Luigi Ballabio

IMPLEMENTING QUANTLIB

Quantitative finance in C++:
an inside look at the architecture
of the QuantLib library

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Contents

1. Introduction

With the enthusiasm of youth, the QuantLib web site used to state that QuantLib aimed at becoming "the standard free/open-source financial library." By interpreting such statement a bit loosely, one might say that it has somewhat succeeded—albeit by employing the rather devious trick of being the first, and thus for some time the *only* open-source financial library[1].

Standard or not, the project is thriving; at the time of this writing, each new release is downloaded a few thousand times, there is a steady stream of contributions from users, and the library seems to be used in the real world—as far as I can guess through the usual shroud of secrecy used in the financial world. All in all, as a project administrator, I can declare myself a happy camper.

But all the more for that, the lack of proper documentation shows. Although a detailed class reference is available (that was an easy task, since it can be generated automatically) it doesn't let one see the forest for the trees; so that a new user might get the impression that the QuantLib developers share the views of the Bellman from Lewis Carroll's *Hunting of the Snark*:

> "What use are Mercator's North Poles and Equators,
> Tropics, Zones and Meridian Lines?"
> So the Bellman would cry: and the crew would reply,
> "They are merely conventional signs!"

The purpose of this book is to fill a part of the existing void. It is a report on the design and implementation of QuantLib, alike in spirit—but, hopefully, with less frightening results—to the *How I did it* book[2] prominently featured in Mel Brooks' *Young Frankenstein*. If you are—or want to be—a QuantLib user, you will find here useful information on the design of the library that might not be readily apparent when reading the code. If you're working in quantitative finance, even if not using QuantLib, you can still read it as a field report on the design of a financial library. You will find that it covers issues that you might also face, as well as some possible solutions and their rationale. Based on your constraints, it is possible—even likely—that you will choose other solutions; but you might profit from this discussion just the same.

In my descriptions, I'll also point out shortcomings in the current implementation; not to disparage the library (I'm pretty much involved in it, after all) but for more useful purposes. On the one hand, describing the existing pitfalls will help developers avoid them; on the other hand, it might show how to improve the library. Indeed, it already happened that reviewing the code for this book caused me to go back and modify it for the better.

[1] A few gentle users happened to refer to our library as "*the* QuantLib." As much as I like the expression, modesty and habit have so far prevented me from using it.

[2] In this case, of course, it would be "How *we* did it."

For reasons of both space and time, I won't be able to cover every aspect of the library. In the first half of the book, I'll describe a few of the most important classes, such as those modeling financial instruments and term structures; this will give you a view of the larger architecture of the library. In the second half, I'll describe a few specialized frameworks, such as those used for creating Monte Carlo or finite-differences models. Some of those are more polished than others; I hope that their current shortcomings will be as interesting as their strong points.

The book is primarily aimed at users wanting to extend the library with their own instruments or models; if you desire to do so, the description of the available class hierarchies and frameworks will provide you with information about the hooks you need to integrate your code with QuantLib and take advantage of its facilities. If you're not this kind of user, don't close the book yet; you can find useful information too. However, you might want to look at the *QuantLib Python Cookbook* instead. It can be useful to C++ users, too.

* * *

And now, as is tradition, a few notes on the style and requirements of this book.

Knowledge of both C++ and quantitative finance is assumed. I've no pretense of being able to teach you either one, and this book is thick enough already. Here, I just describe the implementation and design of QuantLib; I'll leave it to other and better authors to describe the problem domain on one hand, and the language syntax and tricks on the other.

As you already noticed, I'll write in the first person singular. True, it might look rather self-centered—as a matter of fact, I hope you still haven't put down the book in annoyance—but we would feel rather pompous if we were to use the first person plural. The author of this book feels the same about using the third person. After a bit of thinking, I opted for a less formal but more comfortable style (which, as you noted, also includes a liberal use of contractions). For the same reason, I'll be addressing *you* instead of the proverbial acute reader. The use of the singular will also help to avoid confusion; when I use the plural, I describe work done by the QuantLib developers as a group.

