>` conceptually holds `bool`s, `operator[]` for `std::vector<bool>` doesn't return a reference to an element of the container (which is what `std::vector::operator[]` returns for every type *except* `bool`). Instead, it returns an object of type `std::vector<bool>::reference` (a class nested inside `std::vector<bool>`).

`std::vector<bool>::reference` exists because `std::vector<bool>` is specified to represent its `bool`s in packed form, one bit per `bool`. That creates a problem for `std::vector<bool>`'s `operator[]`, because `operator[]` for `std::vector<T>` is supposed to return a `T&`, but C++ forbids references to bits. Not being able to return a `bool&`, `operator[]` for `std::vector<bool>` returns an object that *acts like* a `bool&`. For this act to succeed, `std::vector<bool>::reference` objects must be usable in essentially all contexts where `bool&`s can be. Among the features in `std::vector<bool>::reference` that make this work is an implicit conversion to `bool`. (Not to `bool&`, to *`bool`*. To explain the full set of techniques used by `std::vector<bool>::reference` to emulate the behavior of a `bool&` would take us too far afield, so I'll simply remark that this implicit conversion is only one stone in a larger mosaic.)

With this information in mind, look again at this part of the original code:

```
bool highPriority = features(w)[5];   // declare highPriority's
                                      // type explicitly
```

Here, `features` returns a `std::vector<bool>` object, on which `operator[]` is invoked. `operator[]` returns a `std::vector<bool>::reference` object, which is then implicitly converted to the `bool` that is needed to initialize `highPriority`. `highPriority` thus ends up with the value of bit 5 in the `std::vector<bool>` returned by `features`, just like it's supposed to.

Contrast that with what happens in the `auto`-ized declaration for `highPriority`:

```
auto highPriority = features(w)[5];   // deduce highPriority's
                                      // type
```

Again, `features` returns a `std::vector<bool>` object, and, again, `operator[]` is invoked on it. `operator[]` continues to return a `std::vector<bool>::reference` object, but now there's a change, because `auto` deduces that as the type of `highPriority`. `highPriority` doesn't have the value of bit 5 of the `std::vector<bool>` returned by `features` at all.

The value it does have depends on how `std::vector<bool>::reference` is implemented. One implementation is for such objects to contain a pointer to the machine word holding the referenced bit, plus the offset into that word for that bit. Consider what that means for the initialization of `highPriority`, assuming that such a `std::vector<bool>::reference` implementation is in place.

The call to `features` returns a temporary `std::vector<bool>` object. This object has no name, but for purposes of this discussion, I'll call it *`temp`*. `operator[]` is invoked on *`temp`*, and the `std::vector<bool>::reference` it returns contains a pointer to a word in the data structure holding the bits that are managed by *`temp`*, plus the offset into that word corresponding to bit 5. `highPriority` is a copy of this `std::vector<bool>::reference` object, so `highPriority`, too, contains a pointer to a word in *`temp`*, plus the offset corresponding to bit 5. At the end of the statement, *`temp`* is destroyed, because it's a temporary object. Therefore, `highPriority` contains a dangling pointer, and that's the cause of the undefined behavior in the call to `processWidget`:

```
processWidget(w, highPriority);    // undefined behavior!
                                   // highPriority may contain
                                   // dangling pointer!
```

`std::vector<bool>::reference` is an example of a *proxy class*: a class that exists for the purpose of emulating and augmenting the behavior of some other type. Proxy classes are employed for a variety of purposes. `std::vector<bool>::reference` exists to offer the illusion that `operator[]` for `std::vector<bool>` returns a reference to a bit, for example, and the Standard Library's smart pointer types (see Chapter 4) are proxy classes that graft resource management onto raw pointers. The utility of proxy classes is well-established. In fact, the design pattern "Proxy" is one of the most longstanding members of the software design patterns Pantheon.

Some proxy classes are designed to be apparent to clients. That's the case for `std::shared_ptr` and `std::unique_ptr`, for example. Other proxy classes are designed to act more or less invisibly. `std::vector<bool>::reference` is an example of such "invisible" proxies, as is its C++14 cousin, `std::bitset::reference`.

Also in that camp are some classes in C++ libraries employing a technique known as *expression templates*. Such libraries were originally developed to improve the efficiency of numeric code. Given a class `Matrix` and `Matrix` objects `m1`, `m2`, `m3`, and `m4`, for example, the expression

```
Matrix sum = m1 + m2 + m3 + m4;
```

can be computed much more efficiently if `operator+` for `Matrix` objects returns a proxy for the result instead of the result itself. That is, `operator+` for two `Matrix` objects would return an object of a proxy class such as `Sum<Matrix, Matrix>` instead of a `Matrix` object. As was the case with `std::vector<bool>::reference` and `bool`, there'd be an implicit conversion from the proxy class to `Matrix`, which would permit the initialization of `sum` from the proxy object produced by the expression on the right side of the "=". (The type of that object would traditionally encode the entire initialization expression, i.e., be something like `Sum<Sum<Sum<Matrix, Matrix>, Matrix>, Matrix>`. That's definitely a type from which clients should be shielded.)

As a general rule, "invisible" proxy classes don't play well with `auto`. Objects of such classes are often not designed to live longer than a single statement, so creating variables of those types tends to violate fundamental library design assumptions. That's the case with `std::vector<bool>::reference`, and we've seen that violating that assumption can lead to undefined behavior.

You therefore want to avoid code of this form:

```
auto someVar = expression of "invisible" proxy class type;
```

But how can you recognize when proxy objects are in use? The software employing them is unlikely to advertise their existence. They're supposed to be *invisible*, at least conceptually! And once you've found them, do you really have to abandon `auto` and the many advantages Item 5 demonstrates for it?

Let's take the how-do-you-find-them question first. Although "invisible" proxy classes are designed to fly beneath programmer radar in day-to-day use, libraries using them often document that they do so. The more you've familiarized yourself with the basic design decisions of the libraries you use, the less likely you are to be blindsided by proxy usage within those libraries.

Where documentation comes up short, header files fill the gap. It's rarely possible for source code to fully cloak proxy objects. They're typically returned from functions that clients are expected to call, so function signatures usually reflect their existence. Here's the spec for `std::vector<bool>::operator[]`, for example:

```
namespace std {                     // from C++98/11/14 Standards

  template <class Allocator>
  class vector<bool, Allocator> {
  public:
```

```
    …
    class reference { … };

    reference operator[](size_type n);
    …
  };

}
```

Assuming you know that `operator[]` for `std::vector<T>` normally returns a `T&`, the unconventional return type for `operator[]` in this case is a tip-off that a proxy class is in use. Paying careful attention to the interfaces you're using can often reveal the existence of proxy classes.

In practice, many developers discover the use of proxy classes only when they try to track down mystifying compilation problems or debug incorrect unit test results. Regardless of how you find them, once `auto` has been determined to be deducing the type of a proxy class instead of the type being proxied, the solution need not involve abandoning `auto`. `auto` itself isn't the problem. The problem is that `auto` isn't deducing the type you want it to deduce. The solution is to force a different type deduction. The way you do that is what I call *the typed initializer idiom*.

The typed initializer idiom involves declaring a variable with `auto`, but casting the initialization expression to the type you want `auto` to deduce. Here's how it can be used to force `highPriority` to be a `bool`, for example:

```
auto highPriority = static_cast<bool>(features(w)[5]);
```

Here, `features(w)[5]` continues to return a `std::vector<bool>::reference` object, just as it always has, but the cast changes the type of the expression to `bool`, which `auto` then deduces as the type for `highPriority`. At runtime, the `std::vector<bool>::reference` object returned from `std::vector<bool>::operator[]` executes the conversion to `bool` that it supports, and as part of that conversion, the still-valid pointer to the `std::vector<bool>` returned from `features` is dereferenced. That avoids the undefined behavior we ran into earlier. The index 5 is then applied to the bits pointed to by the pointer, and the `bool` value that emerges is used to initialize `highPriority`.

For the `Matrix` example, the typed initializer idiom would look like this:

```
auto sum = static_cast<Matrix>(m1 + m2 + m3 + m4);
```

Applications of the idiom aren't limited to initializers yielding proxy class types. It can also be useful to emphasize that you are deliberately creating a variable of a type that is different from that generated by the initializing expression. For example, suppose you have a function to calculate some tolerance value:

```
double calcEpsilon();              // return tolerance value
```

`calcEpsilon` clearly returns a `double`, but suppose you know that for your application, the precision of a `float` is adequate, and you care about the difference in size between `float`s and `double`s. You could declare a `float` variable to store the result of `calcEpsilon`,

```
float ep = calcEpsilon();          // impliclitly convert
                                   // double→float
```

but this hardly announces "I'm deliberately reducing the precision of the value returned by the function!" A declaration using the typed initializer idiom, however, does:

```
auto ep = static_cast<float>(calcEpsilon());
```

Similar reasoning applies if you have a floating point expression that you are deliberately storing as an integral value. Suppose you need to calculate the index of an element in a container with random access iterators (e.g., a `std::vector`, `std::deque`, or `std::array`), and you're given a `double` between `0.0` and `1.0` indicating how far from the beginning of the container the desired element is located. (`0.5` would indicate the middle of the container.) Further suppose that you're confident that the resulting index will fit in an `int`. If the container is `c` and the double is `d`, you could calculate the index this way,

```
int index = d * c.size();
```

but this obscures the fact that you're intentionally converting the `double` on the right to an `int`. The typed initializer idiom eliminates makes things transparent:

```
auto index = static_cast<int>(d * c.size());
```

Things to Remember

- "Invisible" proxy types can cause `auto` to deduce the "wrong" type for an initializing expression.
- The typed initializer idiom forces `auto` to deduce the type you want it to have.

Chapter 3 From C++98 to C++11 and C++14

If you're an experienced C++ developer, you understand and are comfortable with C++98 and its common programming idioms. Enums, classes, member functions, inheritance, templates, `const`, using objects to manage resources—you've been there, you've done that. As such, you're likely to view C++11 as C++98 plus a bunch of new features, with C++14 comprising essentially more of the same.

For the most part, that's fine. C++'s legendary commitment to backwards-compatibility means that not only does virtually all legacy source code remain valid, the same is true for most C++ software development techniques. Good practices in C++98 typically remain good practices in C++11. But there are exceptions. In some cases, C++98 language features should generally be eschewed in favor of newer, similar C++11 features that take advantage of the experience the C++ programming community garnered during the 13 year reign of C++98. Examples include using `nullptr` instead of `NULL` or `0` (Item 8), preferring alias declarations over `typedef`s (Item 9), choosing scoped instead of unscoped `enum`s (Item 10), and prohibiting the use of unwanted member functions by `delete`ing them instead of declaring them `private` (Item 11). In other cases, taking advantage of new language features requires modification of some well-entrenched habits. For example, virtual function overrides should now be declared as such (Item 12), some parameters are now better passed by value than by reference-to-`const` (Item 17), calls to `push_back` or `push_front` or `insert` should sometimes be replaced with their emplacement counterparts (Item 18), functions that can potentially run during compilation should be declared `constexpr` (Item 14), and exception specifications should be more widely employed (Item 16). In still other cases, C++11 simply changes the rules of the C++ programming game. Ways this is apparent include that there's now an important syntactic choice to be made when declaring objects (Item 7), `const_iterator`s are substantially more useful than they used to be (Item 13), declaring member functions `const` implies that they're thread-safe (Item 15), and compiler-generated member functions are governed by a set of rules that have been significantly revised (Item 19).

This chapter covers guidelines that will help you update C++98 habits to bring them into accord with C++11 and C++14, but not all guidelines of that nature are in this chapter. Item 5, for example ("Prefer `auto` to explicit type declarations"), belongs here, too, but it fits more naturally into the chapter on `auto`, and the overarching guidance to prefer smart pointers to raw pointers has so many facets, it gets its own chapter (Chapter 4). Still, the Items that follow do a good job of summarizing how effective programming in C++11 and C++14 distinguishes itself from C++98 approaches to accomplishing common development tasks. It demonstrates that being an effective contemporary C++ programmer consists of not just adopting new language features, but also reevaluating techniques and practices proven in C++98.

Item 7: Distinguish `()` and `{}` when creating objects.

Depending on your perspective, syntax choices for object initialization in C++11 embody either an embarrassment of riches or a confusing mess. As a general rule, initialization values may be specified with parentheses, an equals sign, or braces:

```
int x(0);              // initializer is in parentheses
int y = 0;             // initializer follows "="
int z{0};              // initializer is in braces
```

In many cases, it's also possible to use an equals sign and braces together:

```
int z = {0};           // initializer uses "=" and braces
```

For the remainder of this Item, I'll generally ignore the equals-sign-plus-braces syntax, because C++ usually treats it the same as the braces-only version.

The "confusing mess" lobby points out that the use of an equals sign for initialization often misleads C++ newbies into thinking that an assignment is taking place, even though it's not. For built-in types like `int`, the difference is academic, but for user-defined types, it's important to distinguish initialization from assignment, because different function calls are involved:

```
Widget w1;             // call default constructor
Widget w2 = w1;        // not an assignment; calls copy ctor
```

```
w1 = w2;                // an assignment; calls copy operator=
```

Even with several initialization syntaxes, there were some situations where C++98 had no way to express a desired initialization. For example, it wasn't possible to directly indicate that an STL container (e.g., `std::vector<int>`) should be created holding a particular set of values (e.g., 1, 3, and 5).

To address the confusion of multiple initialization syntaxes, as well as the fact that they don't cover all initialization scenarios, C++11 introduces *uniform initialization*: a single initialization syntax that can be used anywhere and can express everything. It's based on braces, and for that reason I prefer the term *braced initialization*. "Uniform initialization" is a concept. "Braced initialization" is a syntactic construct.

Braced initialization lets you express the formerly inexpressible. Using braces, specifying the initial contents of a container is easy:

```
std::vector<int> v{1, 3, 5};   // v's initial content is 1, 3, 5
```

Braces can also be used to specify default initialization values for non-static data members. This capability—new to C++11—is shared with the "=" initialization syntax, but not with parentheses:

```
class Widget {
  …

private:
  int x{0};                    // fine, x's default value is 0
  int y = 0;                   // also fine
  int z(0);                    // error!
};
```

On the other hand, uncopyable objects (e.g., `std::atomics`) may be initialized using braces or parentheses, but not using "=":

```
std::atomic<int> ai1{0};       // fine

std::atomic<int> ai2(0);       // fine

std::atomic<int> ai3 = 0;      // error!
```

Perhaps now you see why braced initialization is called "uniform." Of C++'s three ways to designate an initializing expression (braces, parentheses, and "="), only braces can be used everywhere.

A novel feature of braced initialization is that it prohibits implicit *narrowing conversions* among built-in types. If the value of an expression in a braced initializer isn't guaranteed to be expressible in the type of the object being initialized, the code won't compile:

```
double x, y, z;
…
int sum1{x + y + z};          // error! sum of doubles may
                              // not be expressible as int
```

Initialization using parentheses and "=" doesn't check for narrowing conversions, because that could break too much legacy code:

```
int sum2(x + y + z);          // okay (value of expression
                              // truncated to an int)

int sum3 = x + y + z;         // ditto
```

Another noteworthy characteristic of braced initialization is its immunity to C++'s *most vexing parse*. A side-effect of C++'s rule that anything that can be parsed as a declaration must be interpreted as one, the most vexing parse most frequently afflicts developers when they want to default-construct an object, but inadvertently end up declaring a function, instead. The root of the problem is that if you want to call a constructor with an argument, you can do it like this,

```
Widget w1(10);     // call Widget ctor with argument 10
```

but if you try to call a `Widget` constructor with zero arguments using the analogous syntax, you declare a function instead of an object:

```
Widget w2();       // most vexing parse! declares a function
                   // named w2 that returns a Widget!
```

This trap is particularly odious, because an empty set of parentheses sometimes *does* call a constructor with zero arguments:

```
void f(const Widget& w = Widget());  // w's default value is a
                                     // default-constructed
                                     // Widget
```

Braced initialization eliminates the most vexing parse, yet has no effect on the meaning of initializations that already do what's desired:

```
Widget w1{10};      // as before, calls Widget ctor with arg 10

Widget w2{};        // now calls Widget ctor with no args

void f(const Widget& w = Widget{});  // as before, w's default
                                     // value is a default-
                                     // constructed Widget
```

There's thus a lot to be said for braced initialization. It's the syntax that can be used in the widest variety of contexts, it prevents implicit narrowing conversions, and it's immune to C++'s most vexing parse. A trifecta of goodness, right? So why isn't this Item entitled something like "Use braced initialization syntax"?

The drawback to braced initialization is the sometimes-surprising behavior that accompanies it. Such behavior grows out of the unusually tangled relationship among braced initializers, `std::initializer_list`s, and constructor overload resolution. Their interactions can lead to code that seems like it should do one thing, but actually does another. For example, Item 2 explains that when an `auto`-declared variable has a braced initializer, the type deduced is `std::initializer_list`, even though other ways of declaring a variable with the same initializer would cause `auto` to deduce the type of the initializer:

```
auto v1 = -1;          // -1's type is int, and so is v1's

auto v2(-1);           // -1's type is int, and so is v2's

auto v3{-1};           // -1's type is still int, but
                       // v3's type is std::initializer_list<int>

auto v4 = {-1};        // -1's type remains int, but
                       // v4's type is std::initializer_list<int>
```

In constructor calls, parentheses and braces have the same meaning as long as `std::initializer_list` parameters are not involved:

```
class Widget {
public:
```

```
  Widget(int i, bool b);      // ctors not declaring
  Widget(int i, double d);    // std::initializer_list params
  …
};

Widget w1(10, true);          // calls first ctor

Widget w2{10, true};          // also calls first ctor

Widget w3(10, 5.0);           // calls second ctor

Widget w4{10, 5.0};           // also calls second ctor
```

If, however, one or more constructors declares a parameter of type `std::initializer_list`, calls using the braced initialization syntax strongly prefer the overloads taking `std::initializer_list`s. *Strongly*. If there's *any way* for compilers to construe a call using a braced initializer to be to a constructor taking a `std::initializer_list`, compilers will employ that interpretation. If the `Widget` class above is augmented with a constructor taking a `std::initializer_list<long double>`, for example,

```
class Widget {
public:
  Widget(int i, bool b);                           // as before
  Widget(int i, double d);                         // as before

  Widget(std::initializer_list<long double> il);   // added

  …

};
```

`Widget`s `w2` and `w4` will be constructed using the new constructor, even though the type of the `std::initializer_list` elements (`long double`) is, compared to the non-`std::initializer_list` constructors, a worse match for both arguments!

```
Widget w1(10, true);        // uses parens and, as before,
                            // calls first ctor

Widget w2{10, true};        // uses braces, but now calls
                            // std::init_list ctor (10 and
                            // true convert to long double)

Widget w3(10, 5.0);         // uses parens and, as before,
                            // calls second ctor
```

```
Widget w4{10, 5.0};         // uses braces, but now calls
                            // std::init_list ctor (10 and
                            // 5.0 convert to long double)
```

Compilers' determination to match braced initializers with constructors taking `std::initializer_lists` is so strong, it prevails even if the best-match `std::initializer_list` constructor can't be called. For example, consider this slightly-revised example:

```
class Widget {
public:
  Widget(int i, bool b);                      // as before
  Widget(int i, double d);                    // as before

  Widget(std::initializer_list<bool> il);     // std::init_list
  …                                           // element type is
};                                            // now bool

Widget w{10, 5.0};     // error! requires narrowing conversions
```

Here, compilers will ignore the first two constructors (the second of which offers an exact match on both argument types) and try to call the constructor taking a `std::initializer_list<bool>`. Calling that constructor would require converting an `int` (`10`) and a `double` (`5.0`) to `bool`s. Both conversions would be narrowing (`bool` can't exactly represent either value), and narrowing conversions are prohibited inside braced initializers, so the call is invalid, and the code is rejected.

If there's no way to convert the types of the arguments in a braced initializer to the type taken by a `std::initializer_list`, compilers fall back on normal overload resolution. For example, if we replace the `std::initializer_list<bool>` constructor with one taking a `std::initializer_list<std::string>`, the non-`std::initializer_list` constructors become candidates again, because there is no way to convert `int`s and `bool`s to `std::string`s:

```
class Widget {
public:
  Widget(int i, bool b);                // as before
  Widget(int i, double d);              // as before

  // std::init_list element type is now std::string
  Widget(std::initializer_list<std::string> il);
  …
};
```

```
Widget w1(10, true);     // uses parens, still calls first ctor

Widget w2{10, true};     // uses braces, now calls first ctor

Widget w3(10, 5.0);      // uses parens, still calls second ctor

Widget w4{10, 5.0};      // uses braces, now calls second ctor
```

There are two additional twists to the tale of constructor overload resolution and braced initializers that are worth knowing about:

- **Empty braces mean no arguments, not an empty std::initializer_list.** Specifying constructor arguments with an empty pair of braces is a request to call the default constructor, not a request to call a constructor with an empty `std::initializer_list`:

  ```
  class Widget {
  public:
    Widget();                                 // default ctor
    Widget(std::initializer_list<int> il);    // std::init_list
    …                                         // ctor
  };

  Widget w1;          // calls default ctor

  Widget w2{};        // also calls default ctor
                      // (doesn't create empty std::init_list)

  Widget w3();        // most vexing parse! declares a function!
  ```

  If you *want* to call a `std::initializer_list` constructor with an empty `std::initializer_list`, you do it by making the empty braces a constructor argument—by putting the empty braces inside the parentheses or braces demarcating what you're passing!

  ```
  Widget w4({});      // calls std::init_list ctor
                      // with empty list

  Widget w5{{}};      // ditto
  ```

- **Copy and move constructors are called as usual.** Creating an object from another object of the same type always invokes the conventional copying and moving functions:

  ```
  class Widget {
  public:
  ```

```
    Widget(const Widget& rhs);              // copy ctor
    Widget(Widget&& rhs);                   // move ctor

    Widget(std::initializer_list<int> il);  // std::init_list
                                            // ctor

    operator int() const;                   // convert to int
    …
  };

  auto w6{w5};                 // calls copy ctor, not
                               // std::init_list <int> ctor, even
                               // though Widget converts to int

  auto w7{std::move(w5)};      // ditto, but for move ctor
                               // (Item 25 has info on std::move)
```

At this point, with seemingly arcane rules about braced initializers, `std::initializer_list`s, and constructor overloading burbling about in your brain, you may be wondering how much of this information matters in day-to-day programming. More than you might think. That's because one of the classes directly affected is `std::vector`. `std::vector` has a non-`std::initializer_list` constructor that allows you to specify the initial size of the container and a value each of the initial elements should have, but it also has a constructor taking a `std::initializer_list` that permits you to specify the initial values in the container. If you create a `std::vector` of a numeric type (e.g., a `std::vector<int>`) and you pass two arguments to the constructor, whether you enclose those arguments in parentheses or braces makes a tremendous difference:

```
std::vector<int> v1(10, 20);  // use non-std::init_list ctor:
                              // create 10-element std::vector,
                              // all elements have value of 20

std::vector<int> v2{10, 20};  // use std::init_list ctor:
                              // create 2-element std::vector,
                              // element values are 10 and 20
```

But let's step back from `std::vector` and also from the details of parentheses, braces, and constructor overloading resolution rules. There are two primary takeaways from this discussion. First, as a class author, you need to be aware that if your constructor overloads include one or more functions taking a `std::initializer_list`, client code using braced initialization may see only the `std::initializer_list` overloads. As a result, it's best to design your constructors so that the overload called isn't affected by whether clients use parentheses or braces. In other words, learn from what is now considered to be an error in the design of the `std::vector` interface, and design your classes to avoid it.

An implication is that if you have a class with no `std::initializer_list` constructor and you add one, client code using braced initialization may find that calls that used to resolve to non-`std::initializer_list` constructors now resolve to the new function. Of course, this kind of thing can happen any time you add a new function to a set of overloads: calls that used to resolve to one of the old overloads might start calling the new one. The difference with `std::initializer_list` constructor overloads is that a `std::initializer_list` overload doesn't just compete with other overloads, it overshadows them to the point that the other overloads may not even be considered. So add such overloads only with great deliberation.

The second lesson is that as a class client, you must choose carefully between parentheses and braces when creating objects. Most developers end up choosing one kind of delimiter as a default, using the other only when they have to. Braces-by-default folks are attracted by their unrivaled breadth of applicability, their prevention of narrowing conversions, and their immunity to C++'s most vexing parse. Such folks understand that in some cases (e.g., creation of a `std::vector` with a given size and initial element value), parentheses are required. In contrast, the go-parentheses-go crowd embraces parentheses as their default argument delimiter. They're attracted to its consistency with the C++98 syntactic tradition, its avoidance of the `auto`-deduced-a-`std::initializer_list` problem, and the knowledge that their object creation calls won't be inadvertently waylaid by `std::initializer_list` constructors. They concede that sometimes only braces will do (e.g., when creating a container with particular values). Neither approach is rigorously better than the other. My advice is to pick one and apply it consistently.[†]

[†] The examples in this book reveal that I'm a parentheses-by-default person.

If you're a template author, the parentheses-braces duality for object creation can be especially frustrating, because, in general, it's not possible to know which form should be used. For example, suppose you'd like to create an object of an arbitrary type from an arbitrary number of arguments. A variadic template makes this conceptually straightforward:

```
template<typename T,                  // type of object to create
         typename... Args>            // types of arguments to use
void doSomeWork(const T& obj, Args&&... args)
{
  create local T object from args...

  …

}
```

There are two ways to turn the line of pseudocode into real code (see Item 27 for information about `std::forward`):

```
T localObject(std::forward<Args>(args)...);    // using parens

T localObject{std::forward<Args>(args)...};    // using braces
```

So consider this calling code:

```
std::vector<int> v;
…
doSomeWork(v, 10, 20);
```

If `doSomeWork` uses parentheses when creating `localObject`, the result is a `std::vector` with 10 elements. If `doSomeWork` uses braces, the result is a `std::vector` with 2 elements. Which is correct? The author of `doSomeWork` can't know. Only the caller can.

This is precisely the problem faced by the Standard Library functions `std::make_unique` and `std::make_shared` (see Item 23). These functions resolve the problem by internally using parentheses and documenting this decision as part of their interfaces. This is not the only way of dealing with the issue, however. Alternative designs permit callers to determine whether parentheses or braces should be used in functions generated from a template. A common component of such designs is tag dispatch, which is described in Item 29.[†]

Things to Remember

- Braced initialization is the most widely applicable initialization syntax, it prevents narrowing conversions, and it's immune to C++'s most vexing parse.
- As detailed in Item 2, braced initializers yield `std::initializer_lists` for `auto`-declared objects.
- During constructor overload resolution, braced initializers are matched to `std::initializer_list` parameters, even if other constructors offer seemingly better matches.
- An example of where the choice between parentheses and braces can make a significant difference is creating a `std::vector` with two arguments.
- Choosing between parentheses and braces for object creation inside templates can be challenging.

Item 8: Prefer `nullptr` to `0` and `NULL`.

So here's the deal: `0` is an `int`, not a pointer. If C++ finds itself looking at `0` in a context where only a pointer can be used, it'll grudgingly interpret `0` as a null pointer, but that's a fallback position. C++'s primary policy is that `0` is an `int`, not a pointer.

Practically speaking, the same is true of `NULL`. There is some uncertainty in the details in `NULL`'s case, because implementations are allowed to give `NULL` an integral type other than `int` (e.g., `long`).[*] That's not common, but it doesn't really matter, because the issue here isn't the exact type of `NULL`, it's that neither `0` nor `NULL` has a pointer type.

[†] The treatment in Item 29 is general. For an example of how it can be specifically applied to functions like `doSomeWork`, see the 5 June 2013 entry of *Andrzej's C++ blog*, "Intuitive interface — Part I."

[*] In C, `NULL`'s type can be `void*`, but this has never been legal in C++.

In C++98, the primary implication of this was that overloading on pointer and integral types could lead to surprises. Passing `0` or `NULL` to such overloads never called a pointer overload:

```
void f(int);          // three overloads of f
void f(bool);
void f(void*);

f(0);                 // calls f(int) overload, not f(void*)

f(NULL);              // might not compile, but typically calls
                      // f(int) overload. Never calls f(void*)
```

The uncertainty regarding the behavior of `f(NULL)` is a reflection of the leeway granted to implementations regarding the type of `NULL`. If `NULL` is defined to be, say, `0L` (i.e., `0` as a `long`), the call is ambiguous, because conversion from `long` to `int`, `long` to `bool`, and `0L` to `void*` are considered equally good. The interesting thing about that call is the contradiction between the *apparent* meaning of the source code ("I'm calling `f` with `NULL`—the null pointer") and its *actual* meaning ("I'm calling `f` with some kind of integer—not the null pointer"). This counterintuitive behavior is what led to the guideline for C++98 programmers to avoid overloading on pointer and integral types. That guideline remains valid in C++11, because, the advice of this Item notwithstanding, it's likely that some developers will continue to use `0` and `NULL`, even though `nullptr` is a better choice.

`nullptr`'s advantage is that it doesn't have an integral type. To be honest, it doesn't have a pointer type, either, but you can think of it as a pointer of *all* types. `nullptr`'s actual type is `std::nullptr_t`, and, in a wonderfully circular definition, `std::nullptr_t` is defined to be the type of `nullptr`. The type `std::nulltpr_t` implicitly converts to all raw pointer types, and that's what makes `nullptr` act as if it were a pointer of all types.

Calling the overloaded function `f` with `nullptr` calls the `void*` overload (i.e., the pointer overload), because `nullptr` can't be viewed as anything integral:

```
f(nullptr);           // calls f(void*) overload
```

Using `nullptr` instead of `0` or `NULL` thus avoids overload resolution surprises, but that's not its only advantage. It can also improve code clarity, especially when `auto` variables are involved. For example, suppose you encounter this in a code base:

```
auto result = findRecord( /* arguments */ );

if (result == 0) {
  …
}
```

If you don't happen to know (or be able to easily find out) what `findRecord` returns, it may not be clear whether `result` is a pointer type or an integral type. After all, `0` (what `result` is tested against) could go either way. If you see the following, on the other hand,

```
auto result = findRecord( /* arguments */ );

if (result == nullptr) {
  …
}
```

there's no ambiguity: `result` must be a pointer type.

Where `nullptr` truly shines is when templates enter the picture. Suppose you have some functions that should be called only when the appropriate mutex has been locked. Each function takes a different kind of pointer:

```
int    f1(std::shared_ptr<Widget> spw);  // call these only when
double f2(std::unique_ptr<Widget> upw);  // the appropriate
bool   f3(Widget* pw);                   // mutex is locked
```

Calling code that wants to pass null pointers could look like this:

```
std::mutex f1m, f2m, f3m;         // mutexes for f1, f2, and f3

using MuxGuard =                  // C++11 typedef; see Item 9
  std::lock_guard<std::mutex>;
…

{
  MuxGuard g(f1m);            // lock mutex for f1
  auto result = f1(0);        // pass 0 as null ptr to f1
}                             // unlock mutex

…
```

```
{
  MuxGuard g(f2m);              // lock mutex for f2
  auto result = f2(NULL);       // pass NULL as null ptr to f2
}                               // unlock mutex

…

{
  MuxGuard g(f3m);              // lock mutex for f3
  auto result = f3(nullptr);    // pass nullptr as null ptr to f3
}                               // unlock mutex
```

The failure to use `nullptr` in the first two calls in this code is sad, but the code works, and that counts for something. However, the repeated pattern in the calling code—lock mutex, call function, unlock mutex—is more than sad. It's disturbing. This kind of source code duplication is one of the things that templates are designed to avoid, so let's templatize the pattern:

```
template<typename FuncType,
         typename MuxType,
         typename PtrType>
auto lockAndCall(FuncType func,
                 MuxType& mutex,
                 PtrType ptr) -> decltype(func(ptr))
{
  MuxGuard g(mutex);
  return func(ptr);
}
```

If the return type of this function (`auto … -> decltype(func(ptr))` has you scratching your head, do your head a favor and navigate to Item 3, which explains what's going on. There you'll see that in C++14, the return type could be reduced to a simple `decltype(auto)`:

```
template<typename FuncType,
         typename MuxType,
         typename PtrType>
decltype(auto) lockAndCall(FuncType func,       // C++14 only
                           MuxType& mutex,
                           PtrType ptr)
{
  MuxGuard g(mutex);
  return func(ptr);
}
```

Given the `lockAndCall` template (either version), callers can write code like this:

```
auto result1 = lockAndCall(f1, f1m, 0);          // error!
…
auto result2 = lockAndCall(f2, f2m, NULL);       // error!
…
auto result3 = lockAndCall(f3, f3m, nullptr);    // fine
```

Well, they can write it, but, as the comments indicate, in two of the three cases, the code won't compile. The problem in the first call is that when `0` is passed to `lockAndCall`, template type deduction kicks in to figure out its type. The type of `0` is, was, and always will be `int`, so that's the type of the parameter `ptr` inside the instantiation of this call to `lockAndCall`. Unfortunately, this means that in the call to `func` inside `lockAndCall`, an `int` is being passed, and that's not compatible with the `std::shared_ptr<Widget>` parameter that `f1` expects. The `0` passed in the call to `lockAndCall` was intended to represent a null pointer, but what actually got passed was a run-of-the-mill `int`. Trying to pass this `int` to `f1` as a `std::shared_ptr<Widget>` is a type error. The call to `lockAndCall` with `0`, then, fails, because inside the template, an `int` is being passed to a function that requires a `std::shared_ptr<Widget>`.

The analysis for the call involving `NULL` is essentially the same. When `NULL` is passed to `lockAndCall`, an integral type is deduced for the parameter `ptr`, and a type error occurs when `ptr`—an `int` or `int`-like type—is passed to `f2`, which expects to get a `std::unique_ptr<Widget>`.

In contrast, the call involving `nullptr` has no trouble. When `nullptr` is passed to `lockAndCall`, the type for `ptr` is deduced to be `std::nullptr_t` (i.e., `nullptr`'s type). When `ptr` is passed to `f3`, there's an implicit conversion from `std::nullptr_t` to `void*`, because `std::nullptr_t` objects implicitly convert to all pointer types. (If the idea of there being object*s*—*plural*—of type `std::nullptr_t` seems odd, I agree, it is. But don't worry about it. All objects of type `std::nullptr_t` represent the null pointer, so they all behave the same way. You can create your own such objects if you want to, but given the universal availability of `nullptr`, why would you?)

The fact that template type deduction deduces the "wrong" types for `0` and `NULL` (i.e., their true types, rather than their fallback meaning as a representation for a null pointer) is the most compelling reason to use `nullptr` instead of `0` or `NULL` when you want to refer to a null pointer. With `nullptr`, templates pose no special challenge. With `0` and `NULL`, the challenge is essentially insurmountable: templates always deduce the wrong type. Combined with the fact that `nullptr` doesn't suffer from the overload resolution surprises that `0` and `NULL` are susceptible to, the case is iron-clad. When you want to refer to a null pointer, use `nullptr`, not `0` or `NULL`.

As a coda, it's worth noting that `lockAndCall` is a simplified version of a perfect forwarding template, and the inability to forward `0` and `NULL` as null pointers is an example of a situation where perfect forwarding doesn't work. For details on perfect forwarding and the conditions under which it breaks down, consult Item 32.

Things to Remember

- Prefer `nullptr` to `0` and `NULL`.
- Avoid overloading on integral and pointer types.

Item 9: Prefer alias declarations to `typedef`s.

I'm confident we can agree that using STL containers is a good idea, and I hope that Item 20 convinces you that using `std::unique_ptr` is a good idea, but my guess is that neither of us is fond of writing types like "`std::unique_ptr<std::unordered_map<std::string, std::string>>`" more than once. Just thinking about it probably increases the risk of carpal tunnel syndrome.

Avoiding such medical tragedies is easy. Just introduce a `typedef`:

```
typedef
  std::unique_ptr<std::unordered_map<std::string, std::string>>
  UPtrMapSS;
```

But `typedef`s are so…C++98. They work in C++11, sure, but C++11 also offers *alias declarations*:

```
using UPtrMapSS =
  std::unique_ptr<std::unordered_map<std::string, std::string>>;
```

Given that the typedef and the alias declaration do exactly the same thing (in the Standard, an alias declaration is actually defined to be an alternative way to create a typedef), it's reasonable to wonder whether there is a solid technical reason for preferring one over the other.

There is, but before I get to it, I want to mention that many people find the alias declaration easier to swallow when dealing with types involving function pointers:

```
// FP is a synonym for a pointer to a function taking an int and
// a const std::string& and returning nothing
typedef void (*FP)(int, const std::string&);      // typedef

// same meaning as above
using FP = void (*)(int, const std::string&);     // alias
                                                  // declaration
```

Of course, neither form is particularly easy to choke down, and few people spend much time dealing with synonyms for function pointer types, anyway, so this is hardly a compelling reason to choose alias declarations over typedefs.

But a compelling reason does exist: templates. In particular, alias declarations may be templatized (in which case they're called *alias templates*), while typedefs cannot. This gives C++11 programmers a clear, straightforward mechanism for expressing things that in C++98 had to be hacked together with typedefs nested inside templatized structs. For example, consider defining a synonym for a linked list that uses a custom allocator, MyAlloc. With an alias template, it's a piece of cake:

```
template<typename T>                            // MyAllocList<T>
using MyAllocList = std::list<T, MyAlloc<T>>;   // is synonym for
                                                // std::list<T,
                                                //   MyAlloc<T>>

MyAllocList<Widget> lw;                         // client code
```

With a typedef, you pretty much have to create the cake from scratch:

```
template<typename T>                    // MyAllocList<T>::type
struct MyAllocList {                    // is synonym for
```

```
  typedef std::list<T, MyAlloc<T>> type; // std::list<T,
};                                       //   MyAlloc<T>>

MyAllocList<Widget>::type lw;            // client code
```

It gets worse. If you want to use the `typedef` inside a template for the purpose of creating a linked list holding objects of a type specified by a template parameter, you have to precede the `typedef` name with `typename`:

```
template<typename T>
class Widget {                         // Widget<T> contains
private:                               // a MyAllocList<T>
  typename MyAllocList<T>::type list;  // as a data member
  …
};
```

Here, `MyAllocList<T>::type` refers to a type that's dependent on a template type parameter (`T`). `MyAllocList<T>::type` is thus a *dependent type*, and one of C++'s many endearing rules is that the names of dependent types must be preceded by `typename`.

If `MyAllocList` is defined as an alias template, this need for `typename` vanishes (as does the cumbersome "`::type`" suffix):

```
template<typename T>
using MyAllocList = std::list<T, MyAlloc<T>>;  // as before

template<typename T>
class Widget {
private:
  MyAllocList<T> list;                         // no "typename",
  …                                            // no "::type"
};
```

To you, `MyAllocList<T>` (i.e., use of the alias template) may look just as dependent on the template parameter `T` as `MyhAllocList<T>::type` (i.e., use of the nested `typedef`), but you're not a compiler. When compilers process the `Widget` template and encounter the use of `MyAllocList<T>` (i.e. use of the alias template), they know that `MyAllocList<T>` is the name of a type, because `MyAllocList` is an alias template: it *must* name a type. `MyAllocList<T>` is thus a *non-dependent type*, and a `typename` specifier is neither required nor permitted.

When compilers see MyAllocList<T>::type (i.e., use of the nested typedef) in the Widget template, on the other hand, they can't know for sure that it names a type, because there might be a specialization of MyAllocList that they haven't yet seen where MyAllocList<T>::type refers to something other than a type. That sounds crazy, but don't blame compilers for this possibility. It's the humans who have been known to produce such code.

For example, some misguided soul may have concocted something like this:

```
class Wine { … };

template<>                        // MyAllocList specialization
class MyAllocList<Wine> {         // for T is Wine
private:
  enum class WineType             // see Item 10 for info on
  { White, Red, Rose };           // "enum class"

  WineType type;                  // in this class, type is
  …                               // a data member!
};
```

As you can see, MyAllocList<Wine>::type doesn't refer to a type. If Widget were to be instantiated with Wine, MyAllocList<T>::type inside the Widget template would refer to a data member, not a type. Inside the Widget template, then, whether MyAllocList<T>::type refers to a type is honestly dependent on what T is, and that's why compilers insist on your asserting that it is a type by preceding it with typename.

If you've done any template metaprogramming (TMP), you've almost certainly bumped up against the need to take template type parameters and create revised types from them. For example, given some type T, you might want to strip off any const-or reference-qualifiers that T contains, i.e., you might want to turn const std::string& into std::string. Or you might want to take a type and add const to it or turn it into an lvalue reference, i.e., turn Widget into const Widget or into Widget&. (If you haven't done any TMP, that's too bad, because if you want to be a truly effective C++ programmer, you need to be familiar with at least the basics of this facet of C++. You can see examples of TMP in action, including the kinds of type transformations I just mentioned, in Items 25 and 29.)

C++11 gives you the tools to perform these kinds of transformations in the form of *type traits*, an assortment of templates inside the header `<type_traits>`. There are dozens of type traits in that header, and not all of them perform type transformations, but the ones that do offer a predictable interface. Given a type `T` to which you'd like to apply a transformation, the resulting type is `std::`*`transformation`*`<T>::type`. For example:

```
std::remove_const<T>::type            // yields T from const T

std::remove_reference<T>::type        // yields T from T& and T&&

std::add_lvalue_reference<T>::type    // yields T& from T
```

The comments merely summarize what these transformations do, so don't take them too literally. Before using them on a project, you'd look up the precise specifications, I know.

My motivation here isn't to give you a tutorial on type traits, anyway. Rather, note that application of these transformations entails writing "`::type`" at the end of each use. If you apply them to a type parameter inside a template (which is virtually always how you employ them in real code), you'd also have to precede each use with `typename`. The reason for both of these syntactic speed bumps is that the C++11 type traits are implemented as nested `typedef`s inside templatized `struct`s. That's right, they're implemented using the type synonym technology I've been trying to convince you is inferior to alias templates!

There's a historical reason for that, but we'll skip over it (it's dull, I promise), because the Standardization Committee belatedly recognized that alias templates are the better way to go, and they included such templates in C++14 for all the C++11 type transformations. The aliases have a common form: for each C++11 transformation `std::`*`transformation`*`<T>::type`, there's a corresponding C++14 alias template named `std::`*`transformation`*`_t`. Examples will clarify what I mean:

```
std::remove_const<T>::type            // C++11: const T → T
std::remove_const_t<T>                // C++14 equivalent

std::remove_reference<T>::type        // C++11: T&/T&& → T
std::remove_reference_t<T>            // C++14 equivalent
```

```
std::add_lvalue_reference<T>::type    // C++11: T → T&
std::add_lvalue_reference_t<T>        // C++14 equivalent
```

The C++11 constructs remain valid in C++14, but I don't know why you'd want to use them. Even if you don't have access to C++14, writing the alias templates yourself is child's play. Only C++11 language features are required, and even children can mimic a pattern, right? If you happen to have access to an electronic copy of the C++14 Standard, it's easier still, because all that's required is some copying and pasting. Here, I'll get you started (via copy-and-paste technology):

```
template <class T>
using remove_const_t = typename remove_const<T>::type;

template <class T>
using remove_reference_t = typename remove_reference<T>::type;

template <class T>
using add_lvalue_reference_t =
  typename add_lvalue_reference<T>::type;
```

See? Couldn't be easier.

Things to Remember

- `typedef`s don't support templatization, but alias declarations do.
- Alias templates avoid the "`::type`" suffix and, in templates, the "`typename`" prefix often required to refer to `typedef`s.
- C++14 offers alias templates for all the C++11 type traits transformations.

Item 10: Prefer scoped enums to unscoped enums.

As a general rule, declaring a name inside curly braces limits the visibility of that name to the scope defined by the braces. Not so for the enumerators declared in C- and C++98-style `enum`s. The names of such enumerators belong to the scope containing the `enum`, and that means that nothing else in that scope may have the same name:

```
enum Color { black, white, red };   // black, white, red are
                                    // in same scope as Color

bool white = false;                 // error! white already
                                    // declared in this scope
```

The fact that these enumerator names leak into the scope containing their `enum` definition gives rise to the official name for this kind of `enum`: *unscoped enums*. Their C++11 scoped counterparts, *scoped enums*, don't leak names in this way:

```
enum class Color { black, white, red };  // black, white, red
                                         // are scoped to Color

bool white = false;                  // fine, no other
                                     // "white" in scope

Color c = white;                     // error! no enumerator named
                                     // "white" is in this scope

Color c = Color::white;              // fine

auto c = Color::white;               // also fine (and in accord
                                     // with Item 5's advice)
```

Because scoped `enum`s are declared via "`enum class`", scoped `enum`s are sometimes referred to as *enum classes*.

The reduction in namespace pollution offered by scoped `enum`s is reason enough to prefer them over their unscoped siblings, but scoped `enum`s have a second compelling advantage: their enumerators are much more strongly typed. Enumerators for unscoped `enum`s implicitly convert to integral types (and, from there, to floating point types). Semantic travesties such as the following are therefore perfectly valid:

```
enum Color { black, white, red };        // unscoped enum

std::vector<std::size_t>                 // func. returning
primeFactors(std::size_t x);             // prime factors of x

Color c = red;
…

if (c < 14.5) {                    // compare Color to double (!)

  auto factors =                   // compute prime factors
    primeFactors(c);               // of a color (!)
  …
}
```

Throw a simple "`class`" after "`enum`", however, thus transforming an unscoped `enum` into a scoped one, and it's a very different story, because there are no implicit conversions from enumerators in a scoped `enum` to any other type:

```
enum class Color { black, white, red };  // enum is now scoped

Color c = Color::red;                    // as before, but
…                                        // with scope qualifier

if (c < 14.5) {                // error! can't compare
                               // Color and double

  auto factors =               // error! can't pass Color to
    primeFactors(c);           // function expecting std::size_t
  …
}
```

If you honestly want to perform a conversion from `Color` to a different type, do what you always do to twist the type system to your wanton desires: use a cast:

```
if (static_cast<double>(c) < 14.5) {        // odd code, but
                                            // it's valid

  auto factors =                                  // suspect, but
    primeFactors(static_cast<std::size_t>(c));   // it compiles
  …
}
```

It may seem that scoped `enum`s have a third advantage over unscoped `enum`s, because scoped `enum`s may be forward-declared, i.e., their names may be declared without specifying their enumerators:

```
  enum Color;                 // error!

  enum class Color;           // fine
```

This is misleading. In C++11, unscoped `enum`s may also be forward-declared, but only after a bit of additional work.

Every `enum` in C++ has an integral *underlying type* that is determined by compilers. For an unscoped `enum` like `Color`,

```
enum Color { black, white, red };
```

compilers might choose `char` as the underlying type, because there are only three values to represent. On the other hand, some `enum`s may have a range of values that is much larger, e.g.:

```
enum Status { good = 0,
              failed = 1,
              incomplete = 100,
```

```
                  corrupt = 200,
                  indeterminate = 0xFFFFFFFF
                };
```

Here the values to be represented range from `0` to `0xFFFFFFFF`. Except on very unusual machines (where a `char` consists of at least 32 bits), compilers will have to select an integral type larger than `char` for the underlying representation of `Status` values.

To make efficient use of memory, compiler writers want to choose the smallest underlying type for each `enum` that's sufficient to represent the `enum`'s range of enumerator values. (In some cases, compilers will optimize for speed instead of size, and in that case, they may not choose the smallest permissible underlying type, but they certainly want to be *able* to optimize for minimal size.) To make that possible, C++98 requires that `enum`s be defined (i.e., list all their enumerators) where they're declared. Having seen the range of enumerator values that must be representable, compilers are then in a position to choose a suitable underlying type for that `enum` type.

But the inability to forward-declare `enum`s has drawbacks, too. Perhaps the most notable is the increase in compilation dependencies. Consider again the `Status` `enum`:

```
enum Status { good = 0,
              failed = 1,
              incomplete = 100,
              corrupt = 200,
              indeterminate = 0xFFFFFFFF
            };
```

This is the kind of `enum` that's likely to be used throughout a system, hence included in a header file that every part of the system is dependent on. If a new status value is then introduced,

```
enum Status { good = 0,
              failed = 1,
              incomplete = 100,
              corrupt = 200,
              audited = 500,
              indeterminate = 0xFFFFFFFF
            };
```

it's likely that the entire system will have to be recompiled, even if only a single subsystem—possibly only a single function!—uses the new enumerator. This is the kind of thing that people *hate*. And it's the kind of thing that the ability to forward-declare `enum`s would eliminate. With forward-declared `enum`s, declarations for `enum`-manipulating functions would be freed of their dependencies on the `enum` definitions. For example, here's a perfectly valid C++11 declaration of a scoped `enum` and a function that takes one as a parameter:

```
enum class Status;                    // forward declaration
void continueProcessing(Status s);    // use of fwd-declared enum
```

With this design, the header containing these two declarations requires no recompilation if the enumerators in `Status` are revised. Furthermore, if the enumerators in `Status` are revised (e.g., to add the new enumerator `audited`), but `continueProcessing`'s behavior is unaffected (e.g., because `continueProcessing` doesn't care about the `audited` value), `continueProcessing`'s implementation need not be recompiled, either.

But if code generation requires knowing the size of the enumerators (and it does), how can C++11's scoped `enum`s get away with forward declarations when C++98's unscoped `enum`s can't? That's easy: compilers always know the underlying type for scoped `enum`s.

All scoped `enum`s have a default underlying type of `int`:

```
enum class Status;                  // underlying type is int
```

If you don't like the default, you may specify one explicitly:

```
enum class Status: std::uint32_t;   // underlying type for
                                    // Status is std::uint32_t
                                    // (from <cstdint>)
```

Either way, compilers know the size of the enumerators in a scoped `enum`.

But I said that this isn't really an advantage of scoped `enum`s over unscoped `enum`s. That's because C++11 allows you to specify the underlying type for unscoped `enum`s, too. When you do, those `enum`s can be forward-declared, just like their scoped compatriots:

```
enum Color: std::uint8_t;       // fwd decl for unscoped enum;
                                // underlying type is
                                // std::uint8_t
```

Underlying type specifications aren't restricted to `enum` declarations. You can put them on the definitions, too:

```
enum class Status: std::uint32_t { good = 0,
                                   failed = 1,
                                   incomplete = 100,
                                   corrupt = 200,
                                   audited = 500,
                                   indeterminate = 0xFFFFFFFF
                                 };
```

It should go without saying that the underlying type you specify when you declare an `enum` must match the underlying type you specify when you define the `enum`. In general, mismatches will be diagnosed during compilation, although there are situations where compilers are unable to do this. As long as you put all your `enum` declarations in header files and dutifully `#include` those header files everywhere you use the `enum`s, you'll be fine. If you try to cut corners by skipping an `#include` and manually declaring your `enum` instead, you may not be fine, and the almost invariably resulting overnight debugging sessions should serve to remind you not to commit such crimes against software engineering.