I will describe the evolution of a design when it is interesting on its own, or relevant for the final result. For the sake of clarity, in most cases I'll skip over the blind alleys and wrong turns taken; put together design decisions which were made at different times; and only show the final design, sometimes simplified. This will still leave me with plenty to say: in the words of the Alabama Shakes, "why" is an awful lot of question.

I will point out the use of design patterns in the code I describe. Mind you, I'm not advocating cramming your code with them; they should be applied when they're useful, not for their own sake.[3] However, QuantLib is now the result of several years of coding and refactoring, both based on user feedback and new requirements being added over time. It is only natural that the design evolved toward patterns.

[3]A more thorough exposition of this point can be found in Kerievsky, 2004.

I will apply to the code listings in the book the same conventions used in the library and outlined in appendix B. I will depart from them in one respect: due to the limitations on line length, I might drop the std and boost namespaces from type names. When the listings need to be complemented by diagrams, I will be using UML; for those not familiar with this language, a concise guide can be found in Fowler, 2003.

*   *   *

And now, let's dive.

2. Financial instruments and pricing engines

The statement that a financial library must provide the means to price financial instruments would certainly have appealed to Monsieur de La Palisse. However, that is only a part of the whole problem; a financial library must also provide developers with the means to extend it by adding new pricing functionality.

Foreseeable extensions are of two kinds, and the library must allow either one. On the one hand, it must be possible to add new financial instruments; on the other hand, it must be feasible to add new means of pricing an existing instrument. Both kinds have a number of requirements, or in pattern jargon, forces that the solution must reconcile. This chapter details such requirements and describes the design that allows QuantLib to satisfy them.

2.1 The `Instrument` class

In our domain, a financial instrument is a concept in its own right. For this reason alone, any self-respecting object-oriented programmer will code it as a base class from which specific instruments will be derived.

The idea, of course, is to be able to write code such as

```
for (i = portfolio.begin(); i != portfolio.end(); ++i)
    totalNPV += i->NPV();
```

where we don't have to care about the specific type of each instrument. However, this also prevents us from knowing what arguments to pass to the `NPV` method, or even what methods to call. Therefore, even the two seemingly harmless lines above tell us that we have to step back and think a bit about the interface.

2.1.1 Interface and requirements

The broad variety of traded assets—which range from the simplest to the most exotic—implies that any method specific to a given class of instruments (say, equity options) is bound not to make sense for some other kind (say, interest-rate swaps). Thus, very few methods were singled out as generic enough to belong to the `Instrument` interface. We limited ourselves to those returning its present value (possibly with an associated error estimate) and indicating whether or not the instrument has expired; since we can't specify what arguments are needed,[1] the methods take none; any needed input will have to be stored by the instrument. The resulting interface is shown in the listing below.

[1]Even fancy new C++11 stuff like variadic templates won't help.

Preliminary interface of the `Instrument` class.

```
class Instrument {
  public:
    virtual ~Instrument();
    virtual Real NPV() const = 0;
    virtual Real errorEstimate() const = 0;
    virtual bool isExpired() const = 0;
};
```

As is good practice, the methods were first declared as pure virtual ones; but—as Sportin' Life points out in Gershwin's *Porgy and Bess*—it ain't necessarily so. There might be some behavior that can be coded in the base class. In order to find out whether this was the case, we had to analyze what to expect from a generic financial instrument and check whether it could be implemented in a generic way. Two such requirements were found at different times, and their implementation changed during the development of the library; I present them here in their current form.

One is that a given financial instrument might be priced in different ways (e.g., with one or more analytic formulas or numerical methods) without having to resort to inheritance. At this point, you might be thinking "Strategy pattern". It is indeed so; I devote section 2.2 to its implementation.

The second requirement came from the observation that the value of a financial instrument depends on market data. Such data are by their nature variable in time, so that the value of the instrument varies in turn; another cause of variability is that any single market datum can be provided by different sources. We wanted financial instruments to maintain links to these sources so that, upon different calls, their methods would access the latest values and recalculate the results accordingly; also, we wanted to be able to transparently switch between sources and have the instrument treat this as just another change of the data values.