In view of the fact that scoped `enum`s avoid namespace pollution and aren't susceptible to nonsensical implicit type conversions, it may surprise you to hear that there's at least one situation in C++11 where unscoped `enum`s are sometimes considered useful. That's when referring to fields within `std::tuple`s. For example, suppose we have a tuple holding values for the name, email address, and reputation value for a user at a social networking web site:

```
using UserInfo =                 // type alias; see Item 9
  std::tuple<std::string,        // name
             std::string,        // email
             std::size_t> ;      // reputation
```

Though the comments indicate what each field of the tuple represents, that's probably not very helpful when you encounter code like this in a separate source file:

```
UserInfo uInfo;                  // object of tuple type
…

auto val = std::get<1>(uInfo);   // get value of field 1
```

As a programmer, you have a lot of stuff to keep track of. Should you really be expected to remember that field 1 corresponds to the user's email address? I think not. Use of an unscoped enum avoids the need to:

```
enum UserInfoFields { uiName, uiEmail, uiReputation };

UserInfo uInfo;                        // as before
…

auto val = std::get<uiEmail>(uInfo);   // ah, get value of
                                       // email field
```

You need to use an unscoped `enum` here, because `std::get` requires a `std::size_t` argument, and that means you need to take advantage of the implicit conversion from `UserInfoFields` to `std::size_t` that unscoped `enum`s support.

The corresponding code with scoped `enum`s is substantially more verbose:

```
enum class UserInfoFields { uiName, uiEmail, uiReputation };

UserInfo uInfo;                        // as before
…

auto val =
  std::get<static_cast<std::size_t>(UserInfoFields::uiEmail)>
    (uInfo);
```

The verbosity can be reduced by writing a function that takes an enumerator and returns its corresponding `std::size_t` value, but it's a bit tricky. `std::get` is a template, and the value you provide is a template argument (notice the use of angle brackets, not parentheses), so the function that transforms an enumerator into a `std::size_t` has to produce its result *during compilation*. As Item 14 explains, that means it must be a `constexpr` function. In fact, it should really be a `constexpr` function template, because it should work with any kind of `enum`:

```
template<typename E>
constexpr std::size_t toIndex(E enumerator)
{
```

```
  return static_cast<std::size_t>(enumerator);
}
```

This `toIndex` template permits us to access a field of the tuple this way:

```
auto val = std::get<toIndex(UserInfoFields::uiEmail)>(uInfo);
```

It's still more to write than use of the unscoped `enum`, of course, but it also avoids namespace pollution and inadvertent conversions involving enumerators. In many cases, you may decide that typing a few extra characters is a reasonable price to pay for the ability to avoid an enum technology that dates to a time when the state of the art in digital telecommunications was the 2400-baud modem.

Things to Remember

- C++98-style `enum`s are now known as unscoped `enum`s.
- Enumerators of scoped `enum`s are visible only within the `enum`. They convert to other types only with a cast.
- Both scoped and unscoped `enum`s support specification of the underlying type. The default underlying type for scoped `enum`s is `int`. Unscoped `enum`s have no default underlying type.
- Scoped `enum`s may always be forward-declared. Unscoped `enum`s may be forward declared only if their declaration specifies an underlying type.

Item 11: Prefer deleted functions to private undefined ones.

If you're providing code to other developers, and you want to prevent them from calling a particular function, you generally just don't declare the function. No function declaration, no function to call. Easy, peasy. But sometimes C++ declares functions for you, and if you want to prevent clients from calling those functions, the peasy isn't quite so easy any more.

This situation arises only for the *special member functions*, i.e., the member functions that C++ automatically generates when they're needed. Item 19 discusses these functions in detail, but for now, we'll worry only about the copy constructor and the copy assignment operator. This chapter is devoted to common practices in C++98 that have been superseded by better practices in C++11, and in C++98, if you want to suppress use of a member function, it's almost always the copy constructor, the assignment operator, or both.

The C++98 approach to preventing use of these functions is to declare them `private` and to avoid defining them. For example, near the base of the iostreams hierarchy in the C++ Standard Library is the class template `basic_ios`. All istream and ostream classes inherit (possibly indirectly) from this class. Copying istreams and ostreams is undesirable, because it's not really clear what such operations should do. An `istream` object, for example, represents a stream of input values, some of which may have already been read, and some of which will potentially be read later. If an istream were to be copied, would that entail copying all the values that had already been read as well as all the values that would be read in the future? The easiest way to deal with such questions is to define them out of existence. Prohibiting the copying of streams does just that.

To render istream and ostream classes uncopyable, `basic_ios` is specified in C++98 as follows (including the comments):

```
template <class charT, class traits = char_traits<charT> >
class basic_ios : public ios_base {
public:
  …

private:
  basic_ios(const basic_ios& );             // not defined
  basic_ios& operator=(const basic_ios&);  // not defined
};
```

Declaring these functions `private` prevents clients from calling them. Deliberately failing to define them means that if code that still has access to them (i.e., member functions or `friend`s of the class) uses them, linking will fail due to missing function definitions.

In C++11, there's a better way to achieve essentially the same end: use "`=delete`" to mark the copy constructor and the copy assignment operator as *deleted functions*. Here's the same part of `basic_ios` as it's specified in C++11:

```
template <class charT, class traits = char_traits<charT> >
class basic_ios : public ios_base {
public:
```

```
  …
  basic_ios(const basic_ios& ) = delete;
  basic_ios& operator=(const basic_ios&) = delete;
  …
};
```

The difference between deleting these functions and declaring them `private` may seem more a matter of fashion than anything else, but there's greater substance here than you might think. Deleted functions may not be used in any way, so even code that's in member and `friend` functions will fail to compile if it tries to copy `basic_ios` objects. That's an improvement over the C++98 behavior, where such improper usage wouldn't be diagnosed until link-time.

By convention, deleted functions are declared `public`, not `private`. There's a reason for that. When client code tries to use a member function, C++ checks accessibility before `=delete` status. When client code tries to use a deleted `private` function, some compilers complain only about the function being `private`, even though the function's accessibility doesn't really affect whether it can be used. It's worth bearing this in mind when revising legacy code to replace `private`-and-not-defined member functions with deleted ones, because making the new functions `public` will generally result in superior error messages.

An important advantage of deleted functions is that *any* function may be deleted, while only member functions may be `private`. For example, suppose we have a non-member function that takes an integer and returns whether it's a lucky number:

```
bool isLucky(int number);
```

C++'s C heritage means that pretty much any type that can be viewed as vaguely numerical will implicitly convert to `int`, but some calls that would compile might not make sense:

```
if (isLucky('a')) …             // is 'a' a lucky number?

if (isLucky(true)) …            // is "true"?

if (isLucky(3.5)) …             // should we truncate to 3
                                // before checking for luckiness?
```

If lucky numbers must really be integers, we'd like to prevent calls such as these from compiling.

One way to accomplish that is to create deleted overloads for the types we want to filter out:

```
bool isLucky(int number);            // original function
bool isLucky(char) = delete;         // reject chars
bool isLucky(bool) = delete;         // reject bools
bool isLucky(double) = delete;       // reject doubles and
                                     // floats
```

(The comment on the `double` overload that says that both `double`s and `float`s will be rejected may initially surprise you, but your surprise will dissipate once you recall that, given a choice between converting a `float` to an `int` or to a `double`, C++ prefers the conversion to `double`. Calling `isLucky` with a `float` will therefore call the `double` overload, not the `int` one. Well, it'll try to. The fact that that overload is deleted will prevent the call from compiling.)

Although deleted functions can't be used, they are part of your program. As such, they are taken into account during overload resolution. That's why, with the deleted function declarations above, the undesirable calls to `isLucky` will be rejected:

```
if (isLucky('a')) …           // error! call to deleted function
if (isLucky(true)) …          // error!
if (isLucky(3.5f)) …          // error!
```

Another trick that deleted functions can perform (and that `private` member functions can't) is to prevent use of template instantiations that should be disabled. For example, suppose you need a template that works with built-in pointers (Chapter 4's advice to prefer smart pointers to raw pointers notwithstanding):

```
template<typename T>
void processPointer(T* ptr);
```

There are two special cases in the world of pointers. One is `void*` pointers, because there is no way to dereference them, to increment or decrement them, etc.. The other is `char*` pointers, because they typically represent pointers to C-style strings, not pointers to individual characters. These special cases often call for special handling, and, in the case of the `processPointer` template, let's assume the proper handling is to reject calls using those types. That is, it should not be possible to call `processPointer` with `void*` or `char*` pointers.

That's easily enforced. Just delete those instantiations:

```
template<>
void processPointer<void>(void*) = delete;

template<>
void processPointer<char>(char*) = delete;
```

Now, if calling `processPointer` with a `char*` is invalid, it's probably also invalid to call it with a `const char*`, so that instantiation will typically need to be deleted, too:

```
template<>
void processPointer<const char>(const char*) = delete;
```

If you really want to be thorough, you'll also delete the `const volatile char*` overload, and then you'll get to work on the overloads for pointers to the other standard character types: `std::wchar_t`, `std::char16_t`, and `std::char32_t`.

Interestingly, if you have a function template inside a class, and you'd like to disable some instantiations by declaring them `private` (à la classic C++98 convention), you can't, because it's not possible to give a member function template specialization a different access level from that of the main template. If `processPointer` were a member function template inside `Widget`, for example, and we wanted to disable calls for `void*` pointers, this would be the C++98 approach, though it would not compile:

```
class Widget {
public:
  …
  template<typename T>
  void processPointer(T* ptr)
  { … }

private:
  template<>                              // error!
  void processPointer<void>(void*);
```

```
};
```

The problem is that template specializations must be written at namespace scope, not class scope. This issue doesn't arise for deleted functions, because they don't need a different access level. They can be deleted outside the class (hence at namespace scope):

```
class Widget {
public:
  …
  template<typename T>
  void processPointer(T* ptr)
  { … }

  …

};

template<>                                          // still
void Widget::processPointer<void>(void*) = delete;  // public,
                                                    // but
                                                    // deleted
```

The truth is that the C++98 practice of declaring functions `private` and not defining them was really an attempt to achieve what C++11's deleted functions actually do. As an emulation, the C++98 approach is not as good as the real thing. It doesn't work outside classes, it doesn't always work inside classes, and when it does work, it may not work until link-time. So stick to deleted functions.

Things to Remember

- Prefer deleted functions to private undefined ones.
- Any function may be deleted, including non-member functions and template instantiations.

Item 12: Declare overriding functions `override`.

The world of object-oriented programming in C++ revolves around classes, inheritance, and virtual functions. Among the most fundamental ideas in this world is that virtual function implementations in derived classes *override* the implementations of their base class counterparts. It's disheartening, then, to realize how easily virtual function overriding can go wrong. It's almost as if this part of the language were designed with the idea that Murphy's Law wasn't just to be obeyed, it was to be honored.

Because "overriding" sounds a lot like "overloading," yet is completely unrelated, let me make clear that virtual function overriding is what makes it possible to invoke a derived class function through a base class interface:

```
class Base {
public:
  virtual void doWork();          // base class virtual function
  …
};

class Derived: public Base {
public:
  virtual void doWork();          // overrides Base::doWork
  …                               // ("virtual" is optional
};                                // here")

std::unique_ptr<Base> upb =       // create base class pointer
  std::make_unique<Derived>();    // to derived class object;
                                  // see Item 23 for info on
…                                 // std::make_unique

upb->doWork();                    // call doWork through base
                                  // class ptr; derived class
                                  // function is invoked
```

For overriding to occur, several requirements must be met:

- The base class function must be virtual.
- The base and derived function names must be identical (except in the case of destructors).
- The parameter types of the base and derived functions must be identical.
- The `const`ness of the base and derived functions must be identical.

To these constraints, which have been part of C++ since the beginning, C++11 adds one more:

- The functions' *reference qualifiers* must be identical. Member function reference qualifiers are one of C++11's less-publicized features, so don't be surprised if you've never heard of them. They make it possible to limit use of a member function to lvalues only or to rvalues only. Member functions need not be virtual to use them:

```
class Widget {
public:
  …
  void doWork() &;      // this version of doWork applies only
                        // when *this is an lvalue

  void doWork() &&;     // this version of doWork applies only
};                      // when *this is an rvalue

…

Widget makeWidget();    // factory function (returns rvalue)

Widget w;               // normal object (an lvalue)

…

w.doWork();               // calls Widget::doWork for lvalues
                          // (i.e., Widget::doWork &)

makeWidget().doWork();    // calls Widget::doWork for rvalues
                          // (i.e., Widget::doWork &&)
```

I'll say more about member functions with reference qualifiers later, but for now, simply note that if a virtual function in a base class has a reference qualifier, derived class overrides of that function must have exactly the same reference qualifier. If they don't, the declared functions will still exist in the derived class, but they won't override anything in the base class.

All these requirements for overriding mean that small mistakes can make a big difference. Code with overriding errors is typically valid, but its meaning isn't what you intended. As a result, you can't rely on compilers to notify you if you do something wrong. For example, the following code is completely legal and, at first sight, looks reasonable, but it contains no virtual function overrides—not a single derived class function that is tied to a base class function. Can you identify the problem in each case, i.e., why the derived class function doesn't override the base class function with the same name?

```
class Base {
public:
  virtual void mf1() const;
  virtual void mf2(int x);
```

```
  virtual void mf3() &;
  void mf4() const;
};

class Derived: public Base {
public:
  virtual void mf1();
  virtual void mf2(unsigned int x);
  virtual void mf3() &&;
  void mf4() const;
};
```

Need some help?

- `mf1` is declared `const` in `Base`, but not in `Derived`.
- `mf2` takes an `int` in `Base`, but an `unsigned int` in `Derived`.
- `mf3` is lvalue-qualified in `Base`, but rvalue-qualified in `Derived`.
- `mf4` isn't declared `virtual` in `Base`.

You may think, "Hey, in practice, these things will elicit compiler warnings, so I don't need to worry." Maybe that's true. But maybe it's not. With two of the compilers I checked, the code was accepted without complaint, and that was with all warnings enabled. (Other compilers provided warnings about some—but not all—of the issues.)

Because declaring derived class overrides is important to get right, but easy to get wrong, C++11 gives you a way to make explicit that a derived class function is supposed to override a base class version. Just declare it `override`. Applying this to the example above would yield this derived class:

```
class Derived: public Base {
public:
  virtual void mf1() override;
  virtual void mf2(unsigned int x) override;
  virtual void mf3() && override;
  virtual void mf4() const override;
};
```

This won't compile, of course, because when written this way, compilers will kvetch about all the overriding-related problems. That's exactly what you want, and it's why you should declare all your overriding functions `override`.

The code using override that does compile looks as follows (assuming that the goal is for all functions in Derived to override virtuals in Base):

```
class Base {
public:
  virtual void mf1() const;
  virtual void mf2(int x);
  virtual void mf3() &;
  virtual void mf4() const;
};

class Derived: public Base {
public:
  virtual void mf1() const override;
  virtual void mf2(int x) override;   // note revised param type
  virtual void mf3() & override;
  void mf4() const override;          // adding "virtual" is OK,
};                                    // but not necessary
```

Note that in this example, part of getting things to work involves declaring mf4 virtual in Base. Most overriding-related errors occur in derived classes, but it's possible for things to be incorrect in base classes, too.

A policy of using override on all your derived class overrides can do more than just enable compilers to tell you when would-be overrides aren't overriding anything. It can also help you gauge the ramifications if you're contemplating changing the signature of a virtual function in a base class. If derived classes use override everywhere, you can just change the signature, recompile your system, see how much damage you've caused (e.g., how many derived classes fail to compile), then decide whether the signature change is worth the trouble. Without override, you'd have to hope you have comprehensive unit tests in place, because, as we've seen, derived class virtuals that are supposed to override base class functions, but don't, need not elicit compiler diagnostics.

C++ has always had keywords, but C++11 introduces two *contextual keywords*, override and final. These keywords have the characteristic that they are reserved, but only in certain contexts. In the case of override, it has a reserved meaning only when it occurs at the end of a member function declaration. That means that if you have legacy code that already uses the name override, you don't need to change it for C++11:

```
class Warning {            // potential legacy class from C++98
public:
  …
  void override();         // legal in both C++98 and C++11
  …                        // (with the same meaning)
};
```

That's all there is to say about `override`, but it's not all there is to say about member function reference qualifiers. I promised I'd provide more information on them later, and it's now later.

If we want to write a function that accepts only lvalue arguments, we declare an lvalue reference parameter:

```
void doSomething(Widget& w);      // accepts only lvalue Widgets
```

If we want to write a function that accepts only rvalue arguments, we declare an rvalue reference parameter:

```
void doSomething(Widget&& w);     // accepts only rvalue Widgets
```

Member function reference qualifiers simply make it possible to draw the same distinction for the object on which a member function is invoked, i.e., `*this`. It's precisely analogous to the `const` at the end of a member function declaration, which indicates that the object on which the member function is invoked (i.e., `*this`) is `const`.

The need for reference-qualified member functions is not common, but it does arise. For example, suppose our `Widget` class has a `std::vector` data member, and we offer an accessor function that gives clients direct access to it:

```
class Widget {
public:
  using DataType = std::vector<double>;      // see Item 9 for
  …                                          // info on "using"

  DataType& data() { return values; }
  …

private:
  DataType values;
};
```

This is hardly the most encapsulated design that's seen the light of day, but set that aside and consider what happens in this client code:

```
Widget w;
…
auto vals1 = w.data();                // copy w.values into vals1
```

The return type of `Widget::data` is an lvalue reference (a `std::vector<double>&`, to be precise), and because lvalue references are defined to be lvalues, we're initializing `vals1` from an lvalue. `vals1` is thus copy-constructed from `w.values`, just as the comment says.

Now suppose we have a factory function that creates `Widget`s,

```
Widget makeWidget();
```

and we want to initialize a variable with the `std::vector` inside the `Widget` returned from `makeWidget`:

```
auto vals2 = makeWidget().data();     // copy values inside the
                                      // Widget into vals2
```

Again, `Widgets::data` returns an lvalue reference, and, again, the lvalue reference is an lvalue, so, again, our new object (`vals2`) is copy-constructed from `values` inside the `Widget`. This time, though, the `Widget` is the temporary object returned from `makeWidget` (i.e., an rvalue), so copying the `std::vector` inside it is a waste of time. It'd be preferable to move it, but, because `data` is returning an lvalue reference, the rules of C++ require that compilers generate code for a copy. (There's some wiggle room for optimization through what is known as the "as if rule," but you'd be foolish to rely on your compilers finding a way to take advantage of it.)

What's needed is a way to specify that when `data` is invoked on an rvalue `Widget`, the result should also be an rvalue. Using reference qualifiers to overload `data` for lvalue and rvalue `Widget`s makes that possible:

```
class Widget {
public:
  using DataType = std::vector<double>;
  …
```

```
  DataType& data() &                // for lvalue Widgets,
  { return values; }                // return lvalue

  DataType data() &&                // for rvalue Widgets,
  { return std::move(values); }     // return rvalue
  …

private:
  DataType values;
};
```

Notice the differing return types from the `data` overloads. The lvalue reference overload returns an lvalue reference (i.e., an lvalue), and the rvalue reference overload returns a temporary object (i.e., an rvalue). This means that client code now behaves as we'd like:

```
auto vals1 = w.data();             // calls lvalue overload for
                                   // Widget::data, copy-
                                   // constructs vals1

auto vals2 = makeWidget().data();  // calls rvalue overload for
                                   // Widget::data, move-
                                   // constructs vals2
```

This is certainly nice, but don't let the warm glow of this happy ending distract you from the true point of this Item. That point is that whenever you declare a function in a derived class that's meant to override a virtual function in a base class, be sure to declare that function `override`.

Things to Remember

- Declare overriding functions `override`.
- Member function reference qualifiers make it possible to treat lvalue and rvalue objects (`*this`) differently.

Item 13: Prefer `const_iterator`s to `iterator`s.

`const_iterator`s are the STL equivalent of pointers-to-`const`. They point to values that may not be modified. The standard practice of using `const` whenever possible dictates that you should use `const_iterator`s any time you need an iterator, yet have no need to modify what the iterator points to.

That's as true for C++98 as for C++11 and C++14, but in C++98, `const_iterator`s had only halfhearted support. It wasn't that easy to create them, and once you had one, the ways you could use it were limited. For example, suppose you want to search a `std::vector<int>` for the first occurrence of 1983 (the year "C++" replaced "C with Classes" as the name of the programming language), then insert the value 1998 (the year the first C++ Standard was adopted) at that location. If there's no 1983 in the vector, the insertion should go at the end of the vector. Using `iterator`s in C++98, that was easy:

```
std::vector<int> values;

…

std::vector<int>::iterator it =
  std::find(values.begin(),values.end(), 1983);

values.insert(it, 1998);
```

But `iterator`s aren't really the proper choice here, because this code never modifies what an `iterator` points to. Revising the code to use `const_iterator`s should be trivial, but in C++98, it was anything but. Here's one approach that's conceptually sound, though still not correct:

```
typedef std::vector<int>::iterator IterT;             // type-
typedef std::vector<int>::const_iterator ConstIterT;  // defs

std::vector<int> values;

…

ConstIterT ci =
  std::find(static_cast<ConstIterT>(values.begin()),  // cast
            static_cast<ConstIterT>(values.end()),    // cast
            1983);

values.insert(static_cast<IterT>(ci), 1998);    // may not
                                                // compile; see
                                                // below
```

The `typedef`s aren't required, of course, but they make the casts in the code easier to write. (If you're wondering why I'm showing `typedef`s instead of following the advice of Item 9 to use alias declarations, it's because this example shows C++98 code, and alias declarations are a feature new to C++11.)

The casts in the call to std::find are present because values is a non-const container and, in C++98, there was no simple way to get a const_iterator from a non-const container. The casts aren't strictly necessary, because it was possible to get const_iterators in other ways,† but regardless of how you did it, the process of getting const_iterators to elements of a non-const container involved some amount of contorting.

Once you had the const_iterators, matters often got worse, because in C++98, locations for insertions (and erasures) could be specified only by iterators. const_iterators weren't acceptable. That's why, in the code above, I cast the const_iterator (that I was so careful to get from std::find) into an iterator: passing a const_iterator to insert wouldn't compile.

To be honest, the code I've shown might not compile, either, because there's no portable conversion from a const_iterator to an iterator, not even with a static_cast. Even the semantic sledgehammer known as reinterpret_cast can't do the job. (That's not a C++98 restriction. It's true in C++11 and C++14, too. const_iterators simply don't convert to iterators, no matter how much it might seem like they should.) There are some portable ways to generate iterators that point where const_iterators do, but they're not obvious, not universally applicable, and not worth discussing in this book. Besides, I hope that by now my point is clear: const_iterators were so much trouble in C++98, they were rarely worth the bother. At the end of the day, developers don't use const whenever *possible*, they use it whenever *practical*, and in C++98, const_iterators just weren't that practical.

All that changed in C++11. Now const_iterators are both easy to get and easy to use. The container member functions cbegin and cend produce const_iterators, even for non-const containers, and STL member functions that use iterators to identify positions (e.g., insert and erase) actually use

† For example, you could bind values to a reference-to-const variable, then use that variable in place of values in your code.

const_iterators. Revising the original C++98 code that uses iterators to use const_iterators in C++11 is truly trivial:

```
std::vector<int> values;                          // as before
…
auto it =                                         // use cbegin
  std::find(values.cbegin(),values.cend(), 1983); // and cend
values.insert(it, 1998);
```

Now *that's* code using const_iterators that's practical! If we decide we'd prefer to do a reverse iteration—inserting 1998 at the location of the *last* occurrence of 1983 (or, if there are no such occurrences, at the beginning of the container)—the problem is no more challenging, provided we remember that the way to convert a reverse iterator to a "normal" iterator is to call its base member function:

```
auto it =                                           // use
  std::find(values.crbegin(),values.crend(), 1983); // crbegin
                                                    // and crend
values.insert(it.base(), 1998);
```

About the only situation in which C++11's support for const_iterators comes up a bit short is when you want to write maximally generic library code. Such code takes into account that some containers and container-like data structures offer begin and end (plus cbegin, cend, rbegin, etc.) as *non-member* functions, rather than members. This is the case for built-in arrays, for example, and it's also the case for some third-party libraries with interfaces consisting only of free functions. Maximally generic code thus uses non-member functions rather than assuming the existence of member versions.

For example, we could generalize the code we've been working with into a findAndInsert template as follows:

```
template<typename C, typename V>
void findAndInsert(C& container,          // in container,
                   const V& targetVal,    // find 1st occurrence
                   const V& insertVal)    // of targetVal, then
{                                         // insert insertVal
                                          // there
```

```
  auto it = std::find(std::cbegin(container),  // non-mbr cbegin
                      std::cend(container),    // non-mbr cend
                      targetVal);

  container.insert(it, insertVal);
}
```

This works fine in C++14, but, sadly, not in C++11. Through an oversight during standardization, C++11 added the non-member functions `begin` and `end`, but it failed to add `cbegin`, `cend`, `rbegin`, `rend`, `crbegin`, and `crend`. C++14 rectifies that oversight.

If you're using C++11, you want to write maximally generic code, and none of the libraries you're using provides the missing templates for non-member `cbegin` and friends, you can throw your own implementations together with ease. For example, here's an implementation of non-member `cbegin`:

```
template <class C>
auto cbegin(const C& container)->decltype(std::begin(container))
{
  return std::begin(container);         // see explanation below
}
```

You're surprised to see that non-member `cbegin` doesn't call member `cbegin`, aren't you? I was, too. But follow the logic. This `cbegin` template accepts any type of argument representing a container-like data structure, `C`, and it accesses this argument through its reference-to-`const` parameter, `container`. If `C` is a conventional container type (e.g., a `std::vector<int>`), `container` will be a reference to a `const` version of that container (e.g., a `const std::vector<int>&`). Invoking the non-member `begin` function (provided by C++11) on a `const` container yields a `const_iterator`, and that iterator is what this template returns. The advantage of implementing things this way is that it works even for containers that offer a `begin` member function (which, for containers, is what C++11's non-member `begin` calls), but fail to offer a `cbegin` member. You can thus use this non-member `cbegin` on containers that directly support only `begin`.

This template also works if `C` is a built-in array type. In that case, `container` becomes a reference to a `const` array. C++11 provides a specialized version of non-member `begin` for arrays that returns a pointer to the array's first element. (Iterators into arrays are pointers.) The elements of a `const` array are `const`, so the pointer that non-member `begin` returns for a `const` array is a pointer-to-`const`, and a pointer-to-`const` is, in fact, a `const_iterator` for an array. (For insight into how a template can be specialized for built-in arrays, consult Item 1's discussion of type deduction in templates that take reference parameters to arrays.)

But back to basics. The point of this Item is to encourage you to use `const_iterator`s whenever you can. The fundamental motivation—using `const` whenever it's meaningful—predates C++11, but in C++98, it simply wasn't practical when working with iterators. In C++11, it's eminently practical, and C++14 tidies up the few bits of unfinished business that C++11 left behind.

Things to Remember

- Prefer `const_iterator`s to `iterator`s.
- In maximally generic code, prefer non-member versions of `begin`, `end`, `rbegin`, etc., over their member function counterparts.

Item 14: Use `constexpr` whenever possible.

If there were an award for the most confusing new word in C++11, `constexpr` would probably win it. When applied to objects, it's essentially a beefed-up form of `const`, but when applied to functions, it has a quite different meaning. Cutting through the confusion is worth the trouble, because when `constexpr` corresponds to what you want to express, you definitely want to use it.

Conceptually, `constexpr` indicates a value that's not only constant, its value is known during compilation. The concept is only part of the story, though, because when `constexpr` is applied to functions, things are more nuanced than this suggests. Lest I ruin the surprise ending, for now I'll just say that you can't assume that the results of `constexpr` functions are `const`, nor can you take for granted that their values are known during compilation. Perhaps most intriguingly, these things are *features*. It's *good* that `constexpr` functions need not produce results that are `const` or known during compilation!

But let's begin with `constexpr` objects. Such objects are, in fact, `const`, and they do, in fact, have values that are known at compile-time. (Technically, their values are determined during *translation*, and translation consists not just of compilation but also of linking. Unless you write compilers or linkers for C++, however, this has no effect on you, so you can blithely program as if the values of `constexpr` objects were determined during compilation.)

Values known during compilation are privileged. They may be placed in read-only memory, for example, and, especially for developers of embedded systems, this can be a feature of considerable importance. Of broader applicability is that integral values that are constant and known during compilation can be used in contexts where C++ requires an *integral constant expression*. Such contexts include specification of array sizes, integral template arguments (including lengths of `std::array` objects), enumerator values, alignment specifiers, and more. If you want to use a variable for these kinds of things, you certainly want to declare it `constexpr`, because then compilers will ensure that it has a compile-time value:

```
int sz;                             // non-constexpr variable

…

constexpr auto arraySize1 = sz;     // error! sz's value not
                                    // known at compilation

std::array<int, sz> data1;          // error! same problem

constexpr auto arraySize2 = 10;     // fine, 10 is a
                                    // compile-time constant

std::array<int, arraySize2> data2;  // fine, arraySize
                                    // is constexpr
```

Note that `const` doesn't offer the same guarantee as `constexpr`, because `const` objects need not be initialized with values known during compilation:

```
int sz;                             // as before

…

const auto arraySize = sz;          // fine, arraySize is
                                    // const copy of sz

std::array<int, arraySize> data;    // error! arraySize's value
                                    // not known at compilation
```

Simply put, all `constexpr` objects are `const`, but not all `const` objects are `constexpr`. If you want compilers to guarantee that a variable has a value that can be used in contexts requiring compile-time constants, the tool to reach for is `constexpr`, not `const`.

Usage scenarios for `constexpr` objects become more interesting when `constexpr` functions are involved. Such functions produce compile-time constants *when they are called with compile-time constants*. If they're called with values not known until runtime, they produce runtime values. This may sound as if you don't know what they'll do, but that's the wrong way to think about it. The right way to view it is this:

- `constexpr` functions can be used in contexts that demand compile-time constants. If the values of the arguments you pass to a `constexpr` function in such a context are known during compilation, the result will be computed during compilation. If any of the arguments' values is not known during compilation, your code will be rejected.

- When a `constexpr` function is called with one or more values that are not known during compilation, it acts like a normal function, computing its result at runtime. This means you don't need two functions to perform the same operation, one for compile-time constants and one for all other values. The `constexpr` function does it all.

Suppose we need a data structure to hold the results of an experiment that can be run in a variety of ways. For example, the lights can be on or off as the experiment runs, as can the heater or the wind machine, etc. If there are n binary conditions applicable to the running of the experiment, the number of combinations is 2^n, so we need a data structure with enough room for 2^n values. Assuming each result is an `int` and that n is known (or can be computed) during compilation, a `std::array` could be a reasonable data structure choice. But we'd need a way to compute 2^n during compilation. The C++ Standard Library provides `std::pow`, which is the mathematical functionality we need, but, for our purposes, there are two problems with it. First, `std::pow` works on floating point types, and we need an integral result. Second, `std::pow` isn't `constexpr` (i.e., isn't guaranteed to return a compile-time result when called with compile-time values), so we can't use it to specify the size of a `std::array`.

Fortunately, we can write the `pow` we need. I'll show how to do that in a moment, but first let's look at how it'd be declared and used:

```
constexpr int pow(int base, int exp)    // pow's a constexpr func
{
  …                                     // impl is below
}

constexpr auto numConds = 5;                  // # of conditions

std::array<int, pow(2, numConds)> results;    // results has
                                              // 2^numConds elements
```

Recall that the `constexpr` in front of `pow` doesn't say that `pow` returns a `const` value, it says that if `base` and `exp` are compile-time constants, `pow`'s result may be used as a compile-time constant. If `base` and/or `exp` are not compile-time constants, `pow`'s result will be computed at runtime. That means that `pow` can not only be called to do things like compile-time-compute the size of a `std::array`, it can also be called in runtime contexts such as this:

```
auto base = readFromDB("base");        // get these values
auto exp = readFromDB("exponent");     // at runtime

auto baseToExp = pow(base, exp);       // call pow function
                                       // at runtime
```

Because `constexpr` functions must be able to return compile-time results when called with compile-time values, restrictions are imposed on their implementation. Among these is that, in C++11, there may be only a single executable statement: a `return`. That sounds more limiting than it is, because two tricks can be used to extend the expressiveness of `constexpr` functions beyond what you might think. First, the conditional "`?:`" operator can be used in place of `if-else` statements, and second, recursion can be used instead of loops. `pow` can therefore be implemented like this:

```
constexpr int pow(int base, int exp)
{
  return (exp == 0 ? 1                    // if (exp==0) return 1
```

```
           : base * pow(base, exp - 1));   // else return
}                                          // base*base^exp-1
```

This works, but it's hard to imagine that anybody except a hard-core functional programmer would consider it pretty. In C++14, the restrictions on `constexpr` functions are substantially looser, so the following implementation is valid in C++14:

```
constexpr int pow(int base, int exp)            // C++14 only
{
  if (exp == 0) return 1;

  auto result = base;
  for (int i = 1; i < exp; ++i) result *= base;

  return result;
}
```

`constexpr` functions are limited to taking and returning *literal types*, which essentially means types that can have values determined during compilation. All built-in types qualify, but user-defined types may be literal, too, because constructors and other member functions may be `constexpr`:

```
class Point {
public:
  constexpr Point(double xVal, double yVal)
  : x(xVal), y(yVal)
  {}

  constexpr double xVal() const { return x; }
  constexpr double yVal() const { return y; }

  void setX(double newX) { x = newX; }
  void setY(double newY) { y = newY; }

private:
  double x, y;
};
```

Here, the `Point` constructor can be declared `constexpr`, because if the arguments passed to it are known during compilation, the value of the data members of the constructed `Point` can also be known during compilation. `Point`s so initialized could thus be `constexpr`:

```
constexpr Point p1 { 1, 1 };        // fine, "runs" constexpr
                                    // ctor during compilation
```

```
constexpr Point p2 { 4, 2 };        // also fine
```

Similarly, the getters xVal and yVal can be constexpr, because if they're invoked on a Point object with a value known during compilation (e.g., a constexpr Point object), the values of the data members x and y can be known during compilation. That makes it possible to write constexpr functions that call Point's getters and to initialize constexpr objects with the results of such functions:

```
constexpr Point midpoint(const Point& p1, const Point& p2)
{
  return { (p1.xVal() + p2.xVal()) / 2,    // call constexpr
           (p1.yVal() + p2.yVal()) / 2 };  // member functions
}

constexpr auto mid = midpoint(p1, p2);     // init constexpr
                                           // object w/result of
                                           // constexpr function
```

This is very exciting. It means that the object mid, though its initialization involves calls to constructors, getters, and a non-member function, can be created in read-only memory! It means you could use an expression like mid.xVal() * 10 as an argument to a template or to specify the value of an enumerator! It means that the traditionally fairly strict line between work done during compilation and work done at runtime begins to blur, and in turn some computations traditionally done at runtime can migrate to compile-time. The more code taking part in the migration, the faster your software will run. (Compilation may take longer, however.)

The setter functions setX and setY can't be declared constexpr, because, among other things, they contain an assignment, and assignments are not permitted in constexpr functions, not even in C++14. (For a detailed treatment of the restrictions on constexpr function implementations, consult your favorite references for C++11 and C++14, bearing in mind that C++11 imposes more constraints than C++14.)

The advice of this Item is to use constexpr whenever possible, and by now I hope it's clear why: both constexpr objects and constexpr functions can be employed in a wider range of contexts than non-constexpr objects and functions. By using constexpr whenever possible, you maximize the range of situations in which your objects and functions may be used.

It's important to note that `constexpr` is part of an object's or function's interface. `constexpr` proclaims "I can be used in a context where C++ requires a constant expression." If you declare an object or function `constexpr`, clients may use it in such contexts. If you later decide that your use of `constexpr` was a mistake and you remove it, you may cause arbitrarily large amounts of client code to stop compiling. (The simple act of adding I/O to a function for debugging or performance tuning could lead to such a problem, because I/O statements are generally not permitted in `constexpr` functions.) Part of "whenever possible" in "Use `constexpr` whenever possible" is your willingness to make a long-term commitment to the constraints it imposes on the objects and functions you apply it to.

Things to Remember

- `constexpr` objects are `const` and are initialized with values known during compilation.
- `constexpr` functions produce compile-time results when called with arguments whose values are known during compilation.
- `constexpr` objects and functions may be used in a wider range of contexts than non-`constexpr` objects and functions.
- `constexpr` is part of an object's or function's interface.

Item 15: Make const member functions thread-safe.

If we're working in a mathematical domain, we might find it convenient to have a class representing polynomials. Within this class, it would probably be useful to have a function to compute the root(s) of the polynomial, i.e., values where the polynomial evaluates to zero. Such a function would not modify the polynomial, so it'd be natural to declare it `const`:

```
class Polynomial {
public:
  using RootsType =           // data structure holding values
    std::vector<double>;      // where polynomial evals to zero
  …                           // (see Item 9 for info on "using")

  RootsType roots() const;

  …
```

```
};
```

Computing the roots of a polynomial can be expensive, so we don't want to do it if we don't have to. And if we do have to do it, we certainly don't want to do it more than once. We'll thus cache the root(s) of the polynomial if we have to compute them, and we'll implement `roots` to return the cached value. Here's the basic approach:

```
class Polynomial {
public:
  using RootsType = std::vector<double>;

  RootsType roots() const
  {
    if (!rootsAreValid) {             // if cache not valid

     …                                // compute roots,
                                      // store them in rootVals
     rootsAreValid = true;
    }

    return rootVals;
  }

private:
  mutable bool rootsAreValid { false };   // see Item 7 for info
  mutable RootsType rootVals {};          // on initializers
};
```

Conceptually, `roots` doesn't change the `Polynomial` object on which it operates, but, as part of its caching activity, it may need to modify `rootVals` and `rootsAreValid`. That's a classic use case for `mutable`, and that's why it's part of the declarations for these data members.

Imagine now that two threads simultaneously call `roots` on a `Polynomial` object:

```
Polynomial p;

/*-----  Thread 1  ----- */      /*-------  Thread 2  ------- */

auto rootsOfP = p.roots();       auto valsGivingZero = p.roots();
```

This client code is perfectly reasonable. `roots` is a `const` member function, and that means it represents a read operation. Having multiple threads perform a read operation without synchronization is safe. At least it's supposed to be. In this case, it's not, because inside `roots`, one or both of these threads might try to modify the data members `rootsAreValid` and `rootVals`. That means that this code could have different threads reading and writing the same memory without synchronization, and that's the definition of a data race. This code has undefined behavior.

But there's still nothing wrong with the client code. Clients are supposed to be able to rely on simultaneous reads being safe, and declaring a member function `const` is tantamount to proclaiming it a read operation. The notion that `const` member functions may be safely invoked without synchronization is so deeply engrained in C++11, the Standard Library takes it for granted. If you use any part of the Standard Library on a type where a `const` member function can't safely be called without synchronization, your program has undefined behavior.

The problem here is that `roots` is declared `const`, but it's not thread-safe. The `const` declaration is as correct in C++11 as it would be in C++98 (retrieving the roots of a polynomial doesn't change the value of the polynomial), so what requires rectification is the lack of thread safety.

The easiest way to address the issue is the usual one: employ a `mutex`:

```
class Polynomial {
public:
  using RootsType = std::vector<double>;

  RootsType roots() const
  {
    std::lock_guard<std::mutex> g(m);     // lock mutex

    if (!rootsAreValid) {                 // if cache not valid

     …                                    // compute/store roots

     rootsAreValid = true;
    }

    return rootVals;                      // release mutex
  }

private:
  mutable std::mutex m;
  mutable bool rootsAreValid { false };
  mutable RootsType rootVals {};
};
```

The `std::mutex`, `m`, is declared `mutable`, because locking and unlocking it are non-`const` member functions, and within `roots` (a `const` member function), `m` would otherwise be considered a `const` object.

It's hard to go wrong using a mutex in this kind of context, but sometimes a mutex is overkill. For example, if all you're doing is counting how many times a member function is called, an atomic variable will often be a less expensive way to go. (Whether it actually is less expensive depends on the hardware you're running on and the implementation of mutexes in your Standard Library.) Here's how you can count calls using an atomic variable:

```
class Point {                                    // 2D point
public:
  …

  double distanceFromOrigin() const
  {
    ++callCount;                                 // atomic increment

    return std::sqrt((x * x) + (y * y));
  }

private:
  mutable std::atomic<unsigned> callCount { 0 };
  double x, y;
};
```

All operations on atomic types in the Standard Library are guaranteed to be atomic (i.e., indivisible as observed by other threads), so even though the increment of `callCount` is a read-modify-write operation, you can rely on it proceeding atomically.

In view of the fact that operations on atomic variables are often less expensive than mutex acquisition and release, you may be tempted to lean on atomic variables more heavily than you should. For example, in a class caching an expensive-to-compute `int`, you might try to use a pair of atomic variables instead of a mutex:

```
class Widget {
public:
  …

  int magicValue() const
  {
```

```
    if (cacheValid) return cachedValue;
    else {
      auto val1 = expensiveComputation1();
      auto val2 = expensiveComputation2();
      cachedValue = val1 + val2;                  // uh oh, part 1
      cacheValid = true;                          // uh oh, part 2
      return cachedValue;
    }
  }

private:
  mutable std::atomic<bool> cacheValid{ false };
  mutable std::atomic<int> cachedValue;
};
```

This will work, but sometimes it will work a lot harder than it should. Consider:

- A thread calls `Widget::magicValue`, sees `cacheValid` as `false`, performs the two expensive computations and assigns their sum to `cachedValue`.
- At that point, a second thread calls `Widget::magicValue`, also sees `cacheValid` as `false` and thus carries out the same expensive computations that the first thread has just finished performing. (This "second thread" may in fact be *several* other threads.)

Such behavior is contrary to the goal of caching. Reversing the order of the assignments to `cachedValue` and `CacheValid` eliminates that problem, but the result is even worse:

```
class Widget {
public:
  …

  int magicValue() const
  {
    if (cacheValid) return cachedValue;
    else {
      auto val1 = expensiveComputation1();
      auto val2 = expensiveComputation2();
      cacheValid = true;                           // uh oh, part 1
      return cachedValue = val1 + val2;            // uh oh, part 2
    }
  }

  …

};
```

Imagine that `cacheValid` is `false`, and then:

- One thread calls `Widget::magicValue` and executes through the point where `cacheValid` is set to true.
- At that moment, a second thread calls `Widget::magicValue` and checks `cacheValid`. Seeing it `true`, the thread returns `cachedValue`, even though the first thread has not yet made an assignment to it. The returned value is therefore incorrect.

There's a lesson here. For a single variable or memory location requiring synchronization, use of a `std::atomic` is often adequate, but once you get to two or more variables or memory locations (e.g., distinct elements of a data structure) that require manipulation as a unit, you should reach for a mutex. For `Widget::magicValue`, that would look like this:

```
class Widget {
public:
  …

  int magicValue() const
  {
    std::lock_guard<std::mutex> guard(m);   // lock m

    if (cacheValid) return cachedValue;
    else {
      auto val1 = expensiveComputation1();
      auto val2 = expensiveComputation2();
      cachedValue = val1 + val2;
      cacheValid = true;
      return cachedValue;
    }
  }                                         // unlock m
  …

private:
  mutable std::mutex m;
  mutable int cachedValue;                  // no longer atomic
  mutable bool cacheValid { false };        // no longer atomic
};
```

Regardless of how you make your `const` member functions thread-safe, it's essential that you do. Callers of `const` member functions have a right to assume that their calls will succeed without their performing any synchronization. Implementations of `const` member functions achieve thread safety either by being bitwise `const` (i.e., not modifying any bits making up the value of the object) or by using some kind of internal synchronization, e.g., a mutex or an atomic variable.

Things to Remember

- Make `const` member functions thread safe.
- Use of atomic variables may offer better performance than a mutex, but they're generally only suited for manipulation of a single variable or memory location.

Item 16: Declare functions `noexcept` whenever possible.

In C++98, exception specifications were rather temperamental creatures. You had to summarize the exception types a function might emit, so if the function's implementation was modified, the exception specification might need revision, too. Changing an exception specification could break client code, because callers might be dependent on the original exception specification. Compilers typically offered no help in maintaining consistency among function implementations, exception specifications, and client code. Most programmers ultimately decided that C++98 exception specifications weren't worth the trouble.

Interest in the idea of exception specifications remained strong, however, and as work on C++ progressed, a consensus emerged that the truly meaningful information about a function's exception-emitting behavior was whether it had any. Black or white, either a function might emit an exception or it guaranteed that it wouldn't. This maybe-or-never dichotomy forms the basis of C++11's exception specifications, which essentially replace C++98's. (C++98-style exception specifications remain valid, but they're deprecated.) In C++11, `noexcept` is for functions that guarantee they won't emit an exception.

Whether a function should be so declared is fundamentally a matter of interface design. The exception-emitting behavior of a function is of key interest to clients. Callers can query a function's `noexcept` status, and the results of such a query can affect the exception safety or efficiency of the calling code. As such, whether a function is `noexcept` is as important a piece of information as whether a member function is `const`. Failure to declare a function `noexcept` when you know that it will never emit an exception is simply poor interface specification.

But there's an additional incentive to apply `noexcept` to functions that won't produce exceptions: it permits compilers to generate better object code. To understand why, it helps to examine the difference between the C++98 and C++11 ways of saying that a function won't emit exceptions. Consider a function `f` that promises callers they'll never receive an exception. The two ways of expressing that are:

```
int f(int x) throw();     // no exceptions from f: C++98 style
int f(int x) noexcept;    // no exceptions from f: C++11 style
```

If, at runtime, an exception leaves `f`, `f`'s exception specification is violated. With the C++98 approach, the call stack is unwound to `f`'s caller, and, after some actions not relevant here, program execution is terminated. With the C++11 approach, runtime behavior is a bit different: the stack is only *possibly* unwound before program execution is terminated.

The difference between unwinding the call stack and *possibly* unwinding it has a surprisingly large impact on code generation. In a `noexcept` function, optimizers need not keep the runtime stack in an unwindable state if an exception would propagate out of the function, nor must they ensure that objects in a `noexcept` function are destroyed in the inverse order of construction should an exception leave the function. The result is more opportunities for optimization, not only within the body of a `noexcept` function, but also at sites where the function is called. Such flexibility is present only for `noexcept` functions. Functions with "`throw()`" exception specifications lack it, as do functions with no exception specification at all. The situation can be summarized this way:

```
RetType function(params) noexcept;    // most optimizable
RetType function(params) throw();     // less optimizable
RetType function(params);             // less optimizable
```

This alone should provide sufficient motivation to declare functions `noexcept` whenever you can.

For some functions, the case is even stronger. The move operations are the preeminent example. Suppose you have a C++98 code base making use of `std::vector`s of `Widget`s. `Widget`s are added to the `std::vector`s from time to time, perhaps via `push_back`:

```
std::vector<Widget> vw;
…
Widget w;
…                          // work with w
vw.push_back(w);           // add w to vw
…
```

Assume this code works fine, and you have no interest in modifying it for C++11. However, you do want to take advantage of the fact that C++11's move semantics can improve the performance of legacy code when move-enabled types are involved. You therefore ensure that `Widget` has move operations, either by writing them yourself or by seeing to it that the conditions for their automatic generation are fulfilled (see Item 19).

When a new element is added to a `std::vector` via `push_back`, it's possible that the `std::vector` lacks space for it, i.e., that the `std::vector`'s size is equal to its capacity. When that happens, the `std::vector` allocates a new, larger, chunk of memory to hold its elements, and it transfers the elements from the existing chunk of memory to the new one. In C++98, the transfer was accomplished by copying each element from the old memory to the new memory, then destroying the originals in the old memory. This approach enabled `push_back` to offer the strong exception safety guarantee: if an exception was thrown during the copying of the elements, the state of the `std::vector` remained unchanged, because none of the elements in the original memory was destroyed until all elements had been successfully copied into the new memory.

In C++11, a natural optimization would be to replace the copying of `std::vector` elements with moves. Unfortunately, doing this runs the risk of violating `push_back`'s exception safety guarantee. If *n* elements have been moved from the old memory and an exception is thrown moving element *n+1*, the `push_back` operation can't run to completion. But the original `std::vector` has been modified: *n* of its elements have been moved from. Restoring their original state may not be possible, because attempting to move each object back into the original memory may itself yield an exception.

This is a serious problem, because the behavior of legacy code could depend on `push_back`'s strong exception safety guarantee. Therefore, C++11 implementations can't silently replace copy operations inside `push_back` with moves. They must continue to employ copy operations. *Unless*, that is, it's known that the move operations are guaranteed not to emit exceptions. In that case, replacing element copy operations inside `push_back` with move operations would be safe, and the only side effect would be improved performance.

`std::vector::push_back` takes advantage of this "move if you can, but copy if you must" strategy, and it's not the only function in the Standard Library that does. Other functions sporting the strong exception safety guarantee in C++98 (e.g., `std::vector::reserve`, `std::deque::insert`, etc.) behave the same way. All these functions replace calls to copy operations in C++98 with calls to move operations in C++11 if (and only if) the move operations are known to not emit exceptions. But how can a function know if a move operation won't produce an exception? The answer is obvious: it checks to see if the operation is declared `noexcept`.[*]

`swap` functions comprise another case where `noexcept` is particularly desirable. `swap` is a key component of many STL algorithm implementations, and it's commonly employed in copy assignment operators, too. Its widespread use renders the optimizations that `noexcept` affords especially worthwhile. Furthermore,

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[*] The checking is typically rather roundabout. Functions like `std::vector::push_back` call `std::move_if_noexcept`, a variation of `std::move` that conditionally casts to an rvalue (see Item 25), depending on whether the type's move constructor is `noexcept`. In turn, `std::move_if_noexcept` calls `std::is_nothrow_move_constructible`, and the value of this type trait is set by compilers, based on whether the move constructor has a `noexcept` (or `throw()`) designation.

whether swaps in the Standard Library are noexcept is sometimes dependent on whether user-defined swaps are noexcept. For example, the declarations for the Standard Library's swaps for arrays and for std::pair are:

```
template <class T, size_t N>
void swap(T (&a)[N],
          T (&b)[N]) noexcept(noexcept(swap(*a, *b)));

template <class T1, class T2>
struct pair {
  …
  void swap(pair& p) noexcept(noexcept(swap(first, p.first)) &&
                              noexcept(swap(second, p.second)));
  …
};
```

These functions are *conditionally noexcept*: whether they are noexcept depends on whether the expressions inside the noexcepts are noexcept. Given two arrays of Widget, for example, swapping them is noexcept only if swapping individual elements from the arrays is noexcept, i.e., if swap for Widget is noexcept. The author of Widget's swap thus determines whether swapping arrays of Widget is noexcept. That, in turn, determines whether other swaps, such as the one for arrays of arrays of Widget, are noexcept. Similarly, whether swapping two std::pair objects containing Widgets is noexcept depends on whether swap for Widgets is noexcept. The fact that swapping higher-level data structures can generally be noexcept only if swapping their lower-level constituents is noexcept is the reason why you should strive to offer noexcept swap functions.

By now, I hope you're excited about the optimization opportunities that noexcept affords. Alas, I must temper your enthusiasm. Optimization is important, but correctness is more important. I noted at the beginning of this Item that noexcept is part of a function's interface, so you should declare a function noexcept only if you are willing to commit to a noexcept implementation over the long term. If you declare a function noexcept and later regret that decision, your options are bleak. You can remove noexcept from the function's declaration (i.e., change its interface), thus running the risk of breaking client code. You can change the implementation such that an exception could escape, but keep the original (now incorrect) exception specification. If you do that, your program will be terminated if an exception tries to leave the function. Or you can resign yourself to your existing implementation, abandoning whatever motivated your desire to change the implementation in the first place. None of these options is appealing.

The fact of the matter is that most functions are *exception-neutral*. Such functions throw no exceptions themselves, but functions they call might emit one. When that happens, the calling function allows the emitted exception to pass through on its way to a handler further up the call chain. Exception-neutral functions are never `noexcept`, because they may emit such "just passing through" exceptions. Most functions, therefore, quite properly lack the `noexcept` designation.

Some functions, however, have natural implementations that emit no exceptions, and for a few more—notably the move operations and `swap`—being `noexcept` has such a significant payoff, it's worth implementing them in a `noexcept` manner if at all possible.[†] When you can honestly say that a function should never emit exceptions, you should definitely declare it `noexcept`.

Please note that I said some functions have *natural* `noexcept` implementations. Twisting a function's implementation to permit a `noexcept` declaration is the tail wagging the dog. Is putting the cart before the horse. Is not seeing the forest for the trees. Is…choose your favorite metaphor. If a straightforward function implementation might yield exceptions (e.g., by invoking a function that might throw), the hoops you'll jump through to hide that from callers (e.g., catching all exceptions and replacing them with status codes or special return values) will not only complicate your function's implementation, it will typically complicate code at call sites, too (e.g., code there may have to check for status codes or special return val-

[†] The prescribed declarations for move operations on containers in the Standard Library lack `noexcept`. However, implementers are permitted to strengthen exception specifications for Standard Library functions, and, in practice, it is common for at least some container move operations to be declared `noexcept`. That practice exemplifies this Item's advice. Having found that it's possible to write container move operations such that exceptions never need to be emitted, implementers often declare the operations `noexcept`, even though the Standard does not require them to do so.

ues). The runtime cost of those complications (e.g., extra branches, larger functions that put more pressure on instruction caches, etc.) could exceed any speedup you'd hope to achieve via `noexcept`, plus you'd be saddled with source code that's more difficult to comprehend and maintain. That'd hardly be exemplary software engineering. As a general rule, the only time it makes sense to actively search for a `noexcept` algorithm is when you're implementing the move functions or `swap`.

Two more points about `noexcept` functions are worth mentioning. First, in C++98, it was considered bad style to permit the memory deallocation functions (i.e., `operator delete` and `operator delete[]`) and destructors to emit exceptions, and in C++11, this style rule has been all but upgraded to a language rule. By default, all memory deallocation functions and all destructors—both user-defined and compiler-generated—are implicitly `noexcept`. There's thus no need to declare them `noexcept`. (Doing so doesn't hurt anything, it's just unconventional.) The only time a destructor is not implicitly `noexcept` is when a data member of the class (including inherited members and those contained inside other data members) is of a type that expressly states that its destructor may emit exceptions (e.g., declares it "`noexcept(false)`"). Such destructors are uncommon. There are none in the Standard Library.

Second, let me elaborate on my earlier observation that compilers typically offer no help in identifying inconsistencies between function implementations and their exception specifications. Consider this code, which is perfectly legal:

```
void setup();            // functions defined elsewhere
void cleanup();

void doWork() noexcept
{
  setup();               // set up work to be done

  …                      // do the actual work

  cleanup();             // perform cleanup actions
}
```

Here, `doWork` is declared `noexcept`, even though it calls the non-`noexcept` functions `setup` and `cleanup`. This seems contradictory, but it could be that `setup` and `cleanup` document that they never emit exceptions, even though they're not declared that way. There could be good reasons for their non-`noexcept` declarations. For example, they might be part of a library written in C. (Even functions from the C Standard Library that have been moved into the `std` namespace lack exception specifications, e.g., `std::strlen` isn't declared `noexcept`.) Or they could be part of a C++98 library that decided not to use C++98 exception specifications and hasn't yet been revised for C++11.

Because there are legitimate reasons for `noexcept` functions to rely on code lacking the `noexcept` guarantee, C++ permits such code, and compilers generally don't issue warnings about it.

Things to Remember

- `noexcept` is part of a function's interface, so callers may depend on it.
- `noexcept` functions are more optimizable than non-`noexcept` functions.
- `noexcept` is particularly valuable for the move operations and for `swap`.
- Most functions are exception-neutral rather than `noexcept`.

Item 17: Consider pass by value for cheap-to-move parameters that are always copied.

Some functions take parameters that are, at least under normal circumstances, always copied. Setters are a good example. Setter functions typically take a value and store it in a data member of an object. For such functions to operate with maximal efficiency, they should copy lvalue arguments and move rvalue arguments:

```
class Widget {
public:
  void setName(const std::string& newName)    // take lvalue;
  { name = newName; }                          // copy it

  void setName(std::string&& newName)          // take rvalue;
  { name = std::move(newName); }               // move it
  …

private:
  std::string name;
};
```

This works, but it requires writing two functions that do essentially the same thing. That chafes a bit: two functions to declare, two functions to implement, two functions to document, two functions to maintain. Ugh.

Furthermore, there will be two functions in the object code—something you might care about if you're concerned about your program's footprint. In this case, both functions will probably be inlined, and that's likely to eliminate any bloat issues related to the existence of two functions, but if these functions aren't inlined everywhere, you really will get two functions in your object code. (Inlining might not occur due to the creation of pointers to these functions, calls to these functions occurring inside complicated calling contexts, or building the system with inlining disabled.)

An alternative approach is to make `setName` a template function taking a universal reference (see Item 26):

```
class Widget {
public:
  template<typename T>
  void setName(T&& newName)            // take lvalues and
  { name = std::forward<T>(newName); }  // rvalues; copy
                                        // lvalues, move rvalues
  …

};
```

This reduces the source code you have to deal with, though, assuming this function is called with both lvalues and rvalues, there will still be two functions in the object code. (The template will be instantiated differently for lvalues and rvalues.) Furthermore, the use of universal references has drawbacks. As Item 32 explains, not all argument types can be passed via universal reference, and, as noted in Item 29, if clients pass improper argument types to functions taking universal references, compiler error messages can be, er, challenging.

Wouldn’t it be nice if there were a way to write functions like `setName` such that lvalues were copied, rvalues were moved, there was only one function to deal with (in both source and object code), and the idiosyncrasies of universal references were avoided? As it happens, there is. All you have to do is abandon one of the very first rules you probably learned as a C++ programmer. That rule was to avoid passing objects by value. For parameters like newName in functions like setName, pass by value may be exactly what you want.

Before we discuss *why* pass-by-value is probably a good fit for newName and setName, let's see how it would be implemented.

```
class Widget {
public:
  void setName(std::string newName)    // take lvalue or
  { name = std::move(newName); }       // rvalue; move it

  …

};
```

The only non-obvious part of this code is the application of std::move to the parameter, newName. Typically, std::move is used with rvalue references (see Item 27), but in this case, we know that (1) newName is a completely independent object from whatever the caller passed in, so changing newName won't affect callers and (2) this is the final use of newName, so moving from it won't have any impact on the rest of the function.

The fact that there's only one setName function explains how we avoid code duplication—both in the source file as well as the corresponding object file. We're not using a universal reference, so this approach doesn't lead to odd failure cases or confounding error messages. The question remaining regards the efficiency of this design. We're passing *by value*. Isn't that expensive?

In C++98, it was a reasonable bet that it was, because no matter what callers passed in, the parameter newName would be created by *copy construction*. In C++11, newName will be copy-constructed only for lvalues. For rvalues, it will be *move-constructed*. Here, look:

```
Widget w;

…

std::string widgetID("Bart");

w.setName(widgetID);                 // call setName with lvalue

…
```

```
w.setName(widgetID + "Jenne");      // call setName with rvalue
                                    // (see below)
```

In the first call to `setName` (when `widgetID` is passed), the parameter `newName` is initialized with an lvalue. `newName` is thus copy-constructed, just like it would be in C++98. In the second call, `newName` is initialized with the `std::string` object resulting from a call to `operator+` for `std::string` (i.e., the append operation). That object is an rvalue, and `newName` is therefore move-constructed.

In sum, when callers pass lvalues, they're copied into `newName`, and when callers pass rvalues, they're moved into `newName`, just like we want. Neat, huh?

“It can’t be that simple,” I hear you thinking. “There’s got to be a catch.” Generally, there’s not, but there are some conditions you need to keep in mind. Doing that will be easier if we recap the three versions of `setName` we’ve considered:

```
class Widget {                                        // Approach 1:
public:                                               // overload for
  void setName(const std::string& newName)            // lvalues and
  { name = newName; }                                 // rvalues

  void setName(std::string&& newName)
  { name = std::move(newName); }
  …

private:
  std::string name;
};

class Widget {                                        // Approach 2:
public:                                               // use universal
  template<typename T>                                // reference
  void setName(T&& newName)
  { name = std::forward<T>(newName); }
  …
};

class Widget {                                        // Approach 3:
public:                                               // pass by value
  void setName(std::string newName)
  { name = std::move(newName); }
  …
};
```

And here are the two calling scenarios we’ve examined:

```
Widget w;
…
std::string widgetID("Bart");

w.setName(widgetID);                          // pass lvalue
…
w.setName(widgetID + "Jenne");                // pass rvalue
```

Now consider the cost, in terms of copy and move operations, of setting a `Widget`'s name for the two calling scenarios and each of the three `setName` implementations we've discussed:

- **Overloading:** Regardless of whether an lvalue or an rvalue is passed, the caller's argument is bound to a reference called `newName`. That costs nothing, in terms of copy and move operations. In the lvalue overload, `newName` is copied into `Widget::name`. In the rvalue overload, it's moved. Cost summary: 1 copy for lvalues, 1 move for rvalues.

- **Using a universal reference:** As with overloading, the caller's argument is bound to the reference `newName`. This is a no-cost operation. Due to the use of `std::forward` (see Item 25) lvalue arguments are copied into `Widget::name`, while rvalue arguments are moved. The cost summary is the same as with overloading: 1 copy for lvalues, 1 move for rvalues. This is to be expected. A template taking a universal reference parameter instantiates into two functions, one taking an lvalue reference parameter and one taking its rvalue reference counterpart.

- **Passing by value:** Regardless of whether an lvalue or an rvalue is passed, the parameter `newName` must be constructed. If an lvalue is passed, this costs a copy operation. If an rvalue is passed, it typically costs a move. In the body of the function, `newName` is then unconditionally moved into `Widget::name`. The cost summary is thus 1 copy plus 1 move for lvalues, and 2 moves for rvalues.

Look again at this Item's title:

> Consider pass by value for cheap-to-move parameters that are always copied.

It's worded the way it is for a reason. Three reasons, in fact.

First, you should only *consider* using pass by value. Yes, it requires writing only one function. Yes, it generates only one function in the object code. Yes, it avoids the interface issues associated with universal references (i.e., failure cases and unpleasant error messages). But it has a higher cost than the alternatives. In particular, it costs an extra move for both lvalue and rvalue arguments.

Which brings me to the second caveat. Consider pass by value only *for cheap-to-move parameters*. When moves are cheap, the cost of the extra move is likely to be negligible. But when moves are not cheap, that extra move can incur an expense you can't afford. Item 31 explains that not all types are cheap to move—not even all types in the Standard Library. When moves are not cheap, performing an unnecessary move is analogous to performing an unnecessary copy, and the importance of avoiding unnecessary copy operations is what lead to the C++98 rule about avoiding pass by value in the first place!

Finally, you should consider pass by value only for parameters that are *always copied*. For setter functions (as well as for constructors taking initialization arguments for an object's data members), this condition is typically fulfilled, but consider a function that adds a value to a data structure only if the value satisfies a constraint. Using pass by value, it could be written like this:

```
class Widget {
public:
  bool insert(std::string s)
  {
    if ((s.length() >= MinLen) && (s.length() <= MaxLen)) {
      values.insert(s);
      return true;
    }
    else {
      return false;
    }
  }

  …

private:
  std::unordered_set<std::string> values;
};
```

In this function, we'll pay to construct `s`, even if it's not copied, e.g., if the value passed in is too short or too long. For example, given this code,

```
Widget w;

std::string finalGWTWWords("Tomorrow is another day");
…
auto status = w.insert(finalGWTWWords);
```

we'll pay to copy `finalGWTWWords`, even if its length is less than `MinLen` or greater than `MaxLen`. (Note that we'll really pay for a copy, not a move, because `finalGWTWWords` is an lvalue.) This is hardly an efficiency win.

Even when you're dealing with a function performing an unconditional copy on a type that's known to be cheap to move, there are times when pass by value may not be a suitable design decision. For code that has to be as fast as possible, avoiding even cheap moves can be important. Besides, it's not always clear how many moves are truly being performed. In our `Widget::setName` example, pass by value incurs only a single extra move operation, but suppose that `Widget::setName` called `Widget::validateName`, and this function also passed by value. (Presumably it has a reason for always copying its parameter, e.g., to store it in a data structure of all values it validates.) And suppose that `validateName` called a third function that also passed by value…

You can see where this is headed. When there are chains of function calls, each of which employs pass by value because "it costs only one inexpensive move," the cost for the entire chain of calls may not be something you can tolerate. Using by-reference parameter passing (as is the case with lvalue and rvalue overloads and the use of universal references), chains of calls don't incur this kind of accumulated overhead.

If you were paying particularly close attention during this Item, you probably noticed my comment that there's "generally" no catch to using pass by value, provided the constraints we've discussed are satisfied, i.e., that moving the parameter type is cheap and that the parameter is unconditionally copied. "Generally?," you probably wondered. "Generally?!" "What's up with 'generally'?!"

What's up with "generally" is *the slicing problem*. Pass by value is susceptible to it. Pass by reference isn't. This is well-trod C++98 ground, so I won't dwell on it, but if you have a function that is designed to accept a parameter of a base class type *or any type derived from it*, you don't want to declare a pass-by-value parameter of that type, because you'll "slice off" the derived-class characteristics of any derived type object that may be passed in:

```
class Widget { … };                              // base class

class SpecialWidget: public Widget { … };    // derived class

void processWidget(Widget w);   // func for any kind of Widget,
                                // including derived types;
…                               // suffers from slicing problem

SpecialWidget sw;

…

processWidget(sw);              // processWidget sees a
                                // Widget, not a SpecialWidget!
```

If you're not familiar with the slicing problem, search engines and the Internet are your friend; there's lots of information available. You'll find that the existence of the slicing problem is another reason (on top of the efficiency hit) why pass by value has a shady reputation in C++98. There are good reasons why one of the first things you probably learned about C++ programming was to avoid passing objects by value.

C++11 doesn't fundamentally change the C++98 wisdom regarding pass by value. In general, pass by value still entails a performance hit you'd prefer to avoid, and pass by value can still lead to the slicing problem. What's new in C++11 is the distinction between lvalue and rvalue arguments. Declaring functions that take advantage of move semantics for rvalues requires either writing multiple functions (i.e., overloading for lvalues and rvalues) or using universal references, both of which have drawbacks. For the special case of cheap-to-move types passed to functions that always copy them and where slicing is not a concern, pass by value offers an easy-to-implement alternative that's nearly as efficient as its pass-by-reference competitors, but avoids their disadvantages.

Things to Remember

- For cheap-to-move parameters that are unconditionally copied, pass by value is nearly as efficient as pass by reference, it's easier to implement, and it can generate less object code.
- Pass by value is subject to the slicing problem, so it's typically inappropriate for base class parameter types.

Item 18: Consider emplacement instead of insertion.

If you have a container holding, say, `std::strings`, it seems logical that when you add a new element via an insertion function (i.e., `insert`, `push_front`, `push_back`, or, for `std::forward_list`, `insert_after`), the type of element you'll pass to the function will be `std::string`. After all, that's what the container has in it.

Logical though this may be, it's not always true. Consider this code:

```
std::vector<std::string> vs;         // container of std::string

vs.push_back("xyzzy");               // add string literal
```

Here, the container holds `std::strings`, but what you have in hand—what you're actually trying to `push_back`—is a string literal (i.e., a sequence of characters inside quotes). A string literal is not a `std::string`, and that means that the argument you're passing to `push_back` is not of the type held by the container.

`push_back` for `std::vector` is overloaded for lvalues and rvalues as follows:

```
template <class T,                            // from the C++11
          class Allocator = allocator<T> >    // Standard
class vector {
public:
  …
  void push_back(const T& x);                 // insert lvalue
  void push_back(T&& x);                      // insert rvalue
  …
};
```

In the call

```
vs.push_back("xyzzy");
```

compilers see a mismatch between the type of the argument (const char[6]—see Item 1) and the type of the parameter taken by push_back (std::string). They address the mismatch by generating code to create a temporary std::string object from the string literal, and they pass that temporary object to push_back. In other words, they treat the call as if it had been written like this:

```
vs.push_back(std::string("xyzzy"));  // create temp. std::string
                                     // and pass it to push_back
```

The code compiles and runs, and everybody goes home happy. Everybody except the performance freaks, that is, because the performance freaks recognize that this code isn't as efficient as it should be.

To create a new element in a container of std::strings, they understand, a std::string constructor is going to have to be called, but the code above doesn't call just one constructor. It calls two. Furthermore, it tacks on a call to the std::string destructor, which seems not just gratuitous, but downright, well, tacky.

Here's what happens at runtime in the call to push_back:

1. A temporary std::string object is created from the string literal, "xyzzy". This object has no name; we'll call it *temp*. Construction of *temp* is the first std::string construction. Because it's a temporary object, *temp* is an rvalue.

2. *temp* is passed to the rvalue overload for push_back, where it's bound to the rvalue reference parameter, x. A copy of x is then constructed in the memory for the std::vector. This construction—the *second* one—is what actually creates a new object inside the std::vector. (The constructor that's used to copy x into the std::vector is the move constructor, because x, being an rvalue reference, gets cast to an rvalue before it's copied. For information about the casting of rvalue reference parameters to rvalues, see Item 27.)

3. When push_back returns, *temp* is destroyed, thus calling the std::string destructor.

The performance freaks can't help but notice that if there were a way to take the string literal and pass it directly to the code in step 2 that constructs the `std::string` object inside the `std::vector`, i.e., that performs the only construction that's actually required, we could avoid constructing and destroying *temp*. That would be maximally efficient, and even the performance freaks would go home happy.

Because you're a C++ programmer, there's an above-average chance you're a performance freak. If you're not, you're still probably sympathetic to their point of view. (If you're not at all interested in performance, shouldn't you be in the Python room down the hall?) So I'm pleased to tell you that there is a way to do exactly what is needed for maximal efficiency in the call to `push_back`. It's to not call `push_back`. `push_back` is the wrong function. The function you're looking for is `emplace_back`.

`emplace_back` does exactly what we want: it uses whatever argument is passed to it to construct a new `std::string` directly inside the `std::vector`. No temporaries are involved:

```
vs.emplace_back("xyzzy");    // construct std::string inside
                             // vs directly from "xyzzy"
```

`emplace_back` uses perfect forwarding, so, as long as you don't bump into one of perfect forwarding's limitations (see Item 32), you can pass any number of arguments of any combination of types through `emplace_back`. For example, if you'd like to create a `std::string` in `vs` via the `std::string` constructor taking a character and a repeat count, this would do it:

```
vs.emplace_back(50, 'x');    // insert std::string consisting
                             // of 50 'x' characters
```

`emplace_back` is available for every standard container that supports `push_back`. Similarly, every standard container that supports `push_front` supports `emplace_front`. And every standard container that supports `insert` (which is all but `std::forward_list` and `std::array`) supports `emplace`. The associative containers offer `emplace_hint` to complement their `insert` functions that take a "hint" iterator, and `std::forward_list` has `emplace_after` to match its `insert_after`.

All emplacement functions work the same way as emplace_back: they perfect-forward their arguments to the code that creates a new object in the container. All avoid the cost of type conversions that arise through use of the insertion functions when the type of the passed-in argument doesn't match the type stored in the container. Hence:

```
std::vector<std::string> vs;         // as before
…
auto midPoint = vs.begin() + vs.size() / 2;

vs.insert(midPoint, "hello");        // create temp std::string,
                                     // move temp into vector,
…                                    // destroy temp

midPoint =                           // recompute midpoint
  vs.begin() + vs.size() / 2;

vs.emplace(midPoint, "world");       // create std::string
                                     // directly in vector
```

One of the nicest things about the emplacement functions is that when the type passed is the same as the type stored in the container (i.e., when there's no type mismatch), they're no less efficient than calling their insertion counterparts. This means that you can safely fall into the habit of using the emplacement functions all the time. They're often more efficient than their insert/push_back/push_front siblings, and they're never less efficient.

At the same time, emplacement functions have a couple of sharp edges, and if you're not careful, you can cut yourself. For example, suppose you have a container of std::shared_ptr<Widget>s,

```
std::list<std::shared_ptr<Widget>> ptrs;
```

and you want to add a std::shared_ptr to a Widget that should be released via a custom deleter (see Item 21). Item 23 explains that you should use std::make_shared to create std::shared_ptrs whenever you can, but it also concedes that there are situations where you can't. One such situation is when you want to specify a custom deleter. In that case, you must call new directly to get the raw pointer to be managed by the std::shared_ptr.

If the custom deleter is this function,

```
void killWidget(Widget* pWidget);
```

the code using an insertion function could look like this:

```
ptrs.push_back(std::shared_ptr<Widget>(new Widget, killWidget));
```

It could also look like this, though the meaning would be the same:

```
ptrs.push_back( { new Widget, killWidget } );
```

Either way, a temporary `std::shared_ptr` would be constructed before calling `push_back`. `push_back`'s parameter is a reference to a `std::shared_ptr`, so there has to be a `std::shared_ptr` for this parameter to refer to.

The creation of the temporary `std::shared_ptr` is what `emplace_back` would avoid, but in this case, that temporary is worth far more than it costs. Consider the following potential sequence of events:

1. In either call above, a temporary `std::shared_ptr<Widget>` is constructed to hold the raw pointer resulting from "`new Widget`". Call this object *p*.

2. `push_back` takes *p* by reference. During allocation of a list node to hold a copy of *p*, an out-of-memory exception gets thrown.

3. As the exception propagates out of `push_back`, *p* is destroyed. Being the sole `std::shared_ptr` referring to the `Widget` it's managing, it automatically releases that `Widget`, in this case by calling `killWidget`.

Even though an exception occurred, nothing leaks: the `Widget` created via "`new Widget`" in the call to `push_back` is released in the destructor of the `std::shared_ptr` that was created to manage it (*p*). Life is good.

But now consider what happens if `emplace_back` is called instead of `push_back`:

```
ptrs.emplace_back(new Widget, killWidget);
```

1. The raw pointer resulting from "`new Widget`" is perfect-forwarded to the point inside `push_back` where a list node is to be allocated. That allocation fails, and an out-of-memory exception is thrown.

2. As the exception propagates out of `push_back`, the raw pointer that was the only way to get at the `Widget` on the heap is lost. That `Widget` (and any resources it owns) is leaked.

In this scenario, life is *not* good, and the fault doesn't lie with `std::shared_ptr`. The same kind of problem can arise through the use of `std::unique_ptr` with a custom deleter. Fundamentally, the effectiveness of resource-managing classes like `std::shared_ptr` and `std::unique_ptr` is predicated on resources (such as raw pointers returned from `new`) being *immediately* passed to the constructors of the resource-managing objects. The fact that functions like `std::make_shared` and `std::make_unique` automate this is one of the reasons they're so important.

In calls to the insertion functions of containers holding resource-managing objects (e.g., `std::list<std::shared_ptr<Widget>>`), the functions' parameter types generally ensure that nothing gets between acquisition of a resource (e.g., use of naked `new`) and construction of the object managing the resource. In the emplacement functions, perfect-forwarding defers the creation of the resource-managing objects until they can be constructed in the container's memory, and that opens a window during which exceptions can lead to resource leaks. When working with containers of resource-managing objects, you must take care to ensure that if you choose an emplacement function over its insertion counterpart, you're not paying for improved code efficiency with diminished exception safety.

The fundamental difference between insertion and emplacement functions is that insertion functions take *objects to be inserted*, while emplacement functions take *constructor arguments* for objects to be inserted. One consequence of this—the one driving this Item—is that emplacement functions can be more efficient, but a second consequence is that you may get less benefit from `explicit` constructors than you expect. For example, suppose, in celebration of C++11's support for regular expressions, you create a container of regular expression objects:

```
std::vector<std::regex> regexes;
```

Distracted by your colleagues' quarreling over the ideal number of times per day to check one's Facebook account, you accidently write the following seemingly meaningless code:

```
regexes.emplace_back(nullptr);     // add nullptr to container
                                   // of regexes?
```

You don't notice the error as you type it, and your compilers accept the code without complaint, so you end up wasting a bunch of time debugging. At some point, you discover that you appear to have inserted a null pointer into your container of regular expressions. But how is that possible? Pointers aren't regular expressions, and if you tried to do something like this,

```
std::regex r = nullptr;            // error! won't compile
```

compilers would reject your code. Interestingly, they would also reject it if you called `push_back` instead of `emplace_back`:

```
regexes.push_back(nullptr);        // error! won't compile
```

The curious behavior you're experiencing stems from the fact that `std::regex` objects can be constructed from character strings, i.e., from `const char*` pointers. That's what makes useful code like this legal:

```
std::regex upperCaseWord("[A-Z]+");
```

However, because `nullptr` implicitly converts to all pointer types, the `emplace_back` call that unexpectedly compiles is treated by compilers more or less as if you'd written this:

```
regexes.emplace_back(static_cast<const char*>(nullptr));
```

Creation of a `std::regex` from a character string can exact a comparatively large runtime cost, so, to minimize the likelihood that such an expense will be incurred unintentionally, the `std::regex` constructor taking a `const char*` pointer is `explicit`. That's why these lines don't compile:

```
std::regex r = nullptr;            // error! won't compile

regexes.push_back(nullptr);        // error! won't compile
```

In both cases, we're requesting an implicit conversion from a pointer to a `std::regex`, and the `explicit`ness of that constructor prevents such conversions.

In the call to emplace_back, however, we're not claiming to pass a std::regex object. Instead, we're passing a *constructor argument* for a std::regex object. That's not considered an implicit conversion request. Rather, it's viewed as if you'd written this code:

```
std::regex r(nullptr);           // compiles
```

If the laconic comment "compiles" suggests a lack of enthusiasm, that's good, because this code, though it will compile, has undefined behavior. The std::regex constructor taking a const char* pointer requires that the pointed-to string comprise a valid regular expression, and the null pointer fails that requirement. If you write and compile such code, the best you can hope for is that it crashes at runtime. If you're not so lucky, you and your debugger could be in for a special bonding experience.

Setting aside push_back, emplace_back, and bonding for a moment, notice how these very similar initialization syntaxes yield different results:

```
std::regex r1 = nullptr;         // error! won't compile
std::regex r2(nullptr);          // compiles
```

In the official terminology of the Standard, there are two kinds of initialization: *copy initialization* and *direct initialization*. The syntax used to initialize r1 (employing the equals-sign) is defined to be copy initialization. The syntax used to initialize r2 (with the parentheses, although braces may also be used) is defined to be direct initialization. Copy initialization is not permitted to use explicit constructors. Direct initialization is. That's why the line initializing r1 doesn't compile, but the line initializing r2 does.

But back to push_back and emplace_back (and, more generally, the insertion functions versus the emplacement functions). Insertion functions employ copy initialization, which means they can't make use of explicit constructors. Emplacement functions use direct initialization, so they can. Hence:

```
regexes.emplace_back(nullptr);  // fine, direct init permits
                                // use of explicit
                                // pointer→std::regex ctor
```

```
regexes.push_back(nullptr);       // error! copy init forbids
                                  // use of explicit
                                  // pointer→std::regex ctor
```

The lesson to take away is that when you use an emplacement function, be especially careful to make sure you're passing the correct arguments, because even `explicit` constructors will be considered by compilers as they try to find a way to interpret your code as valid.

Things to Remember

- Emplacement functions are often more efficient than their insertion counterparts, and they're never less efficient.
- For containers of resource-managing objects, emplacement functions may suffer resource leaks that would not arise through use of insertion functions.
- Emplacement functions may perform type conversions that would be rejected by insertion functions.

Item 19: Understand special member function generation.

In official C++ parlance, the "special member functions" are the ones that C++ generates on its own. C++98 has four such functions: the default constructor, the destructor, the copy constructor, and the copy assignment operator. There's fine print, of course. These functions are generated only if they're needed, i.e., if some code uses them without their being expressly declared in the class. A default constructor is generated only if the class declares no constructors at all. (This prevents compilers from creating a default constructor for a class where you've specified that constructor arguments are required.) Generated special member functions are implicitly `inline`, and they're nonvirtual unless the function in question is a destructor in a derived class inheriting from a base class with a virtual destructor. In that case, the compiler-generated destructor is also virtual.

But you already know these things. Yes, yes, ancient history: Mesopotamia, the Shang dynasty, FORTRAN, C++98. But times have changed, and the rules for special member function generation in C++ have changed with them. It's important to be aware of the new rules, because few things are as central to effective C++ programming as knowing when compilers silently insert member functions into your classes.

As of C++11, the special member functions club has two more inductees: the move constructor and the move assignment operator. For a class `Widget`, their signatures are:

```
class Widget {
public:
  …
  Widget(Widget&& rhs);              // move constructor

  Widget& operator=(Widget&& rhs);   // move assignment operator
  …
};
```

The rules governing their generation and behavior are analogous to those for their copying siblings. The move operations are generated only if they're needed, and if they are generated, they perform "memberwise moves" on the data members of the class. That means that the move constructor move-constructs each data member of the class from the corresponding member of its parameter, `rhs`, and the move assignment operator move-assigns each data member of the class from the corresponding member of its parameter, `rhs`. Furthermore, the move constructor move-constructs its base class parts (if there are any), and the move assignment operator move-assigns its base class parts, too.

Now, when I refer to a move operation move-constructing or move-assigning a data member or base class, there is no guarantee that a move will actually take place. "Memberwise moves" are, in reality, more like memberwise move *requests*, because types that aren't *move-enabled* (i.e., that offer no special support for move operations, e.g., most C++98 legacy classes) will be "moved" via their copy operations. The heart of each memberwise "move" is application of `std::move` to the source to be moved from, and the result of this application is used during function overload resolution to determine whether a move or a copy should be performed. Item 25 covers this process in detail. For this Item, simply remember that a memberwise move consists of move operations on data members and base classes that support move operations, but for data members and base classes that offer only copy operations, a memberwise "move" entails making a copy.

As is the case with the copy operations, the move operations aren't generated if you declare them yourself. However, the precise conditions under which they are generated differ a bit from those for the copy operations.

The two copy operations are independent: declaring one doesn't prevent compilers from generating the other. So if you declare a copy constructor, but no copy assignment operator, then write code that requires copy assignment, compilers will generate the copy assignment operator for you. Similarly, if you declare a copy assignment operator, but no copy constructor, yet your code requires copy construction, compilers will generate the copy constructor for you. That was true in C++98, and it's still true in C++11.

The two move operations are not independent. If you declare either, that prevents compilers from generating the other. The rationale is that if you declare, say, a move constructor for your class, you're indicating that there's something about how move construction should be implemented that's different from the default memberwise move that compilers would generate. And if there's something wrong with memberwise move construction, compilers reason, there'd probably be something wrong with memberwise move assignment, too. So declaring a move constructor prevents a move assignment operator from being generated, and declaring a move assignment operator prevents compilers from generating a move constructor.

Furthermore, move operations won't be generated for any class that explicitly declares a copy operation. The justification is that declaring a copy operation (construction or assignment) indicates that the normal approach to copying an object (memberwise copy) isn't appropriate for the class, and compilers figure that if memberwise copy isn't appropriate for the copy operations, memberwise move probably isn't appropriate for the move operations.

This goes in the other direction, too. Declaring a move operation (construction or assignment) in a class prevents compilers from generating copy operations. After all, if memberwise move isn't the proper way to move an object, there's no reason to expect that memberwise copy is the proper way to copy it. This may sound like it could break C++98 code, because the conditions under which the copy operations are generated are more constrained in C++11 than in C++98, but further reflection reveals that this is not the case. C++98 code can't have move operations, because there was no such thing as "moving" objects in C++98. The only way a legacy class can have user-declared move operations is if they were added for C++11, and classes that are modified to take advantage of move semantics have to play by the C++11 rules for special member function generation.

Perhaps you've heard of a guideline known as the *Rule of Three*. The Rule of Three emerged fairly early in the C++ era (the early 1990s), and it states that if you declare any of a copy constructor, copy assignment operator, or destructor, you should declare all three. It grew out of the observation that the need to take over the meaning of a copy operation almost always stemmed from the class performing some kind of resource management, and that almost always implied that (1) whatever resource management was being done in one copy operation probably needed to be done in the other copy operation and (2) the class destructor would also be participating in management of the resource (e.g., releasing it). The classic resource to be managed was memory, and this is why all the Standard Library classes that manage memory (e.g., the STL containers that perform dynamic memory management) all declare "the big three:" both copy operations and a destructor.

A consequence of the Rule of Three is that the presence of a user-declared destructor indicates that simple memberwise copy is unlikely to be appropriate for the copying operations in the class. That, in turn, suggests that if a class declares a destructor, the copy operations probably shouldn't be automatically generated, because they wouldn't do the right thing. At the time C++98 was adopted, the significance of this line of reasoning was not fully appreciated, so in C++98, the existence of a user-declared destructor had no impact on compilers' willingness to generate copy operations. That continues to be the case in C++11, but only because restricting the conditions under which the copy operations are generated would break too much legacy code.

The reasoning behind the Rule of Three remains valid, however, and combined with the observation that declaration of a copy operation precludes the implicit generation of the move operations, C++11 does *not* generate move operations for a class with a user-declared destructor.

So move operations are generated for classes (when needed) only if all of these three things are true:

- No copy operations are declared in the class.
- No move operations are declared in the class.
- No destructor is declared in the class.

At some point, analogous rules may be extended to the copy operations, because C++11 *deprecates* the automatic generation of copy operations for classes declaring copy operations or a destructor. This puts such function generation on death row. Feature deprecation is the Standard's way of issuing a warning that behavior valid in the current Standard is officially frowned upon, and the feature may be removed in a future Standard.

In practice, this means that if you have code that depends on the generation of copy operations in classes declaring a destructor or one of the copy operations, you should think about upgrading these classes to eliminate the dependence. Provided the behavior of the compiler-generated functions is correct (i.e, if memberwise copying of the class's nonstatic data members is what you want), your job is easy, because C++11's "= `default`" lets you say that explicitly:

```
class Widget {
public:
  …
  ~Widget();                              // user-declared dtor

  …                                       // default copy-ctor
  Widget(const Widget&) = default;        // behavior is OK

  Widget&                                 // default copy-assign
    operator=(const Widget&) = default;   // behavior is OK
  …
};
```

In fact, you may want to adopt a policy of manually declaring all the copy and move functions you want your class to support, then using "= `default`" to force compilers to generate the default implementations for the functions where these implementations would be appropriate. It's a bit more work than having compilers silently generate those functions on their own, but it makes your intentions clearer, and it can help you side-step some fairly subtle bugs. For example, suppose you have a class representing a string table, i.e., a data structure that permits fast lookups of string values via an integer ID:

```
class StringTable {
public:
  StringTable() {}
  …                  // functions for insertion, erasure, lookup,
                     // etc., but no copy/move/dtor functionality

private:
  std::map<int, std::string> values;
};
```

Assuming that the class declares no copy operations, no move operations, and no destructor, compilers will automatically generate these functions if they are used. That's very convenient.

But suppose that sometime later, it's decided that logging the default construction and the destruction of such objects would be useful. Adding that functionality is easy:

```
class StringTable {
public:
  StringTable()
  { makeLogEntry("Creating StringTable object"); }     // added

  ~StringTable()                                       // also
  { makeLogEntry("Destroying StringTable object"); }   // added

  …                                    // other funcs as before

private:
  std::map<int, std::string> values;    // as before
};
```

This seems innocuous, but it has a potentially significant side effect: it prevents the move operations from being generated. To be specific, the existence of the user-declared destructor precludes their generation. That's why I've highlighted only the destructor declaration above. The modification to the default constructor and the body of the destructor is irrelevant for this discussion.

Although the addition of the destructor prevents the move operations from coming into existence, generation of the class's copy operations is unaffected. Your code is therefore likely to compile, run, and pass all your functional testing. That includes testing its move functionality, because even though this class is no longer move-enabled, requests to move it will compile and run. Such requests will, as noted earlier in this Item, cause copies to be made. Which means that code "moving" `StringTable` objects actually copies them, i.e., copies the underlying `std::vector<std::string>` objects. And copying a `std::vector<std::string>` is likely to be *orders of magnitude* slower than moving it. The simple act of adding a destructor to the class could thereby have introduced a significant performance problem!

Fixing the problem is easy: just tell your compilers to start generating the move operations again:

```
class StringTable {
public:
  StringTable() { … }                                 // as before
  ~StringTable() { … }                                // as before

  StringTable(StringTable&&) = default;               // move ctor

  StringTable& operator=(StringTable&&) = default;    // move op=

  …                                      // other funcs as before

private:
  std::map<int, std::string> values;    // as before
};
```

But as long as you're doing that, you might as well do the same for the copy operations. That clearly expresses that you desire the compiler-generated copy behavior for this class, and it also future-proofs the class against the day when copy operations are no longer created for classes with user-declared destructors. The result looks like this:

```
class StringTable {
public:
  StringTable() { … }                                 // as before
  ~StringTable() { … }                                // as before

  StringTable(const StringTable&) = default;          // copy ctor
  StringTable(StringTable&&) = default;               // move ctor
```

```
  StringTable&
    operator=(const StringTable&) = default;        // copy op=
  StringTable& operator=(StringTable&&) = default;  // move op=

  …                                                 // as before

private:
  std::map<int, std::string> values;                // as before
};
```

Now, having endured my endless blathering about the rules governing the copy and move operations in C++11, you may wonder when I'll turn my attention to the two other special member functions, the default constructor and the destructor. That time is now, but only for this sentence, because nothing has changed for these member functions: the rules in C++11 are the same as in C++98.

The C++11 rules governing the special member functions are thus:

- **Default constructor**: Same rules as C++98. Generated only if the class contains no user-declared constructors.
- **Destructor**: Same rules as C++98. Virtual only if a base class destructor is virtual.
- **Copy constructor**: Same runtime behavior as C++98. Performs memberwise copying of (nonstatic) class data members. Generated only if the class contains neither a user-declared copy constructor nor any move operations. Generation of this function in a class with a user-declared copy assignment operator or destructor is deprecated.
- **Copy assignment operator**: Same runtime behavior as C++98. Performs memberwise copying of (nonstatic) class data members. Generated only if the class contains neither a user-declared copy assignment operator nor any move operations. Generation of this function in a class with a user-declared copy constructor or destructor is deprecated.
- **Move constructor** and **move assignment operator**: Performs memberwise moving of (nonstatic) class data members. Generated only if the class contains neither user-declared copy operations, move operations, nor destructor.

Note, by the way, that there's nothing in the rules about the existence of a member function *template* preventing compilers from generating the special member functions. That means that if `Widget` looks like this,

```
class Widget {
  …
  template<typename T>                // copy-construct Widget
  Widget(const T& rhs);               // from anything

  template<typename T>                // copy-assign Widget
  Widget& operator=(const T& rhs);    // from anything
  …
};
```

compilers will still generate copy and move operations for `Widget` (assuming the usual conditions governing their generation are fulfilled), even though these templates could be instantiated to produce the signatures for the copy constructor and copy assignment operator. (That would be the case when `T` is `Widget`.) In all likelihood, this will strike you as an edge case barely worth acknowledging, but there's a reason I'm mentioning it. As Item 28 explains, it can have important consequences.

Things to Remember

- The special member functions are those compilers may generate on their own: the default constructor, destructor, copy operations, and move operations.
- Move operations are generated only for classes lacking explicitly-declared move operations, copy operations, and a destructor.
- The copy constructor is generated only for classes lacking an explicitly-declared copy constructor and the move operations. The copy assignment operator is generated only for classes lacking an explicitly-declared copy assignment operator and the move operations. Generation of the copy operations in classes with an explicitly-declared destructor is deprecated,
- Member function templates never suppress generation of special member functions.

Chapter 4 Smart Pointers

Poets and songwriters have a thing about love. And sometimes about counting. Occasionally both. Inspired by the rather different takes on love and counting by Elizabeth Barrett Browning (“How do I love thee? Let me count the ways.”) and Paul Simon (“There must be 50 ways to leave your lover”), we might try to enumerate the reasons why a raw pointer is hard to love:

1. Its declaration doesn’t indicate whether it points to a single object or to an array.

2. Its declaration reveals nothing about whether you should destroy what it points to when you’re done using it, i.e., if the pointer *owns* the thing it points to.

3. If you somehow determine that you should destroy what the pointer points to, there’s no way to tell how. Should you use `delete`, or is there a different destruction mechanism (e.g., a dedicated destruction function the pointer should be passed to)?

4. Even if you manage to find out that `delete` is the way to go, Reason 1 means it’s rarely possible to know whether to use the object form (“`delete`”) or the array form (“`delete []`”). If you use the wrong form, results are undefined.

5. Assuming you ascertain that the pointer owns what it points to and you discover how to destroy it, it’s difficult to ensure that you perform the destruction *exactly once* along every control path in your code (including those due to exceptions). Missing a path leads to resource leaks, and doing the destruction more than once leads to undefined behavior.

6. There’s typically no way to tell if the pointer dangles, i.e., points to memory that no longer holds the object the pointer is supposed to point to. Dangling pointers arise when objects are destroyed while pointers still point to them.

Raw pointers are powerful tools, to be sure, but decades of experience have demonstrated that with only the slightest lapse in concentration or discipline, these tools can turn on their ostensible masters. Surely we can do better.

Smart pointers are one way to address these issues. Smart pointers are wrappers around raw pointers that act much like the raw pointers they wrap, but that avoid many of their pitfalls. You should therefore prefer smart pointers to raw pointers. Smart pointers can do virtually everything raw pointers can, but with far fewer opportunities for error.

There are four smart pointers in C++11: `std::auto_ptr`, `std::unique_ptr`, `std::shared_ptr`, and `std::weak_ptr`. All are designed to help manage the lifetime of dynamically allocated objects, i.e., to avoid resource leaks by ensuring that such objects are destroyed in the appropriate manner at the appropriate time (including in the event of exceptions).

`std::auto_ptr` is a deprecated leftover from C++98. It was an attempt to standardize what later became C++11's `std::unique_ptr`. Doing the job right required move semantics, but C++98 didn't have them. As a workaround, `std::auto_ptr` co-opted its copy operations for moves. This led to surprising code (copying a `std::auto_ptr` sets it to null!) and frustrating usage restrictions (e.g., it's not possible to store `std::auto_ptr`s in containers).

`std::unique_ptr` does everything `std::auto_ptr` does, plus more. It does it as efficiently, and it does it without warping what it means to copy an object. It's better than `std::auto_ptr` in every way. The only legitimate use case for `std::auto_ptr` is a need to compile code with C++98 compilers. Unless you have that constraint, you should replace `std::auto_ptr` with `std::unique_ptr` and never look back.

The smart pointer APIs are remarkably varied. About the only functionality common to all is default construction. Because comprehensive references for these APIs are widely available in both electronic and print form, I'll focus my discussions on information that's often missing from API overviews, e.g., noteworthy use cases, runtime cost analyses, etc. Mastering such information can be the difference between merely using these smart pointers and using them *effectively*.

Item 20: Use `std::unique_ptr` for exclusive-ownership resource management.

When you reach for a smart pointer, `std::unique_ptr` should generally be the one closest at hand. By default, `std::unique_ptr`s are the same size as raw pointers, and for most operations (including dereferencing), they execute exactly the same instructions. This means you can use them even in situations where memory and cycles are tight. If a raw pointer is small enough and fast enough for you, a `std::unique_ptr` almost certainly is, too.

Like `std::auto_ptr` before it, `std::unique_ptr` embodies *exclusive ownership* semantics. A non-null `std::unique_ptr` always owns what it points to. Moving a `std::unique_ptr` transfers ownership from the source pointer to the destination pointer. (The source pointer is set to null.) Copying a `std::unique_ptr` isn't allowed, because if you could copy a `std::unique_ptr`, you'd end up with two `std::unique_ptr`s to the same resource, each thinking it owned (and should therefore destroy) that resource. `std::unique_ptr` is thus a *move-only type*. Upon destruction, a non-null `std::unique_ptr` destroys its resource. By default, resource destruction is accomplished by applying `delete` to the raw pointer inside the `std::unique_ptr`.

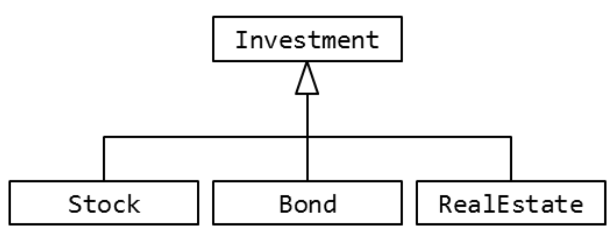
A common use for `std::unique_ptr` is as a factory function return type for objects in a hierarchy. Suppose we have a hierarchy for types of investments (e.g., stocks, bonds, real estate, etc.) with a base class `Investment`.

```
class Investment { … };

class Stock:
  public Investment { … };

class Bond:
  public Investment { … };

class RealEstate:
  public Investment { … };
```



A factory function for such a hierarchy typically allocates an object on the heap and returns a pointer to it, with the caller being responsible for deleting the object when it's no longer needed. That's a perfect match for `std::unique_ptr`, because the caller acquires responsibility for the resource returned by the factory (i.e., exclusive ownership of it), and the `std::unique_ptr` automatically deletes what it points to when it's destroyed. A factory function for the `Investment` hierarchy could be declared like this:

```
template<typename... Ts>            // return std::unique_ptr
std::unique_ptr<Investment>         // to an object created
  makeInvestment(Ts&&... args);     // from the given args
```

Callers could use the returned `std::unique_ptr` in a single scope, as follows,

```
{
  …
  auto pInvestment =                // pInvestment is of type
    makeInvestment( arguments );    // std::unique_ptr<Investment>

  …

}                                   // destroy *pInvestment
```

but they could also use it in ownership-migration scenarios, such as when the `std::unique_ptr` returned from the factory is moved into a container, the container element is subsequently moved into a data member of an object, and that object is later destroyed. When that happens, the object's `std::unique_ptr` data member would also be destroyed, and its destruction would cause the resource returned from the factory to be destroyed. If the ownership chain got interrupted due to an exception or other atypical control flow (e.g., premature function return or `break` from a loop), the `std::unique_ptr` owning the managed resource would eventually have its destructor called,† and the resource it was managing would thereby be destroyed.

By default, that destruction would take place via `delete`, but, during construction, `std::unique_ptr` objects can be configured to use *custom deleters*: arbitrary

---

† There are a few exceptions to this rule. All stem from abnormal program termination. If an exception propagates out of a thread's primary function (e.g., `main`, for the program's initial thread) or if a `noexcept` specification is violated (see Item 16), local objects may not be destroyed, and if `std::abort` is called, they definitely won't be.

functions (or function objects, including those arising from lambda expressions) to be invoked when it's time for their resources to be destroyed. If the object created by `makeInvestment` shouldn't be directly `delete`d, but instead should first have a log entry written, `makeInvestment` could be implemented as follows. (An explanation follows the code, so don't worry if you see something whose motivation is less than obvious.)

```
auto delInvmt = [](Investment* pInvestment)       // custom
                {                                 // deleter
                  makeLogEntry(pInvestment);      // (a lambda
                  delete pInvestment;             // expression)
                };

template<typename... Ts>                          // revised
std::unique_ptr<Investment, decltype(delInvmt)>   // return type
makeInvestment(Ts&&... args)
{
  std::unique_ptr<Investment, decltype(delInvmt)> // ptr to be
    pInv(nullptr, delInvmt);                      // returned

  if ( /* a Stock object should be created */ )
  {
    pInv.reset(new Stock(std::forward<Ts>(args)...));
  }
  else if ( /* a Bond object should be created */ )
  {
    pInv.reset(new Bond(std::forward<Ts>(args)...));
  }
  else if ( /* a RealEstate object should be created */ )
  {
    pInv.reset(new RealEstate(std::forward<Ts>(args)...));
  }

  return pInv;
}
```

In a moment, I'll explain how this works, but first consider how things look if you're a caller. Assuming you store the result of the `makeInvestment` call in an `auto` variable, you frolic in blissful ignorance of the fact that the resource you're using requires special treatment during deletion. In fact, you veritably bathe in bliss, because the use of `std::unique_ptr` means you need not concern yourself with when the resource should be destroyed, much less ensure that the destruction happens exactly once along every control path in the program.

`std::unique_ptr` takes care of all those things automatically. From a client's perspective, `makeInvestment`'s interface is sweet.

The implementation is pretty nice, too, once you understand the following:

- `delInvmt` is the custom deleter for the object returned from `makeInvestment`. All custom deletion functions accept a raw pointer to the object to be destroyed, then do what is necessary to destroy that object. In this case, the action is to call `makeLogEntry` and then apply `delete`. Using a lambda expression to create `delInvmt` is convenient, but, as we'll see shortly, it's also more efficient than writing a conventional function.

- When a custom deleter is to be used, its type must be specified as the second type argument to `std::unique_ptr`. In this case, that's the type of `delInvmt`, and that's why the return type of `makeInvestment` is `std::unique_ptr<Investment, decltype(delInvmt)>`. (For information about `decltype`, see Item 3.)

- The basic strategy of `makeInvestment` is to create a null `std::unique_ptr`, make it point to an object of the appropriate type, and then return it. To associate the custom deleter (`delInvmt`) with `pInv`, we pass that as its second constructor argument.

- As Item 23 explains, it's preferable to use `std::make_unique` rather than `new` to create an object for a `std::unique_ptr` to point to, yet this code uses `new` in several places. That's because `std::make_unique` offers no support for custom deleters. (Of course, it would be possible to encapsulate the use of `new` inside a `std::make_unique`-like template that supported the specification of a custom deleter. If you've been waiting for an opportunity to write some code whose development is "left as an exercise for the reader," here's your chance.)

- Attempting to assign a raw pointer (e.g., from `new`) to a `std::unique_ptr` won't compile, because it would constitute an implicit conversion from a raw to a smart pointer. Such implicit conversions can be problematic, so C++11's smart pointers prohibit them. That's why `reset` is used to have `pInv` assume ownership of the object created via `new`.

- With each use of `new`, we perfect-forward the arguments passed to `makeInvestment` (see Item 27). This makes all the information provided by callers available to the constructors of the objects being created.