We were also concerned with a potential loss of efficiency. For instance, we could monitor the value of a portfolio in time by storing its instruments in a container, periodically poll their values, and add the results. In a simple implementation, this would trigger recalculation even for those instruments whose inputs did not change. Therefore, we decided to add to the instrument methods a caching mechanism: one that would cause previous results to be stored and only recalculated when any of the inputs change.

2.1.2 Implementation

The code managing the caching and recalculation of the instrument value was written for a generic financial instrument by means of two design patterns.

When any of the inputs change, the instrument is notified by means of the Observer pattern (Gamma *et al*, 1995). The pattern itself is briefly described[2] in appendix A; I describe here the participants.

[2]This does not excuse you from reading the Gang of Four book.

Obviously enough, the instrument plays the role of the observer while the input data play that of the observables. In order to have access to the new values after a change is notified, the observer needs to maintain a reference to the object representing the input. This might suggest some kind of smart pointer; however, the behavior of a pointer is not sufficient to fully describe our problem. As I already mentioned, a change might come not only from the fact that values from a data feed vary in time; we might also want to switch to a different data feed. Storing a (smart) pointer would give us access to the current value of the object pointed; but our copy of the pointer, being private to the observer, could not be made to point to a different object. Therefore, what we need is the smart equivalent of a pointer to pointer. This feature was implemented in QuantLib as a class template and given the name of `Handle`. Again, details are given in appendix A; relevant to this discussion is the fact that copies of a given `Handle` share a link to an object. When the link is made to point to another object, all copies are notified and allow their holders to access the new pointee. Furthermore, `Handle`s forward any notifications from the pointed object to their observers.

Finally, classes were implemented which act as observable data and can be stored into `Handle`s. The most basic is the `Quote` class, representing a single varying market value. Other inputs for financial instrument valuation can include more complex objects such as yield or volatility term structures.[3]

Another problem was to abstract out the code for storing and recalculating cached results, while still leaving it to derived classes to implement any specific calculations. In earlier versions of QuantLib, the functionality was included in the `Instrument` class itself; later, it was extracted and coded into another class—somewhat unsurprisingly called `LazyObject`—which is now reused in other parts of the library. An outline of the class is shown in the following listing.

Outline of the `LazyObject` class.

```
class LazyObject : public virtual Observer,
                   public virtual Observable {
  protected:
    mutable bool calculated_;
    virtual void performCalculations() const = 0;
  public:
    void update() { calculated_ = false; }
    virtual void calculate() const {
        if (!calculated_) {
            calculated_ = true;
            try {
                performCalculations();
            } catch (...) {
                calculated_ = false;
                throw;
            }
        }
```

[3]Most likely, such objects ultimately depend on `Quote` instances, e.g., a yield term structure might depend on the quoted deposit and swap rates used for bootstrapping.

```
        }
    };
```

The code is not overly complex. A boolean data member `calculated_` is defined which keeps track of whether results were calculated and still valid. The `update` method, which implements the `Observer` interface and is called upon notification from observables, sets such boolean to `false` and thus invalidates previous results.

The `calculate` method is implemented by means of the Template Method pattern (Gamma *et al*, 1995), sometimes also called *non-virtual interface*. As explained in the Gang of Four book, the constant part of the algorithm (in this case, the management of the cached results) is implemented in the base class; the varying parts (here, the actual calculations) are delegated to a virtual method, namely, `performCalculations`, which is called in the body of the base-class method. Therefore, derived classes will only implement their specific calculations without having to care about caching: the relevant code will be injected by the base class.

The logic of the caching is simple. If the current results are no longer valid, we let the derived class perform the needed calculations and flag the new results as up to date. If the current results are valid, we do nothing.

However, the implementation is not as simple. You might wonder why we had to insert a `try` block setting `calculated_` beforehand and a handler rolling back the change before throwing the exception again. After all, we could have written the body of the algorithm more simply—for instance, as in the following, seemingly equivalent code, that doesn't catch and rethrow exceptions:

```
    if (!calculated_) {
        performCalculations();
        calculated_ = true;
    }
```

The reason is that there are cases (e.g., when the lazy object is a yield term structure which is bootstrapped lazily) in which `performCalculations` happens to recursively call `calculate`. If `calculated_` were not set to `true`, the `if` condition would still hold and `performCalculations` would be called again, leading to infinite recursion. Setting such flag to `true` prevents this from happening; however, care must now be taken to restore it to `false` if an exception is thrown. The exception is then rethrown so that it can be caught by the installed error handlers.