- The custom deleter takes a parameter of type `Investment*`. Regardless of the actual type of object created inside `makeInvestment` (i.e., `Stock`, `Bond`, or `RealEstate`), it will ultimately be `delete`d inside the lambda expression as an `Investment*` object. This means we'll be deleting a derived class object via a base class pointer. For that to work, the base class—`Investment`—must have a virtual destructor:

  ```
  class Investment {
  public:
    …                                             // essential
    virtual ~Investment();                        // design
    …                                             // component!
  };
  ```

In C++14, the existence of function return type deduction (see Item 3) means that `makeInvestment` could be implemented in this simpler and more encapsulated fashion:

```
template<typename... Ts>
auto makeInvestment(Ts&&... args)                 // C++14 only
{
  auto delInvmt = [](Investment* pInvestment)     // this is now
                  {                               // inside
                    makeLogEntry(pInvestment);    // make-
                    delete pInvestment;           // Investment
                  };

  std::unique_ptr<Investment, decltype(delInvmt)>    // as
    pInv(nullptr, delInvmt);                         // before

  if ( … )                                        // as before
  {
    pInv.reset(new Stock(std::forward<Ts>(args)...));
  }
  else if ( … )                                   // as before
  {
    pInv.reset(new Bond(std::forward<Ts>(args)...));
  }
  else if ( … )                                   // as before
  {
    pInv.reset(new RealEstate(std::forward<Ts>(args)...));
```

```
  }
  return pInv;                                   // as before
}
```

At the beginning of this Item, I emphasized that, when using the default deleter (i.e., `delete`), `std::unique_ptr` objects are the same size as raw pointers. When custom deleters enter the picture, this may no longer be the case. Deleters that are function pointers generally cause the size of the `std::unique_ptr` to grow from one word to two. For deleters that are function objects, the change in size depends on how much state is stored in the function object. Stateless function objects (e.g., from lambda expressions with no captures) incur no size penalty, and this means that when a custom deleter can be implemented as either a function or a capture-less lambda expression, the lambda is preferable:

```
auto delInvmt1 = [](Investment* pInvestment)      // custom
                 {                                // deleter
                   makeLogEntry(pInvestment);     // as
                   delete pInvestment;            // stateless
                 };                               // lambda

template<typename... Ts>                          // return type
std::unique_ptr<Investment, decltype(delInvmt1)>  // has size of
makeInvestment(Ts&&... args);                     // Investment*


void delInvmt2(Investment* pInvestment)           // custom
{                                                 // deleter
  makeLogEntry(pInvestment);                      // as function
  delete pInvestment;
}

template<typename... Ts>                 // return type has
std::unique_ptr<Investment,              // size of Investment*
                void (*)(Investment*)>   // plus at least size
makeInvestment(Ts&&... args);            // of function pointer!
```

Function object deleters with extensive state can yield `std::unique_ptr` objects of significant size. However, large function objects are often ill-advised on other grounds, and there are ways to make them smaller; see **Error! Reference source not found.**. If you find yourself with a custom deleter with significant state, you probably need to change your design.

Factory functions are not the only common use case for `std::unique_ptr`s. They're even more popular as a mechanism for implementing the Pimpl Idiom. The code for that isn't complicated, but in some cases it's less than straightforward, so I'll refer you to Item 24, which is dedicated to the topic.

`std::unique_ptr` comes in two forms, one for individual objects (`std::unique_ptr<T>`) and one for arrays (`std::unique_ptr<T[]>`). As a result, there's never any ambiguity about what kind of entity a `std::unique_ptr` points to. The `std::unique_ptr` API is designed to match the form you're using. For example, there's no indexing operator (`operator[]`) for the single-object form, while the array form lacks dereferencing operators (`operator*` and `operator->`).

The existence of `std::unique_ptr` for arrays should be of only intellectual interest to you, because `std::array`, `std::vector`, and `std::string` are virtually always better data structure choices than raw arrays. The only situation I can conceive of when a `std::unique_ptr<T[]>` would make sense would be when you're using a C-like API that returns a raw pointer to a heap array that you assume ownership of.

`std::unique_ptr` is the C++11 way to express exclusive ownership, but one of its most attractive features is that it easily and efficiently converts to a `std::shared_ptr`:

```
std::shared_ptr<Investment> sp =    // converts std::unique_ptr
  makeInvestment( arguments );      // to std::shared_ptr
```

This is a key part of why `std::unique_ptr` is so well suited as a factory function return type. Factory functions can't know whether callers will want to use exclusive-ownership semantics for the object they return or whether shared ownership (i.e., `std::shared_ptr`) would be more appropriate. By returning a `std::unique_ptr`, factories provide callers with the most efficient smart pointer, but they don't impede callers from replacing it with its more flexible sibling. (For information about `std::shared_ptr`, proceed to Item 21.)

Things to Remember

- `std::unique_ptr` is a small, fast, move-only smart pointer for managing resources with exclusive-ownership semantics.

- By default, resource destruction takes place via `delete`, but custom deleters can be specified. Stateful deleters and function pointers as deleters increase the size of `std::unique_ptr` objects.
- Converting a `std::unique_ptr` to a `std::shared_ptr` is easy.

Item 21: Use `std::shared_ptr` for shared-ownership resource management.

Programmers using languages with garbage collection point and laugh at what C++ programmers go through to prevent resource leaks. "How primitive!", they jeer. "Didn't you get the memo from Lisp in the 1960s? Machines should manage resource lifetimes, not humans." C++ developers roll their eyes. "You mean the memo where the only resource is memory and the timing of resource reclamation is nondeterministic? We prefer the generality and predictability of destructors, thank you." But our bravado is part bluster. Garbage collection really is convenient, and manual lifetime management really can seem akin to constructing a mnemonic memory circuit using stone knives and bear skins. Why can't we have the best of both worlds: a system that works automatically (like garbage collection), yet applies to all resources and has predictable timing (like destructors)?

`std::shared_ptr` is the C++11 way of binding these worlds together. An object accessed via `std::shared_ptrs` has its lifetime managed by those pointers through *shared ownership*. No specific `std::shared_ptr` owns the object. Instead, all `std::shared_ptrs` pointing to it collaborate to ensure its destruction at the point where it's no longer needed. When the last `std::shared_ptr` pointing to an object stops pointing there (e.g., because the `std::shared_ptr` is destroyed or made to point to a different object), that `std::shared_ptr` destroys the object it points to. As with garbage collection, clients need not concern themselves with managing the lifetime of pointed-to objects, but as with destructors, the timing of the objects' destruction is deterministic.

A `std::shared_ptr` can tell whether it's the last one pointing to a resource by consulting the resource's *reference count*: a value associated with the resource that keeps track of how many `std::shared_ptrs` point to it. `std::shared_ptr` constructors increment this count (usually—see below), `std::shared_ptr` destructors decrement it, and copy assignment operators do both. (If `sp1` and `sp2` are `std::shared_ptr`s, the assignment "`sp1 = sp2`" modifies `sp1` such that it points to the object pointed to by `sp2`. The net effect of the assignment, then, is that the reference count for the object originally pointed to by `sp1` is decremented, while that for the object pointed to by `sp2` is incremented.) If a `std::shared_ptr` sees a reference count of zero after performing a decrement, no more `std::shared_ptr`s point to the resource, so the `std::shared_ptr` destroys it.

The existence of the reference count has performance implications:

- **std::shared_ptrs are twice the size of a raw pointer**, because they internally contain a raw pointer to the resource as well as a raw pointer to the resource's reference count.†

- **Memory for the reference count must be dynamically allocated**. Conceptually, the reference count is associated with the object being pointed to, but pointed-to objects know nothing about this. They thus have no place to store a reference count. Storage for the count is hence dynamically allocated. Item 23 explains that the cost of this allocation (but not the allocation itself) is avoided when the `std::shared_ptr` is created by `std::make_shared`, but there are situations where `std::make_shared` can't be used. Either way, the reference count is stored as dynamically allocated runtime data.

- **Increments and decrements of the reference count must be atomic**, because there can be simultaneous readers and writers in different threads. For example, a `std::shared_ptr` pointing to a resource in one thread could be executing its destructor (hence decrementing the reference count for the resource it points to), while, in a different thread, a `std::shared_ptr` to the same object could be copied (and therefore incrementing the same reference count). Atomic operations are typically slower than non-atomic operations, so

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† This implementation is not required by the Standard, but there are sound technical reasons why every Standard Library implementation I'm familiar with employs it.

even though reference counts are usually only a word in size, you should assume that reading and writing them is comparatively costly.

Did I pique your curiosity when I wrote that `std::shared_ptr` constructors only "usually" increment the reference count for the object they point to? Creating a new `std::shared_ptr` pointing to an object always yields one more `std::shared_ptr` pointing to that object, so why mustn't we *always* increment the reference count?

Move construction, that's why. Move-constructing a `std::shared_ptr` from another `std::shared_ptr` sets the source `std::shared_ptr` to null, and that means that the old `std::shared_ptr` stops pointing to the resource at the moment the new `std::shared_ptr` starts. As a result, no reference count manipulation is required. Moving `std::shared_ptr`s is therefore faster than copying them: copying requires incrementing the reference count, but moving doesn't. This is as true for assignment as for construction, so move construction is faster than copy construction, and move assignment is faster than copy assignment.

Like `std::unique_ptr` (see Item 20), `std::shared_ptr` uses `delete` as its default resource-destruction mechanism, but it also supports custom deleters. The design of this support differs from that for `std::unique_ptr`, however. For `std::unique_ptr`, the type of the deleter is part of the type of the smart pointer. For `std::shared_ptr`, it's not:

```
auto loggingDel = [](Widget *pw)        // custom deleter
                  {                     // (as in Item 20)
                    makeLogEntry(pw);
                    delete pw;
                  };

std::unique_ptr<                        // deleter type is
  Widget, decltype(loggingDel)          // part of ptr type
  > upw(new Widget, loggingDel);

std::shared_ptr<Widget>                 // deleter type is not
  spw(new Widget, loggingDel);          // part of ptr type
```

The `std::shared_ptr` design is more flexible. Consider two `std::shared_ptr<Widget>`s, each with a custom deleter of a unique type (e.g., because the custom deleters are specified via lambda expressions):

```
auto customDeleter1 = [](Widget *pw) { … };  // custom deleters,
auto customDeleter2 = [](Widget *pw) { … };  // each with a
                                             // different type

std::shared_ptr<Widget> pw1(new Widget, customDeleter1);
std::shared_ptr<Widget> pw2(new Widget, customDeleter2);
```

Because `pw1` and `pw2` have the same type, they can be placed in a container of objects of that type:

```
std::vector<std::shared_ptr<Widget>> vpw { pw1, pw2 };
```

They could also be assigned to one another, and they could each be passed to a function taking a parameter of type `std::shared_ptr<Widget>`. None of these things can be done with `std::unique_ptr`s that differ in the types of their custom deleters, because the type of the custom deleter would affect the type of the `std::unique_ptr`.

In another difference from `std::unique_ptr`, specifying a custom deleter doesn't change the size of a `std::shared_ptr` object. Regardless of deleter, a `std::shared_ptr` object is two pointers in size. That's great news, but it should make you vaguely uneasy. Custom deleters can be function objects, and function objects can contain arbitrary amounts of data. That means they can be arbitrarily large. How can a `std::shared_ptr` refer to a deleter of arbitrary size without using any more memory?

It can't. It may have to use more memory. However, that memory isn't part of the `std::shared_ptr` object. It's on the heap (or, if the creator of the `std::shared_ptr` took advantage of `std::shared_ptr` support for custom allocators, it's wherever the memory managed by that allocator is located). I remarked earlier that a `std::shared_ptr` object contains a pointer to the reference count for the object it points to. That's true, but it's a bit misleading, because the reference count is part of a larger data structure known as the *control block*. There's a control block for each object managed by `std::shared_ptr`s. The control block contains, in addition to the reference count, a copy of the custom deleter, if one has been specified. If a custom allocator was specified, the control block contains a copy of that, too. (As Item 23 explains, it also contains a secondary reference count known as the weak count, but we'll ignore that in this Item.)

The control block is created by the function creating the first `std::shared_ptr` to the object. At least that's what's supposed to happen. In general, it's impossible for a function creating a `std::shared_ptr` to an object to know whether some other `std::shared_ptr` already points to that object, so the following rules for control block creation are used:

- **std::make_shared (see Item 23) always creates a control block.** It manufactures a new object to point to, so there is certainly no control block for that object at the time `std::make_shared` is called.
- **When a std::shared_ptr constructor is called with a raw pointer, it creates a control block for the object the raw pointer points to.** The thinking here is that if you wanted to create a `std::shared_ptr` from an object that already had a control block, you'd use a `std::shared_ptr` or a `std::weak_ptr` (see Item 22) as a constructor argument, not a raw pointer. `std::shared_ptr` constructors taking `std::shared_ptrs` or `std::weak_ptrs` as constructor arguments don't create new control blocks, because they know that the smart pointers passed to them already point to control blocks.

  If a `std::shared_ptr` is created from a raw pointer that's null, by the way, there's no object to associate the control block with, so no control block is created.

A consequence of these rules is that constructing more than one `std::shared_ptr` from a single raw pointer gives you a complimentary ride on the particle accelerator of undefined behavior, because the pointed-to object will have multiple control blocks. Multiple control blocks means multiple reference counts, and multiple reference counts means the object will be destroyed multiple times (once for each reference count). That means that code like this is bad, bad, bad:

```
auto pw = new Widget;
…
std::shared_ptr<Widget> spw1(pw, loggingDel);  // create control
                                               // block for *pw
…
```

```
std::shared_ptr<Widget> spw2(pw, loggingDel);  // create 2nd
                                               // control block
                                               // for *pw!
```

The creation of the raw pointer `pw` to a dynamically allocated object is bad, because it runs contrary to the advice behind this entire chapter: to prefer smart pointers to raw pointers. (If you've forgotten the motivation for that advice, turn to page 148 to refresh your memory.) But set that aside. The line creating `pw` is a stylistic abomination, but at least it doesn't cause undefined program behavior. The real problem here is that the constructor for `spw1` is called with a raw pointer, so it creates a control block (and thereby a reference count) for what's pointed to. In this case, that's `*pw` (i.e., the object pointed to by `pw`). In and of itself, that's okay, but the constructor for `spw2` is called with the same raw pointer, so it also creates a control block (hence a reference count) for `*pw`. `*pw` thus has two reference counts, each of which will eventually become zero, and that will ultimately lead to an attempt to destroy `*pw` twice. The second destruction is responsible for the undefined behavior.

There are at least two lessons regarding `std::shared_ptr` use here. First, try to avoid passing raw pointers to a `std::shared_ptr` constructor. The usual alternative is to use `std::make_shared` (see Item 23), but in the example above, we're using custom deleters, and that's not possible with `std::make_shared`. Second, if you must pass a raw pointer to a `std::shared_ptr` constructor, pass the result of `new` directly instead of going through a raw pointer variable. If the first part of the code above were rewritten like this,

```
std::shared_ptr<Widget> spw1(new Widget,    // direct use of new
                             loggingDel);
```

it'd be a lot harder to create a second `std::shared_ptr` from the same raw pointer. Instead, the author of the code creating `spw2` would naturally use `spw1` as an initialization argument (i.e., would call the `std::shared_ptr` copy constructor), and that would pose no problem whatsoever:

```
std::shared_ptr<Widget> spw2(spw1);     // spw2 uses same
                                        // control block as spw1
```

An especially surprising way that using raw pointer variables as `std::shared_ptr` constructor arguments can lead to multiple control blocks involves the `this` pointer. Suppose our program uses `std::shared_ptr`s to manage `Widget` objects, and we have a data structure that keeps track of `Widget`s that have been processed:

```
std::vector<std::shared_ptr<Widget>> processedWidgets;
```

Further suppose that `Widget` has a member function that does the processing:

```
class Widget {
public:
  …
  void process();
  …
};
```

Here's a reasonable-looking approach for `Widget::process`:

```
void Widget::process()
{
  …                                       // process the Widget

  processedWidgets.emplace_back(this);    // add it to list of
}                                         // processed Widgets;
                                          // this is wrong!
```

The comment about this being wrong says it all—or at least most of it. (The part that's wrong is the passing of `this`, not the use of `emplace_back`. If you're not familiar with `emplace_back`, see Item 18.) This code will compile, but it's passing a raw pointer (`this`) to a container of `std::shared_ptr`s. The `std::shared_ptr` thus constructed will create a new control block for the pointed-to `Widget` (`*this`). That doesn't sound harmful until you realize that if there are `std::shared_ptr`s outside the member function that already point to that `Widget`, it's game, set, and match for undefined behavior.

The `std::shared_ptr` API includes a facility for just this kind of situation. It has probably the oddest of all names in the Standard C++ Library: `std::enable_shared_from_this`. That's a template for a base class you inherit from if you want a class managed by `std::shared_ptr`s to be able to safely create a `std::shared_ptr` from a `this` pointer. In our example, `Widget` would inherit from `std::enable_shared_from_this` as follows:

```
class Widget: public std::enable_shared_from_this<Widget> {
public:
  …
  void process();
  …
};
```

As I said, `std::enable_shared_from_this` is a base class template. Its type parameter is always the name of the class being derived, so `Widget` inherits from std::enable_shared_from_this<Widget>. If the idea of a derived class inheriting from a base class templatized on the derived class makes your head hurt, try not to think about it. The code is completely legal, and the design pattern behind it is so well established, it has a standard name, albeit one that's almost as odd as `std::enable_shared_from_this`. The name is *The Curiously Recurring Template Pattern (CRTP)*. If you'd like to learn more about it, unleash your search engine, because here we need to get back to `std::enable_shared_from_this`.

`std::enable_shared_from_this` defines a member function that creates a `std::shared_ptr` to the current object, but it does it without duplicating control blocks. The member function is `shared_from_this`, and you use it in member functions whenever you want a `std::shared_ptr` that points to the same object as the `this` pointer. Here's a safe implementation of `Widget::process`:

```
void Widget::process()
{
  // as before, process the Widget
  …

  // add std::shared_ptr to current object to processedWidgets
  processedWidgets.emplace_back(shared_from_this());
}
```

Internally, `shared_from_this` looks up the control block for the current object, and it creates a new `std::shared_ptr` that refers to that control block. The design relies on the current object having an associated control block. For that to be the case, there must be an existing `std::shared_ptr` (e.g., one outside the member function calling `shared_from_this`) that points to the current object. If no such `std::shared_ptr` exists (i.e., if the current object has no associated control block), `shared_from_this` throws an exception.

At this point, you may only dimly recall that our discussion of control blocks was motivated by a desire to understand the costs associated with `std::shared_ptr`s. Now that we understand how to avoid creating too many control blocks, let's return to the original topic.

A control block is typically only a few words in size, although custom deleters and allocators may make it larger. The usual control block implementation is more sophisticated than you might expect. It makes use of inheritance, and there's even a virtual function. (It's used to ensure that the pointed-to object is properly destroyed.) That means that using `std::shared_ptr`s also incurs the cost of the machinery for the virtual function used by the control block.

Having read about dynamically allocated control blocks, arbitrarily large deleters and allocators, virtual function machinery, and atomic reference count manipulations, your enthusiasm for `std::shared_ptr`s may have waned somewhat. That's fine. They're not the best solution to every resource management problem. But for the functionality they provide, `std::shared_ptr`s exact a very reasonable cost. Under typical conditions, where the default deleter and default allocator are used and where the `std::shared_ptr` is created by `std::make_shared`, the control block is only about three words in size, and its allocation is essentially free. (It's incorporated into the memory allocation for the object being pointed to. For details, see Item 23.) Dereferencing a `std::shared_ptr` is no more expensive than dereferencing a raw pointer. Performing an operation requiring a reference count manipulation (e.g., copy construction or copy assignment, destruction) entails one or two atomic operations, but these operations typically map to individual machine instructions, so although they may be expensive compared to non-atomic instructions, they're still just single instructions. The virtual function machinery in the control block is used only once per object managed by `std::shared_ptr`s: when the object is destroyed.

In exchange for these rather modest costs, you get automatic lifetime management of dynamically allocated resources. Most of the time, using `std::shared_ptr` is vastly preferable to trying to manage the lifetime of an object with shared ownership by hand. If you find yourself doubting whether you can afford use of `std::shared_ptr`, reconsider whether you really need shared ownership. If exclusive ownership will do or even *may* do, `std::unique_ptr` is a better choice. Its performance profile is close to that for raw pointers, and "upgrading" from `std::unique_ptr` to `std::shared_ptr` is easy, because a `std::shared_ptr` can be created from a `std::unique_ptr`.

The reverse is not true. Once you've turned lifetime management of a resource over to a `std::shared_ptr`, there's no changing your mind. Even if the reference count is one, you can't reclaim ownership of the resource in order to, say, have a `std::unique_ptr` manage it. The ownership contract between a resource and the `std::shared_ptr`s that point to it is of the 'til-death-do-us-part variety. No divorce, no annulment, no exceptions.

Something else `std::shared_ptr`s can't do is work with arrays. In yet another difference from `std::unique_ptr`, `std::shared_ptr` has an API that's designed only for pointers to single objects. There's no `std::shared_ptr<T[]>`. From time to time, "clever" programmers stumble on the idea of using a `std::shared_ptr<T>` to point to an array, specifying a custom deleter to perform an array delete (i.e., `delete []`). This can be made to compile, but it's a horrible idea. For one thing, `std::shared_ptr` offers no `operator[]`, so indexing into the array requires awkward expressions based on pointer arithmetic. For another, `std::shared_ptr` supports derived-to-base pointer conversions that make sense for single objects, but that open holes in the type system when applied to arrays. (For this reason, the `std::unique_ptr<T[]>` API prohibits such conversions.) Most importantly, given the variety of C++11 alternatives to built-in arrays (e.g., `std::array`, `std::vector`, `std::string`), declaring a smart pointer to a dumb array is almost always a sign of bad design.

Things to Remember

- `std::shared_ptr`s offer convenience approaching that of garbage collection for the shared lifetime management of arbitrary resources.

- Compared to `std::unique_ptr`, `std::shared_ptr` objects are twice as big, incur overhead for control blocks, and require atomic reference count manipulations.
- Default resource destruction is via `delete`, but custom deleters are supported. The type of the deleter is independent of the type of the `std::shared_ptr`.
- Avoid creating `std::shared_ptr`s from variables of raw pointer type.

Item 22: Use `std::weak_ptr` for `std::shared_ptr`-like pointers that can dangle.

Paradoxically, it can be convenient to have a smart pointer that acts like a `std::shared_ptr` (see Item 21), but that doesn't participate in the shared ownership of the pointed-to resource. In other words, a pointer like `std::shared_ptr` that doesn't affect an object's reference count. This kind of smart pointer has to contend with a problem unknown to `std::shared_ptr`s: the possibility that what it points to has been destroyed. A truly smart pointer would deal with this problem by tracking when it *dangles*, i.e., when the object it is supposed to point to no longer exists. That's precisely the kind of smart pointer `std::weak_ptr` is.

You may be wondering how a `std::weak_ptr` could be useful. You'll probably wonder even more when you examine the `std::weak_ptr` API. It looks anything but smart. `std::weak_ptr`s can't be dereferenced, nor can they be tested for nullness. That's because `std::weak_ptr` isn't a standalone smart pointer. It's an augmentation of `std::shared_ptr`.

The relationship begins at birth. `std::weak_ptr`s are typically created from `std::shared_ptr`s. They point to the same place as the `std::shared_ptr`s initializing them, but they don't affect the reference count of the object they point to:

```
auto spw =                       // after spw is constructed,
  std::make_shared<Widget>();    // the pointed-to Widget's
                                 // ref count (RC) is 1. (See
                                 // Item 23 for info on
                                 // std::make_shared.)
…
```

```
std::weak_ptr<Widget> wpw(spw);  // wpw points to same Widget
                                 // as spw. RC remains 1

…

spw = nullptr;                   // RC goes to 0, and the
                                 // Widget is destroyed.
                                 // wpw now dangles
```

`std::weak_ptr`s that dangle are said to have *expired*. You can test for this directly,

```
if (!wpw.expired()) …            // if wpw points to an object…
```

but often what you desire is a check to see if a `std::weak_ptr` has expired and, if it hasn't (i.e., if it's not dangling), to access the object it points to. Alas, this is easier desired than done. Because `std::weak_ptrs` lacks dereferencing operations, there's no way to write the code. Even if there were, separating the check and the dereference would introduce a race condition: between the call to `expired` and the dereferencing action, another thread might reassign or destroy the last `std::shared_ptr` pointing to the object, thus causing that object to be destroyed. In that case, your dereference would yield undefined behavior.

What you need is an atomic operation that checks to see if the `std::weak_ptr` has expired and, if not, gives you access to the object it points to. This is done by creating a `std::shared_ptr` from the `std::weak_ptr`. The operation comes in two forms, depending on what you'd like to have happen if the `std::weak_ptr` has expired when you try to create a `std::shared_ptr` from it. One form is `std::weak_ptr::lock`, which returns a `std::shared_ptr`. The `std::shared_ptr` is null if the `std::weak_ptr` has expired:

```
std::shared_ptr<Widget> spw1 = wpw.lock();  // if wpw's expired,
                                            // spw1 is null

auto spw2 = wpw.lock();                     // same as above,
                                            // but uses auto
```

The other form is the `std::shared_ptr` constructor taking a `std::weak_ptr` as an argument. In this case, if the `std::weak_ptr` has expired, an exception is thrown:

```
std::shared_ptr<Widget> spw3(wpw);    // if wpw's expired,
                                      // throw std::bad_weak_ptr
```

But you're probably still wondering about how `std::weak_ptr`s can be useful. Consider a factory function that produces smart pointers to read-only objects based on a unique ID. In accord with Item 20's advice regarding factory function return types, it returns a `std::unique_ptr`:

```
std::unique_ptr<const Widget> loadWidget(WidgetID id);
```

If `loadWidget` is an expensive call (e.g., because it performs file or database I/O) and it's common for IDs to be used repeatedly, a reasonable optimization would be to write a function that does what `loadWidget` does, but also caches its results. Clogging the cache with every `Widget` that has ever been requested can lead to performance problems of its own, however, so another reasonable optimization would be to destroy cached `Widget`s when they're no longer in use.

For this caching factory function, a `std::unique_ptr` return type is not a good fit. The caller should certainly receive a smart pointer to the cached object, and the caller should certainly determine the lifetime of that object, but the cache needs a pointer to the object, too. The cache's pointer needs to be able to detect when it dangles, because when a factory client is finished using an object returned by the factory, that object will be destroyed, and the corresponding cache entry will dangle. The cached pointer should therefore be a `std::weak_ptr`—a pointer that can detect when it dangles. That means that the factory's return type should be a `std::shared_ptr`, because `std::weak_ptr`s can detect when they dangle only when an object's lifetime is managed by `std::shared_ptr`s.

Here's a quick-and-dirty implementation of a caching version of `loadWidget`:

```
std::shared_ptr<const Widget> fastLoadWidget(WidgetID id)
{
  using SPType = std::shared_ptr<const Widget>;
  using WPType = std::weak_ptr<const Widget>;

  static std::unordered_map<WidgetID, WPType> cache;

  auto retPtr = cache[id].lock();     // retPtr points to cached
                                      // object or is null
```

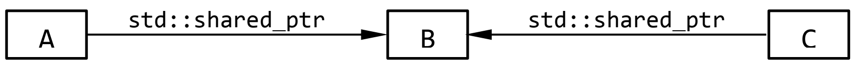
```
  if (!retPtr) {                                  // if not in
                                                  // cache,
    retPtr = static_cast<SPType>(loadWidget(id)); // load it
    cache[id] = static_cast<WPType>(retPtr);      // cache it
  }

  return retPtr;
}
```

This implementation employs one of C++11's hash table containers (`std::unordered_map`), though it doesn't show the `WidgetID` hashing and equality-comparison functions that would also have to be present.

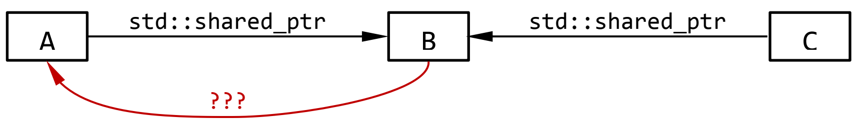
There are two smart pointer type conversions in the code, both made obvious by the use of `static_casts`. In the assignment to `retPtr` (a `std::shared_ptr`), the `std::unique_ptr` returned from `loadWidget` is used to create a temporary `std::shared_ptr` (via the alias `SPType`) to act as the source of the assignment. In the following line, `retPtr` (still a `std::shared_ptr`) is used to create a temporary `std::weak_ptr` (via the alias `WPType`) that is moved into the cache (via assignment to `cache[id]`). Neither cast is doing anything underhanded. Each simply causes a smart pointer object of one type to be constructed from a smart pointer object of a different type.

This implementation of `fastLoadWidget` ignores the fact that the cache may accumulate expired `std::weak_ptrs` corresponding to `Widgets` that are no longer in use (and have therefore been destroyed). The implementation can be refined, but rather than spend time on an issue that lends no additional insight into `std::weak_ptrs`, let's consider a second use case: the Observer design pattern. The primary components of this pattern are subjects (objects whose state may change) and observers (objects to be notified when state changes occur). In most implementations, each subject contains a data member holding pointers to its observers. That makes it easy for subjects to issue state change notifications. Subjects have no interest in controlling the lifetime of their observers (i.e., when they're destroyed), but they have a great interest in making sure that if an observer gets destroyed, subjects don't try to subsequently access it. A reasonable design is for each subject to hold a container of `std::weak_ptrs` to its observers, thus making it possible for the subject to ensure that the pointers don't dangle when it tries to use them.

As a final example of `std::weak_ptr`s utility, consider a data structure with objects `A`, `B`, and `C` in it, where `A` and `C` share ownership of `B` and therefore hold `std::shared_ptr`s to it:



Suppose it'd be useful to also have a pointer from `B` back to `A`. What kind of pointer should this be?



There are three choices:

- **A raw pointer.** With this approach, if `A` is destroyed, but `C` continues to point to `B`, `B` will contain a pointer to `A` that will dangle. `B` won't be able to detect that, so `B` may inadvertently dereference the dangling pointer. That would yield undefined behavior.

- **A std::shared_ptr.** In this design, `A` and `B` contain `std::shared_ptr`s to one another. The resulting `std::shared_ptr` cycle (`A` points to `B` and `B` points to `A`) will prevent both `A` and `B` from being destroyed. Even if `A` and `B` are unreachable from other program data structures (i.e., because `C` no longer points to `B`), each will have a reference count of one. If that happens, `A` and `B` will have been leaked, for all practical purposes: it will be impossible for the program to access them, yet their resources will never be reclaimed.

- **A std::weak_ptr.** This avoids both problems above. If `A` is destroyed, `B`'s pointer back to it will dangle, but `B` will be able to detect that. Furthermore, though `A` and `B` will point to one another, `B`'s pointer won't affect `A`'s reference count, hence can't keep `A` from being destroyed when `std::shared_ptr`s no longer point to it.

The `std::weak_ptr` is clearly the best of these choices. However, it's worth noting that the need to employ `std::weak_ptrs` to break prospective cycles of `std::shared_ptrs` is not terribly common. In strictly hierarchal data structures such as trees, child nodes are typically owned only by their parents. When a parent node is destroyed, its child nodes should be destroyed, too. Links from parents to children are thus generally best represented by `std::unique_ptrs`. Back-links from children to parents can be safely implemented as raw pointers, because a child node should never have a lifetime longer than its parent. There's thus no risk of a child node dereferencing a dangling parent pointer.

Of course, not all pointer-based data structures are strictly hierarchical, and when that's the case, as well as in situations such as caching and the implementation of lists of observers, it's nice to know that `std::weak_ptr` stands at the ready.

From an efficiency perspective, the `std:weak_ptr` story is essentially the same as that for `std::shared_ptr`. `std::weak_ptr` objects are the same size as `std::shared_ptr` objects, they make use of the same control blocks as `std::shared_ptrs` (see Item 21), and operations such as construction, destruction, and assignment involve atomic reference count manipulations. That probably surprises you, because I wrote at the beginning of this Item that `std::weak_ptrs` don't participate in reference counting. Except that's not quite what I wrote. What I wrote was that `std::weak_ptrs` don't participate in the *shared ownership* of objects and hence don't affect the *pointed-to object's reference count*. There's actually a second reference count in the control block, and it's this second reference count that `std::weak_ptrs` manipulate. For details, continue on to Item 23.

Things to Remember

- Use `std::weak_ptr` for `std::shared_ptr`-like pointers that can dangle.
- Potential use cases for `std::weak_ptr` include caching, observer lists, and the prevention of `std::shared_ptr` cycles.

Item 23: Prefer `std::make_unique` and `std::make_shared` to direct use of `new`.

Let's begin by leveling the playing field for `std::make_unique` and `std::make_shared`. `std::make_shared` is part of C++11, but, sadly, `std::make_unique` isn't. It joined the Standard Library as of C++14. If you're using C++11, never fear, because a basic version of `std::make_unique` is easy to write yourself. Here, look:

```
template<typename T, typename... Args>
std::unique_ptr<T> make_unique(Args&&... args)
{
  return std::unique_ptr<T>(new T(std::forward<Args>(args)...));
}
```

As you can see, `make_unique` simply perfect-forwards its arguments to the constructor of the object being created, constructs a `std::unique_ptr` from the raw pointer `new` produces, and returns the `std::unique_ptr` so created. This form of the function doesn't support arrays or custom deleters (see Item 20), but it demonstrates that, with only a little effort, you can create `make_unique` yourself, if you need to.[†]

`std::make_unique` and `std::make_shared` are two of the three *make functions*: functions that take an arbitrary set of arguments, perfect-forward them to the constructor for a dynamically-allocated object, and return a smart pointer to that object. The third make function is `std::allocate_shared`. It acts just like `std:make_shared`, except its first argument is an allocator object to be used for the dynamic memory allocation.

Even the most trivial comparison of smart pointer creation using and not using a `make` function reveals the first reason why using such functions is preferable. Consider:

[†] To create a full-featured `make_unique` with the smallest effort possible, search for the standardization document that gave rise to it, then copy the implementation you'll find there. The document you want is N3588 by Stephan T. Lavavej, dated 2013-03-15.

```
auto upw1(std::make_unique<Widget>());      // with make func
std::unique_ptr<Widget> upw2(new Widget);   // without make func

auto spw1(std::make_shared<Widget>());      // with make func
std::shared_ptr<Widget> spw2(new Widget);   // without make func
```

I've highlighted the essential difference: the versions using `new` repeat the type being created, but the `make` functions don't. Repeating types runs afoul of a key tenet of software engineering: code duplication should be avoided. Duplication in source code increases compilation times, can lead to bloated object code, and generally renders a code base more difficult to work with. It often evolves into inconsistency in a code base, and inconsistency in a code base often leads to bugs. Besides, typing something twice takes more effort than typing it once, and who's not a fan of reducing their typing burden?

The second reason to prefer `make` functions has to do with exception safety. Suppose we have a function to process a `Widget` in accord with some priority:

```
void processWidget(std::shared_ptr<Widget> spw, int priority);
```

Passing the `std::shared_ptr` by value may look suspicious, but Item 17 explains that if `processWidget` always makes a copy of the `std::shared_ptr` (e.g., by storing it in a data structure tracking `Widget`s that have been processed), this can be a reasonable design choice.

Now suppose we have a function to compute the relevant priority,

```
int computePriority();
```

and we use that in a call to `processWidget` that uses `new` instead of `std::make_shared`:

```
processWidget(std::shared_ptr<Widget>(new Widget),  // potential
              computePriority());                   // resource
                                                    // leak!
```

As the comment indicates, this code could leak the `Widget` conjured up by `new`. But how? Both the calling code and the called function are using `std::shared_ptr`s, and `std::shared_ptr`s are designed to prevent resource leaks. They automatically destroy what they point to when the last `std::shared_ptr` pointing there goes away. If everybody is using `std::shared_ptrs` everywhere, how can this code leak?

The answer has to do with compilers' translation of source code into object code. At runtime, the arguments for a function must be evaluated before the function can be invoked, so in the call to `processWidget`, the following things must occur before `processWidget` can begin execution:

- The expression "`new Widget`" must be evaluated, i.e., a `Widget` must be created on the heap.
- The constructor for the `std::shared_ptr<Widget>` responsible for managing the pointer produced by `new` must be executed.
- `computePriority` must run.

Compilers are not required to generate code that executes them in this order. "`new Widget`" must be executed before the `std::shared_ptr` constructor may be called, because the result of that `new` is used as an argument to that constructor, but `computePriority` may be executed before those calls, after them, or, crucially, *between* them. That is, compilers may emit code to execute the operations above in this order:

1. Perform "`new Widget`".
2. Execute `computePriority`.
3. Run `std::shared_ptr` constructor.

If such code is generated and, at runtime, `computePriority` produces an exception, the dynamically allocated `Widget` from Step 1 will be leaked, because it will never be stored in the `std::shared_ptr` that's supposed to start managing it in Step 3.

Using `std::make_shared` avoids this problem. Calling code would look like this:

```
processWidget(std::make_shared<Widget>(),    // no potential
              computePriority());           // resource leak
```

At runtime, either `std::make_shared` or `computePriority` will be called first. If it's `std::make_shared`, the raw pointer to the dynamically allocated `Widget` is safely stored in the returned `std::shared_ptr` before `computePriority` is called. If `computePriority` then yields an exception, the `std::shared_ptr` destructor will see to it that the `Widget` it owns is destroyed. And if `computePriority` is called first and yields an exception, `std::make_shared` will not be invoked, and there will hence be no dynamically allocated `Widget` to worry about.

If we replace `std::shared_ptr` and `std::make_shared` with `std::unique_ptr` and `std::make_unique`, exactly the same reasoning applies. Using `std::make_unique` instead of `new` is thus just as important in writing exception-safe code as using `std::make_shared`.

A special feature of `std::make_shared` (compared to direct use of `new`) is improved efficiency. Using `std::make_shared` allows compilers to generate smaller, faster code that employs leaner data structures. Consider the following direct use of `new`:

```
std::shared_ptr<Widget> spw(new Widget);
```

It's obvious that this code entails a memory allocation, but it actually requires two. Item 21 explains that every `std::shared_ptr` points to a control block containing, among other things, the reference count for the pointed-to object. Memory for this control block is allocated in the `std::shared_ptr` constructor. Direct use of `new`, then, requires one memory allocation for the `Widget` and a second allocation for the control block.

If `std::make_shared` is used instead,

```
auto spw = std::make_shared<Widget>();
```

one allocation suffices. That's because `std::make_shared` allocates a single chunk of memory to hold both the `Widget` object and the control block. This optimization reduces the static size of the program, because the code contains only one memory allocation call, and it increases the speed of the executable code, because memory is allocated only once. Furthermore, using `std::make_shared` obviates the need for some of the bookkeeping information in the control block, thus reducing the total memory footprint for the program.

The efficiency analysis for `std::make_shared` is equally applicable to `std::allocate_shared`, so the performance advantages of `std::make_shared` extend to that `make` function, as well.

Clearly, the argument for preferring `make` functions over direct use of `new` is a strong one. Despite their software engineering, exception-safety, and efficiency advantages, however, this Item's guidance is to *prefer* the `make` functions, not to rely on them exclusively. That's because there are circumstances where they can't or shouldn't be used.

For example, none of the `make` functions permit the specification of custom deleters (see Items 20 and 21), but both `std::unique_ptr` and `std::shared_ptr` have constructors that do. Given a custom deleter for a `Widget`,

```
auto widgetDeleter = [](Widget* pw) { … };
```

creating a smart pointer using it is straightforward using `new`:

```
std::unique_ptr<Widget, decltype(widgetDeleter)>
  upw(new Widget, widgetDeleter);

std::shared_ptr<Widget> spw(new Widget, widgetDeleter);
```

There's no way to do the same thing with a `make` function.

Item 7 explains that when creating an object whose type overloads constructors both with and without `std::initializer_list` parameters, creating the object using braces calls the `std::initializer_list` constructor, while creating the object using parentheses calls the non-`std::initializer_list` constructor. The `make` functions perfect-forward their parameters to an object's constructor, but do they do so using parentheses or using braces? For some types, this seemingly trivial syntactic detail can make a big difference. For example, in these calls,

```
auto upv = std::make_unique<std::vector<int>>(10, 20);

auto spv = std::make_shared<std::vector<int>>(10, 20);
```

do the resulting smart pointers point to `std::vector`s with 10 elements, each of value 20, or to `std::vector`s with two elements, one with value 10 and the other with value 20? Or is the result indeterminate?

The good news is that it's not indeterminate: both calls create `std::vector`s of size 10 with all values set to 20. That means that within the `make` functions, the perfect forwarding code uses parentheses, not braces. The bad news is that if you want to achieve the effect of using braces, you must use `new` directly. Using a `make` function would require the ability to perfect-forward a braced initializer through a function, but, as `Item 32` explains, braced initializers can't be perfect-forwarded.

For `std::unique_ptr`, these two scenarios (custom deleters and braced initializers) are the only ones where its `make` function can't be used. For `std::shared_ptr` and its `make` functions, there are two more. Both are edge cases, but some developers live on the edge, and you may be one of them.

Some classes define their own versions of `operator new` and `operator delete`. The presence of these functions implies that the global memory allocation and deallocation routines for objects of these types are inappropriate. Often, these class-specific routines are designed only to allocate and deallocate chunks of memory of precisely the size of objects of the class, e.g., `operator new` and `operator delete` for class `Widget` are often designed only to handle allocation and deallocation of chunks of memory of exactly size `sizeof(Widget)`. Such routines are a poor fit for `std::shared_ptr`'s support for custom allocation (via `std::allocate_shared`) and deallocation (via custom deleters), because the amount of memory that `std::allocate_shared` requests isn't the size of the dynamically allocated object, it's the size of that object *plus* the size of a control block. Consequently, using `make` functions to create objects of types with class-specific versions of `operator new` and `operator delete` is typically a poor idea.

The size and speed advantages of `std::make_shared` vis-à-vis direct use of `new` stem from `std::shared_ptr`'s control block being placed in the same chunk of memory as the managed object. When that object's reference count goes to zero, the object is destroyed (i.e., its destructor is called). However, the memory it occupies can't be released until the control block has also been destroyed, because the same chunk of dynamically allocated memory contains both.

As I noted, the control block contains bookkeeping information beyond just the reference count itself. The reference count tracks how many `std::shared_ptr`s refer to the control block, but the control block contains a second reference count, one that tallies how many `std::weak_ptr`s refer to the control block. This second reference count is known as the *weak count*.[†] When a `std::weak_ptr` checks to see if it has expired (see Item 21), it does so by examining the reference count (not the weak count) in the control block that it refers to. If the reference count is zero (i.e., if the pointed-to object has no `std::shared_ptr`s referring to it and has thus been destroyed), the `std::weak_ptr` has expired. Otherwise, it hasn't.

As long as `std::weak_ptr`s refer to a control block (i.e., the weak count is greater than zero), that control block must continue to exist. And as long as a control block exists, the dynamically allocated memory containing it must remain allocated. The memory allocated by a `std::shared_ptr` `make` function, then, can't be deallocated until the last `std::shared_ptr` *and* the last `std::weak_ptr` referring to it has been destroyed.

When the final `std::shared_ptr` referring to a control block is destroyed, the object it referred to is destructed, but the memory that object occupied remains allocated until the final `std::weak_ptr` referring to the control block is also destroyed. If the object type is quite large and the time between destruction of the last `std::shared_ptr` and the last `std::weak_ptr` is significant, the result could be notable lags between when an object is destroyed and when the memory it occupied is freed:

[†] In practice, the value of the weak count isn't always equal to the number of outstanding `std::weak_ptr`s, because library implementers have found ways to encode additional information that permits the generation of better code. For purposes of this Item, we'll ignore this discrepancy and assume that the weak count's value is the number of `std::weak_ptr`s referring to the control block.

```
class ReallyBigType { … };

auto pBigObj =                          // create very large
  std::make_shared<ReallyBigType>();    // object via
                                        // std::make_shared

…             // create std::shared_ptrs and std::weak_ptrs to
              // large object, use them to work with it

…             // final std::shared_ptr to object destroyed here,
              // but std::weak_ptrs to it remain

…             // during this period, memory formerly occupied
              // by large object remains allocated

…             // final std::weak_ptr to object destroyed here;
              // memory for control block and object is released
```

With a direct use of `new`, the memory for the `ReallyBigType` object can be released as soon as the last `std::shared_ptr` to it is destroyed:

```
class ReallyBigType { … };              // as before

std::shared_ptr<ReallyBigType> pBigObj(new ReallyBigType);
                                        // create very large
                                        // object via new

…             // as before, create std::shared_ptrs and
              // std::weak_ptrs to object, use them with it

…             // final std::shared_ptr to object destroyed here,
              // but std::weak_ptrs to it remain;
              // memory for object is deallocated

…             // during this period, only memory for the
              // control block remains allocated

…             // final std::weak_ptr to object destroyed here;
              // memory for control block is released
```

Should you find yourself in a situation where use of `std::make_shared` is impossible or inappropriate, you'll want to guard yourself against the kind of exception-safety problems we saw earlier. The best way to do that is to make sure that when you use `new` directly, you pass the result to a smart pointer constructor in *a statement that does nothing else*. This prevents compilers from generating code corresponding to operations being inserted between the use of `new` and the call of the constructor for the smart pointer that will manage the `new`ed object.

As an example, consider a minor revision to the exception-unsafe call to the `processWidget` function we examined earlier. This time, we'll specify a custom deleter:

```
void cusDel(Widget *ptr);                      // custom deleter
```

Here's the exception-unsafe call:

```
processWidget(                                    // as before,
  std::shared_ptr<Widget>(new Widget, cusDel),    // potential
  computePriority()                               // resource
);                                                // leak!
```

Recall: if `computePriority` is called after "`new Widget`" but before the `std::shared_ptr` constructor, and if `computePriority` yields an exception, the dynamically allocated `Widget` will be leaked.

In this example, the need for a custom deleter precludes use of `std::make_shared`, so the way to avoid the problem is to put the allocation of the `Widget` and the construction of the `std::shared_ptr` into their own statement, then call `processWidget` with the `std::shared_ptr` object:

```
std::shared_ptr<Widget> spw(new Widget, cusDel);

processWidget(spw, computePriority());
```

This works, because a `std::shared_ptr` assumes ownership of the raw pointer passed to its constructor, even if that constructor yields an exception. In this example, if `pw`'s constructor throws an exception (e.g., due to an inability to dynamically allocate memory for a control block), it's still guaranteed that `cusDel` will be invoked on the pointer resulting from "`new Widget`".

That's interesting and worth knowing, but it's also typically irrelevant, because in most cases, there's no reason not to use a `make` function. And unless you have a compelling reason for doing otherwise, using a `make` function is what you should do.

Things to Remember

- Compared to direct use of `new`, the `make` functions eliminate source code duplication, improve exception safety, and, for `std::make_shared` and `std::allocate_shared`, generate code that's smaller and faster.
- Situations where use of the `make` functions is inappropriate include the need to specify custom deleters and a desire to pass braced initializers.
- For `std::shared_ptr`s, additional situations where `make` functions may be ill-advised include (1) classes with custom memory management and (2) systems with memory concerns, very large objects, and `std::weak_ptr`s that outlive the corresponding `std::shared_ptr`s.

Item 24: When using the Pimpl Idiom, define special member functions in the implementation file.

If you've ever had to combat excessive build times, you're familiar with the *Pimpl* ("pointer to implementation") *Idiom*. That's the technique whereby you replace the data members of a class with a pointer to an implementation class (or struct), put the data members that used to be in the primary class into the implementation class, and access those data members indirectly through the pointer. For example, suppose `Widget` looks like this:

```
class Widget {                     // in header "widget.h"
public:
  Widget();
  …

private:
  std::string name;
  std::vector<double> data;
  Gadget g1, g2, g3;
};
```

Because `Widget`'s data members are of types `std::string`, `std::vector`, and `Gadget`, headers for those types must be present for `Widget` to compile, and that means that `Widget` clients must `#include <string>`, `<vector>`, and `gadget.h`. Those headers increase the compilation time for `Widget` clients, plus they make those clients dependent on the contents of the headers. If a header's content changes, `Widget` clients must recompile. The standard headers `<string>` and

`<vector>` don't change very often, but it could be that `gadget.h` is subject to frequent revision.

Applying the Pimpl Idiom in C++98 could have `Widget` replace its data members with a raw pointer to a struct that has been declared, but not defined:

```
class Widget {                    // still in header "widget.h"
public:
  Widget();
  ~Widget();                      // dtor is needed—see below
  …

private:
  struct Impl;                    // declare implementation struct
  Impl *pImpl;                    // and pointer to it
};
```

Because `Widget` no longer mentions the types `std::string`, `std::vector`, and `Gadget`, `Widget` clients no longer need to `#include` the headers for these types. That speeds compilation, and it also means that if something in these headers changes, `Widget` clients are unaffected.

A type that has been declared, but not defined, is known as an *incomplete type*. `Widget::Impl` is such a type. There are very few things you can do with an incomplete type, but declaring a pointer to it is one of them. The Pimpl Idiom takes advantage of that.

Part 1 of the Pimpl Idiom is the declaration of a data member that's a pointer to an incomplete type. Part 2 is the dynamic allocation and deallocation of the object that holds the data members that used to be in the original class. The allocation and deallocation code goes in the implementation file, e.g., for `Widget`, in `widget.cpp`:

```
#include "widget.h"               // in impl. file "widget.cpp"
#include "gadget.h"
#include <string>
#include <vector>

struct Widget::Impl {             // definition of Widget::Impl
  std::string name;               // with data members formerly
  std::vector<double> data;       // in Widget
  Gadget g1, g2, g3;
};
```

```
Widget::Widget()                 // allocate data members for
: pImpl(new Impl)                // this Widget object
{}

Widget::~Widget()                // destroy data members for
{ delete pImpl; }                // this object
```

Here I'm showing `#include` directives to make clear that the overall dependencies on the headers for `std::string`, `std::vector`, and `Gadget` continue to exist. However, these dependencies have been moved from `widget.h` (which is visible to and used by `Widget` clients) to `widget.cpp` (which is visible to and used only by the `Widget` implementer). I've also highlighted the code that dynamically allocates and deallocates the `Impl` object. The need to deallocate this object when a `Widget` is destroyed is what necessitates the `Widget` destructor.

But I've shown you C++98 code, and that reeks of a bygone millennium. It uses raw pointers and raw `new` and raw `delete` and it's all just so…raw. This chapter is built on the idea that smart pointers are preferable to raw pointers, and if what we want is to dynamically allocate a `Widget::Impl` object inside the `Widget` constructor and have it destroyed at the same time the `Widget` is, `std::unique_ptr` (see Item 20) is precisely the tool we need. Replacing the raw `pImpl` pointer with a `std::unique_ptr` yields this code for the header file,

```
class Widget {                       // in "widget.h"
public:
  Widget();
  …

private:
  struct Impl;
  std::unique_ptr<Impl> pImpl;       // use smart pointer
};                                   // instead of raw pointer
```

and this for the implementation file:

```
#include "widget.h"                  // in "widget.cpp"
#include "gadget.h"
#include <string>
#include <vector>

struct Widget::Impl {                // as before
  std::string name;
  std::vector<double> data;
```

```
  Gadget g1, g2, g3;
};

Widget::Widget()                     // per Item 23, create
: pImpl(std::make_unique<Impl>())    // std::unique_ptr
{}                                   // via std::make_unique
```

You'll note that the `Widget` destructor is no longer present. That's because we have no code to put into it. `std::unique_ptr` automatically deletes what it points to when it (the `std::unique_ptr`) is destroyed, so we need not delete anything ourselves. That's one of the attractions of smart pointers: they eliminate the need for us to sully our hands with manual resource release.

This code compiles, but, alas, the most trivial client use doesn't:

```
#include "widget.h"

Widget w;                            // error!
```

The error message you get depends on the compiler you're using, but the text generally mentions something about applying `sizeof` or `delete` to an incomplete type. Those operations aren't among the very few things you can do with such types.

This apparent failure of the Pimpl Idiom using `std::unique_ptr`s is alarming, because (1) `std::unique_ptr` is advertised as supporting incomplete types, and (2) the Pimpl Idiom is one of `std::unique_ptr`s most common use cases. Fortunately, getting the code to work is easy. All that's required is a basic understanding of the cause of the problem.

The issue arises due to the code that's generated when `w` is destroyed (e.g., goes out of scope). At that point, its destructor is called. In the class definition using `std::unique_ptr`, we didn't declare a destructor, because we didn't have any code to put into it. In accord with the usual rules for compiler-generated special member functions (see Item 19), the compiler generates a destructor for us. Within that destructor, the compiler inserts code to call the destructor for `Widget`'s data member, `pImpl`. `pImpl` is a `std::unique_ptr<Widget::Impl>`, i.e., a `std::unique_ptr` using the default deleter. The default deleter is a function that uses `delete` on the raw pointer inside the `std::unique_ptr`. Prior to using de-

`lete`, however, implementations typically have the default deleter employ C++11's `static_assert` to ensure that the raw pointer doesn't point to an incomplete type. When the compiler generates code for the destruction of the `Widget` `w`, then, it encounters a `static_assert` that fails, and that's what leads to the error message.† This message is associated with the point where `w` is destroyed, because `Widget`'s destructor, like all compiler-generated special member functions, is implicitly `inline`. The message itself often refers to the line where `w` is created, because it's the source code explicitly creating the object that leads to its later implicit destruction.

Fixing the problem is easy. You just need to make sure that at the point where the code to destroy the `std::unique_ptr<Widget::Impl>` is generated, `Widget::Impl` is a complete type. The type becomes complete when its definition has been seen, and `Widget::Impl` is defined inside `widget.cpp`. The key to successful compilation, then, is to have the compiler see the body of `Widget`'s destructor (i.e., the place where the compiler will generate code to destroy the `std::unique_ptr` data member) only inside `widget.cpp` after `Widget::Impl` has been defined.

Arranging for that is simple. Declare (but don't define!) `Widget`'s destructor in `widget.h`,

```
class Widget {                     // as before, in "widget.h"
public:
  Widget();
  ~Widget();                       // declaration only!
  …

private:                           // as before
  struct Impl;
  std::unique_ptr<Impl> pImpl;
};
```

† Implementations need not have a `static_assert` in the default deleter. Nor, for that matter, are they required to reject code deleting an incomplete type. But all implementations I'm familiar with take steps to ensure that code involving the destruction of a `std::unique_ptr` to an incomplete type won't compile.

and define it in `widget.cpp` after `Widget::Impl` has been defined:

```
#include "widget.h"                 // as before, in "widget.cpp"
#include "gadget.h"
#include <string>
#include <vector>

struct Widget::Impl {               // as before, definition of
  std::string name;                 // Widget::Impl
  std::vector<double> data;
  Gadget g1, g2, g3;
};

Widget::Widget()                    // as before
: pImpl(std::make_unique<Impl>())
{}

Widget::~Widget()                   // ~Widget definition
{}
```

This works well, and it requires the least typing, but if you want to emphasize that the compiler-generated destructor would do the right thing—that the only reason you declared it was to cause its definition to be generated in `Widget`'s implementation file, you can define the destructor body with `=default`:

```
Widget::~Widget() = default;        // same effect as above
```

Classes using the Pimpl Idiom are natural candidates for move support, because compiler-generated move operations do exactly what's desired: perform a move on the underlying `std::unique_ptr`. As Item 19 explains, the declaration of a destructor in `Widget` prevents compilers from generating the move operations, so if you want move support, you must declare the functions yourself. Given that the compiler-generated versions would behave correctly, you might be tempted to implement them thusly:

```
class Widget {                                  // still in
public:                                         // "widget.h"
  Widget();
  ~Widget();

  Widget(Widget&& rhs) = default;               // right idea,
  Widget& operator=(Widget&& rhs) = default;    // wrong code!

  …
```

```
private:                                       // as before
  struct Impl;
  std::unique_ptr<Impl> pImpl;
};
```

This approach leads to the same kind of problem as declaring the class without a destructor, and for the same fundamental reason. The compiler-generated move assignment operator needs to destroy the object pointed to by `pImpl` before reassigning it, but in the `Widget` header file, `pImpl` points to an incomplete type. The situation is different for the move constructor. The problem there is that compilers typically generate code to destroy `pImpl` in the event that an exception arises inside the move constructor, and destroying `pImpl` requires that `Impl` be complete.

Because the problem is the same as before, so is the fix: move the definition of the move operations into the implementation file:

```
class Widget {                       // still in "widget.h"
public:
  Widget();
  ~Widget();

  Widget(Widget&& rhs);              // declarations
  Widget& operator=(Widget&& rhs);   // only

  …

private:                             // as before
  struct Impl;
  std::unique_ptr<Impl> pImpl;
};


#include <string>                    // as before,
…                                    // in "widget.cpp"

struct Widget::Impl { … };           // as before

Widget::Widget()                     // as before
: pImpl(std::make_unique<Impl>())
{}

Widget::~Widget() = default;         // as before

Widget::Widget(Widget&& rhs) = default;              // defini-
Widget& Widget::operator=(Widget&& rhs) = default;   // tions
```

The Pimpl Idiom is a way to reduce compilation dependencies between a class's implementation and the class's clients, but, conceptually, use of the idiom doesn't change what the class represents. The original `Widget` class contained `std::string`, `std::vector`, and `Gadget` data members, and, assuming that `Gadget`s, like `std::string`s and `std::vector`s, can be copied, it would make sense for `Widget` to support the copy operations. We have to write these functions ourselves, because (1) compilers won't generate copy operations for classes with move-only types like `std::unique_ptr` and (2) even if they did, the generated functions would copy only the `std::unique_ptr` (i.e., perform a *shallow copy*), and we want to copy what the pointer points to (i.e., perform a *deep copy*).

In a ritual that is by now familiar, we declare the functions in the header file and implement them in the implementation file:

```
class Widget {                     // still in "widget.h"
public:
  …                                // other funcs, as before

  Widget(const Widget& rhs);                 // declarations
  Widget& operator=(const Widget& rhs);      // only

private:                                     // as before
  struct Impl;
  std::unique_ptr<Impl> pImpl;
};


#include "widget.h"                // as before,
…                                  // in "widget.cpp"

struct Widget::Impl { … };         // as before

Widget::~Widget() = default;       // other funcs, as before

Widget::Widget(const Widget& rhs)               // copy ctor
: pImpl(std::make_unique<Impl>(*rhs.pImpl))
{}

Widget& Widget::operator=(const Widget& rhs)    // copy operator=
{
  if (this != &rhs) {              // detect self-assignment
    *pImpl = *rhs.pImpl;
  }
```

```
  return *this;
}
```

Both function implementations are conventional. In each case, we simply copy the fields of the Impl struct from the source object (rhs) to the destination object (*this). Rather than copy the fields one by one, we take advantage of the fact that compilers will create the copy operations for Impl, and these operations will copy each field automatically. We thus implement Widget's copy operations by calling Widget::Impl's compiler-generated copy operations. In the copy constructor, note that we still follow the advice of Item 23 to prefer use of std::make_unique over direct use of new, and in the copy assignment operator, we adhere to common C++ convention by doing nothing if we detect that an object is being assigned to itself.

For purposes of implementing the Pimpl Idiom, std::unique_ptr is the smart pointer to use, because the pImpl pointer inside an object (e.g., inside a Widget) has exclusive ownership of the corresponding implementation object (e.g., the Widget::Impl object). Still, it's interesting to note that if we were to use std::shared_ptr instead of std::unique_ptr for pImpl, we'd find that the advice of this Item no longer applied. There'd be no need to declare a destructor in Widget, and without a user-declared destructor, compilers would happily generate the move operations, which would do exactly what we'd want them to. That is, given this code in widget.h,

```
class Widget {                      // in "widget.h"
public:
  Widget();
  …                                 // no declarations for dtor
                                    // or move operations
private:
  struct Impl;
  std::shared_ptr<Impl> pImpl;      // std::shared_ptr
};                                  // instead of std::unique_ptr
```

and this client code that #includes widget.h,

```
Widget w1;

auto w2(std::move(w1));             // move-construct w2

w1 = std::move(w2);                 // move-assign w1
```

everything would compile and run as we'd hope: `w1` would be default-constructed, its value would be moved into `w2`, that value would be moved back into `w1`, and then both `w1` and `w2` would be destroyed (thus causing the pointed-to `Widget::Impl` object to be destroyed).

The difference in behavior between `std::unique_ptr` and `std::shared_ptr` for `pImpl` pointers stems from the differing ways that these smart pointers support custom deleters. For `std::unique_ptr`, the type of the deleter is part of the type of the smart pointer, and this makes it possible for compilers to generate smaller runtime data structures and faster runtime code. A consequence of this greater efficiency is that pointed-to types must be complete when compiler-generated special functions (e.g., destructors or move operations) are used. For `std::shared_ptr`, the type of the deleter is not part of the type of the smart pointer. This necessitates larger runtime data structures and somewhat slower code, but pointed-to types need not be complete when compiler-generated special functions are employed.

For the Pimpl Idiom, there's not really a trade-off between the characteristics of `std::unique_ptr` and `std::shared_ptr`, because the relationship between classes like `Widget` and classes like `Widget::Impl` is exclusive ownership, and that makes `std::unique_ptr` the proper tool for the job. Nevertheless, it's worth knowing that in other situations—situations where shared ownership exists (and `std::shared_ptr` is hence a good design choice), there's no need to jump through the function-definition hoops that use of `std::unique_ptr` entails.

Things to Remember

- The Pimpl Idiom decreases build times by reducing compilation dependencies between class implementations and class clients.
- For `std::unique_ptr pImpl` pointers, declare special member functions in the class header, but implement them in the implementation file. Do this even if the default function implementations are acceptable.
- The above advice applies to `std::unique_ptr`, but not to `std::shared_ptr`.

Chapter 5 Rvalue References, Move Semantics, and Perfect Forwarding

When you first learn about them, move semantics and perfect forwarding seem pretty straightforward:

- **Move semantics** makes it possible for compilers to replace expensive copying operations with less expensive moves. In the same way that copy constructors and copy assignment operators give developers control over what it means to copy objects, move constructors and move assignment operators offer control over the semantics of moving.

- **Perfect forwarding** makes it possible to write function templates that take arbitrary arguments and forward them to other functions such that the target functions receive exactly the same arguments as were passed to the forwarding functions.

Rvalue references are the glue that ties these two rather disparate features together. They're the underlying language mechanism that makes both move semantics and perfect forwarding possible.

The more experience you have with these features, the more you realize that your initial impression was based on only the metaphorical tip of the proverbial iceberg. The world of move semantics, perfect forwarding, and rvalue references is more nuanced than it appears. `std::move` doesn't move anything, for example, and perfect forwarding is imperfect. Move operations aren't always cheaper than copying; when they are, they're not always as cheap as you'd expect; and they're not always called in a context where moving is valid. The construct `T&&` doesn't always represent an rvalue reference.

No matter how far you dig into these features, it can seem that there's always more to uncover. Fortunately, there is a limit to the depths of move semantics, perfect forwarding, and rvalue references. This chapter will take you to the bedrock. Once you arrive, this part of C++11 will make a lot more sense. You'll know the usage conventions for `std::move` and `std::forward`, for example. You'll be comfortable with the ambiguous nature of "T&&". You'll understand the reasons for the surprisingly varied behavioral profiles of move operations. All those pieces will come together and fall into place. At that point, you'll be back where you started, because move semantics, perfect forwarding, and rvalue references will once again seem pretty straightforward. But this time, they'll stay that way.

In the Items in this chapter, it's especially important to bear in mind that a parameter is always an lvalue, even if its type is an rvalue reference. That is, given

```
void f(Widget&& w);
```

the parameter `w` is an lvalue, even though its type is rvalue-reference-to-`Widget`. (If this surprises you, please review the overview of lvalues and rvalues that begins on page **Error! Bookmark not defined.**.)

Item 25: Understand `std::move` and `std::forward`.

It's useful to approach `std::move` and `std::forward` in terms of what they *don't* do. `std::move` doesn't move anything. `std::forward` doesn't forward anything. At runtime, neither does anything at all. That's because they generate no executable code. Not a single byte.

`std::move` and `std::forward` are merely functions that perform casts. `std::move` unconditionally casts its argument to an rvalue, while `std::forward` performs this cast only if a particular condition is fulfilled. That's it. The explanation leads to a new set of questions, but, fundamentally, that's the complete story.

To make the story more concrete, here's a sample implementation of `std::move` in C++11. It's not fully conforming to the details of the Standard, but it's very close.

```
template<typename T>                       // in namespace std
typename remove_reference<T>::type&&
move(T&& param)
{
  using ReturnType =                       // alias declaration;
    typename remove_reference<T>::type&&;  // see Item 9

  return static_cast<ReturnType>(param);
}
```

I've highlighted two parts of the code for you. One is the name of the function, because the return type specification is rather noisy, and I don't want you to lose your bearings in the din. The other thing is the cast that comprises the essence of the function. As you can see, `std::move` takes a reference to an object (a universal reference, to be precise (see Item 26)) and it returns a reference to the same object.

The "`&&`" part of the function's return type implies that `std::move` returns an rvalue reference, but, as Item 30 explains, if the type `T` happens to be an lvalue reference, `T&&` would become an lvalue reference. To prevent this from happening, the type trait (see Item 9) `std::remove_reference` is applied to `T`, thus ensuring that "`&&`" is applied to a type that isn't a reference. That guarantees that `std::move` truly returns an rvalue reference, and that's important, because rvalue references returned from functions are rvalues. (Why? Because the C++ Standard says they are.) Thus, `std::move` casts its argument to an rvalue, and that's all it does.

As an aside, `std::move` can be implemented with less fuss in C++14. Thanks to function return type deduction (see Item 3) and to the Standard Library's alias template `std::remove_reference_t` (see Item 9), `std::move` can be written this way:

```
template<typename T>                          // C++14 only; still
decltype(auto) move(T&& param)                // in namespace std
{
  using ReturnType = remove_reference_t<T>&&;
  return static_cast<ReturnType>(param);
}
```

Easier on the eyes, no?

Because `std::move` does nothing but cast its argument to an rvalue, there have been suggestions that a better name for it might be something like `rvalue_cast`. Be that as it may, the name we have is `std::move`, so it's important to remember what `std::move` does and doesn't do. It does cast. It doesn't move.

Of course, rvalues are candidates for moving, so applying `std::move` to an object tells the compiler that that object is eligible to be moved from. That's why std::move has the name it does: to make it easy to designate objects that may be moved from.

Actually, rvalues are only *usually* candidates for moving. Suppose you're writing a function taking a std::string parameter, and you know that inside your function, you'll copy that parameter. Flush with the advice proffered by Item 17, you declare a by-value parameter:

```
void f(std::string s);        // s to be copied, so per Item 17,
                              // pass by value
```

But suppose you also know that inside f, you only need to read s's value; you'll never need to modify it. In accord with the time-honored tradition of using const whenever possible, you revise your declaration such that s is const:

```
void f(const std::string s);
```

Finally, assume that at the end of f, s will be copied into some data structure. Except that you don't want to pay for the copy, so, again in accord with Item 17, you apply std::move to s to turn it into an rvalue:

```
struct SomeDataStructure {
  std::string name;
  …
};

SomeDataStructure sds;

void f(const std::string s)
{
  …                           // read operations on s

  sds.name = std::move(s);   // "move" s into sds.name; this code
}                            // doesn't do what it seems to!
```

This code compiles. This code links. This code runs. This code sets sds.name to the value you expect. The only thing separating this code from a perfect realization of your vision is that s is not moved into sds.name, it's *copied*. Sure, s is cast to an rvalue by std::move, but s is declared as a const std::string, so before the cast, s is an lvalue const std::string, and the result of the cast is an rvalue const std::string, but throughout it all, s remains const.

Consider the effect that has when compilers have to determine which `std::string` assignment operator to call. There are two possibilities:

```
class string {              // std::string is actually a
public:                     // typedef for std::basic_string<char>
  …
  string& operator=(const string& rhs);  // copy assignment
  string& operator=(string&& rhs);       // move assignment
  …
};
```

In our function `f`, the result of `std::move(s)` is an rvalue of type `const std::string`. That rvalue can't be passed to `std::string`'s move assignment operator, because the move assignment operator takes an rvalue reference to a *non-*`const` `std::string`. The rvalue can, however, be passed to the copy assignment operator, because an lvalue reference-to-`const` is permitted to bind to a `const` rvalue. The statement

```
  sds.name = std::move(s);
```

therefore invokes the *copy* assignment operator in `std::string`, even though `s` has been cast to an rvalue! Such behavior is essential to maintaining `const`-correctness. Moving a value out of an object generally modifies the object, so the language should not permit `const` objects to be passed to functions (such as move assignment operators) that could modify them.

There are two lessons to be drawn from this example. First, don't declare objects `const` if you want to be able to move from them. Move requests on `const` objects are silently transformed into copy operations.

Second, `std::move` not only doesn't actually move anything, it doesn't even guarantee that the object it's casting will be eligible to be moved. The only thing you know for sure about an object that has been `std::move`d is that it's an rvalue.

The story for `std::forward` is similar to that for `std::move`, but whereas `std::move` *unconditionally* casts its argument to an rvalue, `std::forward` does it only under certain conditions. `std::forward` is a *conditional* cast. To understand when it casts and when it doesn't, recall how `std::forward` is typically used. The most common scenario is a function template taking a universal reference parameter that is to be passed to another function:

```
void process(const Widget& lvalParam);    // process lvalues
void process(Widget&& rvalParam);         // process rvalues

template<typename T>                      // template that passes
void logAndProcess(T&& param)             // param to process
{
  auto now =                              // get current time
    std::chrono::system_clock::now();

  makeLogEntry("Calling 'process'", now);
  process(std::forward<T>(param));

}
```

Consider two calls to `logAndProcess`, one with an lvalue, the other with an rvalue:

```
Widget w;

logAndProcess(w);                   // call with lvalue
logAndProcess(std::move(w));        // call with rvalue
```

Inside `logAndProcess`, the parameter `param` is passed to the function `process`. `process` is overloaded for lvalues and rvalues. When we call `logAndProcess` with an lvalue, we naturally expect that lvalue to be forwarded to `process` as an lvalue, and when we call `logAndProcess` with an rvalue, we expect the rvalue overload of `process` to be invoked.

But `param`, like all function parameters, is an lvalue. Every call to `process` inside `logAndProcess` will thus want to invoke the lvalue overload for `process`. To prevent this, we need a mechanism for `param` to be cast to an rvalue if and only if the argument with which `param` was initialized—the argument passed to `logAndProcess`—was an rvalue. This is precisely what `std::forward` does. That's why `std::forward` is a *conditional* cast: it casts to an rvalue only if its argument was initialized with an rvalue.

You may wonder how `std::forward` can know whether its argument was initialized with an rvalue. In the code above, for example, how can `std::forward` tell whether `param` was initialized with an lvalue or an rvalue? The brief answer is that

that information is encoded in `logAndProcess´s` template parameter `T`. That parameter is then passed to `std::forward`, which recovers the encoded information. Item 30 covers all the details, but for now, simply accept that `T` will be an lvalue reference only if `param` was initialized with an lvalue. That means that `std::forward` can, in concept, be implemented something like this:

```
template<typename T>                     // conceptual impl. of
T&&                                      // std::forward (in
forward(T&& param)                       // namespace std)
{
  if (is_lvalue_reference<T>::value) {   // if T indicates lvalue
    return param;                        // return param as lvalue
  } else {                               // else
    return move(param);                  // return param as rvalue
  }
}
```

Don't be misled by `forward`'s return type declaration into thinking that it returns an rvalue reference. Item 30 will make clear that when an lvalue is being returned from this function, `std::forward`'s return type will be an lvalue reference.

Note that this is a *conceptual* implementation. This code won't even compile for some uses, and when it does compile, it'll generate runtime code. Real `std::forward` implementations compile for all uses, and they never generate runtime code. For purposes of understanding how `std::forward` determines whether to cast to an rvalue, however, this suffices.

Given that both `std::move` and `std::forward` boil down to casts, the only difference being that `std::move` always casts, while `std::forward` only sometimes does, you may wonder whether we can dispense with `std::move` and just use `std::forward` everywhere. From a purely technical perspective, the answer is yes: `std::forward` can do it all. `std::move` isn't necessary. (Strictly speaking, neither function is *necessary*, because we could write our own casts everywhere, but I hope we agree that that would be, well, yucky.)

`std::move`'s advantage is convenience. Consider a conventional move constructor for a class with a single data member of type `std::string`:

```
class Widget {
public:
```

```
  Widget(Widget&& rhs)                        // conventional
  : s(std::move(rhs.s)) {}                    // move constructor
  …

private:
  std::string s;
};
```

If we wanted to implement the same behavior using `std::forward` instead of `std::move`, we'd have to write it this way:

```
class Widget {
public:
  Widget(Widget&& rhs)                        // move ctor using
  : s(std::forward<std::string>(rhs.s)) {}    // std::forward
  …                                           // instead of
};                                            // std::move
```

Note first that `std::move` requires only a function argument (i.e., `rhs.s`), while `std::forward` requires both a function argument (`rhs.s`) and a template type argument (`std::string`). Note second that the type we pass to `std::forward` should be a non-reference, because that's the standard mechanism for encoding that the argument being passed is an rvalue (see Item 30). Together, this means that `std::move` requires less typing than `std::forward`, and it spares us the trouble of passing a type argument that encodes that the argument we're passing is an rvalue.

More importantly, the use of `std::move` conveys the use of an unconditional cast to an rvalue, while the use of `std::forward` indicates a cast to an rvalue only for references to which rvalues have been bound. Those are two very different actions. The first one typically sets up a move, while the second one just passes—*forwards*—an object to another function in a way that retains its original lvalueness or rvalueness. Because these actions are so different, it's good that we have two different functions (and function names) to distinguish them.

Things to Remember

- `std::move` performs an unconditional cast to an rvalue. In and of itself, it doesn't move anything.

- `std::forward` casts its argument to an rvalue only if that argument is bound to an rvalue.
- Neither `std::move` nor `std::forward` do anything at runtime.

Item 26: Distinguish universal references from rvalue references.

It's been said that the truth shall set you free, but under the right circumstances, a well-chosen lie can be equally liberating. This entire Item is such a lie. Because we're dealing with software, however, let's eschew the word "lie" and instead say that this Item comprises an *abstraction*.

To declare an rvalue reference to some type `T`, you write `T&&`. It thus seems reasonable to assume that if you see "`T&&`" in source code, you're looking at an rvalue reference. Alas, it's not quite that simple:

```
void f(Widget&& param);              // rvalue reference

Widget&& var1 = Widget();            // rvalue reference

auto&& var2 = var1;                  // not rvalue reference

template<typename T>
void f(std::vector<T>&& param);      // rvalue reference

template<typename T>
void f(T&& param);                   // not rvalue reference
```

In fact, "`T&&`" has two different meanings. One is rvalue reference, of course. Such references behave exactly the way you expect: they bind only to rvalues, and their primary *raison d'être* is to identify objects that may be moved from.

The other possible meaning for "`T&&`" is *either* rvalue reference *or* lvalue reference. Such references look like rvalue references in the source code (i.e., "`T&&`"), but they can behave as if they were lvalue references (i.e., "`T&`"). Their dual nature permits them to bind to rvalues (like rvalue references) as well as lvalues (like lvalue references). Furthermore, they can bind to `const` or non-`const` objects, to `volatile` or non-`volatile` objects, even to objects that are both `const` and `volatile`. They can bind to virtually *anything*. Such unprecedentedly flexible references deserve a name of their own. I call them *universal references*.

Universal references arise in two contexts. The most common is function template parameters, such as this example from the sample code above:

```
template<typename T>
void f(T&& param);             // param is a universal reference
```

The second context is `auto` declarations, including this one from the sample code above:

```
auto&& var2 = var1;            // var2 is a universal reference
```

What these contexts have in common is the presence of *type deduction*. In the template `f`, the type of `param` is being deduced, and in the declaration for `var2`, `var2`'s type is being deduced. Compare that with the following examples (also from the sample code above), where type deduction is missing. If you see "`T&&`" without type deduction, you're looking at an rvalue reference:

```
void f(Widget&& param);        // no type deduction;
                               // param is an rvalue reference

Widget&& var1 = Widget();      // no type deduction;
                               // var1 is an rvalue reference
```

Because universal references are references, they must be initialized. The initializer for a universal reference determines whether it represents an rvalue reference or an lvalue reference. If the initializer is an rvalue, the universal reference corresponds to an rvalue reference. If the initializer is an lvalue, the universal reference corresponds to an lvalue reference. For universal references that are function parameters, the initializer is provided at the call site:

```
template<typename T>
void f(T&& param);     // param is a universal reference

Widget w;
f(w);                  // lvalue passed to f; param's type is
                       // Widget& (i.e., an lvalue reference)

f(std::move(w));       // rvalue passed to f; param's type is
                       // Widget&& (i.e., an rvalue reference)
```

For a reference to be universal, type deduction is necessary, but it's not sufficient. The *form* of the reference declaration must also be correct, and that form is quite constrained. It must be precisely "T&&". Look again at this example from the sample code we saw earlier:

```
template<typename T>
void f(std::vector<T>&& param);   // param is an rvalue reference
```

When f is invoked, the type T will be deduced (unless the caller explicitly specifies it, an edge case we'll not concern ourselves with). But the form of param's type declaration isn't "T&&," it's "std::vector<T>&&." That rules out the possibility that param is a universal reference. param is therefore an rvalue reference, something that your compilers will be happy to confirm for you if you try to pass an lvalue to f:

```
std::vector<int> v;
f(v);                              // error! can't bind lvalue to
                                   // rvalue reference
```

Even the simple presence of a const qualifier is enough to disqualify a reference from being universal:

```
template<typename T>
void f(const T&& param);          // param is an rvalue reference
```

If you're in a template and you see a function parameter of type "T&&," you might think you can assume that it's a universal reference. You can't. That's because being in a template doesn't guarantee the presence of type deduction. Consider this push_back member function in std::vector:

```
template<class T, class Allocator = allocator<T>>  // from C++
class vector {                                      // Standard
public:
  void push_back(T&& x);
  …
};
```

push_back's parameter certainly has the right form for a universal reference, but there's no type deduction in this case. That's because push_back can't exist without a particular vector instantiation for it to be part of, and the type of that instantiation fully determines the declaration for push_back. That is, saying

```
std::vector<Widget> v;
```

causes

```
class vector<Widget, allocator<Widget>> {
public:
  void push_back(Widget&& x);              // rvalue reference
  …
};
```

to be generated, and now you can see clearly that `push_back` employs no type deduction. This `push_back` for `vector<T>` (there are two—the function is overloaded) always declares a parameter of type rvalue-reference-to-T.

In contrast, the conceptually similar `emplace_back` member function in `std::vector` *does* employ type deduction:

```
template<class T, class Allocator = allocator<T>>  // still from
class vector {                                     // C++
public:                                            // Standard
  template <class... Args>
  void emplace_back(Args&&... args);
  …
};
```

Here, the type parameter `Args` is independent of `vector`'s type parameter `T`, so `Args` must be deduced each time `emplace_back` is called. (Okay, `Args` is really a parameter pack, not a type parameter, but for purposes of this discussion, we can treat it as if it were a type parameter.)

The fact that `emplace_back`'s type parameter is named `Args`, yet it's still a universal reference, reinforces my earlier comment that it's the *form* of a universal reference that must be "`T&&`". There's no requirement that you use the name `T`. For example, the following template takes a universal reference, because the form ("*`type`*`&&`") is right, and `param`'s type will be deduced (again, excluding the corner case where the caller explicitly specifies the type):

```
template<typename MyTemplateType>         // param is a
void someFunc(MyTemplateType&& param);    // universal reference
```

I remarked earlier that `auto` variables can also be universal references. To be more precise, variables declared with the type `auto&&` are universal references, because type deduction takes place and they have the correct form ("`T&&`"). `auto` universal references are not as common as universal references used for function template parameters, but they do crop up from time to time in C++11. They crop up a lot more in C++14, because C++14 lambda expressions may declare `auto&&` parameters. For example, if you wanted to write a C++14 lambda to record the time taken in an arbitrary function invocation, you could do this:

```
auto timeFuncInvocation = [](auto&& func, auto&&... args)
  {
    start timer;
    std::forward<decltype(func)>(func)(        // invoke func on
      std::forward<decltype(args)>(args)...    // args in C++14
      );
    stop timer and record elapsed time;
  };
```

If your reaction to the "`std::forward<decltype(`*blah blah blah*`)>`" code inside the lambda is, "What the...?!", that probably just means you haven't yet read Item 35. Don't worry about it. The important thing in this Item is the `auto&&` parameters that the lambda declares. `func` is a universal reference that can be bound to any callable entity, lvalue or rvalue. `args` is one or more universal references (i.e., a universal reference parameter pack) that can be bound to any number of objects of arbitrary types. The result, thanks to `auto` universal references, is that `timeFuncInvocation` can time pretty much any function execution. (For information on the difference between "any" and "pretty much any," turn to Item 32.)

Bear in mind that this entire Item—the foundation of universal references—is a lie…er, an abstraction. The underlying truth is known as *reference-collapsing*, a topic to which Item 30 is dedicated. But the truth doesn't make the abstraction any less useful. Distinguishing between rvalue references and universal references will help you read source code more accurately ("Does that "`T&&`" I'm looking at bind to rvalues only or to everything?"), and it will avoid ambiguities when you communicate with your colleagues ("I'm using a universal reference here, not an rvalue reference…"). It will also allow you to make sense of Items 27 and 28, which rely on the distinction. So embrace the abstraction. Revel in it. Just as Newton's laws of motion (which are technically incorrect) are typically just as useful as and easier to apply than Einstein's theory of general relativity ("the truth"), so is the notion of universal references normally preferable to working through the details of reference-collapsing.

Things to Remember

- If a variable or parameter has type T&& for some deduced type T, it's a universal reference.
- If the form of the type isn't precisely T&&, or if type deduction does not occur, T&& denotes an rvalue reference.
- Universal references correspond to rvalue references if they're initialized with rvalues. They correspond to lvalue references if they're initialized with lvalues.

Item 27: Use std::move on rvalue references, std::forward on universal references.

Rvalue references bind only to objects that are candidates for moving. If you have an rvalue reference parameter, you *know* that the object it's bound to may be moved:

```
class Widget {
  Widget(Widget&& rhs);          // rhs definitely refers to an
  …                              // object eligible for moving
};
```

That being the case, you'll want to pass such objects to other functions in a way that permits those functions to take advantage of the object's rvalueness. The way to do that is to cast parameters bound to such objects to rvalues. As Item 25 explains, that's not only what std::move does, it's what it was created for:

```
class Widget {
public:
  Widget(Widget&& rhs)                  // rhs is rvalue reference
  : name(std::move(rhs.name)),
    p(std::move(rhs.p))
    { … }
  …

private:
  std::string name;
  std::shared_ptr<SomeDataStructure> p;
};
```

A universal reference, on the other hand (see Item 26), *might* be bound to an object that's eligible for moving. Universal references should be cast to rvalues only if they were initialized with rvalues. Item 25 explains that this is precisely what `std::forward` does:

```
class Widget {
public:
  template<typename T>
  void setName(T&& newName)                 // newName is
  { name = std::forward<T>(newName); }      // universal reference

  …
};
```

In short, rvalue references should be *unconditionally cast* to rvalues (via `std::move`) when forwarding them to other functions, because they're *always* bound to rvalues, and universal references should be *conditionally cast* to rvalues (via `std::forward`) when forwarding them, because they're only *sometimes* bound to rvalues.

Item 25 explains that using `std::forward` on rvalue references can be made to exhibit the proper behavior, but the source code is wordy and unidiomatic, so you should avoid using `std::forward` with rvalue references. Even worse is the idea of using `std::move` with universal references, because that can have the effect of unexpectedly modifying lvalues (e.g., local variables):

```
class Widget {
public:
  template<typename T>
  void setName(T&& newName)         // universal reference
  { name = std::move(newName); }    // compiles, but is
  …                                 // bad, bad, bad!

private:
  std::string name;
  std::shared_ptr<SomeDataStructure> p;
};

std::string getWidgetName();        // factory function

Widget w;

auto n = getWidgetName();           // n is local variable

w.setName(n);                       // moves n into w!

…                                   // n's value now unknown
```

Here, the local variable `n` is passed to `w.setName`, which the caller can be forgiven for assuming is a read-only operation. But because `setName` internally uses `std::move` to unconditionally cast its reference parameter to an rvalue, `n`'s value will be moved into `w.name`, and `n` will come back from the call to `setName` with an unspecified value. That's the kind of behavior that can move callers to despair—possibly to violence.

You might argue that `setName` shouldn't have declared its parameter to be a universal reference. Such references can't be `const` (see Item 26), yet `setName` surely shouldn't modify its parameter. You might point out that if `setName` had simply been overloaded for `const` lvalues and for rvalues, the whole problem could have been avoided. Like this:

```
class Widget {
public:
  void setName(const std::string& newName)      // set from
  { name = newName; }                            // const lvalue

  void setName(std::string&& newName)           // set from
  { name = std::move(newName); }                 // rvalue

  …
};
```

That would certainly work in this case, but there are drawbacks. First, it's more source code to write and maintain (two functions instead of a single template). Second, it can be less efficient. For example, consider this use of `setName`:

```
w.setName("Adela Novak");
```

With the version of `setName` taking a universal reference, the string literal `"Adela Novak"` would be passed to `setName`, where it would be conveyed to the constructor for the `std::string` inside `w`. `w`'s `name` data member would thus be constructed directly from the string literal; no temporary `std::string` objects would arise. With the overloaded versions of `setName`, however, a temporary `std::string` object would be created for `setName`'s parameter to bind to, and this temporary `std::string` would then be moved into `w`'s data member. A call to `setName` would thus entail execution of one `std::string` constructor (to create the temporary), one `std::string` move constructor (to move `newName` into `w.name`), and one `std::string` destructor (to destroy the temporary). That's almost certainly a more expensive execution sequence than invoking only the `std::string` constructor taking a `const char*` pointer. The additional cost is likely to vary from implementation to implementation, and whether that cost is worth worrying about will vary from application to application and library to library, but the fact is that replacing a template taking a universal reference with a pair of functions overloaded on lvalue references and rvalue references is likely to incur a runtime cost in some cases. If we generalize the example such that `Widget`'s data member may be of an arbitrary type (rather than knowing that it's `std::string`), the performance gap can widen considerably, because not all types are as cheap to move as `std::string` (see Item 31).

The most serious problem with overloading on lvalues and rvalues, however, isn't the volume or idiomaticity of the source code, nor is it the code's runtime performance. It's its lack of scalability. `Widget::setName` takes only one parameter, so only two overloads are necessary in this example, but for functions taking more parameters, each of which could be an lvalue or an rvalue, the number of overloads grows geometrically: n parameters necessitates 2^n overloads. And that's not the worst of it. Some functions—function templates, actually—take an *unlimited* number of parameters, each of which could be an lvalue or rvalue. The poster children for such functions are `std::make_shared`, and, as of C++14, `std::make_unique` (see Item 23). Check out the declarations of their most commonly-used overloads:

```
template<class T, class... Args>                  // from C++11
shared_ptr<T> make_shared(Args&&... args);        // Standard

template<class T, class... Args>                  // from C++14
unique_ptr<T> make_unique(Args&&... args);        // Standard
```

For functions like this, overloading on lvalues and rvalues is not an option: universal references are the only way to go. And inside such functions, I assure you, `std::forward` is applied to the universal reference parameters when they're passed to other functions. Which is exactly what you should do.

Well, usually. Eventually. But not necessarily initially. In some cases, you'll want to use the object bound to an rvalue reference or a universal references more than once in a single function, and you'll want to make sure that it's not moved from until you're otherwise done with it. In that case, you'll want to apply `std::move` (for rvalue references) or `std::forward` (for universal references) to only the *final* use of the reference. For example:

```
template<typename T>                          // text is
void setSignText(T&& text)                    // univ. reference
{
  sign.setText(text);                         // use text, but
                                              // don't modify it

  auto now =                                  // get current time
    std::chrono::system_clock::now();

  signHistory.add(now,
                  std::forward<T>(text));     // conditionally cast
}                                             // text to rvalue
```

Here, we want to make sure that `text`'s value doesn't get changed by `sign.setText`, because we want to use that value when we call `signHistory.add`. Ergo the use of `std::forward` on only the final use of the universal reference.

For `std::move`, the same thinking applies (i.e., apply `std::move` to an rvalue reference the last time it's used), but it's important to note that in a few cases, you'll want to call `std::move_if_noexcept` instead of `std::move`. To learn when and why, consult Item 16.

If you're in a function that returns *by value*, and you're returning an object bound to an rvalue reference or a universal reference, you'll want to apply `std::move` or `std::forward` when you return the reference. To see why, consider an `operator+` function to add two matrices together, where the left-hand matrix is known to be an rvalue (and can hence have its storage reused to hold the sum of the matrices):

```
Matrix operator+(Matrix&& lhs,        // by-value return
                 const Matrix& rhs)
{
  lhs += rhs;
  return std::move(lhs);              // move lhs into return value
}
```

By casting `lhs` to an rvalue in the `return` statement (via `std::move`), `lhs` will be moved into the function's return value location. If the call to `std::move` were omitted,

```
Matrix operator+(Matrix&& lhs,       // as above
                 const Matrix& rhs)
{
  lhs += rhs;
  return lhs;                        // copy lhs into return value
}
```

the fact that `lhs` is an lvalue would force compilers to instead *copy* it into the return value location. Assuming that the `Matrix` type supports move construction that is more efficient than copy construction, using `std::move` in the `return` statement yields more efficient code.

If `Matrix` does not support moving, casting it to an rvalue won't hurt, because the rvalue will simply be copied by `Matrix`'s copy constructor (see Item 25). If `Matrix` is later revised to support moving, `operator+` will benefit from that change the next time it (`operator+`) is compiled. That being the case, there's nothing to be lost (and much to be gained) by applying `std::move` to rvalue references being returned from functions that return by value.

The situation is similar for universal references and `std::forward`. Consider a function (really a function template) `reduceAndCopy` that takes a possibly-unreduced `Fraction` object, reduces it, and then returns a copy of the reduced value. If the original object is an rvalue, its value should be moved into the return value (thus avoiding the expense of making a copy), but if the original is an lvalue, an actual copy must be created. Hence:

```
template<typename T>                 // universal reference param,
Fraction reduceAndCopy(T&& frac)     // by-value return
{
  frac.reduce();
  return std::forward<T>(frac);      // move rvalue into return
}                                    // value, copy lvalue
```

If the call to `std::forward` were omitted, `frac` would be unconditionally copied into `reduceAndCopy`'s return value.

Some programmers take the information above and try to extend it to cover situations where it doesn't apply. "If applying `std::move` to an rvalue reference parameter being copied into a return value turns a copy construction into a move construction," they reason, "I can perform the same optimization on local variables that I'm returning." In other words, they figure that given a function returning a local variable by value, such as this,

```
Widget makeWidget()          // "Copying" version of makeWidget
{
  Widget w;                  // local variable

  …                          // configure w

  return w;                  // "copy" w into return value
}
```

they can "optimize" it by turning the "copy" into a move:

```
Widget makeWidget()          // Moving version of makeWidget
{
  Widget w;
  …
  return std::move(w);       // move w into return value
}
```

My liberal use of quotation marks should have tipped you off that this line of reasoning is flawed. But why is it flawed?

It's flawed, because the Standardization Committee is way ahead of such programmers when it comes to this kind of optimization. It was recognized long ago that the "copying" version of `makeWidget` can avoid the need to copy the local variable `w` by constructing it in the memory set aside for the function's return value. This is known as the *return value optimization* (RVO), and it's been expressly blessed by the C++ Standard for as long as there's been one.

Wording such a blessing is finicky business, because you want to permit such *copy elision* only in places where it won't affect the observable behavior of the software. Paraphrasing the legalistic (arguably toxic) prose of the Standard, this particular blessing says that compilers may elide the copying (or the moving) of a local variable (or a parameter that was passed by value) in a function returning by value if (1) the type of the local variable is the same as that returned by the function and

(2) the local variable is what's being returned. With that in mind, look again at the "copying" version of `makeWidget`:

```
Widget makeWidget()          // "Copying" version of makeWidget
{
  Widget w;
  …
  return w;                  // "copy" w into return value
}
```

Both conditions are fulfilled here, and you can trust me when I tell you that every decent C++ compiler will employ the RVO to avoid copying `w`. That means that the "copying" version of `makeWidget` doesn't, in fact, copy anything—at least not in a release build.

The moving version of `makeWidget` does just what its name says it does (assuming `Widget` offers a move constructor): it moves the contents of `w` into `makeWidget`'s return value location. But why don't compilers use the RVO to eliminate the move, again constructing `w` in the memory set aside for the function's return value? The answer is simple: they're not allowed to. Condition (2) stipulates that the RVO may be performed only if what's being returned is a local variable, but that's not what the moving version of `makeWidget` is doing. Look again at its `return` statement:

```
return std::move(w);
```

What's being returned here isn't `w`, it's *the result of calling a function*, namely, `std::move`. Returning the result of a function call doesn't satisfy the conditions required for the RVO to be valid, so compilers must move `w` into the function's return value location. Developers trying to help their compilers optimize by applying `std::move` to a local variable that's being returned are actually limiting the optimization options available to the compilers! There are situations where applying `std::move` to a local variable can be a reasonable thing to do (i.e., when you're passing it to a function and you know you won't be using the variable any more), but as part of a `return` statement when the RVO would otherwise be available is assuredly not one of them.

Things to remember

- Apply `std::move` to rvalue references and `std::forward` to universal references the last time each is used.
- Do the same thing for rvalue references and universal references being returned from functions that return by value.
- Never apply `std::move` or `std::forward` to local objects (including by-value parameters) if they would otherwise be eligible for the return value optimization.

Item 28: Avoid overloading on universal references.

Suppose you need to write a function that takes a name as a parameter, logs the current date and time, then adds the name to a global data structure. That is, you need to write a function that looks something like this:

```
std::set<std::string> names;            // global data structure

void logAndAdd(const std::string& name)
{
  auto now =                            // get current time
    std::chrono::system_clock::now();

  log(now, "logAndAdd");                // make log entry

  names.emplace(name);                  // add name to global
}                                       // structure; Item 18
                                        // has info on emplace
```

This isn't unreasonable code, but it's not as efficient as it could be. Consider three potential calls:

```
std::string petName("Darla");

logAndAdd(petName);                   // pass lvalue std::string

logAndAdd(std::string("Persephone")); // pass rvalue std::string

logAndAdd("Patty Dog");               // pass string literal
```

In the first call, `logAndAdd`'s parameter `name` is bound to the variable `petName`. Within `logAndAdd`, `name` is ultimately passed to `names.emplace`. Because `name` is an lvalue, it is copied into `names`. There's no way to avoid that copy, because an lvalue (`petName`) was passed into `logAndAdd` in the first place.

In the second call, the parameter `name` is bound to an rvalue (the temporary `std::string` explicitly created from `"Persephone"`). `name` itself is an lvalue, so it's copied into `names`, but we recognize that, in principle, its value could be moved into `names`. In this call, we pay for a copy, but we should be able to get by with only a move.

In the third call, the parameter `name` is again bound to an rvalue, but this time it's to a temporary `std::string` that's implicitly created from `"Patty Dog"`. As in the second call, `name` is copied into `names`, but in this case, the argument originally passed to `logAndAdd` was a string literal. Had that string literal been passed directly to the call to `emplace`, there would have been no need to create a temporary `std::string` at all. Instead, `emplace` would have used the string literal to create the `std::string` object directly inside the `std::set`. In this third call, then, we're paying to copy a `std::string`, yet there's really no reason to pay even for a move, much less a copy.

We can eliminate the inefficiencies in the second and third calls by rewriting `logAndAdd` to take a universal reference (see Item 26) and, in accord with Item 27, `std::forward`ing this reference to `emplace`. The results speak for themselves:

```
template<typename T>
void logAndAdd(T&& name)
{
  auto now = std::chrono::system_clock::now();
  log(now, "logAndAdd");
  names.emplace(std::forward<T>(name));
}

std::string petName("Darla");          // as before

logAndAdd(name);                       // as before, copy
                                       // lvalue into set

logAndAdd(std::string("Persephone"));  // move rvalue instead
                                       // of copying it

logAndAdd("Patty Dog");                // create std::string
                                       // in set instead of
```

```
                                       // copying a temporary
                                       // std::string
```

Hurray, optimal efficiency!

Were this the end of the story, we could stop here and go home happy, but I haven't told you that clients don't always have direct access to the names that `logAndAdd` requires. Some clients have only an index that `logAndAdd` uses to look up the corresponding name in a table. To support such clients, `logAndAdd` is overloaded:

```
std::string nameFromIdx(int idx);      // return name
                                       // corresponding to idx

void logAndAdd(int idx)
{
  auto now = std::chrono::system_clock::now();
  log(now, "logAndAdd");
  names.emplace(nameFromIdx(idx));
}
```

Resolution of calls to the two overloads works as expected:

```
std::string petName("Darla");          // as before

logAndAdd(petName);                    // as before, these
logAndAdd(std::string("Persephone"));  // calls all invoke
logAndAdd("Patty Dog");                // the T&& overload

logAndAdd(22);                         // calls int overload
```

Actually, resolution works as expected only if you don't expect too much. Suppose a client has a `short` holding an index and passes that to `logAndAdd`:

```
short nameIdx;
…                                      // give nameIdx a value

logAndAdd(nameIdx);                    // error!
```

The comment on the last line isn't terribly illuminating, so let me explain what happens here.

There are two `logAndAdd` overloads. The one taking a universal reference can deduce `T` to be `short`, thus yielding an exact match. The overload with an `int` parameter can match the `short` argument only with a promotion. Per the normal overload resolution rules, an exact match beats a match with a promotion, so the universal reference overload is invoked.

Within that overload, the parameter `name` is bound to the `short` that's passed in. `name` is then `std::forward`ed to the `emplace` member function on a `std::set<std::string>`, which, in turn, dutifully forwards it to the `std::string` constructor. There is no constructor for `std::string` that takes a `short`, so the `std::string` constructor call inside the call to `set::emplace` inside the call to `logAndAdd` fails. All because the universal reference overload was a better match for a `short` argument than an `int`.

Functions taking universal references are the greediest functions in C++. They instantiate to create exact matches for almost any type of argument. (The few kinds of arguments where this isn't the case are described in Item 32.) This is why combining overloading and universal references is almost always a bad idea: the universal reference overload vacuums up far more argument types than the developer doing the overloading generally expects.

An easy way to topple into this pit is to write a perfect forwarding constructor. A small modification to the `logAndAdd` example demonstrates the problem. Instead of writing a function that can take either a `std::string` or an index that can be used to look up a `std::string`, imagine a class `Person` to which we can pass either a `std::string` or an index:

```
class Person {
public:
  template<typename T>
  explicit Person(T&& n)            // perfect forwarding ctor;
  : name(std::forward<T>(n)) {}     // initializes data member

  explicit Person(int idx)          // int ctor
  : name(nameFromIdx(idx)) {}
  …

private:
  std::string name;
};
```

As was the case with `logAndAdd`, passing an integral type other than `int` (e.g., `std::size_t`, `short`, `long`, etc.) will call the universal reference constructor overload instead of the `int` overload, and that will lead to compilation failures. The problem is much worse in this case, however, because there's more overloading present in `Person` that meets the eye. Item 19 explains that, under the appropriate conditions, C++ will generate both copy and move constructors, and this is true even if the class contains a templatized constructor that could be instantiated to produce the signature of the copy or move constructor. If the copy and move constructors for `Person` are thus generated, `Person` will effectively look like this:

```
class Person {
public:
  template<typename T>        // perfect forwarding ctor
  explicit Person(T&& n);

  explicit Person(int idx);   // int ctor

  Person(const Person& rhs);  // copy ctor (compiler-generated)

  Person(Person&& rhs);       // move ctor (compiler-generated)
  …

};
```

This leads to behavior that's intuitive only if you've spent so much time around compilers and compiler-writers, you've forgotten what it's like to be human:

```
Person p("Bart");

auto clone(p);                // create new Person from p;
                              // this won't compile!
```

Here we're trying to create a `Person` from another `Person`, which seems like about as obvious a case for copy construction as one can get. (`p`'s an lvalue, so we can banish any thoughts we might have about the "copying" being accomplished through a move operation.) But this code won't call the copy constructor. It will call the perfect-forwarding constructor. That function will then try to initialize `Person`'s `std::string` data member with a `Person` object (`p`). `std::string` having no constructor taking a `Person`, your compilers will throw up their hands in exasperation, possibly punishing you with a long and incomprehensible error message as an expression of their displeasure.

"Why," you might wonder, "does the perfect-forwarding constructor get called instead of the copy constructor? We're initializing a `Person` with another `Person`!"

Indeed we are, but compilers are sworn to uphold the rules of C++, and the rules of relevance here are the ones governing the resolution of calls to overloaded functions.

Compilers reason as follows. `clone` is being initialized with a non-`const` lvalue (`p`), and that means that the templatized constructor can be instantiated to take a non-`const` lvalue of type `Person`. After such instantiation, the `Person` class looks like this:

```
class Person {
public:
  explicit Person(Person& n);  // instantiated from perfect-
                               // forwarding template

  explicit Person(int idx);    // as before

  Person(const Person& rhs);   // copy ctor (compiler-generated)

  …

};
```

In the statement,

```
auto clone(p);
```

`p` could be passed to either the copy constructor or the instantiated template. Calling the copy constructor would require adding `const` to `p` to match the copy constructor's parameter's type, but calling the instantiated template requires no such addition. The overload generated from the template is thus a better match, so compilers do what they're designed to do: generate a call to the better-matching function. "Copying" non-`const` lvalues of type `Person` is thus handled by the perfect-forwarding constructor, not the copy constructor.

If we change the example slightly so that the object to be copied is `const`, we hear an entirely different tune:

```
const Person cp("Bart");      // object is now const

auto clone(cp);               // calls copy constructor!
```

Because the object to be copied is now `const`, it's an exact match for the parameter taken by the copy constructor. The templatized constructor can be instantiated to have the same signature,

```
class Person {
public:
  explicit Person(const Person& n);     // instantiated from
                                        // template

  Person(const Person& rhs);            // copy ctor
                                        // (compiler-generated)
  …
};
```

but this doesn't matter, because one of the overloading-resolution rules in C++ is that in situations where a template instantiation and a non-template function (i.e., a "normal" function) are equally good matches for a function call, the normal function is preferred. The copy constructor (a normal function) thereby trumps an instantiated template with the same signature.