A few more methods are provided in `LazyObject` which enable users to prevent or force a recalculation of the results. They are not discussed here. If you're interested, you can heed the advice often given by master Obi-Wan Kenobi: "Read the source, Luke."

Aside: const or not const?

It might be of interest to explain why `NPV_` is declared as `mutable`, as this is an issue which often arises when implementing caches or lazy calculations. The crux of the matter is that the `NPV` method is logically a `const` one: calculating the value of an instrument does not modify it. Therefore, a user is entitled to expect that such a method can be called on a `const` instance. In turn, the `const`ness of `NPV` forces us to declare `calculate` and `performCalculations` as `const`, too. However, our choice of calculating results lazily and storing them for later use makes it necessary to assign to one or more data members in the body of such methods. The tension is solved by declaring cached variables as `mutable`; this allows us (and the developers of derived classes) to fulfill both requirements, namely, the `const`ness of the `NPV` method and the lazy assignment to data members.

Also, it should be noted that the C++11 standard now requires `const` methods to be thread-safe; that is, two threads calling `const` members at the same time should not incur in race conditions (to learn all about it, see Sutter, 2013). To make the code conform to the new standard, we should protect updates to `mutable` members with a mutex. This would likely require some changes in design.

The `Instrument` class inherits from `LazyObject`. In order to implement the interface outlined earlier, it decorates the `calculate` method with code specific to financial instruments. The resulting method is shown in the listing below, together with other bits of supporting code.

Excerpt of the `Instrument` class.

```
class Instrument : public LazyObject {
  protected:
    mutable Real NPV_;
  public:
    Real NPV() const {
        calculate();
        return NPV_;
    }
    void calculate() const {
        if (isExpired()) {
            setupExpired();
            calculated_ = true;
        } else {
            LazyObject::calculate();
        }
    }
    virtual void setupExpired() const {
        NPV_ = 0.0;
    }
};
```

Once again, the added code follows the Template Method pattern to delegate instrument-specific calculations to derived classes. The class defines an `NPV_` data member to store the result of the calculation; derived classes can declare other data members to store specific results.[4] The body of the `calculate` method calls the virtual `isExpired` method to check whether the instrument is an expired one. If this is the case, it calls another virtual method, namely, `setupExpired`, which has the responsibility of giving meaningful values to the results; its default implementation sets `NPV_` to `0` and can be called by derived classes. The `calculated_` flag is then set to `true`. If the instrument is not expired, the `calculate` method of `LazyObject` is called instead, which in turn will call `performCalculations` as needed. This imposes a contract on the latter method, namely, its implementations in derived classes are required to set `NPV_` (as well as any other instrument-specific data member) to the result of the calculations. Finally, the `NPV` method ensures that `calculate` is called before returning the answer.

2.1.3 Example: interest-rate swap

I end this section by showing how a specific financial instrument can be implemented based on the described facilities.

The chosen instrument is the interest-rate swap. As you surely know, it is a contract which consists in exchanging periodic cash flows. The net present value of the instrument is calculated by adding or subtracting the discounted cash-flow amounts depending on whether the cash flows are paid or received.

Not surprisingly, the swap is implemented[5] as a new class deriving from `Instrument`. Its outline is shown in the following listing.