(If you're wondering why compilers generate a copy constructor when they could instantiate a templatized constructor to get the signature that the copy constructor would have, review Item 19.)

The interaction among perfect-forwarding constructors and compiler-generated copy and move operations develops even more wrinkles when inheritance enters the picture. In particular, the conventional implementations of derived class copy and move operations behave quite surprisingly. Here, take a look:

```
class SpecialPerson: public Person {
public:
  SpecialPerson(const SpecialPerson& rhs)  // copy ctor; calls
  : Person(rhs)                            // base class
  { … }                                    // forwarding ctor!

  SpecialPerson(SpecialPerson&& rhs)       // move ctor; calls
  : Person(std::move(rhs))                 // base class
  { … }                                    // forwarding ctor!
};
```

As the comments indicate, the derived class copy and move constructors don't call their base class's copy and move constructors, they call the base class's perfect-forwarding constructor! To understand why, note that the derived class functions are using arguments of type `SpecialPerson` to pass to their base class (they actually pass `const SpecialPerson`s, but in this case, `const` is immaterial), then work through the template instantiation and overloading-resolution consequences for the constructors in class `Person`. Ultimately, the code won't compile, because there's no `std::string` constructor taking a `SpecialPerson`.

I hope that by now I've convinced you that overloading on universal reference parameters is something you should avoid if at all possible. But if overloading on universal references is a bad idea, what do you do if you need a function that forwards most argument types, yet needs to treat some argument types in a special fashion? That egg can be unscrambled in a number of ways. So many, in fact, that I've devoted an entire Item to them. It's Item 29. The next Item. Keep reading, you'll bump right into it.

Things to Remember

- Overloading on universal references almost always leads to the universal reference overload being called more frequently than expected.
- Perfect-forwarding constructors are especially problematic, because they're typically better matches than copy constructors for non-const lvalues, and they can hijack derived class calls to base class copy and move constructors.

Item 29: Familiarize yourself with alternatives to overloading on universal references.

Item 28 explains that overloading on universal references can lead to a variety of problems, both for freestanding and for member functions (especially constructors). Yet it also gives examples where such overloading could be useful. If only it would behave the way we'd like! This Item explores ways to achieve the desired behavior, either through designs that avoid overloading on universal references or by employing them in ways that constrain the types of arguments they can match.

The discussion that follows builds on the examples introduced in Item 28. If you haven't read that Item recently, you'll want to review it before continuing.

Abandoning overloading

The first example in Item 28, `logAndAdd`, is representative of the many functions that can avoid the drawbacks of overloading on universal references by simply using different names for the would-be overloads. The two `logAndAdd` overloads, for example, could be broken into `logAndAddName` and `logAndAddNameIdx`. Alas, this approach won't work for the second example we considered, the `Person` constructor, because constructor names are fixed by the language. Besides, who wants to give up overloading?

Passing by `const T&`

An alternative is to revert to C++98 and replace pass-by-universal-reference with pass-by-(lvalue)-reference-to-`const`. In fact, that's the first approach Item 28 considers (on page 213). The drawback is that the design isn't as efficient as we'd prefer. Knowing what we now know about the interaction of universal references and overloading, giving up some efficiency to keep things simple might be a more attractive trade-off than it initially appeared.

Passing by value

An approach that often allows you to dial up performance without any increase in complexity is to replace pass-by-reference parameters with, counterintuitively, pass-by-value. "Pass by reference" here refers to *any kind* of reference. This strategy can supplant both C++98's pass-by-lvalue-reference-to-`const` and C++11's pass-by-universal-reference. The design adheres to the advice in Item 17 to pass objects by value when you know you'll copy them, so I'll defer to that Item for a detailed discussion of how things work and how efficient they are. Here, I'll just show how the technique could be used in the `Person` example:

```
class Person {
public:
  Person(std::string n)          // replaces T&& ctor; see
  : name(std::move(n)) {}        // Item 17 for use of std::move

  Person(int idx)                // as before
  : name(nameFromIdx(idx)) {}
  …
```

```
private:
  std::string name;
};
```

Because there's no `std::string` constructor taking only an integer, all `int` and `int`-like arguments to a `Person` constructor (e.g., `std::size_t`, `short`, `long`, etc.) get funneled to the `int` overload. Similarly, all arguments of type `std::string` (and things from which `std::strings` can be created, e.g., literals such as `"Ruth"`) get passed to the constructor taking a `std::string`. There are thus no surprises for callers. You could argue, I suppose, that some people might be surprised that using `0` or `NULL` to indicate a null pointer would invoke the `int` overload, but such people should be referred to Item 8 and required to read it repeatedly until the thought of using `0` or `NULL` as a null pointer makes them recoil.

Tag dispatch

Neither pass by lvalue-reference-to-`const` nor pass by value offer support for perfect forwarding. If your motivation for the use of a universal reference is perfect forwarding, you have to use a universal reference; there's no other choice. Yet we don't want to abandon overloading. So if we don't give up overloading and we don't give up universal references, how can we avoid overloading on universal references?

It's actually not that hard. Calls to overloaded functions are resolved by looking at all the parameters of all the overloads as well as all the arguments at the call site, then choosing the function with the best overall match—taking into account all parameter/argument combinations. A universal reference parameter generally provides an exact match for whatever's passed in, but if the universal reference is part of a parameter list containing other parameters that are *not* universal references, sufficiently poor matches on the non-universal reference parameters can knock an overload with a universal reference out of the running. That's the basis behind the *tag dispatch* approach, and an example will make the foregoing description easier to understand.

We'll apply tag dispatch to the `logAndAdd` example from page 214. Here's that code, to save you the trouble of looking it up:

```
std::set<std::string> names;           // global data structure

template<typename T>                   // make log entry, add
void logAndAdd(T&& name)               // name to data structure
{
  auto now = std::chrono::system_clock::now();
  log(now, "logAndAdd");
  names.emplace(std::forward<T>(name));
}
```

By itself, this function works fine, but were we to introduce the overload taking an `int` that's used to look up objects by index, we'd be back in the troubled land of Item 28. The goal of this Item is to avoid that. Rather than adding the overload, we'll reimplement `logAndAdd` to delegate to two other functions, one for integral values and one for everything else. `logAndAdd` itself will accept all argument types, both integral and non-integral.

The two functions doing the real work will be named `logAndAddImpl`, i.e., we'll use overloading. One of the functions will take a universal reference. So we'll have both overloading and universal references. But each function will also take a second parameter, one that indicates whether the argument being passed is integral. This second parameter is what will prevent us from tumbling into the morass described in Item 28, because we'll arrange it so that the second parameter will be the factor that determines which overload is selected.

Yes, I know, "Blah, blah, blah. Stop talking and show me the code!" No problem. Here's an almost- correct version of the updated `logAndAdd`:

```
template<typename T>
void logAndAdd(T&& name)
{
  logAndAddImpl(std::forward<T>(name),
                std::is_integral<T>());     // not quite correct
}
```

This function forwards its parameter to `logAndAddImpl`, but it also passes an argument indicating whether the type it received (`T`) is integral. At least, that's what it's supposed to do. For integral arguments that are rvalues, it's also what it does. But, as Item 30 explains, if an lvalue argument is passed to the universal reference `name`, the type deduced for `T` will be an lvalue reference. So if an lvalue of type `int` is passed to `logAndAdd`, `T` will be deduced to be `int&`. `int&` is not an integral type, because references aren't integral types. That means that `std::is_integral<T>` will be false for any lvalue argument, even if the argument really does represent an integral value.

Recognizing the problem is tantamount to identifying the solution, because the ever-handy Standard C++ Library has a type trait, `std::remove_reference`, that does both what its name suggests and what we need: remove any reference qualifiers from a type. The proper way to write `logAndAdd` is therefore:

```
template<typename T>
void logAndAdd(T&& name)
{
  logAndAddImpl(
    std::forward<T>(name),
    std::is_integral<typename std::remove_reference<T>::type>()
  );
}
```

This does the trick. (In C++14, you can save a few keystrokes by using `std::remove_reference_t<T>` in place of the highlighted text. For details, see Item 9.)

With that taken care of, we can shift our attention to the function being called, `logAndAddImpl`. There are two overloads, and the first is applicable only to non-integral types (i.e., to types where `std::is_integral<typename std::remove_reference<T>::type>` is false):

```
template<typename T>                              // non-integral
void logAndAddImpl(T&& name, std::false_type)     // argument:
{                                                 // add it to
  auto now = std::chrono::system_clock::now();    // global data
  log(now, "logAndAdd");                          // structure
  names.emplace_back(std::forward<T>(name));
}
```

This is straightforward code, once you understand the mechanics behind the highlighted parameter. Conceptually, `logAndAdd` passes a boolean to `logAndAddImpl` indicating whether an integral type was passed to `logAndAdd`, but `true` and `false` are *runtime* values, and we need to use overload resolution—a *compile-time* phenomenon—to choose the correct `logAndAddImpl` overload. That means we need a *type* that corresponds to `true` and a different type that corresponds to false. This need is common enough that the Standard Library provides what is required under the names std::true_type and std::false_type. The argument passed to logAndAddImpl by logAndAdd is an object of a type that inherits from std::true_type if T is integral and from std::false_type if T is not integral. The net result is that this logAndAddImpl overload is a viable candidate for the call in logAndAdd only if T is not an integral type.

The second overload covers the opposite case: when T is an integral type. In that event, logAndAddImpl simply finds the name corresponding to the passed-in index and passes that name back to logAndAdd:

```
std::string nameFromIdx(int idx);             // as in Item 28

void logAndAddImpl(int idx, std::true_type)   // integral
{                                             // argument: look
  logAndAdd(anyFromIdx(idx));                 // up name and
}                                             // call logAndAdd
                                              // with it
```

By having logAndAddImpl for an index look up the corresponding name and pass it to logAndAdd (from where it will be std::forwarded to the other logAndAddImpl overload), we avoid the need to put the logging code in both logAndAddImpl overloads.

In this design, the types std::true_type and std::false_type are "tags" whose only purpose is to force overload resolution to go the way we want. Notice that we don't even name those parameters. They serve no purpose at runtime, and in fact we hope that compilers will recognize that tag parameters are unused and will optimize them out of the program's execution image. (Some compilers do, at least some of the time.) The call to the overloaded implementation functions inside logAndAdd "dispatches" the work to the correct overload by causing the proper tag object to be created. Hence the name for this design: *tag dispatch*. It's a standard building block of template metaprogramming, and the more you look at code inside contemporary C++ libraries, the more often you'll encounter it.

For our purposes, what's important about tag dispatch is less how it works and more how it permits us to combine universal references and overloading without the problems described in Item 28. The dispatching function—logAndAdd—takes an unconstrained universal reference parameter, but this function is not overloaded. The implementation functions—`logAndAddImpl`—are overloaded, and one takes a universal reference parameter, but resolution of calls to these functions depends not just on the universal reference parameter, but also on the tag parameter, and the tag values are designed so that no more than one overload will ever be a viable match. As a result, it's the tag that determines which overload gets called. The fact that the universal reference parameter will always generate an exact match for its argument is immaterial.

Tag dispatch constructors

A keystone of tag dispatch is the existence of a single (unoverloaded) function as the client API. This single function dispatches the work to be done to the implementation functions. Creating an unoverloaded dispatch function is usually easy, but the second problem case Item 28 considers, that of the perfect-forwarding constructor for the `Person` class (see page 216), is an exception. Compilers may generate copy and move constructors themselves, so even if you write only one constructor and use tag dispatch within it, some constructor calls may be handled by compiler-generated functions that bypass the tag dispatch system.

Frankly, the real problem is not that the compiler-generated functions sometimes bypass the tag dispatch design, it's that they don't *always* pass it by. We virtually always want the copy constructor for a class to handle requests to copy lvalues of that type, but, as Item 28 demonstrates, providing a constructor taking a universal reference causes the universal reference constructor (instead of the copy constructor) to be called when copying non-`const` lvalues.

What we need is a way to tell compilers, "Look, when I'm constructing an object from another object of the same type, just do the normal thing: copy each member of an lvalue object, and move each member of an rvalue object. Don't worry about whether the initializing object is `const` or not, just do a normal copy or move." Brace yourself for good news, because there is, in fact, a way to say that.

Before we see what it is, let's look at a tag-dispatching `Person` constructor. The design is identical to that we saw for `logAndAdd`, but we'll apply a minor twist. We'll take advantage of C++11's constructor delegation to have other constructors act as implementation functions. Using constructor delegation isn't necessary in this example, but it's a good habit to get into in contexts such as this, because it also works with `const` and reference data members, which may be initialized only during construction. The constructors we'll delegate to aren't designed to be called directly, so we'll declare them `private`.

Here's the code, where I'm employing C++14's `std::remove_reference_t<T>` instead of C++11's wordier "`typename std::remove_reference<T>::type`":

```
class Person {
public:
  template<typename T>               // dispatch to other ctors
  explicit Person(T&& initVal)       // via ctor delegation
  : Person(
      initVal,
      std::is_integral<std::remove_reference_t<T>>()  // C++14
    )                                                 // only
  {}

  …

private:
  template<typename T>                      // private ctor for
  Person(T&& n, std::true_type)             // integral args
  : Person(nameFromIdx(std::forward<T>(n)))
  {}

  template<typename T>                      // private ctor for
  Person(T&& n, std::false_type)            // non-integral args
  : name(std::forward<T>(n))
  {}

  std::string name;                         // as in Item 28
};
```

Our goal is to modify this class so that the universal reference constructor never gets invoked if a `Person` is created from another `Person`.

Our approach is based on three observations. First, a class may contain variants of the copy operations. In particular, classes may specify different copy constructors for `const` and non-`const` objects. Second, `=default` can be used to get the "normal" implementation of any special member function (see Item 19), including all copy operation variants. Third, as Item 28 explains, if a template can be instantiated with the same signature as a non-template function, calls to that function signature invoke the normal function, not the template instantiation.

So what we'll do is manually declare the copy and move operation signatures we want to behave "normally," (i.e., to not use tag dispatch), and we'll implement them using `=default`. The existence of these functions will prevent the universal reference constructor from being instantiated with their signatures. Hence:

```
class Person {
public:
  template<typename T>                // as before,
  explicit Person(T&& initVal);       // tag-dispatching ctor

  Person(const Person&) = default;    // copy-construct from
                                      // const lvalue

  Person(Person&) = default;          // copy-construct from
                                      // non-const lvalue

  Person(Person&&) = default;         // move-construct
                                      // from (non-const) rvalue
  …
};
```

You might wonder why there's only a single move constructor here, i.e., why there's no "move constructor" taking a `const Person&&`. That's because the only valid move constructor signature is the one above; there's no `const` variant. Item 25 explains that it makes no sense to try to move from a `const` object, so C++ doesn't recognize a constructor taking a `const` rvalue reference as a special member function.

Because this Item is already too long, I'll leave it to you to verify that when `Person` is defined like this, creation of a `Person` from another `Person` will bypass the universal reference constructor and do the "normal" thing, regardless of whether the source object is an lvalue or an rvalue and regardless of whether it's `const`.

Item 28 points out that a second problem with tag-dispatching constructors is that they interact poorly with inheritance, and it gives this example:

```
class SpecialPerson: public Person {
public:
  SpecialPerson(const SpecialPerson& rhs)  // copy ctor; calls
```

```
  : Person(rhs)                         // base class
  { … }                                 // forwarding ctor!

  SpecialPerson(SpecialPerson&& rhs)    // move ctor; calls
  : Person(std::move(rhs))              // base class
  { … }                                 // forwarding ctor!
};
```

The good news is that if you can live with the compiler-generated copy and move operations, this problem doesn't arise. Such operations will call their base class counterparts, just as you'd hope.

If you need to implement these functions yourself, you have to make sure that you pass base class arguments to your base class constructors. That's not what happens in the code above. There, both `SpecialPerson` constructors pass `rhs` as an argument to the `Person` constructor, but `rhs`'s basic type is `SpecialPerson`, not `Person`. That will cause the universal reference constructor in `Person` to instantiate and "steal" what you'd like to be calls to the `Person` copy and move constructors. The solution is to cast away the derived-ness of the argument you pass to the base class by casting it to a base class reference:

```
class SpecialPerson: public Person {
public:
  SpecialPerson(const SpecialPerson& rhs)          // now calls
  : Person(static_cast<const Person&>(rhs))        // base copy
  { … }                                            // ctor

  SpecialPerson(SpecialPerson&& rhs)               // now calls
  : Person(static_cast<Person&&>(std::move(rhs)))  // base move
  { … }                                            // ctor
};
```

Note how the copy constructor casts `rhs` to an lvalue reference, while the move constructor casts it to an rvalue reference. Subtilties such as this are one of the reasons you should really try to follow Item 19's advice to avoid writing your own copy and move operations.

Trade-offs

The first three techniques considered in this Item—abandoning overloading, passing by `const T&`, and passing by value—specify a type for each parameter in the function(s) to be called. Tag dispatch uses perfect forwarding, hence doesn't specify types for the parameters. This fundamental decision—to specify a type or not—has important consequences.

As a rule, perfect forwarding is more efficient, because it avoids the creation of temporary objects solely for the purpose of conforming to the type of a parameter declaration. In the case of the `Person` constructor, perfect forwarding permits a string literal such as `"Nancy"` to be forwarded to the constructor for the `std::string` inside `Person`, whereas techniques not using perfect forwarding must create a temporary `std::string` object from the string literal to satisfy the parameter specification for the `Person` constructor.

But perfect forwarding has drawbacks. One is that some kinds of arguments can't be perfect-forwarded, even though they can be passed to functions taking specific types. Item 32 explores these perfect forwarding failure cases.

A second issue is the comprehensibility of error messages when clients pass invalid arguments. Suppose, for example, a client creating a `Person` object passes a string literal made up of `char16_t`s (a type introduced in C++11 to represent 16-bit characters) instead of `char`s (which is what a `std::string` consists of):

```
Person p(u"Konrad Zuse");    // "Konrad Zuse" consists of
                             // characters of type std::char16_t
```

With the first three approaches examined in this Item, compilers will see that the available constructors take either `int` or `std::string`, and they'll produce a more or less straightforward message explaining that there's no conversion from `char16_t*` to `int` or `std::string`.

With an approach based on universal reference parameters, however, the `char16_t*` pointer gets bound to the constructor's parameter without complaint. From there it's forwarded to the constructor of `Person`'s `std::string` data member, and it's only at that point that the mismatch between what the caller passed in (essentially a `char16_t*` pointer) and what's required (any type acceptable to the `std::string` constructor) is discovered. The resulting error message is likely to be, er, impressive. With one of the compilers I use, it's 158 lines long. In this example, the universal reference is forwarded only once (from the `Person` constructor to the `std::string` constructor), but the more complex the system, the more likely that a universal reference is forwarded through several layers of function calls before finally arriving at a site that knows what argument type(s) are acceptable. The more times the universal reference is forwarded, the more baffling the error message when something goes wrong. Many developers find that this issue alone is grounds to reserve universal reference parameters for interfaces where performance is a foremost concern.

Things to Remember

- Alternatives to the combination of universal references and overloading include the use of distinct function names, passing parameters by (lvalue)-reference-to-`const`, passing parameters by value, and using tag dispatch.
- Universal reference parameters often have efficiency advantages, but they also have usability disadvantages.

Item 30: Understand reference collapsing.

Item 25 remarks that when an argument is passed to a template function, the deduced type for the template parameter encodes whether that argument is an lvalue or an rvalue. The Item fails to mention that this happens only when the argument is used to initialize a parameter that's a universal reference, but there's a good reason for the omission: universal references aren't introduced until Item 26. Together, these observations about universal references and lvalue/rvalue encoding mean that for this template,

```
template<typename T>
void func(T&& param);
```

the deduced template parameter `T` will encode whether the argument passed to `param` was an lvalue or an rvalue.

The encoding mechanism is simple. When an lvalue is passed as an argument, `T` is deduced to be an lvalue reference. When an rvalue is passed, `T` is deduced to be a non-reference. (Note the asymmetry: lvalues are encoded as lvalue references, but rvalues are encoded as *non-references*.) Hence:

```
Widget widgetFactory();      // function returning rvalue
```

```
Widget w;                        // a variable (an lvalue)

func(w);                         // call func with lvalue; T deduced
                                 // to be Widget&

func(widgetFactory());           // call func with rvalue; T deduced
                                 // to be Widget
```

In both calls to `func`, a `Widget` is passed, yet because one `Widget` is an lvalue and one is an rvalue, different types are deduced for the template parameter `T`. This, as we shall soon see, is what determines whether universal references become rvalue references or lvalue references, and it's also the underlying mechanism through which `std::forward` does its work.

Before we can look more closely at `std::forward` and universal references, we must observe that references to references are illegal in C++. Should you be so bold as to try to declare one, your compilers will reprimand you:

```
int x;
…
auto& & rx = x;    // error! can't declare reference to reference
```

But consider what happens when an lvalue is passed to a template function taking a universal reference:

```
template<typename T>
void func(T&& param);     // as before

func(w);                  // invoke func with lvalue;
                          // T deduced as Widget&
```

If we take the type deduced for `T` (i.e., `Widget&`) and use it to instantiate the specific function we're calling, we get this:

```
void func(Widget& && param);
```

A reference to a reference! And yet compilers issue no protest. We know from Item 26 that because the universal reference `param` is being initialized with an lvalue, `param`'s type is supposed to be an lvalue reference, but how does the compiler get from the result of taking the deduced type for `T` and substituting it into the template to the following, which is the ultimate function signature?

```
void func(Widget& param);
```

The answer is *reference collapsing*. Yes, *you* are forbidden from declaring references to references, but *compilers* may do it in particular contexts, template instantiation being among them. When compilers generate references to references, reference collapsing dictates what happens next.

There are two kinds of references (lvalue and rvalue), so there are four possible reference-reference combinations (lvalue to lvalue, lvalue to rvalue, rvalue to lvalue, and rvalue to rvalue). If a reference to a reference arises in a context where this is permitted (e.g., during template instantiation), the references *collapse* to a single reference according to this simple rule:

- If either reference is an lvalue reference, the result is an lvalue reference. Otherwise the result is an rvalue reference.

In our example above, substitution of the deduced type `Widget&` into the template `func` yields an rvalue reference to an lvalue reference, and the reference-collapsing rule tells us that the result is an lvalue reference.

Reference collapsing is a key part of what makes `std::forward` work. Item 25 introduces the following conceptual implementation:

```
template<typename T>                      // conceptual impl.
T&& forward(T&& param)                    // of std::forward
{                                         // (in namespace std)
  if (is_lvalue_reference<T>::value) {    // if T indicates lvalue
    return param;                         // return param as lvalue
  } else {                                // else
    return move(param);                   // return param as rvalue
  }
}
```

A real `std::forward` implementation looks more like this:

```
template<typename T>                      // in namespace std
T&& forward(T&& param)
{
  return static_cast<T&&>(param);
}
```

This isn't quite standards-conformant (I've omitted a few interface details), but it makes clear that, as Item 25 claims, `std::forward` is simply a cast.

But how does this work? As explained in Item 27, `std::forward` is generally used on universal reference parameters, so a typical use case could look like this:

```
template<typename T>
void f(T&& fParam)
{
  …                                   // do some work
  func(std::forward<T>(fParam));      // forward fParam to func
}
```

Because `fParam` is a universal reference, we know that the type parameter `T` will encode whether the argument passed to `f` (i.e., the expression used to initialize `fParam`) was an lvalue or an rvalue. `std::forward`'s job is to cast `fParam` (an lvalue) to an rvalue if and only if `T` encodes that the argument passed to `f` was an rvalue, i.e., if `T` is a non-reference type. Let's go through this step by step.

Suppose that the argument passed to `f` is an lvalue of type `Widget`. In that case, `T` will be deduced as `Widget&`. The call to `std::forward` will instantiate as `std::forward<Widget&>`. Plugging `Widget&` into the above implementation yields

```
Widget& && forward(Widget& && param)
{ return static_cast<Widget& &&>(param); }
```

which, after reference collapsing, becomes:

```
Widget& forward(Widget& param)
{ return static_cast<Widget&>(param);   }
```

So when an lvalue argument is passed to the function template `f`, `std::forward` is instantiated to take and return an lvalue reference. Lvalue references are, by definition, lvalues, so an lvalue argument passed to `f` will be forwarded to `func` as an lvalue, just like it's supposed to be.

Now suppose that the argument passed to `f` is an rvalue of type `Widget`. In this case, the deduced type for the `f`'s type parameter, `T`, will simply be `Widget`. The call inside `f` to `std::forward` will thus be to `std::forward<Widget>`. Substituting `Widget` for `T` in `std::forward` gives this:

```
Widget&& forward(Widget&& fwdParam)
{ return static_cast<Widget&&>(param); }
```

No references to references arise in this case, so no reference collapsing occurs. Because rvalue references returned from functions are defined to be rvalues, this means that `std::forward` will turn `f`'s parameter `fParm` (an lvalue) into an rvalue. The end result is that an rvalue argument passed to `f` will be forwarded to `func` as an rvalue, which is precisely what is supposed to happen.

Reference collapsing occurs in four contexts. The first and most common is template instantiation. The second is type generation for `auto` variables. The details are essentially the same as for templates, because type deduction for `auto` variables is essentially the same as type deduction for templates (see Item 2). Consider again this example from earlier in the Item:

```
template<typename T>
void func(T&& param);

Widget widgetFactory();      // function returning rvalue

Widget w;                    // a variable (an lvalue)

func(w);                     // call func with lvalue; T deduced
                             // to be Widget&

func(widgetFactory());       // call func with rvalue; T deduced
                             // to be Widget
```

This example can be mimicked in `auto` form. The declaration

```
auto&& w1 = w;
```

initializes `w1` with an lvalue, thus deducing the type `Widget&` for `auto`. Plugging `Widget&` in for `auto` in the declaration for `w1` yields this reference-to-reference code,

```
Widget& && w1 = w;
```

which, after reference collapsing, becomes

```
Widget& w1 = w;
```

As a result, `w1` is an lvalue reference.

On the other hand, this declaration,

```
auto&& w2 = widgetFactory();
```

initializes `w2` with an rvalue, causing the non-reference type `Widget` to be deduced for `auto`. Substituting `Widget` for `auto` gives us this:

```
Widget&& w2 = widgetFactory();
```

There are no references to references here, so we're done: `w2` is an rvalue reference.

We're now in a position to truly understand the universal references introduced in Item 26. A universal reference isn't a new kind of reference, it's simply an rvalue reference in a reference collapsing context. The concept of universal references is useful, because it frees you from having to recognize the existence of reference collapsing contexts, to mentally deduce different types for lvalues and rvalues, and to apply the reference collapsing rule after mentally substituting the deduced types into the contexts in which they occur.

I said there were four such contexts, but we've discussed only two: template instantiation and `auto` type generation. The third is the generation and use of `typedef`s and alias declarations (see Item 9). If, during creation or evaluation of a `typedef`, references to references arise, reference collapsing intervenes to eliminate them. For example, suppose we have a `Widget` class template with an embedded `typedef` for an rvalue reference type,

```
template<typename T>
class Widget {
public:
  typedef T&& RvalueRefToT;
  …
};
```

and suppose we instantiate `Widget` with an lvalue reference type:

```
Widget<int&> w;
```

Substituting `int&` for `T` in the `Widget` template gives us the following `typedef`:

```
typedef int& && RvalueRefToT;
```

Reference collapsing reduces it to this,

```
typedef int& RvalueRefToT;
```

which makes clear that the name we chose for the `typedef` is perhaps not as descriptive as we'd hoped: *`RvalueRef`*`ToT` is a `typedef` for an *lvalue reference* when `Widget` is instantiated with an lvalue reference type.

The final context in which reference collapsing takes place is uses of `decltype`. If, during evaluation of an expression involving `decltype`, a reference to reference arises, reference collapsing will kick in to eliminate it.

Things to Remember

- Reference collapsing occurs in four contexts: template instantiation, `auto` type generation, creation and use of `typedef`s and alias declarations, and `decltype`.
- When compilers generate a reference to a reference in a reference collapsing context, the result becomes a single reference. If either of the original references is an lvalue reference, the result is an lvalue reference. Otherwise it's an rvalue reference.
- Universal references are rvalue references in reference collapsing contexts.

Item 31: Assume that move operations are not present, not cheap, and not used.

Move semantics is arguably *the* premier feature of C++11. "Moving containers is now as cheap as copying pointers!," you're likely to hear, and "Copying temporary objects is now so efficient, coding to avoid it is tantamount to premature optimization!" Such sentiments are easy to understand. Move semantics is truly an important feature. It doesn't just allow compilers to replace expensive copy operations with comparatively cheap moves, it actually *requires* that they do so (when the proper conditions are fulfilled). Take your C++98 code base, recompile with a C++11-conformant compiler and Standard Library, and—*shazam!*—your software runs faster!

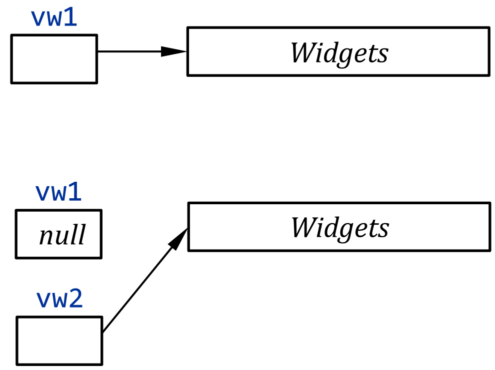
Move semantics can really pull that off, and that grants the feature an aura worthy of legend. Legends, however, are generally the result of exaggeration. The purpose of this Item is to keep your expectations grounded.

Let's begin with the observation that many types fail to support move semantics. The entire C++98 Standard Library was overhauled for C++11 to add move operations for types where moving could be implemented faster than copying, and the implementation of the library components was revised to take advantage of these operations, but chances are that you're working with a code base that has not been completely revised to take advantage of C++11. For types in your applications (or in the libraries you use) where no modifications for C++11 have been made, the existence of move support in your compilers is likely to do you little good. True, C++11 is willing to generate move operations for classes that lack them, but that happens only for classes declaring no copy operations, move operations, or destructors (see Item 19). Data members or base classes that can't be moved will also suppress compiler-generated move operations. For types without explicit support for moving and that don't qualify for compiler-generated move operations, there is no reason to expect C++11 to deliver any kind of performance improvement over C++98.

Even types with explicit move support may not benefit as much as you'd hope. All containers in the standard C++11 library support moving, for example, but it would be a mistake to assume that moving all containers is cheap. For some containers, this is because there's no truly cheap way to move their contents. For others, it's because the truly cheap move operations the containers offer come with caveats the container elements can't satisfy.

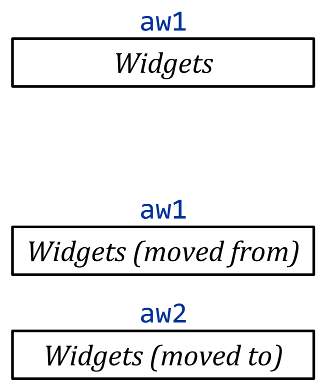
Consider `std::array`, a new container in C++11. `std::array` is essentially a built-in array with an STL interface. This is fundamentally different from the other standard containers, each of which store their contents on the heap. Objects of such container types hold (as data members), conceptually, only a pointer to the heap memory storing the contents of the container. (The reality is more complex, but for purposes of this analysis, the differences are not important.) The existence of this pointer makes it possible to move the contents of an entire container in constant time: just move the pointer to the container's contents from the source container to the target, and set the source's pointer to null:

```
std::vector<Widget> vw1;

// put data into vw1

…

// move vw1 into vw2. Runs in
// constant time. Only ptrs
// in vw1 and vw2 are modified
auto vw2 = std::move(vw1);
```



`std::array` objects lack such a pointer, because the data for a `std::array`'s contents are stored directly in the `std::array` object:

```
std::array<Widget, 10000> aw1;

// put data into aw1

…

// move aw1 into aw2. Runs in
// linear time. All elements in
// aw1 are moved into aw2
auto aw2 = std::move(aw1);
```



Note that the elements in `aw1` are *moved* into `aw2`. Assuming that `Widget` is a type where moving is faster than copying, moving a `std::array` of `Widget` will be faster than copying the same `std::array`. So `std::array` certainly offers move support. Yet both moving and copying a `std::array` have linear-time computational complexity, because each element in the container must be copied or moved. This is far from the "moving a container is now as cheap as assigning a couple of pointers" claim that one sometimes hears.

On the other hand, `std::string` offers constant-time moves and linear-time copies. That makes it sound like moving is faster than copying, but that may not be the case. Many string implementations employ the *small string optimization* (SSO). With the SSO, "small" strings (typically those with a capacity of no more than 15 characters) are stored in a buffer within the `std::string` object; no heap-allocated storage is used. Moving small strings using an SSO-based implementation is no faster than copying them, because the copy-only-a-pointer trick that generally underlies the performance advantage of moves over copies isn't applicable.

The motivation for the SSO is extensive evidence that for many applications, short strings are the norm. Using an internal buffer to store such strings' values eliminates the need to dynamically allocate memory for them, and that's typically an efficiency win. An implication of the win, however, is that moves are no faster than copies, though one could just as well take a glass-half-full approach and say that for such strings, copying is no slower than moving.

Even for types supporting speedy move operations, some seemingly sure-fire move situations can still end up making copies. Item 16 explains that some container operations in the Standard Library offer the strong exception safety guarantee, and that to ensure that legacy C++98 code dependent on these exception safety guarantees isn't broken when upgrading to C++11, the underlying copy operations may be replaced with move operations only if the move operations are known not to throw. A consequence is that even if a type offers move operations that are more efficient than the corresponding copy operations, and even if, at a particular point in the code, a move operation would generally be appropriate (e.g., if the source object is an rvalue), compilers might still be forced to invoke a copy operation, because the corresponding move operation isn't declared `noexcept`.

There are thus several scenarios in which C++11's move semantics do you no good:

- **No move operations:** The object to be moved from fails to offer move operations. The move request therefore becomes a copy request.
- **Move not faster:** The object to be moved from has move operations that are no faster than its copy operations.
- **Move not usable:** The context in which the moving would take place requires a nothrow move operation, but that operation isn't declared `noexcept`.

It's worth mentioning, too, another scenario where move semantics offers no efficiency gain:

- **Source object is lvalue:** With very few exceptions (see e.g., Item 27) only rvalues may be used as the source of a move operation.

But the title of this Item is to *assume* that move operations are not present, not cheap, and not used. This is typically the case in generic code, e.g., when writing templates, because you don't know all the types you're working with. In such circumstances, you must be as conservative about copying objects as you were in C++98—before move semantics existed. This is also the case for "unstable" code, i.e., code where the characteristics of the types being used are subject to relatively frequent modification.

Often, however, you know the types your code uses, and you can rely on their characteristics not changing (e.g., whether they support inexpensive move operations). When that's the case, you don't need to make assumptions. You can simply look up the move support details for the types you're using. If those types offer cheap move operations, and if you're using objects in contexts where those move operations will be invoked, there's no need for assumptions: you can safely rely on move semantics to replace copy operations with their less expensive move counterparts.

Things to remember

- Assume that move operations are not present, not cheap, and not used.
- In code with known types or support for move semantics, there is no need for assumptions.

Item 32: Familiarize yourself with perfect forwarding failure cases.

One of the features most prominently emblazoned on the C++11 box is perfect forwarding. *Perfect* forwarding. It's *perfect*! Alas, tear the box open, and you'll find that there's "perfect" (the ideal), and then there's "perfect" (the reality). C++11's perfect forwarding is very good, but it achieves true perfection only if you're willing to overlook an epsilon or two. This Item is devoted to familiarizing you with the epsilons.

Before embarking on our epsilon exploration, it's worthwhile to review what's meant by "perfect forwarding." "Forwarding" just means that one function passes—*forwards*—its parameters to another function. The goal is for the second function (the one being forwarded to) to receive the same objects that the first function (the one doing the forwarding) received. That rules out by-value parameters, because they're *copies* of what the original caller passed in; we want the forwarded-to function to be able to work with the originally-passed-in objects. Pointer parameters are also ruled out, because we don't want to force callers to pass pointers. When it comes to general-purpose forwarding, we'll be dealing with parameters that are references.

Perfect forwarding means we don't just forward objects, we also forward their salient characteristics: their types, whether they're lvalues or rvalues, and whether they're `const` or `volatile`. In conjunction with the observation that we'll be dealing with reference parameters, this implies that we'll be using universal references (see Item 26), because only universal reference parameters encode information about the lvalueness and rvalueness of the arguments that are passed to them.

Let's assume we have some function `f`, and we'd like to write a function (in truth, a function template) that forwards to it. The core of what we need looks like this:

```
template<typename T>
void fwd(T&& param)                   // accept any argument
{
  f(std::forward<T>(param));          // forward it to f
}
```

Forwarding functions are, by their nature, generic. The `fwd` template, for example, accepts any type of argument, and it forwards whatever it gets. A logical extension of this genericity is for forwarding functions to be not just templates, but *variadic* templates, thus accepting any number of arguments. The variadic form for `fwd` looks like this:

```
template<typename... Ts>
void fwd(Ts&&... params)              // accept any arguments
{
```

```
  f(std::forward<Ts>(params)...);    // forward them to f
}
```

This is the form you'll see in, among other places, the standard containers' emplacement functions (see Item 18) and the smart pointer factory functions, `std::make_shared` and `std::make_unique` (see Item 23).

Given our target function `f` and our forwarding function `fwd`, perfect forwarding *fails* if calling `f` with a particular argument does one thing, but calling `fwd` with the same argument does something different:

```
f( expression );       // if this does one thing,
fwd( expression );     // but this does something else, fwd fails
                       // to perfectly forward expression to f
```

Several kinds of arguments lead to this kind of failure. Knowing what they are and how to work around them is important, so let's tour the arguments that can't be perfect-forwarded.

Braced initializers

Suppose `f` is declared like this:

```
void f(const std::vector<int>& v);
```

In that case, calling `f` with a braced initializer compiles,

```
f({ 1, 2, 3 });        // fine, "{1, 2, 3}" implicitly
                       // converted to std::vector<int>
```

but passing the same braced initializer to `fwd` doesn't compile:

```
fwd({ 1, 2, 3 });      // error! doesn't compile
```

That's because the use of a braced initializer is a perfect forwarding failure cases.

All such failure cases have the same cause. In a direct call to `f` (such as `f({ 1, 2, 3 })`), compilers see the types of arguments passed at the call site, and they see the types of the parameters declared by `f`. They compare the arguments at the call site to the parameter declarations to see if they're compatible, and, if necessary, they perform implicit type conversions to make the call succeed.

In the example above, they generate a temporary `std::vector<int>` object from `{ 1, 2, 3 }` so that `f`'s parameter `v` has a `std::vector<int>` object to bind to.

When calling `f` indirectly through the forwarding function template `fwd`, compilers no longer compare the arguments passed at `fwd`'s call site to the parameter declarations in `f`. Instead, they *deduce* the types of the arguments being passed to `fwd`, and they compare the deduced types to `f`'s parameter declarations. Perfect forwarding fails when either of the following occurs:

- **Compilers are unable to deduce a type** for one or more of `fwd`'s parameters. In this case, the code fails to compile.

- **Compilers deduce the "wrong" type** for one or more of `fwd`'s parameters. Here, "wrong" could mean that `fwd`'s instantiation won't compile with the types that were deduced, but it could also mean that the call to `f` using `fwd`'s deduced types behaves differently from a direct call to `f` with the arguments that were passed to `fwd`. One source of such divergent behavior would be if `f` were an overloaded function name, and, due to "incorrect" type deduction, the overload of `f` called inside `fwd` were different from the overload that would be invoked if `f` were called directly.

In the "`fwd({ 1, 2, 3 })`" call above, the problem is that passing a braced initializer to a function template parameter that's not declared to be a `std::initializer_list` is decreed to be, as the Standard puts it, a "non-deduced context." In plain English, that means that compilers are forbidden from deducing a type for the expression `{ 1, 2, 3 }` in the call to `fwd`, because `fwd`'s parameter isn't declared to be a `std::initializer_list`. Being prevented from deducing a type for `fwd`'s parameter, compilers must understandably reject the call.

Interestingly, Item 2 explains that type deduction succeeds for `auto` variables initialized with a braced initializer. Such variables are deemed to be `std::initializer_list` objects, and this affords a simple workaround for cases where the type the forwarding function should deduce is a std::initializer_list: declare a local variable using auto, then pass the local variable to the forwarding function:

```
auto il = { 1, 2, 3 };      // il's type deduced to be
                            // std::initializer_list<int>

fwd(il);                    // fine, perfect-forwards il to f
```

0 or NULL as null pointers

Item 8 explains that when you try to pass 0 or NULL as a null pointer to a template, type deduction goes awry, deducing an integral type (typically int) instead of a pointer type for the argument you pass. The result is that neither 0 nor NULL can be perfect-forwarded as a null pointer. The fix is easy, however: pass nullptr instead of 0 or NULL. For details, consult Item 8.

Declaration-only integral static const data members

As a general rule, there's no need to define integral static const data members in classes; declarations alone suffice. That's because compilers perform *const-propagation* on such members' values, thus eliminating the need to set aside memory for them. For example, consider this code:

```
class Widget {
public:
  static const std::size_t MinVals = 28; // MinVals' declaration
  …
};
…                                        // no defn. for MinVals

std::vector<int> widgetData;
widgetData.reserve(Widget::MinVals);     // use of MinVals
```

Here, we're using Widget::MinVals (henceforth simply MinVals) to specify widgetData's initial capacity, even though MinVals lacks a definition. Compilers work around the missing definition (as they are required to do) by plopping the value 28 into all places where MinVals is mentioned; the fact that no storage has been set aside for MinVals' value is unproblematic. If MinVals' address were to be taken (e.g., if somebody created a pointer to MinVals), then MinVals would require storage (so that the pointer had something to point to), and the code above, though it would compile, would fail at link-time until a definition for `MinVals` was provided.

With that in mind, imagine that `f` (the function `fwd` forwards its argument to) is declared like this:

```
void f(std::size_t val);
```

Calling `f` with `MinVals` is fine, because compilers will just replace `MinVals` with its value:

```
f(Widget::MinVals);         // fine, treated as "f(28)"
```

Alas, things may not go so smoothly if we try to call `f` through `fwd`:

```
fwd(Widget::MinVals);       // error! shouldn't link
```

This code will compile, but it shouldn't link. If that reminds you of what happens if we write code that takes `MinVals`' address, that's good, because the underlying problem is the same.

Although nothing in the source code takes `MinVals`' address, `fwd`'s parameter is a universal reference, and references, in the code generated by compilers, are usually treated like pointers. In the program's underlying binary code (and on the hardware), pointers and references are essentially the same thing. At this level, there's truth to the adage that references are simply pointers that are automatically dereferenced. That being the case, passing `MinVals` by reference is effectively the same as passing it by pointer, and as such, there has to be some memory for the pointer to point to. Passing integral `static const` data members by reference, then, generally requires that they be defined, and that requirement can cause code using perfect forwarding to fail where the equivalent code without perfect forwarding succeeds.

But perhaps you noticed the weasel words I sprinkled through the preceding discussion. The code "shouldn't" link. References are "usually" treated like pointers. Passing integral `static const` data member by reference "generally" requires that they be defined. It's almost like I know something I don't really want to tell you…

That's because I do. According to the Standard, passing `MinVals` by reference requires that it be defined. But not all build systems (i.e., compiler-linker combinations) enforce this requirement. So, depending on your build system, you may find that you can perfect-forward integral `static const` data members that haven't been defined. If you do, congratulations, but there is no reason to expect such code to port. To make it portable, simply provide a definition for the integral `static const` data member in question. For `MinVals`, that'd look like this:

```
const std::size_t Widget::MinVals;     // in Widget's .cpp file
```

Note that the definition doesn't repeat the initializer (28, in the case of `MinVals`). Don't stress over this detail, however. If you forget and provide the initializer in both places, your compilers will complain, thus reminding you to specify it only once.

Overloaded function names and template names

Suppose our function `f` (the one we keep wanting to forward arguments to via `fwd`) can have its behavior customized by passing it a function that does some of its work. Assuming this function takes and returns `int`s, `f` could be declared like this:

```
void f(int (*pf)(int));          // pf = "processing function"
```

It's worth noting that `f` could also be declared using a simpler non-pointer syntax. Such a declaration would look like this, though it'd have the same meaning as the declaration above:

```
void f(int pf(int));             // declares same f as above
```

Either way, now suppose we have an overloaded function, `processVal`:

```
int processVal(int value);
int processVal(int value, int priority);
```

We can pass `processVal` to `f`,

```
f(processVal);                   // fine
```

but it's something of a surprise that we can. `f` demands a pointer to a function as its argument, but `processVal` isn't a function pointer or even a function, it's the name of two different functions. However, compilers know which `processVal` they need: the one matching `f`'s parameter type. They thus choose the `processVal` taking one `int`, and they pass that function's address to `f`.

What makes this work is that `f`'s declaration lets compilers figure out which version of `processVal` is required. `fwd`, however, being a function template, doesn't have any information about what type it needs, and that makes it impossible for compilers to determine which overload should be passed:

```
fwd(processVal);              // error! which processVal?
```

`processVal` alone has no type. Without a type, there can be no type deduction, and without type deduction, we're left with another perfect forwarding failure case.

The same problem arises if we try to use a function template instead of (or in addition to) an overloaded function name. A function template doesn't represent one function, it represents *many* functions:

```
template<typename T>
void workOnVal(T param)       // template for processing values
{ … }

fwd(workOnVal);               // error! which workOnVal
                              // instantiation?
```

The way to get a perfect-forwarding function like `fwd` to accept an overloaded function name or a template name is to manually specify the overload or instantiation you want to have forwarded. For example, you can create a function pointer of the same type as `f`'s parameter, initialize that pointer with `processVal` or `workOnVal` (thus causing the proper version of `processVal` to be selected or the proper instantiation of `workOnVal` to be generated), and pass the pointer to `fwd`:

```
using ProcessFuncType =                        // make typedef;
  int (*)(int);                                // see Item 9

ProcessFuncType processValPtr = processVal;    // specify needed
                                               // signature for
                                               // processVal

fwd(processValPtr);                            // fine
```

```
fwd(static_cast<ProcessFuncType>(workOnVal));  // also fine
```

Of course, this requires that you know the type of function pointer that `fwd` is forwarding to. It's not unreasonable to assume that a perfect-forwarding function will document that. After all, perfect-forwarding functions are designed to accept *anything*, so if there's no documentation telling you what to pass, how would you know?

Bitfields

The final failure case for perfect forwarding is when a bitfield is used as a function argument. To see what this means in practice, observe that an IPv4 header can be modeled as follows:†

```
struct IPv4Header {
  std::uint32_t version:4,
                IHL:4,
                DSCP:6,
                ECN:2,
                totalLength:16;
  …
};
```

If our long-suffering function `f` (the perennial target of our forwarding function `fwd`) is declared to take a `std::size_t` parameter, calling it with, say, the `totalLength` field of an `IPv4Header` object compiles without fuss:

```
void f(std::size_t sz);        // function to call

IPv4Header h;
…
f(h.totalLength);              // fine
```

Trying to forward `h.totalLength` to `f` via `fwd`, however, is a different story:

```
fwd(h.totalLength);            // error!
```

† This assumes that bitfields are laid out lsb (least significant bit) to msb (most significant bit). C++ doesn't guarantee that, but compilers often provide a mechanism that allows programmers to control bitfield layout.

The problem is that `fwd`'s parameter is a reference, and `h.totalLength` is a non-`const` bitfield. That may not sound so bad, but the C++ Standard condemns the combination in unusually clear prose: "A non-`const` reference shall not be bound to a bit-field." There's an excellent reason for the prohibition. Bitfields may consist of arbitrary parts of machine words (e.g., bits 3-5 of a 32-bit `int`), but there's no way to directly address such things. I mentioned earlier that references and pointers are the same thing at the hardware level, and just as there's no way to create a pointer to arbitrary bits (C++ dictates that the smallest thing you can point to is a `char`), there's no way to bind a reference to arbitrary bits, either.

Working around the impossibility of perfect-forwarding a bitfield is easy, once you realize that any function that accepts a bitfield as an argument will receive a *copy* of the bitfield's value. After all, no function can bind a reference to a bitfield, nor can any function accept pointers to bitfields, because pointers to bitfields don't exist. The only kinds of parameters to which a bitfield can be passed are by-value parameters and, counterintuitively, references-to-`const`. In the case of by-value parameters, the called function obviously receives a copy of the value in the bitfield, and it turns out that in the case of a reference-to-`const` parameter, the Standard requires that the reference actually bind to a *copy* of the bitfield's value that's stored in an object of some standard integral type (e.g., `int`). References-to-`const` don't bind to bitfields, they bind to "normal" objects into which the values of the bitfields have been copied.

The key to passing a bitfield into a perfect-forwarding function, then, is to take advantage of the fact that the forwarded-to function will always receive a copy of the bitfield's value. You can thus make a copy yourself and call the forwarding function with the copy. In the case of our example with `IPv4Header`, this code would do the trick:

```
// copy bitfield value; see Item 6 for info on init. form
auto length = static_cast<std::uint16_t>{h.totalLength};

fwd(length);                        // forward the copy
```

Upshot

In most cases, perfect forwarding works exactly as advertised. You rarely have to think about it. But when it doesn't work—when reasonable-looking code fails to compile or, worse, compiles, but doesn't behave the way you anticipate, it's important to know about perfect forwarding's imperfections. Equally important is knowing how to work around them. In most cases, this is straightforward.

Things to remember

- Perfect forwarding fails when template type deduction fails or when it deduces the wrong type.
- The kinds of arguments that lead to perfect forwarding failure are braced initializers, null pointers expressed as `0` or `NULL`, declaration-only integral `const static` data members, template and overloaded function names, and bitfields.

Chapter 6 Lambda Expressions

Lambda expressions—*lambdas*—are a game-changer in C++ programming. That's somewhat surprising, because they bring no new expressive power to the language. Everything a lambda can do is something you can do by hand with a bit more typing. But lambdas are such a convenient way to create function objects, the impact on day-to-day C++ software development is enormous. Without lambdas, the STL "`_if`" algorithms (e.g., `std::find_if`, `std::remove_if`, `std::count_if`, etc.) tend to be employed with only the most trivial predicates, but when lambdas are available, use of these algorithms with nontrivial conditions blossoms. The same is true of algorithms that can be customized with comparison functions (e.g., `std::sort`, `std::nth_element`, `std::lower_bound`, etc.). Outside the STL, lambdas make it possible to quickly create custom deleters for `std::unique_ptr` and `std::shared_ptr` (see Items 20 and 21), and they make the specification of predicates for condition variables in the threading API equally straightforward. Beyond the Standard Library, lambdas facilitate the on-the-fly specification of callback functions, interface adaption functions, and context-specific functions for one-off calls. Lambdas really make C++ a more pleasant programming language.

The Items in this chapter cover important dos and don'ts for effective software development with lambdas. The chapter begins with an admonition to steer clear of what initially looks like an attractive feature: default capture modes. It then addresses how to accomplish move capture in C++14 (where it's more or less directly supported) and C++11 (where the way is more circuitous). That's followed by a C++14-specific Item on implementing perfect-forwarding with generic lambdas, and the chapter concludes with an Item explaining why programmers accustomed to `std::bind` should switch to lambdas.

The vocabulary associated with lambdas can be confusing. Here's a brief refresher:

- A *lambda expression* is just that: an expression. It's part of the source code. In

```
std::find_if(container.begin(), container.end(),
             [](auto val) { return 0 < val && val < 10; });
```

the highlighted expression is the lambda.

- A *closure* is the runtime object created by a lambda. Closures hold copies of all captured data (although by-reference captures are typically optimized away). In the call to `std::find_if` above, the closure is the object that's passed at runtime as the third argument to `std::find_if`. (The first two arguments are the begin and end iterators for *`container`*.)

- A *closure class* is a class from which a closure is instantiated. Each lambda causes compilers to generate a unique closure class. The statements inside a lambda become executable instructions in the member functions of its closure class (modulo inlining and other optimizations).

A lambda is often used to create a closure that's used only as an argument to a function. That's the case in the call to `std::find_if` above. However, closures may generally be copied, so it's usually possible to have multiple closures of a closure type corresponding to a single lambda. For example, in the following code,

```
{                                       // begin a scope

  int x;                                // x is local variable
  …

  auto c1 =                             // c1 is copy of the
    [x](int y) { return x * y = 5; };   // closure produced
                                        // by the lambda

  auto c2 = c1;                         // c2 is copy of c1

  auto c3 = c2;                         // c3 is copy of c2

  …

}                                       // end the scope
```

`c1`, `c2`, and `c3` are all copies of the closure produced by the lambda.

Informally, it's perfectly acceptable to blur the lines between lambdas, closures, and closure classes. But in the Items that follow, it's often important to distinguish what exists during compilation (lambdas and closure classes), what exists at runtime (closures), and how they relate to one another.

Item 33: Avoid default capture modes.

There are two default capture modes in C++11: by-reference and by-value. Default by-reference capture can lead to easy-to-overlook dangling references. Default by-value capture lures you into thinking you're immune to that problem (you're not), and it lulls you into thinking your closures are self-contained (they may not be).

That's the executive summary for this Item. If you're more engineer than executive, you'll want some meat on those bones, so let's start with the danger of default by-reference capture.

A by-reference capture causes the code inside the lambda to refer to a local variable or a parameter that's available in the scope where the lambda is defined. If the lifetime of a closure created from that lambda exceeds the lifetime of the local variable or parameter, the reference in the code will dangle. For example, suppose we have a container of filtering functions, each of which takes an `int` and returns a `bool` indicating whether a passed-in value satisfies the filter:

```
using FilterContainer =                       // typedef;
  std::vector<std::function<bool(int)>>;      // see Item 9

FilterContainer filters;                      // filtering funcs
```

We could add a filter for multiples of 5 like this:

```
filters.emplace_back(                         // see Item 18 for
  [](int value) { return value % 5 == 0; }    // info on
);                                            // emplace_back
```

However, it may be that we need to compute the divisor at runtime, i.e., we can't just hard-code 5 into the lambda. So adding the filter might look more like this:

```
void addDivisorFilter()
{
  auto calc1 = computeSomeValue1();
  auto calc2 = computeSomeValue2();

  auto divisor = computeDivisor(calc1, calc2);

  filters.emplace_back(                              // danger!
    [&](int value) { return value % divisor == 0; }  // divisor
  );                                                 // might
}                                                    // dangle!
```

This code is a problem waiting to happen. The lambda refers to the local variable `divisor`, but that variable ceases to exist when `addDivisorFilter` returns. That's immediately after `filters.emplace_back` returns, so the function that's added to `filters` is essentially dead on arrival. Using that filter yields undefined behavior from virtually the moment it's created.

Now, the same problem would exist if `divisor`'s by-reference capture were explicit,

```
  filters.emplace_back(
    [&divisor](int value)                 // danger! divisor can
    { return value % divisor == 0; }      // still dangle!
  );
```

but with an explicit capture, it's easier to see that the viability of the lambda is dependent on `divisor`'s lifetime. Also, writing out the name, "divisor," reminds us to ensure that `divisor` lives at least as long as the lambda's closures. That's a more specific memory jog than the general "make sure nothing dangles" admonition that "`[&]`" conveys.

If you know that the lambda will be used only once (e.g., in a call to an STL algorithm), there is no risk that its closure will outlive the local variables and parameters in the environment where the lambda is created. In that case, you might argue, there's no risk of dangling references, hence no reason to avoid a default by-reference capture mode. For example, our filtering lambda might be used only as an argument to C++11's `std::all_of`, which returns whether all elements in a range satisfy a condition:

```
template<typename C>
void workWithContainer(const C& container)
{
  auto calc1 = computeSomeValue1();              // as above
  auto calc2 = computeSomeValue2();              // as above

  auto divisor = computeDivisor(calc1, calc2);   // as above

  using ContElemT = typename C::value_type;      // type of
                                                 // elements in
                                                 // container

  if (std::all_of(                               // if all values
        container.begin(), container.end(),      // in container
```

```
        [&](const ContElemT& value)           // are multiples
        { return value % divisor == 0; })     // of divisor...
      ) {
    …                                         // they are...
  } else {
    …                                         // at least one
  }                                           // isn't...
}
```

It’s true, this is safe, but its safety is somewhat precarious. If the lambda were found to be useful in other contexts (e.g., as a function to be added to the `filters` container) and was copy-and-pasted into a context where its closure could outlive `divisor`, you’d be back in dangle-city, and there’d be nothing in the capture clause to specifically remind you to perform lifetime analysis on `divisor`.

Long-term, it’s simply better software engineering to explicitly list the local variables and parameters that a lambda depends on.

By the way, the ability to use `auto` in C++14 lambda parameter specifications means that the code above can be simplified in C++14. The `ContElemT` typedef can be eliminated, and the `if` condition can be revised as follows:

```
if (std::all_of(container.begin(), container.end(),
                [&](const auto& value)               // C++14
                { return value % divisor == 0; }))   // only
```

One way to solve our problem with `divisor` would be a default by-value capture mode. That is, we could add the lambda to `filters` as follows:

```
filters.emplace_back(                                // now
  [=](int value) { return value % divisor == 0; }    // divisor
);                                                   // can't
                                                     // dangle
```

This suffices for this example, but, in general, default by-value capture isn’t the anti-dangling elixir you might imagine. The problem is that if you capture a pointer by value, you copy the pointer into the closures arising from the lambda, but you don’t prevent code outside the lambda from `delete`ing the pointer and causing your copies to dangle.

“That could never happen!,” you protest. “Having read Chapter 4, I worship at the house of smart pointers. Only loser C++98 programmers use raw pointers and `de-`

lete." That may be true, but it's irrelevant, because you do, in fact, use raw pointers, and they can, in fact, be deleted out from under you. It's just that in your modern C++ programming style, there's often little sign of it in the source code.

Suppose one of the things Widgets can do is add entries to the container of filters:

```
class Widget {
public:
  …                                  // ctors, etc.

  void addFilter() const;            // add an entry to filters

private:
  int divisor;                       // used in Widget's filter
};
```

Widget::addFilter could be defined like this:

```
void Widget::addFilter() const
{
  filters.emplace_back(
    [=](int value) { return value % divisor == 0; }
  );
}
```

To the blissfully uninitiated, this looks like safe code. The lambda is dependent on divisor, but the default by-value capture mode ensures that divisor is copied into any closures arising from the lambda, right?

Wrong. Completely wrong. Horribly wrong. Fatally wrong.

Captures apply only to non-static local variables (including parameters) visible in the scope where the lambda is created. In the body of Widget::addFilter, divisor is not a local variable, it's a data member of the Widget class. It can't be captured. Yet if the default capture mode is eliminated, the code won't compile:

```
void Widget::addFilter() const
{
  filters.emplace_back(                               // error!
    [](int value) { return value % divisor == 0; }  // divisor
  );                                                  // not
}                                                     // available
```

Furthermore, if an attempt is made to explicitly capture divisor (either by value or by reference—it doesn't matter), the capture won't compile, because divisor isn't a local variable or a parameter:

```
void Widget::addFilter() const
{
  filters.emplace_back(
    [divisor](int value)                // error! no local
    { return value % divisor == 0; }    // divisor to capture
  );
}
```

So if the default by-value capture clause isn't capturing divisor, yet without the default by-value capture clause, the code won't compile, what's going on?

The explanation hinges on your implicit use of a raw pointer: this. Every non-static member function has a this pointer, and you use that pointer every time you mention a data member of the class. Inside any Widget member function, for example, compilers internally replace uses of divisor with this->divisor. In the version of Widget::addFilter with a default by-value capture,

```
void Widget::addFilter() const
{
  filters.emplace_back(
    [=](int value) { return value % divisor == 0; }
  );
}
```

what's being captured is the Widget's this pointer, not divisor. Compilers treat the code as if it had been written as follows:

```
void Widget::addFilter() const
{
  auto currentObjectPtr = this;

  filters.emplace_back(
    [currentObjectPtr](int value)
    { return value % currentObjectPtr->divisor == 0; }
  );
}
```

Understanding this is tantamount to understanding that the viability of the closures arising from this lambda are tied to the lifetime of the Widget whose this pointer they contain a copy of. In particular, consider this code, which, in accord with Chapter 4, uses pointers of only the smart variety:

```
using FilterContainer =                    // as before
  std::vector<std::function<bool(int)>>;

FilterContainer filters;                   // as before

void doSomeWork()
{
  auto pw =                      // create Widget; see
    std::make_unique<Widget>();  // Item 23 for
                                 // std::make_unique

  pw->addFilter();               // add filter that uses
                                 // Widget::divisor
  …
}                                // destroy Widget; filter
                                 // now holds dangling pointer!
```

When a call is made to `doSomeWork`, a filter is created that depends on the `Widget` object produced by `std::make_unique`, i.e., a filter that contains a copy of a pointer to that `Widget`—the `Widget`'s `this` pointer. This filter is added to `filters`, but when `doSomeWork` finishes, the `Widget` is destroyed by the `std::unique_ptr` managing its lifetime (see Item 20). From that point on, `filters` contains an entry with a dangling pointer.

This particular problem can be solved by making a local copy of the data member you want to capture and then capturing the copy:

```
void Widget::addFilter() const
{
  auto divisorCopy = divisor;                // copy data member

  filters.emplace_back(
    [divisorCopy](int value)                 // capture the copy
    { return value % divisorCopy == 0; }     // use the copy
  );
}
```

To be honest, if you take this approach, default by-value capture will work, too,

```
void Widget::addFilter() const
{
  auto divisorCopy = divisor;                // copy data member
```

```
  filters.emplace_back(
    [=](int value)                               // capture the copy
    { return value % divisorCopy == 0; }         // use the copy
  );
}
```

but why tempt fate? A default capture mode is what made it possible to accidentally capture `this` when you thought you were capturing `divisor` in the first place.

In C++14, a better way to capture a data member is to use generalized lambda capture (see Item 34):

```
void Widget::addFilter() const
{
  filters.emplace_back(                      // C++14 only:
    [divisor = divisor](int value)           // copy divisor to closure
    { return value % divisor == 0; }         // use the copy
  );
}
```

There's no such thing as a default capture mode for a generalized lambda capture, however, so even in C++14, the advice of this Item—to avoid default capture modes—stands.

An additional drawback to default by-value captures is that they can suggest that the corresponding closures are self-contained and insulated from changes to data outside the closures. In general, that's not true, because lambdas may be dependent not just on local variables and parameters (which may be captured), but also on objects with *static storage duration*. Such objects are defined at global or namespace scope or are declared `static` inside classes, functions, or files. These objects can be used inside lambdas, but they can't be captured. Yet specification of a default by-value capture mode can lend the impression that they are. Consider this revised version of the `addDivisorFilter` template we saw earlier:

```
void addDivisorFilter()
{
  static auto calc1 = computeSomeValue1();      // now static
  static auto calc2 = computeSomeValue2();      // now static

  static auto divisor =                         // now static
    computeDivisor(calc1, calc2);
```

```
  filters.emplace_back(
    [=](int value)                           // captures nothing!
    { return value % divisor == 0; }   // refers to above static
  );

  ++divisor;                                 // modify divisor
}
```

A casual reader of this code could be forgiven for seeing "`[=]`" and thinking, "Okay, the lambda makes a copy of all the objects it uses and is therefore self-contained." But it's not self-contained. This lambda doesn't use any non-static local variables, so nothing is captured. Rather, the code for the lambda refers to the `static` variable `divisor`. When, at the end of each invocation of `addDivisorFilter`, `divisor` is incremented, any lambdas that have been added to `filters` via this function will exhibit new behavior (corresponding to the new value of `divisor`). Practically speaking, this lambda captures `divisor` by reference, a direct contradiction to what the default by-value capture clause seems to imply. If you stay away from default by-value capture clauses, you eliminate the risk of your code being misread in this way.

Things to Remember

- Default by-reference capture can lead to hidden dangling references.
- Default by-value capture is susceptible to hidden dangling pointers (especially `this`), and it misleadingly suggests that lambdas are self-contained.

Item 34: Use init capture to move objects into closures.

Sometimes neither by-value capture nor by-reference capture is what you want. If you have a move-only object (e.g., a `std::unique_ptr` or a `std::future`) that you want to get into a closure, C++11 offers no way to do it. If you have an object that's expensive to copy but cheap to move (e.g., most containers in the Standard Library), and you'd like to get that object into a closure, you'd much rather move it than copy it. Again, however, C++11 gives you no way to accomplish that.

But that's C++11. C++14 is a different story. It offers direct support for moving objects into closures. If your compilers are C++14-compliant, rejoice and read on. If you're still working with C++11 compilers, you should rejoice and read on, too, because there are ways to approximate move capture in C++11.

The absence of move capture was recognized as a shortcoming even as C++11 was adopted. The straightforward remedy would have been to add it in C++14, but the Standardization Committee chose a different path. They introduced a new capture mechanism that's so flexible, capture-by-move is only one of the tricks it can perform. The new capability is called *init capture*. It can do virtually everything the C++11 capture forms can do, plus more. The one thing you can't express with an init capture is a default capture mode, but Item 33 explains that you should stay away from those, anyway. (For situations covered by C++11 captures, init capture's syntax is a bit wordier, so in cases where a C++11 capture gets the job done, it's perfectly reasonable to use it.)

Using an init capture makes it possible for you to specify

1. **the name of a data member** in the closure class generated from the lambda and
2. **an expression** initializing that data member.

Here's how you can use init capture to move a `std::unique_ptr` into a closure:

```
class Widget {                          // some useful type
public:
  …

  bool isValidated() const;
  bool isProcessed() const;
  bool isArchived() const;

private:
  …
};


auto pw = std::make_unique<Widget>();   // create Widget; see
                                        // Item 23 for info on
                                        // std::make_unique

…                                       // configure *pw
```

```
auto func = [pw = std::move(pw)]              // init data mbr
            { return pw->isValidated()        // in closure w/
                     && pw->isArchived(); };  // std::move(pw)
```

The highlighted text comprises the init capture. To the left of the "=" is the name of the data member in the closure class you're specifying, and to the right is the initializing expression. Interestingly, the scope on the left of the "=" is different from the scope on the right. The scope on the left is that of the closure class. The scope on the right is the same as where the lambda is being defined. In the example above, the name `pw` on the left of the "=" refers to a data member in the closure class, while the name `pw` on the right refers to the object declared above the lambda, i.e., the variable initialized by the call to `std::make_unique`. So "`pw = std::move(pw)`" means "create a data member `pw` in the closure, and initialize that data member with the result of applying `std::move` to the local variable `pw`."

As usual, code in the body of the lambda is in the scope of the closure class, so uses of `pw` there refer to the closure class data member.

The comment "configure `*pw`" in this example indicates that after the `Widget` is created by `std::make_unique` and before the `std::unique_ptr` to that `Widget` is captured by the lambda, the `Widget` is modified in some way. If no such configuration is necessary, i.e., if the `Widget` created by `std::make_unique` is in a state suitable to be captured by the lambda, the local variable `pw` is unnecessary, because the closure class's data member can be directly initialized by `std::make_unique`:

```
auto func = [pw = std::make_unique<Widget>()]  // init data mbr
            { return pw->isValidated()         // in closure w/
                     && pw->isArchived(); };   // result of call
                                               // to make_unique
```

This should make clear that the C++14 notion of "capture" is considerably generalized from C++11, because in C++11, it's not possible to capture the result of an expression. As a result, another name for init capture is *generalized lambda capture*.

But what if one or more of the compilers you use lacks support for C++14's init capture? How can you accomplish move capture in a language lacking support for move capture?

Remember that a lambda expression is simply a way to cause a class to be generated and an object of that type to be created. There is nothing you can do with a lambda that you can't do by hand. The example C++14 code we just saw, for example, can be written in C++11 like this:

```
class IsValAndArch {                          // "is validated
public:                                       // and archived"
  using DataType = std::unique_ptr<Widget>;

  explicit IsValAndArch(DataType&& ptr)       // Item 27 explains
  : pw(std::move(ptr)) {}                     // use of std::move

  bool operator()() const
  { return pw->isValidated() && pw->isArchived(); }

private:
  DataType pw;
};

auto func = IsValAndArch(std::make_unique<Widget>());
```

That's more work than writing the lambda, but it doesn't change the fact that if you want a class in C++11 that supports move-initialization of its data members, the only thing between you and your desire is a bit of time with your keyboard.

If you want to stick with lambdas (and given their convenience, you probably do), move capture can be emulated in C++11 by

1. **moving the object to be captured into a function object produced by `std::bind`** and
2. **giving the lambda a reference to the "captured" object**.

If you're familiar with `std::bind`, the code is pretty straightforward. If you're not familiar with `std::bind`, the code takes a little getting used to, but it's worth the trouble.

Suppose you'd like to create a local `std::vector`, put an appropriate set of values into it, then move it into a closure. In C++14, this is easy:

```
std::vector<double> data;                  // object to be moved
                                           // into closure

…                                          // populate data
```

```
auto func = [data = std::move(data)]      // C++14 init capture
            { /* uses of data */ };
```

I've highlighted key parts of this code: the type of object you want to move (`std::vector<double>`), the name of that object (`data`), and the initializing expression for the init capture (`std::move(data)`). The C++11 equivalent is as follows, where I've highlighted the same key things:

```
std::vector<double> data;                 // as above

…                                         // as above

auto func =
  std::bind(                              // C++11 emulation
    [](std::vector<double>& data)         // of init capture
    { /* uses of data */ },
    std::move(data)
  );
```

Like lambda expressions, `std::bind` produces function objects. I call function objects returned by `std::bind` *bind objects*. The first argument to `std::bind` is always something callable (e.g., a callable entity). Subsequent arguments represent values to be passed to the first argument.

A bind object contains copies of all the arguments passed to `std::bind`. For each lvalue argument, the corresponding object in the bind object is copy constructed. For each rvalue, it's move constructed. In this example, the second argument is an rvalue (the result of `std::move`—see Item 25), so `data` is move-constructed into the bind object. This move construction is the crux of move capture emulation, because moving an rvalue into a bind object is how we work around the inability to move an rvalue into a C++11 closure.

When a bind object is "called" (i.e., its function call operator is invoked) the objects it stores are passed to the callable entity originally passed to `std::bind`. In this example, that means that when `func` (the bind object) is called, the move-constructed copy of `data` inside `func` is passed as an argument to the lambda that was passed to `std::bind`.

This lambda is the same as the lambda we'd use in C++14, except a parameter, `data`, has been added to correspond to our pseudo-move-captured object. This parameter is an lvalue reference to the copy of `data` in the bind object. (It's not an rvalue reference, because although the expression used to initialize the copy of `data` ("`std::move(data)`") is an rvalue, the copy of `data` itself is an lvalue.) Uses of `data` inside the lambda will thus operate on the move-constructed copy of `data` inside the bind object.

Because a bind object stores copies of all the arguments passed to `std::bind`, the bind object in our example contains a copy of the closure produced by the lambda that is its first argument. The lifetime of the closure is therefore the same as the lifetime of the bind object. That's important, because it means that as long as the closure exists, the bind object containing the pseudo-move-captured object exists, too.

If this is your first exposure to `std::bind`, you may need to consult your favorite C++11 reference before all the details of the foregoing discussion fall into place. Even if that's the case, these fundamental points should be clear:

- It's not possible to move-construct an object into a C++11 closure, but it is possible to move-construct an object into a C++11 bind object.

- Emulating move-capture in C++11 consists of move-constructing an object into a bind object, then passing the move-constructed object to the lambda by reference.

- Because the lifetime of the bind object is the same as that of the closure, it's possible to treat objects in the bind object as if they were in the closure.

As a second example of using `std::bind` to emulate move capture, here's the C++14 code we saw earlier to create a `std::unique_ptr` in a closure:

```
auto func = [pw = std::make_unique<Widget>()]    // as before,
            { return pw->isValidated()           // create pw
                     && pw->isArchived(); };     // in closure
```

And here's the C++11 emulation:

```
auto func = std::bind(
              [](std::unique_ptr<Widget>& pw)
              { return pw->isValidated()
```

```
                        && pw->isArchived(); },
              std::make_unique<Widget>()
            );
```

It's ironic that I'm showing how to use `std::bind` to work around limitations in C++11 lambdas, because in Item 36, I advocate the use of lambdas over `std::bind`. However, that Item explains that there are some cases in C++11 where `std::bind` can be useful, and this is one of them. (In C++14, features such as init capture and `auto` parameters eliminate those cases.)

Things to Remember

- Use C++14's init capture to move objects into closures.
- In C++11, emulate init capture via hand-written classes or `std::bind`.

Item 35: Use `decltype` on `auto&&` parameters to `std::forward` them.

One of the most exciting features of C++14 is generic lambdas—lambdas that use `auto` in their parameter specifications. The implementation of this feature is straightforward: the `operator()` in the closure class arising from the lambda is a template. Given this lambda, for example,

```
auto f = [](auto x){ return func(normalize(x)); };
```

the closure class's function call operator looks like this:

```
class SomeCompilerGeneratedClassName {
public:
  template<typename T>                    // see Item 3 for
  auto operator()(T x) const              // auto return type
  { return func(normalize(x)); }

  …                                       // other closure class
};                                        // functionality
```

In this example, the only thing the lambda does with its parameter `x` is forward it to `normalize`. If `normalize` treats lvalues differently from rvalues, this lambda isn't really written properly, because it always passes an lvalue (the parameter `x`) to `normalize`, even if the argument that was passed to the lambda was an rvalue.

The correct way to write the lambda is to have it perfect-forward `x` to `normalize`. Doing that requires two changes to the code. First, `x` has to become a universal reference (see Item 26), and second, it has to be passed to `normalize` via `std::forward` (see Item 27). In concept, these are trivial modifications:

```
auto f = [](auto&& x)
         { return func(normalize(std::forward<???>(x))); };
```

Between concept and realization, however, is the question of what type to pass to `std::forward`, ie., to determine what should go where I've written `???` above.

Normally, when you employ perfect forwarding, you're in a template function taking some type parameter `T`, so you just write `std::forward<T>`. In the lambda, though, there's no type parameter `T` available to you. There is a `T` in the templatized `operator()` inside the closure class generated by the lambda, but it's not possible to refer to it from the lambda, so it does you no good.

Item 30 explains that if an lvalue argument is passed to a universal reference parameter, the type of that parameter becomes an lvalue reference. If an rvalue is passed, the parameter becomes an rvalue reference. This means that in our lambda, we can determine whether the argument passed was an lvalue or an rvalue by inspecting the type of the parameter, `x`. `decltype` gives us a way to do that (see Item 3). If an lvalue was passed in, `decltype(x)` will produce a type that's an lvalue reference. If an rvalue was passed, `decltype(x)` will produce an rvalue reference type.

Item 30 also explains that when calling `std::forward`, the type argument should be an lvalue reference for lvalues, and it should be a non-reference for rvalues. In our lambda, if `x` is bound to an lvalue, `decltype(x)` will yield an lvalue reference, which is exactly what `std::forward` wants. However, if `x` is bound to an rvalue, `decltype(x)` will yield an rvalue reference—not the non-reference that `std::forward` expects.

But look at the sample implementation for `std::forward` from Item 30:

```
template<typename T>                       // from Item 30
T&& forward(T&& param)
{
```

```
  return static_cast<T&&>(param);
}
```

If client code wants to perfect-forward an rvalue of type `Widget`, it'll call `std::forward` with the type `Widget` (i.e, a non-reference type), and the `std::forward` template will be instantiated to yield this function:

```
Widget&& forward(Widget&& param)            // instantiation of
{                                           // std::forward when
  return static_cast<Widget&&>(param);      // T is Widget
}
```

But consider what would happen if the client code wanted to perfect-forward the same rvalue of type `Widget`, but instead of following the convention of specifying `T` to be a non-reference type, it specified it to be an rvalue reference. That is, consider what would happen if `T` were specified to be `Widget&&`. After instantiation of `std::forward` but before reference collapsing (once again, see Item 30), `std::forward` would look like this:

```
Widget&& && forward(Widget&& && param)      // instantiation of
{                                           // std::forward when
  return static_cast<Widget&& &&>(param);   // T is Widget&&
}                                           // (before reference-
                                            // collapsing)
```

Applying the reference-collapsing rule that an rvalue reference to an rvalue reference becomes a single rvalue reference, this instantiation emerges:

```
Widget&& forward(Widget&& param)            // instantiation of
{                                           // std::forward when
  return static_cast<Widget&&>(param);      // T is Widget&&
}                                           // (after reference-
                                            // collapsing)
```

If you compare this instantiation with the one that results when `std::forward` is called with `T` set to `Widget`, you'll see that they're identical. That means that calling `std::forward` with a non-reference type yields the same result as calling it with an rvalue reference type.

That's wonderful news, because `decltype(x)` yields an rvalue reference type when an rvalue is passed as an argument to our lambda's parameter `x`. We established above that when an lvalue is passed to our lambda, `decltype(x)` yields the proper type to pass to `std::forward`, and now we realize that for rvalues, `decltype(x)` yields a type to pass to `std::forward` that's not conventional, but that nevertheless yields the same outcome as the conventional type. So for both lvalues and rvalues, passing `decltype(x)` to `std::forward` gives us the result we want. Our perfect-forwarding lambda can therefore be written like this:

```
auto f =
  [](auto&& x)
  { return func(normalize(std::forward<decltype(x)>(x))); };
```

From there, it's just a hop, skip, and three dots to a perfect-forwarding lambda that accepts not just a single parameter, but any number of parameters, because C++14 lambdas can also be variadic:

```
auto f =
  [](auto&&... x)
  { return func(normalize(std::forward<decltype(x)>(x)...)); };
```

Things to Remember

- Use `decltype` on `auto&&` parameters to `std::forward` them.

Item 36: Prefer lambdas to `std::bind`.

`std::bind` is the C++11 successor to C++98's `std::bind1st` and `std::bind2nd`, but, informally, it's been part of the Standard Library since 2005. That's when the Standardization Committee adopted a document known as TR1, which included `bind`'s specification. (In TR1, `bind` was in a different namespace, so it was `std::tr1::bind`, not `std::bind`, and a few interface details were different.) This history means that some programmers have a decade or more of experience using `std::bind`. If you're one of them, you may be reluctant to abandon a tool that's served you well. That's understandable, but in this case, change is good, because in C++11, lambdas are almost always a better choice than `std::bind`. As of C++14, the case for lambdas isn't just stronger, it's downright iron-clad.

This Item assumes that you're familiar with `std::bind`. If you're not, you'll want to acquire a basic understanding before continuing. Such an understanding is worthwhile in any case, because you never know when you might encounter uses of `std::bind` in a code base you have to read or maintain.

The most important reason to prefer lambdas over `std::bind` is that lambdas are more readable. Suppose, for example, we have a function to set up an audible alarm:

```
// typedef for a point in time (see Item 9 for syntax)
using Time = std::chrono::time_point<std::chrono::steady_clock>;

// see Item 10 for "enum class"
enum class Sound { Beep, Siren, Whistle };

// typedef for a length of time
using Duration = std::chrono::steady_clock::duration;

// at time t, make sound s for duration d
void setAlarm(Time t, Sound s, Duration d);
```

Further suppose that at some point in the program, we've determined we'll want an alarm that will go off an hour after it's set and that will stay on for 30 seconds. The alarm sound, however, remains undecided. We can write a lambda that revises `setAlarm`'s interface so that only a sound needs to be specified:

```
// setSoundL ("L" for "lambda") is a function object allowing a
// sound to be specified for a 30-sec alarm to go off an hour
// after it's set
auto setSoundL =
  [](Sound s)
  {
    // make std::chrono components available w/o qualification
    using namespace std::chrono;

    setAlarm(steady_clock::now() + hours(1),  // alarm to go off
             s,                                // in an hour for
             seconds(30));                     // 30 seconds
  };
```

I've highlighted the call to `setAlarm` inside the lambda. This is a normal-looking function call, and even a reader with little lambda experience can see that the parameter `s` passed to the lambda is passed as an argument to `setAlarm`.

The corresponding `std::bind` call looks like this:

```
using namespace std::chrono;           // as above

using namespace std::placeholders;     // needed for use of "_1"

auto setSoundB =                       // "B" for "bind"
  std::bind(setAlarm,
```

```
             steady_clock::now() + hours(1),
             _1,
             seconds(30));
```

I'd like to highlight the call to `setAlarm` here as I did above, but there's no call to highlight. Readers of this code simply have to know that calling `setSoundB` invokes `setAlarm` with the time and duration specified in the call to `std::bind`. To the uninitiated, the placeholder "`_1`" is essentially magic, but even readers in the know have to mentally map from the number in that placeholder to its position in the `std::bind` parameter list in order to understand that the first argument in a call to `setSoundB` is passed as the second argument to `setAlarm`. The type of this argument is not identified in the call to `std::bind`, so readers have to consult the `setAlarm` declaration to determine what kind of argument to pass to `setSoundB`.

If `setAlarm` is overloaded, the situation becomes more interesting. Suppose there's an overload taking a fourth parameter specifying the alarm volume:

```
enum class Volume { Normal, Loud, LoudPlusPlus };

void setAlarm(Time t, Sound s, Duration d, Volume v);
```

The lambda continues to work as before, because overload resolution chooses the three-argument version of `setAlarm`:

```
auto setSoundL =                              // same as before
  [](Sound s)
  {
    using namespace std::chrono;

    setAlarm(steady_clock::now() + hours(1),  // fine, calls
             s,                               // 3-arg version
             seconds(30));                    // of setAlarm
  };
```

The `std::bind` call, on the other hand, now fails to compile:

```
auto setSoundB =
  std::bind(setAlarm,                         // error! which
            steady_clock::now() + hours(1),   // setAlarm?
            _1,
            seconds(30));
```

The problem is that compilers have no way to determine which of the two `setAlarm` functions they should pass to `std::bind`. All they have is a function name, and the name alone is ambiguous.

To get the `std::bind` call to compile, `setAlarm` must be cast to the proper function pointer type:

```
using SetAlarm3ParamType = void(*)(Time t, Sound s, Duration d);

auto setSoundB =                                              // now
  std::bind(static_cast<SetAlarm3ParamType>(setAlarm),  // okay
            steady_clock::now() + hours(1),
            _1,
            seconds(30));
```

But this brings up another difference between lambdas and `std::bind`. Inside the function call operator for `setSoundL` (i.e., the function call operator of the lambda's closure class), the call to `setAlarm` is a normal function invocation that can be inlined by compilers in the usual fashion. Furthermore, C++ specifies that the function call operator on the closure class resulting from the lambda is `inline`, so in a call to the lambda, it's entirely possible that the body of `setAlarm` is inlined at the call site:

```
setSoundL(Sound::Siren);       // body of setAlarm may
                               // well be inlined here
```

The call to `std::bind`, however, passes a function pointer to `setAlarm`, and that means that inside the function call operator for `setSoundB` (i.e., the function call operator for the class of the object returned by `std::bind`), the call to `setAlarm` takes place through a function pointer. Compilers are much less likely to inline function calls through function pointers, and that means that calls to `setAlarm` through `setSoundB` are less likely to be fully inlined than those through `setSoundL`:

```
setSoundB(Sound::Siren);       // body of setAlarm is less
                               // likely to be inlined here
```

It's thus probable that using lambdas generates faster code than using `std::bind`.

The `setAlarm` example involves only a simple function call. If you want to do anything more complicated, the scales tip even further in favor of lambdas. For example, consider this C++14 lambda, which returns whether its argument is between a minimum value (`lowVal`) and a maximal value (`highVal`), where `lowVal` and `highVal` are local variables:

```
auto betweenL =
  [lowVal, highVal]
  (const auto& val)                          // C++14 only
  { return lowVal <= val && val <= highVal; };
```

`std::bind` can express the same thing, but the construct is an example of job security through code obscurity:

```
using namespace std::placeholders;           // as above

auto betweenB =
  std::bind(std::logical_and<>(),            // C++14 only
            std::bind(std::less_equal<>(), _1, lowVal),
            std::bind(std::less_equal<>(), _1, highVal));
```

Within this use of `std::bind`, I'm taking advantage of the C++14 feature of not having to specify a template type argument for the standard operator templates (e.g., `std::logical_and`, `std::less_equal`, etc.). In C++11, we'd have to specify the types we wanted to compare, and the `std::bind` call would look like this:

```
using namespace std::placeholders;

auto betweenB =                              // C++11 version
  std::bind(std::logical_and<bool>(),
            std::bind(std::greater_equal<int>(), _1, lowVal),
            std::bind(std::less_equal<int>(), _1, highVal));
```

Of course, in C++11, the lambda couldn't take an `auto` parameter, so it'd have to commit to a type, too:

```
auto betweenL =                              // C++11 version
  [lowVal, highVal]
  (int x)
  { return x >= lowVal && x <= highVal; };
```

Either way, I hope we can agree that the lambda version is not just shorter, but also more comprehensible and maintainable.

Earlier, I remarked that for those with little `std::bind` experience, its placeholders (e.g., `_1`, `_2`, etc.) are essentially magic. But it's not just the behavior of the placeholders that's opaque. Suppose we have a function to create compressed copies of Widgets,

```
enum class CompLevel { Low, Normal, High };  // compression
                                             // level

Widget compress(const Widget& w,             // make compressed
                CompLevel lev);              // copy of w
```

and we want to create a function object that allows us to specify how much a particular `Widget w` should be compressed. This use of `std::bind` will create such an object:

```
Widget w;

using namespace std::placeholders;

auto compressRateB = std::bind(compress, w, _1);
```

Now, when we pass `w` to `std::bind`, it has to be stored for the later call to `compress`. It's stored inside the object `compressRate`, but how is it stored—by value or by reference? It makes a difference, because if `w` is modified between the call to `std::bind` and a call to `compressRate`, storing `w` by reference will reflect the changes, while storing it by value won't.

The answer is that it's stored by value, but the only way to know that is to memorize how `std::bind` works; there's no sign of it in the call to `std::bind`.[†] Contrast that with a lambda approach, where whether `w` is captured by value or by reference is explicit:

```
auto compressRateL =                         // w is captured by
  [w](CompLevel lev)                         // value; lev is
  { return compress(w, lev); };              // passed by value
```

[†] `std::bind` always copies its arguments, but callers can achieve the effect of having an argument stored by reference by applying `std::ref` to it. The result of

```
auto compressRateB = std::bind(compress, std::ref(w), _1);
```

is that `compressRateB` acts as if it holds a reference to `w`, rather than a copy. A lambda, of course, would simply use an explicit by-reference capture mode to achieve this effect.

Equally explicit is how parameters are passed to the lambda. Here, it's clear that the parameter `lev` is passed by value. Hence:

```
compressRateL(CompLevel::High);              // arg is passed
                                             // by value
```

But in the call to the object resulting from `std::bind`, how is the argument passed?

```
compressRateB(CompLevel::High);              // how is arg
                                             // passed?
```

Again, the only way to know is to memorize how `std::bind` works. (The answer is that all arguments passed to objects created by `std::bind` are passed by reference, because the function call operator for such objects uses perfect forwarding.)

Compared to lambdas, then, code using `std::bind` is less readable, less expressive, and less efficient. In C++14, there are no reasonable use cases for `std::bind`. In C++11, however, `std::bind` can be justified in two constrained situations:

- **Move capture**. C++11 lambdas don't offer move capture, but it can be emulated through a combination of a lambda and `std::bind`. For details, consult Item 34, which also explains that in C++14, lambdas' support for init capture eliminates the need for the emulation.

- **Polymorphic function objects**. Because the function call operator on the object returned from `std::bind` uses perfect forwarding, it can accept arguments of any type (modulo the restrictions on perfect forwarding described in Item 32). This can be useful when you want to bind an object with a templatized function call operator. For example, given this class,

  ```
  class PolyWidget {
  public:
      template<typename T>
      void operator()(const T& param);
      …
  };
  ```

  `std::bind` can bind a `PolyWidget` as follows:

  ```
  PolyWidget pw;
  ```

```
auto boundPW = std::bind(pw, _1);
```

boundPW can then be called with different types of arguments:

```
boundPW(1930);              // pass int to
                            // PolyWidget::operator()

boundPW(nullptr);           // pass nullptr to
                            // PolyWidget::operator()

boundPW("Rosebud");         // pass string literal to
                            // PolyWidget::operator()
```

There is no way to do this with a C++11 lambda. In C++14, however, it's easily achieved via a lambda with an `auto` parameter:

```
auto boundPW = [pw](const auto& param)    // C++14 only
               { pw(param); };
```

These are edge cases, of course, and they're transient edge cases at that, because compilers supporting C++14 lambdas are increasingly common.

When `bind` was unofficially added to C++ in 2005, it was a big improvement over its 1998 predecessors. The addition of lambda support to C++11 rendered `std::bind` all but obsolete, however, and as of C++14, there are just no use cases for it.

Things to Remember

- Lambas are more readable, more expressive, and more efficient than using `std::bind`.
- In C++11 only, `std::bind` may be useful for implementing move capture or for binding objects with templatized function call operators.

Chapter 7 The Concurrency API

One of C++11's great triumphs is the incorporation of concurrency into the language and library. Programmers familiar with other threading APIs (e.g., pthreads or Windows' Threads) are sometimes surprised at the comparatively Spartan feature set that C++ offers, but that's because a great deal of C++'s support for concurrency is in the form of constraints on compiler-writers. The resulting language assurances mean that for the first time in C++'s history, programmers can write multithreaded programs with standard behavior across all computing platforms. This establishes a solid foundation on which expressive libraries can be built, and the concurrency elements of the Standard Library (tasks, futures, threads, mutexes, condition variables, atomic objects, and more) are merely the beginning of what is sure to become an increasingly rich set of tools for the development of concurrent C++ software.

The existing features are impressive in their own right, of course, and this chapter focuses on the questions that inform their effective application. What are the differences between tasks and threads, and which should be used when? What behavioral guarantees does `std::async` offer, and how can they be controlled? What are the implications of the varying behaviors of thread handle destructors? What are the pros and cons of different inter-thread event communication strategies? How do `std::atomics` differ from `volatile`s, and what is the proper application of each? The coming pages address these issue, and more.

In the Items that follow, bear in mind that the Standard Library has two templates for futures: `std::future` and `std::shared_future`. In many cases, the distinction is not important, so I often simply talk about *futures*, by which I mean both kinds.

Item 37: Prefer task-based programming to thread-based.

If you want to run a function `doAsyncWork` asynchronously, you have two basic choices. You can create a `std::thread` and run `doAsyncWork` on it, thus employing a *thread-based* approach:

```
int doAsyncWork();
std::thread t(doAsyncWork);
```

Or you can pass `doAsyncWork` to `std::async`, a strategy known as *task-based*:

```
auto fut = std::async(doAsyncWork);        // "fut" for "future"
```

In such calls, the callable entity passed to `std::async` (e.g., `doAsyncWork`) is considered a *task*.

The task-based approach is typically superior to its thread-based counterpart, and the tiny amount of code we've seen already demonstrates some reasons why. Here, `doAsyncWork` produces a return value, which we can reasonably assume the code invoking `doAsyncWork` is interested in. With the thread-based invocation, there's no straightforward way to get access to it. With the task-based approach, it's easy, because the future returned from `std::async` offers the `get` function. The `get` function is even more important if `doAsyncWork` emits an exception, because `get` provides access to that, too. With the thread-based approach, if `doAsyncWork` throws, the program dies (via a call to `std::terminate` or, if there was one, the function most recently specified via `std::set_terminate`).

A more fundamental difference between thread-based and task-based programming is the higher level of abstraction that task-based embodies. It frees you from the details of thread management, an observation that reminds me that I need to summarize the three meanings of "thread" in concurrent C++ software:

- *Hardware threads* are the threads that actually perform computation. Contemporary machine architectures offer one or more hardware threads per CPU core.
- *Software threads* (also known as *OS threads* or *system threads*) are the threads that the operating system† manages across all processes and schedules for execution on hardware threads. Typically, it's possible to create many more software threads than hardware threads, because when a software thread is

† Assuming you have one. Some embedded systems don't.

blocked (e.g., on I/O or waiting for a mutex or condition variable), throughput can be improved by executing other, unblocked, threads.

- `std::threads` are objects in a C++ process that act as handles to underlying software threads. Some `std::thread` objects represent "null" handles, i.e., correspond to no software thread, because they're in a default-constructed state (hence have no function to execute), have been moved from (the moved-to `std::thread` then acts as the handle to the underlying software thread), have been `joined` (the function they were to run has finished), or `detached` (the connection between them and their underlying software thread has been severed).

Software threads are a limited resource. If you try to create more than the system can offer, a `std::system_error` exception is thrown. This is true even if the function you want to run can't throw. For example, even if `doAsyncWork` is `noexcept`,

```
int doAsyncWork() noexcept;          // see Item 16 for noexcept
```

this statement could result in an exception:

```
std::thread t(doAsyncWork);          // throws if no more
                                     // threads are available
```

Well-written software must somehow deal with this possibility, but how? One approach is to run `doAsynchWork` on the current thread, but that could lead to unbalanced loads and, if the current thread is a GUI thread, responsiveness issues. Another option is to wait for some existing software threads to complete and then try to create a new `std::thread` again, but it's possible that the existing threads are waiting for an action that `doAsyncWork` is supposed to perform (e.g., produce a result or notify a condition variable).

Even if you don't run out of threads, you can have trouble with *oversubscription*. That's when there are more ready-to-run (i.e., unblocked) software threads than hardware threads. When that happens, the thread scheduler (typically part of the OS) time-slices the software threads on the hardware. When one thread's time-slice is finished and another's begins, a context switch is performed. Such context switches increase the overall thread management overhead of the system, and they can be particularly costly when the hardware thread on which a software thread is scheduled is on a different core than the software thread was for its last time-slice. In that case, (1) the CPU caches are typically cold for that software thread and (2) the running of the "new" software thread on that core "pollutes" the CPU caches for "old" threads that had been running on that core and are likely to be scheduled to run there again.

Avoiding oversubscription is difficult, because the optimal ratio of software to hardware threads depends on how often the software threads are runnable, and that can change dynamically, e.g., when a program goes from an I/O-heavy region to a computation-heavy region. The best ratio of software to hardware threads is also dependent on the cost of context switches and how effectively the software threads use the CPU caches. Furthermore the number of hardware threads and the details of the CPU caches (e.g., how large they are and their relative speeds) depend on the machine architecture, so even if you tune your application to avoid oversubscription (while still keeping the hardware busy) on one platform, there's no guarantee that your solution will work well on other kinds of machines.

Your life will be easier if you dump these problems on somebody else, and using `std::async` does exactly that.

```
auto fut = std::async(doAsyncWork);   // onus of thread mgmt is
                                      // on implementer of
                                      // the Standard Library
```

This call shifts all the thread management responsibility to the implementers of the C++ Standard Library. For example, you don't need to worry about an out-of-threads exception arising, because this call will never yield one. "How can that be?", you might wonder. "If I ask for more software threads than the system can provide, why does it matter whether I do it by creating `std::threads` or by calling `std::async`?" It matters, because `std::async`, when called in this form (i.e., with the default launch policy—see Item 38), doesn't guarantee that it will create a new software thread. Rather, it permits the scheduler to arrange for the specified function (in this example, `doAsyncWork`) to be run on the current thread, and the scheduler will take advantage of that freedom if the system is oversubscribed or is out of threads.

If you pulled this "run it on the current thread" trick yourself, of course, I remarked that it could lead to load-balancing or responsiveness issues, and those issues don't go away simply because it's `std::async` and the runtime scheduler that confront them instead of you. When it comes to load-balancing, however, the runtime scheduler is likely to have a more comprehensive picture of what's happening on the machine than you do, because it manages the threads from all processes, not just the one your code is running in.

With `std::async`, responsiveness on a GUI thread can still be problematic, because the scheduler has no way of knowing which of your threads has tight responsiveness requirements. In that case, you'll want to pass the `std::launch::async` launch policy to `std::async`. That will ensure that the function you want to run really executes on a different thread (see Item 38). However, you'll have to be prepared for the possibility of an exception, because `std::async` called with `std::launch::async` can run out of threads and emit a `std::system_error` exception, just like the `std::thread` constructor can.

State-of-the-art thread schedulers employ system-wide thread pools to avoid oversubscription, and they improve load balancing across hardware cores through work-stealing algorithms. The C++ Standard does not require the use of thread pools or work-stealing, but it's deliberately written to permit them, and some vendors already take advantage of this technology in their Standard Library implementations. More are expected to follow. If you take a task-based approach to your concurrent programming, you automatically reap the benefits of such technology as it becomes more widespread. If, on the other hand, you program directly with `std::threads`, you assume the burden of dealing with thread exhaustion, oversubscription, and load balancing yourself, not to mention how your solutions to these problems mesh with the solutions implemented in programs running in other processes on the same machine.

Compared to thread-based programming, a task-based design spares you the travails of manual thread management, and it provides a natural way to examine the results of asynchronously executed functions (i.e., return values or exceptions). Nevertheless, there are some situations where using threads directly may be appropriate. They include:

- **You need access to the API of the underlying threading implementation**. The C++ concurrency API is typically implemented using a lower-level platform-specific API, usually pthreads or Windows' Threads. Those APIs are currently richer than what C++ offers. (For example, C++ has no notion of thread priorities or affinities.) To provide access to the API of the underlying threading implementation, `std::thread` objects offer the `native_handle` member function. There is no counterpart to this functionality for `std::futures` (i.e., what `std::async` returns).

- **You need to and are able to optimize thread usage for your application**. This could be the case, for example, if you're developing server software with a known execution profile that will be deployed as the only significant process on a machine with fixed hardware characteristics.

- **You need to implement threading technology beyond the C++ concurrency API**, e.g., thread pools on platforms where your C++ implementations don't offer them.

These are uncommon cases, however. Most of the time, you should choose task-based designs instead of programming with threads.

Things to Remember

- The `std::thread` API offer no direct way to get return values from asynchronously-run functions, and if those functions throw, the program is terminated.
- Thread-based programming calls for manual management of thread exhaustion, oversubscription, load balancing, and adaptation to new platforms.
- Task-based programming via `std::async` with the default launch policy suffers from none of these drawbacks.

Item 38: Specify `std::launch::async` if asynchronicity is essential.

When you call `std::async` to execute a function (or other callable entity), you're generally intending to run the function asynchronously. But that's not necessarily what you're asking `std::async` to do. You're really requesting that the function be run in accord with a `std::async` *launch policy*. There are two standard policies, each represented by an enumerator in the `std::launch` scoped `enum`. (See Item 10 for information on scoped `enum`s.) Assuming a function `f` is passed to `std::async` for execution,

- The **`std::launch::async`** launch policy means that `f` must be run asynchronously, i.e., on a different thread.
- The **`std::launch::deferred`** launch policy means that `f` may run only when `get` or `wait` is called on the future returned by `std::async`.† That is, `f`'s execution is *deferred* until such a call is made. When `get` or `wait` is invoked, `f` will execute synchronously, i.e., on the thread that made the invocation. (The caller will block until `f` finishes running.) If neither `get` nor `wait` is ever called, `f` will never run.

Perhaps surprisingly, `std::async`'s default launch policy—the one it uses if you don't expressly specify one—is neither of these. Rather, it's these or-ed together. The following two calls have exactly the same meaning:

```
auto fut1 = std::async(f);                     // run f using
                                               // default launch
                                               // policy

auto fut2 = std::async(std::launch::async |    // run f either
                       std::launch::deferred,  // async or
                       f);                     // deferred
```

The default policy thus permits `f` to be run either asynchronously or synchronously. As Item 37 points out, this flexibility permits `std::async` and the thread-

† This is not rigorously true. What matters isn't the future on which `get` or `wait` is invoked, it's the shared state to which the future refers. (Item 40 discusses the relationship between futures and shared states.) Because `std::futures` support moving and can also be used to construct `std::shared_futures`, and because `std::shared_futures` can be copied, the future object referring to the shared state arising from the call to `std::async` to which `f` was passed is likely to be different from the one returned by `std::async`. That's a mouthful, however, so it's common to fudge the truth and simply talk about invoking `get` or `wait` on the future returned from `std::async`.

management components of the Standard Library to assume full responsibility for thread creation and destruction, avoidance of oversubscription, and load balancing. That's among the things that make concurrent programming with `std::async` so convenient.

But using `std::async` with the default launch policy has some noteworthy implications. Given a thread `t` executing this statement,

```
auto fut = std::async(f);                  // run f using default
                                           // launch policy
```

- It's not possible to predict whether `f` will run concurrently with `t`, because `f` might be scheduled to run deferred.
- It's not possible to predict whether `f` runs on a thread different from `t`.
- It may not be possible to predict whether `f` runs at all, because it may not be possible to guarantee that `get` or `wait` will be called on the future corresponding to `f` along every path through the program.

The default launch policy's scheduling flexibility often mixes poorly with the use of `thread_local` variables, because it means that if `f` reads or writes such *thread-local storage* (TLS), it's not possible to predict which thread's variables will be accessed:

```
auto fut = std::async(f);          // TLS for f possibly for
                                   // different thread, but
                                   // possibly for current thread
```

It also complicates `wait`-based loops using timeouts, because calling `wait_for` or `wait_until` on a task (see Item 37) that's deferred yields the value `std::launch::deferred`. This means that the following loop, which looks like it should eventually terminate, may, in reality, run forever:

```
void f()                                         // f sleeps for
{                                                // 1 second,
  std::this_thread::sleep_for(                   // then returns
    std::chrono::seconds(1)
  );
}
```

```
auto fut = std::async(f);                      // run f
                                               // asynchronously
                                               // (conceptually)

while (fut.wait_for(                           // loop until f
         std::chrono::milliseconds(100)) !=    // has finished
       std::future_status::ready)              // running...
{                                              // which may
  …                                            // never happen!
}
```

If f runs concurrently with the thread calling std::async (i.e., if the launch policy chosen for f is std::launch::async), there's no problem here, but if f is deferred, fut.wait_for will always return std::future_status::deferred. That will never be equal to std::future_status::ready, so the loop will never terminate.

This kind of bug is easy to overlook during development and unit testing, because it's likely to manifest itself only under heavy loads. Those are the conditions that push the machine towards oversubscription or thread exhaustion, and that's when a task is most likely to be deferred. After all, if the hardware isn't threatened by oversubscription or thread exhaustion, there's no reason for the runtime system not to schedule the task for concurrent execution.

The fix is simple: just check the future corresponding to the std::async call to see whether the task is deferred, and, if so, avoid entering the timeout-based loop. Unfortunately, there's no direct way to ask a future whether its task is deferred. Instead, you have to call a timeout-based function—a function such as wait_for. Of course, you don't really want to wait for anything, you just want to see if the return value is std::future_status::deferred, so stifle your mild disbelief at the necessary circumlocution and call wait_for with a zero timeout:

```
auto fut = std::async(f);                        // as above

if (fut.wait_for(std::chrono::seconds(0)) !=     // if task
    std::future_status::deferred)                // isn't
{                                                // deferred...

  while (fut.wait_for(                           // infinite loop
           std::chrono::milliseconds(100)) !=    // no longer
           std::future_status::ready) {          // possible
```

```
    …                   // fut is neither deferred nor ready, so
                        // do concurrent work until it's ready
  }

  …                     // fut is ready

} else {

  …                     // task is deferred, so use wait or
                        // get to call it synchronously
}
```

C++14 offers nothing to improve testing a future to see if it corresponds to a deferred task, but it does make the specification of time durations more palatable, because it takes advantage of C++11’s support for user-defined literals to offer suffixes for seconds (`s`), milliseconds (`ms`), hours (`h`), etc. These suffixes are implemented in the `std::literals` namespace, so the above code can be rewritten as follows:

```
using namespace std::literals;          // for duration suffixes

if (fut.wait_for(0s) != std::future_status::deferred) { // C++14
  while (fut.wait_for(100ms) !=                         // only
         std::future_status::ready) {

    …

  }

  …                                     // as before
```

The upshot of these various considerations is that using `std::async` with the default launch policy for a task is fine as long as the following conditions are fulfilled:

- Execution of the task need not run concurrently with the calling thread.
- It doesn’t matter which thread’s `thread_local` variables are read or written.
- There’s either (1) a guarantee that `get` or `wait` will always be called on the future returned by `std::async` or (2) it’s acceptable that the task may never be executed.
- Code using `wait_for` or `wait_until` always checks for deferred status.

If any of these conditions fails to hold, you probably want to guarantee that `std::async` will schedule the task for truly asynchronous execution. The way to do that is to pass `std::launch::async` as the first argument when you make the call:

```
auto fut = std::async(std::launch::async, f);  // launch f
                                               // asynchronously
```

In fact, having a function that acts like `std::async`, but that automatically uses `std::launch::async` as the launch policy, is a convenient tool to have around, so it's nice that it's easy to write:

```
template<typename F, typename... Args>
inline
std::future<typename std::result_of<F(Args...)>::type>
reallyAsync(F&& f, Args&&... args)          // return future
{                                           // for asynchronous
  return std::async(std::launch::async,     // call to f(args...)
                    std::forward<F>(f),
                    std::forward<Args>(args)...);
}
```

This function takes an executable entity `f` and zero or more arguments `args` and perfect-forwards them (see Item 27) to `std::async`, passing `std::launch::async` as the launch policy. Like `std::async`, it returns a `std::future` for the result of invoking `f` on `args`. Determining the type of that result is easy, because the type trait `std::result_of` gives it to you. (See Item 9 for information on type traits.)

`reallyAsync` is used just like `std::sync`, except that, as Item 37 explains, it may emit an exception indicating that it's not possible to create a new thread:

```
auto fut = reallyAsync(f);              // run f asynchronously or
                                        // throw std::system_error
```

In C++14, the ability to deduce `reallyAsync`'s return type streamlines the function declaration:

```
template<typename F, typename... Args>
inline
auto                                           // C++14 only
reallyAsync(F&& f, Args&&... args)
{
```

```
  return std::async(std::launch::async,
                    std::forward<F>(f),
                    std::forward<Args>(args)...);
}
```

This version makes it even clearer that `reallyAsync` does nothing but invoke `std::async` with the `std::launch::async` launch policy.

Things to Remember

- The default launch policy for `std::async` permits both asynchronous and synchronous task execution.
- This flexibility leads to uncertainty when accessing `thread_locals`, implies that the task may never execute, and complicates program logic for timeout-based `wait` calls.
- Specify `std::launch::async` if asynchronous task execution is essential.

Item 39: Make `std::threads` unjoinable on all paths.

Every `std::thread` object is in one of two states: *joinable* or *unjoinable*. A joinable `std::thread` corresponds to an underlying asynchronous thread of execution that is or could be running. A `std::thread` corresponding to an underlying thread that's blocked or waiting to be scheduled is joinable, for example.

An unjoinable `std::thread` is what you'd expect: a `std::thread` that's not joinable. Unjoinable `std::thread` objects include:

- **Default-constructed `std::threads`**. Such `std::threads` have no function to execute, hence don't correspond to an underlying thread of execution.
- **`std::thread` objects that have been moved from**. The result of a move is that the underlying thread of execution a `std::thread` used to correspond to (if any) now corresponds to a different `std::thread`.
- **`std::threads` that have been `joined`**. After a `join`, a `std::thread`'s underlying thread of execution has finished running.

- **std::threads that have been detached**. A detach severs the connection between a std::thread object and the underlying thread of execution it corresponds to.

One reason a std::thread's joinability is important is that if the destructor for a joinable thread is invoked, execution of the program is terminated.

For example, suppose we have a function doWork that takes a filtering function, filter, and a maximum value, maxVal, as parameters. doWork checks to make sure that all conditions necessary for its computation are satisfied, then performs the computation with all the values between 0 and maxVal that pass the filter. If it's time-consuming to do the filtering and it's also time-consuming to determine whether doWork's conditions are satisfied, it would be reasonable to do those two things concurrently. We might come up with code like this:

```
constexpr int tenMillion = 10000000;          // see Item 14
                                              // for constexpr

bool doWork(std::function<bool(int)> filter,  // returns whether
            int maxVal = tenMillion)          // computation was
{                                             // performed

  std::vector<int> vals;                      // values that
                                              // satisfy filter

  std::thread t([&filter, maxVal, &vals]      // compute vals'
                {                             // content
                  for (auto i = 0; i <= maxVal; ++i)
                   { if (filter(i)) vals.push_back(i); }
                });

  if (conditionsAreSatisfied()) {
    t.join();                                 // let t finish
    performComputation(vals);
    return true;                              // computation was
  }                                           // performed

  return false;                               // computation was
};                                            // not performed
```

Before I explain why this code is problematic, I'll remark that tenMillion's initializing value can be made more readable in C++14 by taking advantage of C++14's ability to use an apostrophe as a digit separator:

```
constexpr auto tenMillion = 10'000'000;        // C++ 14 only
```

But back to `doWork`. If *`conditionsAreSatisfied()`* returns `true`, all is well, but if it returns `false` or throws an exception, the `std::thread` object `t` will be joinable when its destructor is called at the end of `doWork`. That would cause program execution to be terminated.

You might wonder why the `std::thread` destructor behaves this way. It's because the two other obvious options are arguably worse. They are:

- **An implicit `join`**. In this case, a `std::thread`'s destructor would wait for its underlying asynchronous thread of execution to complete. That sounds reasonable, but it could lead to performance anomalies that would be difficult to track down. For example, it would be counterintuitive that `doWork` would wait for its filter to be applied to all values if *`conditionsAreSatisfied()`* had already returned `false`.

- **An implicit `detach`**. In this case, a `std::thread`'s destructor would sever the connection between the `std::thread` object and its underlying thread of execution. The underlying thread would continue to run. This sounds no less reasonable than the `join` approach, but the debugging problems it can lead to are actually worse. In `doWork`, for example, `vals` is a local stack variable that is captured by reference. It's also modified inside the lambda (via the call to `push_back`). Suppose, then, that while the lambda is running asynchronously, *`conditionsAreSatisfied()`* returns `false`. In that case, `doWork` would return, and its local variables (including `vals`) would be destroyed. Its stack frame would be popped, and execution of its thread would continue at `doWork`'s call site.

  Statements following that call site would, at some point, make additional function calls, and at least one such call would probably end up using some or all of the memory that had once been occupied by the `doWork` stack frame. Let's call such a function `f`. While `f` was running, the lambda that `doWork` initiated would still be running asynchronously. That lambda could call `push_back` on the stack memory that used to be `vals`, but that is now somewhere inside `f`'s stack frame. Such a call would modify the memory that used to be `vals`, and that means that from `f`'s perspective, the content of memory in its stack frame could spontaneously change! Imagine the fun you'd have debugging *that*.

The Standardization Committee decided that the consequences of destroying a joinable thread were sufficiently dire that they essentially banned it (by specifying that destruction of a joinable thread causes program termination).

This puts the onus on you to ensure that if you use a `std::thread` object, it's made unjoinable on every path out of the scope in which it's defined. But covering every path can be complicated. It includes flowing off the end of the scope as well as jumping out via a `return`, `continue`, `break`, `goto` or exception. That can be a lot of paths.

Any time you want to perform some action along every path out of a scope, the normal approach is to put that action in the destructor of a local object. Such objects are known as *RAII objects*, and the classes they come from are known as *RAII classes*. (*RAII* itself stands for "resource acquisition is initialization," although the crux of the technique is destruction, not initialization). RAII classes are common in the Standard Library. Examples include the STL containers (each container's destructor destroy the container's contents and releases its memory), the standard smart pointers (Items 20-22 explain that `std::unique_ptr`'s destructor invokes its deleter on the object it points to, and the destructors in `std::shared_ptr` and `std::weak_ptr` decrement reference counts), `std::fstream` objects (their destructors close the files they correspond to), and many more. And yet there is no standard RAII class for `std::thread` objects—perhaps because the Standardization Committee, having rejected both `join` and `detach` as default options, simply didn't know what such a class should do.

Fortunately, it's not difficult to write one yourself. For example, the following class allows callers to specify a `std::thread` member function (e.g., `join` or `detach`) that should be called when a `ThreadRAII` object (an RAII object for a `std::thread`) is destroyed:

```
class ThreadRAII {
public:
  using RAIIAction =                // type of mbr func to
    void (std::thread::*)();        // invoke in ThreadRAII dtor
```

```
  ThreadRAII(std::thread&& t, RAIIAction a)  // in dtor,
  : action(a), t(std::move(t)) {}            // invoke a on t

  ~ThreadRAII()                              // see below for
  { if (t.joinable()) (t.*action)(); }       // joinability test

  std::thread& get() { return t; }           // see below

private:
  RAIIAction action;
  std::thread t;
};
```

With any luck, this code is largely self-explanatory, but the following points may be helpful:

- The constructor accepts only `std::thread` rvalues, because we want to move the passed-in `std::thread` into the `ThreadRAII` object.

- The parameter order in the constructor is designed to be intuitive to callers (specifying the `std::thread` first and the destructor action second makes more sense than vice-versa), but the member initialization list is designed to match the order of the data members' declarations. That order puts the `std::thread` object last. In this class, the order makes no difference, but in general, it's possible for the initialization of one data member to depend on another, and because `std::thread` objects may start running a function immediately after they are initialized, it's a good habit to declare them last in a class. That guarantees that at the time they are constructed, all the data members that precede them have already been initialized and can therefore be safely accessed by the asynchronously running thread that corresponds to the `std::thread` data member.

- `ThreadRAII` offers a `get` function to provide access to the underlying `std::thread` object. This is analogous to the `get` functions offered by the standard smart pointer classes that give access to their underlying raw pointers. Providing `get` avoids the need for `ThreadRAII` to replicate the full `std::thread` interface, and it also means that `ThreadRAII` objects can be used in contexts where `std::thread` objects are required, e.g., because an interface requires that a reference to a `std::thread` be passed.

- Before the `ThreadRAII` destructor invokes the action `a` on the `std::thread` object `t`, it checks to make sure that `t` is joinable. This is necessary, because invoking `join` or `detach` on an unjoinable thread yields undefined behavior, and it's possible that a client constructed a `std::thread`, created a `ThreadRAII` object from it, used `get` to acquire access to `t`, and then did a move from `t` or called `join` or `detach` on it. Each of those actions would render `t` unjoinable.

  If you're worried that in the statement,

  ```
  if (t.joinable()) (t.*action)();
  ```

  a race condition exists, because between execution of `t.joinable()` and `(t.*action)()`, another thread could render `t` unjoinable, your intuition is commendable, but your fears are unfounded. A `std::thread` object can change state from joinable to unjoinable only through a member function call, e.g., `join`, `detach`, or a move operation. At the time a `ThreadRAII` object's destructor is invoked, no other thread should be making member function calls on that object. If there are simultaneous calls, there is certainly a race condition, but the race isn't inside the destructor, it's in the client code that is trying to invoke two member functions (the destructor and something else) on one object at the same time. In general, simultaneous member function calls on a single object are safe only if all are to `const` member functions (see Item 15).

Employing `ThreadRAII` in our `doWork` example would look like this:

```
bool doWork(std::function<bool(int)> filter,  // as before
            int maxVal = tenMillion)
{
  std::vector<int> vals;                      // as before

  ThreadRAII t(
    std::thread([&filter, maxVal, &vals]      // use RAII object
                {
                  for (auto i = 0; i <= maxVal; ++i)
                    { if (filter(i)) vals.push_back(i); }
                }),
                &std::thread::join           // RAII action
  );
```

```
  if (conditionsAreSatisfied()) {
    t.get().join();                             // let t finish
    performComputation(vals);
    return true;
  }

  return false;
};                                              // join thread
                                                // running lambda
```

In this case, we've chosen to do a `join` on the asynchronously running thread in the `ThreadRAII` destructor, because, as we saw earlier, doing a `detach` could lead to some truly nightmarish debugging. We also saw earlier that doing a `join` could lead to performance anomalies (that, to be frank, could also be unpleasant to debug), but given a choice between undefined behavior (which `detach` would get us), program termination (which use of a raw `std::thread` would yield), or performance anomalies, performance anomalies seems like the best of a bad lot.

Alas, Item 41 demonstrates that using `ThreadRAII` to perform a `join` on `std::thread` destruction can sometimes lead not just to a performance anomaly, but to a hung program. The "proper" solution to these kinds of problems would be to communicate to the asynchronously running lambda that we no longer need its work and that it should return early, but there's no support in C++11 or C++14 for *interruptible threads*. They can be implemented by hand, but that's a topic beyond the scope of this book.[†]

Item 19 explains that because `ThreadRAII` declares a destructor, there will be no compiler-generated move operations, but there is no reason `ThreadRAII` objects shouldn't be movable. If compilers were to generate these functions, the functions would do the right thing, so explicitly requesting their creation is appropriate:

```
class ThreadRAII {
public:
  using RAIIAction = void (std::thread::*)();        // as before
```

[†] A nice treatment of this topic is in Anthony Williams' *C++ Concurrency in Action* (Manning Publications, 2012), section 9.2.

```
  ThreadRAII(std::thread&& thread, RAIIAction a)    // as before
  : action(a), t(std::move(thread)) {}

  ~ThreadRAII()                                     // as before
  { if (t.joinable()) (t.*action)(); }

  ThreadRAII(ThreadRAII&&) = default;               // support
  ThreadRAII& operator=(ThreadRAII&&) = default;    // moving

  std::thread& get() { return t; }

private:                                            // as before
  RAIIAction action;
  std::thread t;
};
```

A class like `ThreadRAII` helps avoid early program termination due to destruction of joinable `std::threads`, but the drawbacks associated with `join`-on-destruction and `detach`-on-destruction may convince you that a better solution is to follow the advice of Item 37 and stay away from `std::threads` in the first place. Doing that would allow you to deal with futures instead of `std::threads`, and futures don't invoke `std::terminate` in their destructors. What they do in their destructors is sufficiently interesting, however, that it's worth an Item of its own. That Items is Item 40. It's coming right up.

Things to Remember

- Make `std::threads` unjoinable on all paths.
- `join`-on-destruction can lead to difficult-to-debug performance anomalies.
- `detach`-on-destruction can lead to difficult-to-debug undefined behavior.

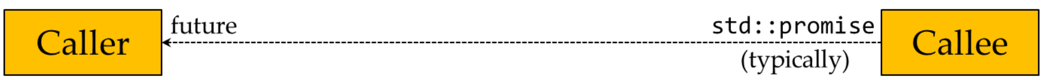
Item 40: Be aware of varying thread handle destructor behavior.

Item 39 explains that a joinable `std::thread` corresponds to an underlying system thread of execution. A future for a non-deferred task (see Item 38) has a similar relationship to a system thread. As such, both `std::thread` objects and future objects can be thought of as *handles* to system threads.

From this perspective, it's interesting that `std::threads` and futures have such different behaviors in their destructors. As noted in Item 39, destruction of a joinable `std::thread` terminates your program, because the two obvious alternatives—an implicit `join` and an implicit `detach`—were considered worse choices. Yet destruction of a future sometimes performs an implicit `join`, sometimes it performs an implicit `detach`, and sometimes it does neither. It never causes program termination.

This thread handle behavioral bouillabaisse deserves closer examination.

We'll begin with the observation that a future is one end of a communications channel through which a callee transmits a result to a caller.[†] The callee (running asynchronously, except in the case of deferred tasks) writes the result of its computation into the communications channel (typically via a `std::promise` object), and the caller reads that result using a future. You can think of it as follows, where the dashed arrow shows the flow of information from callee to caller:



But where is the callee's result stored? The callee could finish before the caller invokes `get` on a corresponding future, so the result can't be stored in the callee's `std::promise`. That object, being local to the callee, would be destroyed when the callee finished.

The result can't be stored in the caller's future, either, because (among other reasons) a `std::future` may be used to create a `std::shared_future` (thus transferring ownership of the callee's result from the `std::future` to the `std::shared_future`), which may then be copied many times after the original `std::future` is destroyed. Given that not all result types can be copied (e.g., `std::unique_ptr`—see Item 20) and that the result must live at least as long as the last future referring to it, which of the potentially many futures corresponding to the callee would be the one to contain its result?

[†] Item 41 explains that the kind of communications channel associated with a future can be employed for other purposes. For this Item, however, we'll consider only its use as a mechanism for a callee to convey its result to a caller.

Because neither objects associated with the callee nor objects associated with the caller are suitable places to store the callee's result, it's stored in a location outside both. This location is known as the *shared state*. The shared state is typically represented by a heap-based object, but its type, interface, and implementation are not specified by the Standard. Standard Library authors are free to implement shared states in any way they like.

We can envision the relationship among the callee, the caller, and the shared state like this, where dashed arrows once again represent the flow of information:

The existence of the shared state is important, because the behavior of a future's destructor—the topic of this Item—is determined by the shared state associated with the future. In particular,

- **The destructor for the last future referring to a shared state for a non-deferred task launched via `std::async` blocks** until the task completes. In essence, the destructor for such a future does an implicit `join` on the thread on which the asynchronously-executing task is running.

- **The destructor for all other futures simply destroys the future object**. For asynchronously running tasks, this amounts to an implicit `detach` on the underlying thread. For deferred tasks for which this is the final future, it means that the deferred task will never run.

These rules sound more complicated than they are. What we're really dealing with is a simple "normal" behavior and one lone exception to it. The "normal" behavior is that a future's destructor destroys the future object. That's it. It doesn't `join` with anything, it doesn't `detach` from anything, it doesn't run anything. It just destroys the future's data members. (Well, okay, it does one more thing. It also decrements the reference count inside the shared state that's manipulated by both the futures referring to it and the callee's `std::promise`. This reference count makes it possible for the library to know when the shared state can be destroyed. For information about reference counting, see Item 21.)

The exception to this normal behavior arises only for a future for which all of the following apply:

- **It refers to a shared state that was created due to a call to `std::async`**.
- **The task's launch policy is `std::launch::async`** (see Item 38), either because that was chosen by the runtime system or because it was specified in the call to `std::async`.
- **The future is the last future referring to the shared state**. For `std::futures`, this will always be the case. For `std::shared_futures`, however, if other `std::shared_futures` refer to the same shared state as the future being destroyed, the future being destroyed follows the "normal" behavior (i.e., it simply destroys its data members).

Only when all of these conditions are fulfilled does a future's destructor exhibit special behavior, and that behavior is to block until the asynchronously running task completes. Practically speaking, this amounts to an implicit `join` on the thread running the `std::async`-created task.

It's not uncommon to hear this exception to "normal" future destructor behavior summarized as "Futures from `std::async` block in their destructors." To a first approximation, that's correct, but sometimes you need more than a first approximation. Now you know the truth in all its glory and wonder.

What you may wonder is why there's a special rule for shared states for non-deferred tasks that are launched by `std::async`. It's a reasonable question. From what I can tell, the Standardization Committee wanted to avoid the problems associated with an implicit `detach` (see Item 39), but they didn't want to adopt as radical a policy as mandatory program termination (as they did for joinable `std::threads`—again, see Item 39), so they compromised on an implicit `join`. The decision was not without controversy, and there was serious talk about abandoning this behavior for C++14. In the end, however, no change was made, so the behavior of destructors for futures is consistent in C++11 and C++14.

The API for futures offers no way to determine whether a future refers to a shared state arising from a call to `std::async`, so given a random future object, it's not possible to know whether it will block in its destructor waiting for an asynchronously running task to finish. This has some interesting implications:

```
// this container might block in its dtor, because one or more
// contained futures could refer to shared state for a non-
// deferred task launched via std::async
std::vector<std::future<void>> futs;   // see Item 41 for info
                                       // on std::future<void>

class Widget {                         // Widget objects might
public:                                // block in their dtors
  …

private:
  std::shared_future<double> fut;
};

void doWork(std::future<int> fut);     // fut might block
                                       // in its dtor
                                       // (see Item 17 for info
                                       // on by-value params)
```

Of course, if you have a way of knowing that a given future *does not* satisfy the conditions that trigger the special destructor behavior (e.g., due to program logic), you're assured that that future won't block in its destructor. For example, only shared states arising from calls to `std::async` qualify for the special behavior, but there are other ways that shared states get created. One is the use of `std::packaged_task`. A `std::packaged_task` object prepares a function (or other callable entity) for asynchronous execution by wrapping it such that its result is put into a shared state. A future referring to that shared state can then be obtained via `std::packaged_task`'s `get_future` function:

```
int calcValue();                      // func to run

std::packaged_task<int()>             // wrap calcValue so it
  pt(calcValue);                      // can run asynchronously

auto ptFut = pt.get_future();         // get future for pt
```

Once created, the std::packaged task pt can be run on a thread. (It could be run via a call to std::async, too, but if you want to run a task using std::async, there's little reason to create a std::packaged task, because std::async does everything std::packaged_task does before it schedules the task for execution.)

std::packaged_tasks aren't copyable, so when pt is passed to the std::thread constructor, it must be cast to an rvalue (via std::move—see Item 25), thus ensuring that it will be moved into the data area associated with the thread, not copied:

```
std::thread t(std::move(pt));          // run pt on t
```

At this point, we know that the future ptFut doesn't refer to a shared state created by a call to std::async, so its destructor will behave normally. We can therefore call the doWork function (declared above) without fear that when doWork's by-value parameter fut is destroyed, it will block waiting for t to finish.

std::packaged_task::get_future returns a std::future object, which is a move-only type, so for the call to doWork to compile, we must apply std::move to ptFut , just as we did when passing pt to the std::thread constructor:

```
doWork(std::move(ptFut));              // doWork won't block on t
```

This example actually lends some insight into the normal behavior for future destructors, but it's easier to see if the statements are put together inside a scope:

```
{                                         // begin scope
  std::packaged_task<int()>               // as above
    pt(calcValue);
  auto ptFut = pt.get_future();           // as above
  std::thread t(std::move(pt));           // as above
  doWork(std::move(ptFut));               // as above
  …                                       // see below
}                                         // end scope
```

The most interesting code here is the "…" that follows the call to `doWork` and precedes the end of the scope. What makes it interesting is what can happen to the `std::thread` object `t` inside the "…" region. There are three basic possibilities:

- **Nothing happens to `t`**. In this case, `t` will be joinable at the end of the scope. That will cause the program to be terminated (see Item 39).
- **A `join` is done on `t`**. In this case, there would be no need for `ptFut` (or the parameter `fut`) to block in its destructor, because the `join` call is already present in the calling code.
- **A `detach` is done on `t`**. In this case, there would be no need for `ptFut` (or `fut`) to `detach` in its destructor, because the calling code already does that.

In other words, when you have a future corresponding to a shared state that arose due to a `std::packaged_task`, there's usually no need to adopt a special destruction policy, because the decision among termination, joining, or detaching will be made in the code that manipulates the `std::thread` on which the `std::packaged_task` is typically run.

Things to Remember

- Future destructors normally just destroy the future's data members.
- The final future referring to a shared state for a non-deferred task launched via `std::async` blocks until the task completes.

Item 41: Consider void futures for one-shot event communication.

Sometimes it's useful for a task to tell a second (asynchronously-running) task that a particular event has occurred, because the second task can't proceed until the event has taken place. Perhaps a data structure has been initialized, a stage of computation has been completed, or a significant sensor value has been detected. When that's the case, what's the best way for this kind of inter-thread communication to take place?

An obvious approach is to use a condition variable. If we call the task that detects the condition the *detecting task* and the task reacting to the condition the *reacting task*, the strategy is simple: the reacting task waits on a condition variable (*condvar*), and the detecting thread notifies that condvar when the event occurs. Given

```
std::condition_variable cv;          // condvar for event
std::mutex m;                        // mutex for use with cv
```

the code in the detecting task is as simple as simple can be:

```
…                                    // detect event
cv.notify_one();                     // tell reacting task
```

If there were multiple reacting tasks to be notified, it would be appropriate to replace `notify_one` with `notify_all`, but for now, we'll assume there's only one reacting task.

The code for the reacting task is a bit more complicated, because before calling `wait` on the condvar, it must lock the mutex through a `std::unique_lock` object. (Locking a mutex before waiting on a condition variable is typical for threading libraries. The need to lock the mutex through a `std::unique_lock` object is simply part of the C++11 API.) Here's the conceptual approach, although by this point in this book, you probably suspect that when I call code "conceptual," it's not really correct. Your suspicion is well-founded, but set that aside for a moment:

```
…                                      // prepare to react
{                                      // open critical section
  std::unique_lock<std::mutex> lk(m);  // lock mutex
  cv.wait(lk);                         // wait for notify;
                                       // this isn't correct!
  …                                    // react to event
                                       // (mutex is locked)
}                                      // close crit. section;
                                       // unlock mutex via
                                       // lk's dtor
```

```
…                                        // continue reacting
                                         // (mutex now unlocked)
```

The first issue with this code is what's sometimes termed a *code smell*: even if the code works, something doesn't seem quite right. In this case, the odor emanates from the need to use a mutex. Mutexes are used to control access to shared data, but it's entirely possible that the detecting and reacting tasks have no need for such mediation. For example, the detecting task might be responsible for initializing a global data structure, then turning it over to the reacting task for use. If the detecting task never accesses the data structure after initializing it, and if the reacting task never accesses it before the detecting task indicates that it's ready, the two tasks will stay out of each other's way through program logic. There will be no need for a mutex. The fact that the condvar approach requires one leaves behind the unsettling aroma of suspect design.

Even if you look past that, there are two other problems you should definitely pay attention to:

- **If the detecting task notifies the condvar before the reacting task `waits`, the reacting task will hang**. In order for notification of a condvar to wake another task, the other task must be waiting on that condvar. If the detecting task happens to execute the notification before the reacting task executes the `wait`, the reacting task will miss the notification, and it will wait forever.

- **The `wait` statement fails to account for spurious wakeups**. A fact of life in threading APIs (in many languages—not just C++) is that code waiting on a condition variable may be awakened even if the condvar wasn't notified. Such awakenings are known as *spurious wakeups*. Proper code deals with them by confirming that the condition being waited for has actually occurred, and it does this as its first action after waking. The C++ condvar API makes this exceptionally easy, because it permits a lambda (or other callable entity) that tests for the waited-for condition to be passed to `wait`. That is, the `wait` call in the reacting task could be written like this:

  ```
  cv.wait(lk,
          []{ return whether the event has occurred; });
  ```

> Taking advantage of this capability requires that the reacting task be able to determine whether the condition it's waiting for is true. But in the scenario we've been considering, the condition it's waiting for is the occurrence of an event that the detecting thread is responsible for recognizing. The reacting thread may have no way of determining whether the event it's waiting for has taken place. That's why it's waiting on a condition variable!

There are many situations where having tasks communicate using a condvar is an good fit for the problem at hand, but this doesn't seem to be one of them.

For many developers, the next trick in their bag is a shared boolean flag. The flag is initially `false`. When the detecting thread recognizes the event of interest, it sets the flag:

```
std::atomic<bool> flag(false);      // shared flag; see
                                    // Item 42 for std::atomic

…                                   // detect event
flag = true;                        // tell reacting task
```

For its part, the reacting thread simply polls the flag. When it sees that the flag is set, it knows that the event it's been waiting for has occurred:

```
…                                   // prepare to react
while (!flag);                      // wait for event
…                                   // react to event
```

This approach suffers from none of the drawbacks of the condvar-based design. There's no need for a mutex, no problem if the detecting task sets the flag before the reacting task starts polling, and nothing akin to a spurious wakeup. Good, good, good.

Less good is the cost of polling in the reacting task. During the time the task is waiting for the flag to be set, the task is essentially blocked, yet it's still running. As such, it occupies a hardware thread that another task might be able to make use of, it incurs the cost of a context switch each time it starts or completes its timeslice, and it could keep a core running that might otherwise be shut down to save power.

A truly blocked task would do none of these things. That's an advantage of the condvar-based approach, because a task in a wait call is truly blocked.

But there's another way to block a task—one that doesn't suffer from the problems associated with condition variables. It's to have the reacting task wait on a future that's set by the detecting task. This may seem like an odd idea. After all, Item 40 explains that a future represents the receiving end of a communications channel from a callee to a (typically asynchronous) caller, and here there's no callee-caller relationship between the detecting and reacting tasks. However, Item 40 also notes that a communications channel whose transmitting end is a std::promise and whose receiving end is a future can be used for more than just callee-caller communication. Such a communications channel can be used in any situation where you need to transmit information from one place in your program to another. In this case, we'll use it to transmit information from the detecting task to the reacting task, and the information we'll convey will be that the event of interest has taken place.

The design is simple. The detecting task has a std::promise object (i.e., the writing end of the communications channel), and the reacting task has a corresponding future. When the detecting task sees that the event of interest has occurred, it sets the std::promise (i.e., write into the communications channel). Meanwhile, the reacting task waits on its future. That wait blocks the reacting task until the std::promise has been set.

Now, both std::promise and futures (i.e., std::future and std::shared_future) are templates that require a type parameter. That parameter indicates the type of data to be transmitted through the communications channel. In our case, however, there's no data to be conveyed. The only thing of interest to the reacting task is that its future has been set (via the corresponding std::promise). What we need for the std::promise and future templates is a type that indicates that no data is to be conveyed across the communications channel. That type is void. The detecting task will thus use a std::promise<void>, and the reacting task a std::future<void> or std::shared_future<void>. The detecting task will set its std::promise<void> when the event of interest occurs, and the reacting task will `wait` on its future. Even though the reacting task won't receive any data from the detecting task, the communications channel will permit the reacting task to know when the detecting task has "written" its `void` data by calling `set_value` on its `std::promise`.

So given

```
std::promise<void> p;                 // promise for
                                      // communications channel
```

the detecting task's code is trivial,

```
…                                     // detect event

p.set_value();                        // tell reacting task
```

and the reacting task's code is equally simple:

```
…                                     // prepare to react

p.get_future().wait();                // wait on future
                                      // corresponding to p

…                                     // react to event
```

Like the approach using a flag, this design requires no mutex, works regardless of whether the detecting task sets its `std::promise` before the reacting task `wait`s, and is immune to spurious wakeups. (Only condition variables are susceptible to that problem.) Like the condvar-based approach, the reacting task is truly blocked after making the `wait` call, so it consumes no system resources while waiting. Perfect, right?

Not exactly. Sure, a future-based approach skirts those shoals, but there are other hazards to worry about. For example, Item 40 explains that between a `std::promise` and a future is a shared state, and shared states are typically dynamically allocated. You should therefore assume that this design incurs the cost of heap-based memory allocation and deallocation.

Perhaps more importantly, a `std::promise` may be set only once. The communications channel between a `std::promise` and a future is a *one-shot* mechanism: it can't be used repeatedly. This is a notable difference from the condvar- and flag-based designs, both of which can be used to communicate multiple times. (A condvar can be repeatedly notified, and a flag can always be cleared and set again.)

The one-shot restriction isn't as limiting as you might think. Suppose you'd like to create a system thread in a suspended state. That is, you'd like to get all the overhead associated with thread creation out of the way, so that when you're ready to execute something on the thread, the normal thread-creation latency will be avoided. Or you might want to create a suspended thread so that you could configure it before letting it run. Such configuration might include things like setting its priority or core affinity. The C++ concurrency API offers no way to do those things, but `std::thread` objects offer the `native_handle` member function, the result of which is intended to give you access to the platform's underlying threading API (usually POSIX threads or Windows threads). The lower-level API often does make it possible to configure thread characteristics such as priority and affinity.

Assuming you want to suspend a thread only once (after creation, but before it's running its thread function), a design using a `void` future is a reasonable choice. Here's the essence of the technique:

```
std::promise<void> p;

void react();                        // func for reacting task

void detect()                        // func for detecting task
{
  std::thread t([]                   // create thread
                {
                  p.get_future().wait();     // suspend t until
                  react();                   // future is set
                });
  …                                  // here, t is suspended
                                     // prior to call to react

  p.set_value();                     // unsuspend t (and thus
                                     // call reset)

  …                                  // do additional work

  t.join();                          // make t unjoinable
};                                   // (see Item 39)
```

Because it's important that `t` become unjoinable on all paths out of `detect`, use of an RAII class like Item 39's `ThreadRAII` seems like it would be advisable. Code like this comes to mind:

```
void detect()
{
  ThreadRAII tr(                           // use RAII object
    std::thread([]
                {
                  p.get_future().wait();
                  react();
                }),
    &std::thread::join                     // risky! (see below)
  );

  …                                        // t's suspended here

  p.set_value();                           // unsuspend t

  …

};
```

This looks safer than it is. The problem is that if in the first "…" region (the one with the "t's suspended here" comment), an exception is emitted, `set_value` will never be called on `p`. That means that the call to `wait` inside the lambda that's running on `t` will never return. That, in turn, means that `t` will never finish running, and that's a problem, because the RAII object `tr` has been configured to perform a `join` on `t` in `tr`'s destructor. In other words, if an exception is emitted from the first "…" region of code, this function will hang, because `tr`'s destructor will never complete.

There are ways to address this problem, but I'll leave them in the form of the hallowed exercise for the reader.† Here, I'd like to show how the original code (i.e., not using `ThreadRAII`) can be extended to suspend and then unsuspend not just one reacting task, but many. It's a simple generalization, because the key is to use `std::shared_futures` instead of a `std::future` in the `react` code. Once you

† A reasonable place to begin researching the matter is the 24 December 2013 blog post, "ThreadRAII + Thread Suspension = Trouble?"

know that the std::future's share member function transfers ownership of its shared state to the std::shared_future object produced by share, the code nearly writes itself. The only subtlety is that each reacting thread needs its own copy of the std::shared_future that refers to the shared state, so the std::shared_future obtained from share is captured by value by the lambdas running on the reacting threads:

```
std::promise<void> p;                // as before

void detect()                        // now for multiple
{                                    // reacting tasks

  auto sf = p.get_future().share();  // sf's type is
                                     // std::shared_future<void>

  std::vector<std::thread> vt;              // container for
                                            // reacting threads

  for (int i = 0; i < threadsToRun; ++i) {
    vt.emplace_back([sf]{ sf.wait();        // wait on local
                          react(); });      // copy of sf; see
  }                                         // Item 18 for info
                                            // on emplace_back

  …                                  // detect hangs if
                                     // this "…" code throws!

  p.set_value();                     // unsuspend all threads

  …

  for (auto& t : vt) t.join();       // make all threads
};                                   // unjoinable; see Item 2
                                     // for info on "auto&"
```

The fact that design using futures can achieve this effect is noteworthy, and that's why you should consider it for one-shot event communication. Other approaches also work, however. Use of a boolean flag yields source code that's just as simple, but its tradeoffs are different: reacting threads don't block (bad), but there's no need for use of the heap (good). A condvar-based design could also be made to work here, but because there's no shared data to protect by the mutex a condvar requires, that approach isn't really appropriate.

Things to Remember

- For simple event communication, condvar-based designs require a superfluous mutex, impose constraints on the relative progress of detecting and reacting tasks, and require reacting tasks to verify that the event has taken place.
- Designs employing a boolean flag avoid those problems, but are based on polling, not blocking.
- Using `std::promises` and futures dodges these issue, but it uses heap memory for shared states, and it's limited to one-shot communication.

Item 42: Use `std::atomic` for concurrency, `volatile` for special memory.

Poor `volatile`. So misunderstood. It shouldn't even be in this chapter, because it has nothing to do with concurrent programming. But in other programming languages (e.g., Java and C#), it is useful for such programming, and even in C++, some compilers have imbued `volatile` with semantics that render it helpful in concurrent software (but only when compiled with those compilers). It's thus worthwhile to discuss `volatile` in a chapter on currency if for no other reason than to dispel the confusion surrounding it.

The C++ feature that programmers sometimes confuse `volatile` with—the feature that definitely does belong in this chapter—is the `std::atomic` template. Instantiations of this template (e.g., `std::atomic<int>`, `std::atomic<bool>`, `std::atomic<Widget*>`, etc.) offer operations that are guaranteed to be seen as atomic by other threads. Operations on `std::atomic` objects behave as if they were inside a mutex-protected critical section, but the operations are generally implemented using special machine instructions that are more efficient than they would be if a mutex were employed.

Consider this code using `std::atomic`:

```
std::atomic<int> ai(0);     // atomically initialize ai to 0
ai = 10;                    // atomically set ai to 10
std::cout << ai;            // atomically read ai's value
```

```
++ai;                          // atomically increment ai to 11
ai--;                          // atomically decrement ai to 10
```

During execution of these statements, other threads reading `ai` may see only values of 0, 10, or 11. No other values are possible (assuming, of course, that this is the only thread modifying `ai`).

Two aspects of this example are worth noting. First, in the "`std::cout << ai;`" statement, the fact that `ai` is a `std::atomic` guarantees only that the read of `ai` is atomic. There is no guarantee that the entire statement proceeds atomically. Between the time `ai`'s value is read and `operator<<` is invoked to write it to the standard output, another thread—possibly several threads—may have modified `ai`'s value. That has no effect on the behavior of the statement, because `operator<<` for `int`s uses a by-value parameter for the `int` to output (the outputted value will therefore be the one that was read from `ai`), but it's important to understand that what's atomic in that statement is nothing more than the read of `ai`.

The second noteworthy aspect of the example is the behavior of the last two statements—the increment and decrement of `ai`. These are each read-modify-write (RMW) operations, yet, they execute atomically. This is one of the nicest characteristics of the `std::atomic` types: all the member functions, including those comprising RMW operations, are guaranteed to be seen by other threads as atomic.

In contrast, the corresponding code using `volatile` guarantees virtually nothing in a multithreaded context:

```
volatile int vi(0);            // initialize vi to 0
vi = 10;                       // set vi to 10
std::cout << vi;               // read vi's value
++vi;                          // increment vi to 11
vi--;                          // decrement vi to 10
```

During execution of this code, if other threads are reading the value of `vi`, they may see anything (e.g, -12, 68, 4090727—anything!). Such code would have undefined behavior, because these statements modify `vi`, so if other threads are reading `vi` at the same time, there are simultaneous readers and writers of memory that's neither `std::atomic` nor protected by a mutex, and that's the definition of a data race.

As a concrete example of how the behavior of `std::atomics` and `volatiles` can differ in a multithreaded program, consider a simple counter of each type that's incremented by multiple threads. We'll initialize each to 0:

```
std::atomic<int> ac(0);    // "atomic counter"
volatile int vc(0);        // "volatile counter"
```

We'll then increment each counter one time in two simultaneously-running threads:

```
/*-----  Thread 1  ----- */     /*-------  Thread 2  ------- */
         ac++;                             ac++;
         vc++;                             vc++;
```

When both threads have finished, `ac`'s value (i.e., the value of the `std::atomic`) must be 2, because each increment occurs as an indivisible operation. `vc`'s value, on the other hand, need not be 2, because its increments may not occur atomically. Each increment consists of reading `vc`'s value, incrementing the value that was read, and writing the result back into `vc`. But these three operations are not guaranteed to proceed atomically for `volatile` objects, so it's possible that the component parts of the two increments of `vc` are interleaved as follows:

1. Thread 1 reads `vc`'s value, which is 0.
2. Thread 2 reads `vc`'s value, which is still 0.
3. Thread 1 increments the 0 it read to 1, then writes that value into `vc`.
4. Thread 2 increments the 0 it read to 1, then writes that value into `vc`.

`vc`'s final value is therefore 1, even though it was incremented twice.

This is not the only possible outcome. `vc`'s final value is, in general, not predictable, because `vc` is involved in a data race, and the Standard's decree that data races cause undefined behavior means that compilers may generate code to do literally anything. Compilers don't use this leeway to be malicious, of course. Rather, they perform optimizations that would be valid in programs without data races, and these optimizations yield unexpected and unpredictable behavior in programs where races are present.

The use of RMW operations isn't the only situation where `std::atomics` comprise a concurrency success story and `volatile`s suffer ignominious failure. Suppose one task computes an important value needed by a second task. When the first task has computed the value, it must communicate this to the second task. Item 41 explains that one way for the first task to communicate the availability of the desired value to the second task is by using a `std::atomic<bool>`. Code in the task computing the value would look something like this:

```
std::atomic<bool> valAvailable(false);
auto imptValue = computeImportantValue();  // compute value
valAvailable = true;                       // tell other task
                                           // it's available
```

As humans reading this code, we know it's crucial that the assignment to `imptValue` take place before the assignment to `valAvailable`, but all compilers see is a pair of assignments to independent variables. As a general rule, compilers are permitted to reorder such unrelated assignments. That is, given this sequence of assignments (where `a`, `b`, `x`, and `y` correspond to independent variables),

```
a = b;
x = y;
```

compilers may generally reorder them as follows:

```
x = y;
a = b;
```

Even if compilers don't reorder them, the underlying hardware might do it (or might make it seem to other cores as if it had), because that can sometimes make the code run faster.

However, the use of `std::atomics` imposes restrictions on how code can be reordered, and one such restriction is that no code that, in the source code, precedes a write of a `std::atomic` variable may take place (or appear to other cores to take place) afterwards. That means that in our code,

```
auto imptValue = computeImportantValue();  // compute value
valAvailable = true;                        // tell other task
                                            // it's available
```

not only must compilers retain the order of the assignments to `imptValue` and `valAvailable`, they must generate code that ensures that the underlying hardware does, too. As a result, declaring `valAvailable` as `std::atomic` ensures that our critical ordering requirement—`imptValue` must be seen by all threads to change no later than `valAvailable` does—is maintained.

Declaring `valAvailable` as `volatile` doesn't impose the same code reordering restrictions:

```
volatile bool valAvailable(false);
auto imptValue = computeImportantValue();
valAvailable = true;  // other threads might see this assignment
                      // before the one to imptValue!
```

Here, compilers might flip the order of the assignments to `imptValue` and `valAvailable`, and even if they don't, they might fail to generate machine code that would prevent the underlying hardware from making it possible for code on other cores to see `valAvailable` change before `imptValue`.

These two issues—no guarantee of operation atomicity and insufficient restrictions on code reordering—explain why `volatile`'s not useful for concurrent programming, but it doesn't explain what it is useful for. In a nutshell, it's for telling compilers that they're dealing with memory that doesn't behave normally.

"Normal" memory has the characteristic that if you write a value to a memory location, the value remains there until something overwrites it. So if I have a normal `int`,

```
int x;
```

and a compiler sees the following sequence of operations on it,

```
auto y = x;             // read x
y = x;                  // read x again
```

the compiler can optimize the generated code by eliminating the assignment to y, because it's redundant with y's initialization.

Normal memory also has the characteristic that if you write a value to a memory location, never read it, and then write to that memory location again, the first write can be eliminated, because it was never used. So given these two adjacent statements,

```
x = 10;                 // write x
x = 20;                 // write x again
```

compilers can eliminate the first one. That means that if we have this in the source code,

```
auto y = x;             // read x
y = x;                  // read x again

x = 10;                 // write x
x = 20;                 // write x again
```

compilers can treat it as if it had been written like this:

```
auto y = x;             // read x

x = 20;                 // write x
```

Lest you wonder who'd write code that performs these kinds of redundant reads and superfluous writes (technically known as *redundant loads* and *dead stores*), the answer is that humans don't write it directly—at least we hope they don't. However, after compilers take reasonable-looking source code and perform template instantiation, inlining, and various common kinds of reordering optimizations, it's not uncommon for the result to have redundant loads and dead stores that compilers can get rid of.

Such optimizations are valid only if memory behaves normally. "Special" memory doesn't. Probably the most common kind of special memory is memory used for *memory-mapped I/O*. Locations in such memory actually communicate with peripherals, e.g., external sensors or displays, printers, network ports, etc. rather than reading or writing normal memory (e.g., RAM). In such a context, consider again the code with seemingly redundant reads:

```
auto y = x;             // read x
y = x;                  // read x again
```

If x corresponds to, say, the temperature reported by a temperature sensor, the second read of x is not redundant, because the temperature may have changed between the first and second reads.

It's a similar situation for seemingly superfluous writes. In this code, for example,

```
x = 10;                 // write x
x = 20;                 // write x again
```

if x corresponds to the control port for a radio transmitter, it could be that the code is issuing commands to the radio, and the value 10 corresponds to a different command from the value 20. Optimizing out the first assignment would change the sequence of commands sent to the radio.

`volatile` is the way we tell compilers that we're dealing with special memory. Its meaning to compilers is "Don't perform any optimizations on operations on this memory." So if x corresponds to special memory, it'd be declared `volatile`:

```
volatile int x;
```

Consider the effect that has on our original code sequence:

```
auto y = x;             // read x
y = x;                  // read x again (can't be optimized away)

x = 10;                 // write x
x = 20;                 // write x again (can't be optimized away)
```

This is precisely what we want if x is memory-mapped (or has been mapped to a memory location shared across processes, etc.).

Pop quiz! In that last piece of code, what is `y`'s type: `int` or `volatile int`?†

The fact that seemingly redundant loads and dead stores must be preserved when dealing with special memory explains, by the way, why `std::atomic`s are unsuitable for this kind of work. Compilers are permitted to eliminate such redundant operations on `std::atomic`s. The code isn't written quite the same way it is for `volatile`s, but if we overlook that for a moment and focus on what compilers are permitted to do, we can say that, conceptually, compilers may take this,

```
std::atomic<int> x;

auto y = x;            // conceptually read x (see below)
y = x;                 // conceptually read x again (see below)

x = 10;                // write x
x = 20;                // write x again
```

and optimize it to this:

```
auto y = x;            // conceptually read x (see below)
x = 20;                // write x
```

For special memory, this is clearly unacceptable behavior.

Now, as it happens, neither of these two statements will compile when `x` is `std::atomic`:

```
auto y = x;            // error!
y = x;                 // error!
```

That's because the copy operations for `std::atomic` are deleted (see Item 11). And with good reason. Consider what would happen if the initialization of `y` with `x` compiled. Because `x` is `std::atomic`, `y`'s type would be deduced to be

† `y`'s type is `auto`-deduced, so it uses the rules described in Item 2. Those rules dictate that for the declaration of non-reference non-pointer types (which is the case for `y`), `const` and `volatile` qualifiers are dropped. `y`'s type is therefore simply `int`. This means that redundant reads of and writes to `y` can be eliminated. In the example, compilers must perform both the initialization of and the assignment to `y`, because `x` is `volatile`, so the second read of `x` might yield a different value from the first one.

`std::atomic`, too (see Item 2.) I remarked earlier that one of the best things about `std::atomics` is that all their operations are atomic, but in order for the copy construction of `y` from `x` to be atomic, compilers would have to generate code to read `x` and write `y` in a single atomic operation. Hardware generally can't do that, so copy construction isn't supported for `std::atomic` types. Copy assignment is deleted for the same reason, which is why the assignment from `x` to `y` won't compile. (The move operations aren't explicitly declared in `std::atomic`, so, per the rules for compiler-generated special functions described in Item 19, `std::atomic` offers neither move construction nor move assignment.)

It's possible, of course, to get the value of `x` into `y`, but it requires use of `std::atomic`'s member functions `load` and `store`. The `load` member function reads a `std::atomic`'s value atomically, while the `store` member function writes it atomically. To initialize `y` with `x`, then, followed by putting `x`'s value in `y`, the code must be written like this:

```
std::atomic<int> y(x.load());       // read x
y.store(x.load());                  // read x again
```

This compiles, but the fact that reading `x` (via `x.load()`) is a separate function call from initializing or storing to `y` makes clear that there is no reason to expect either statement as a whole to execute as a single atomic operation.

Given that code, compilers could "optimize" it by storing `x`'s value in a register instead of reading it twice:

```
register = x.load();                // read x into register
std::atomic<int> y(register);       // init y with register value
y.store(register);                  // store register value into y
```

The result, as you can see, reads from `x` only once, and that's the kind of optimization that must be avoided when dealing with special memory. (The optimization isn't permitted for `volatile` variables.)

The situation should thus be clear:

- std::atomic is useful for concurrent programming, but not for accessing special memory.
- volatile is useful for accessing special memory, but not for concurrent programming.

Because std::atomic and volatile serve different purposes, they can even be used together:

```
volatile std::atomic<int> vai;    // operations on vai are
                                  // atomic and can't be
                                  // optimized away
```

This could be useful if vai corresponded to a memory-mapped I/O location that was concurrently accessed by multiple threads.

As a final note, some developers prefer to use std::atomic's load and store member functions even when they're not syntactically required, because it makes explicit in the source code that the variables involved aren't "normal." Emphasizing that fact isn't unreasonable. Accessing a std::atomic is typically much slower than accessing a non-std::atomic, and we've already seen that the use of std::atomics prevents compilers from performing certain kinds of statement reorderings that would otherwise be permitted. Calling out loads and stores of std::atomics can therefore help identify potential scalability chokepoints. From a correctness perspective, *not* seeing a call to store on a variable meant to communicate information to other threads (e.g., a flag indicating the availability of data) could mean that the variable wasn't declared std::atomic when it should have been.

This is more a stylistic issue, however, and as such is quite different from the choice between std::atomic and volatile. std::atomic is a tool for writing concurrent software. volatile is a tool for working with special memory.

Things to Remember

- std::atomic is for data accessed from multiple threads without using mutexes.

- `volatile` is for memory where reads and writes should never be optimized away.