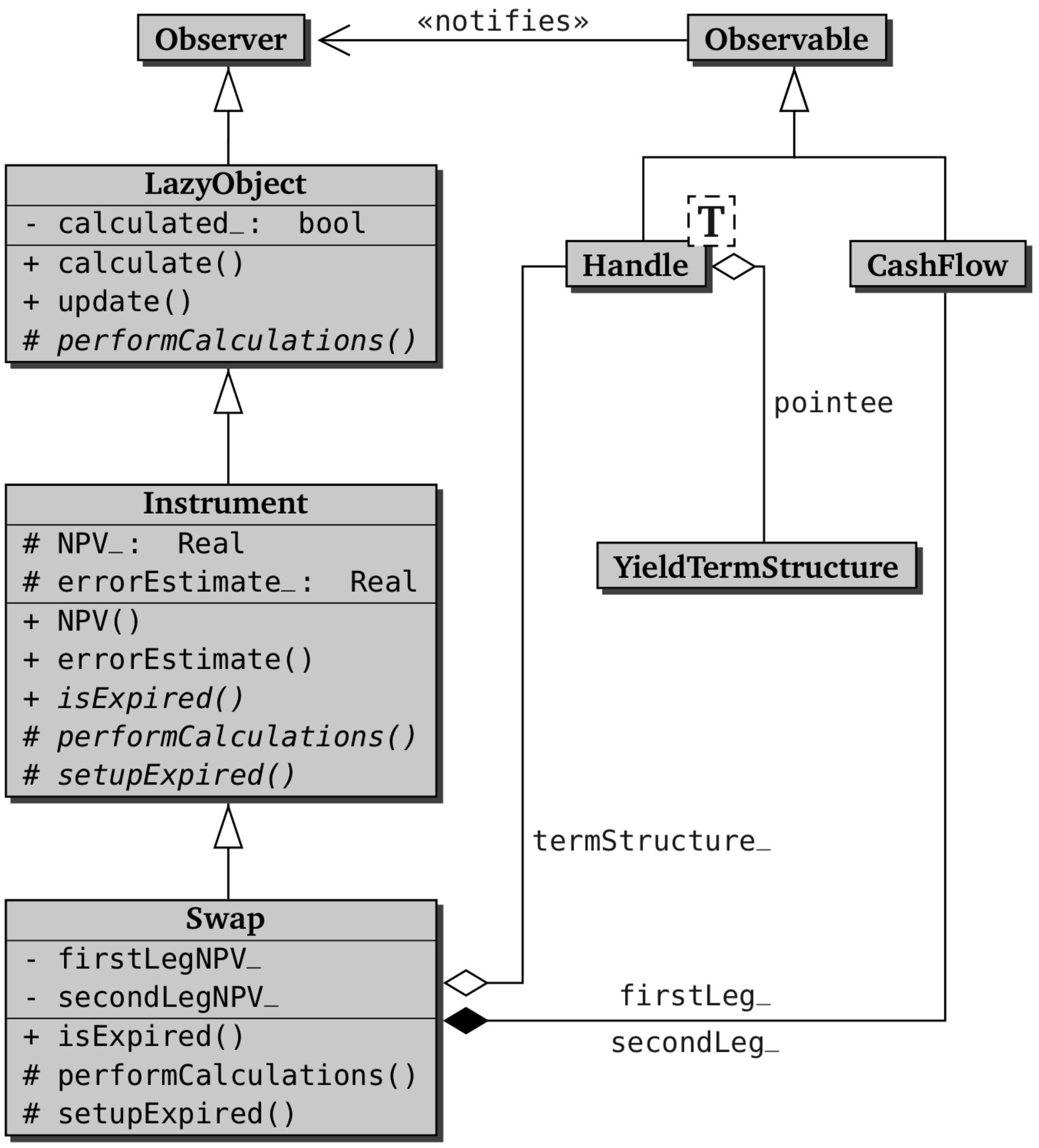
Partial interface of the `Swap` class.

```
class Swap : public Instrument {
  public:
    Swap(const vector<shared_ptr<CashFlow> >& firstLeg,
         const vector<shared_ptr<CashFlow> >& secondLeg,
         const Handle<YieldTermStructure>& termStructure);
    bool isExpired() const;
    Real firstLegBPS() const;
    Real secondLegBPS() const;
  protected:
    // methods
    void setupExpired() const;
    void performCalculations() const;
    // data members
    vector<shared_ptr<CashFlow> > firstLeg_, secondLeg_;
    Handle<YieldTermStructure> termStructure_;
    mutable Real firstLegBPS_, secondLegBPS_;
};
```

[4]The `Instrument` class also defines an `errorEstimate_` member, which is omitted here for clarity of exposition. The discussion of `NPV_` applies to both.

[5]The implementation shown in this section is somewhat outdated. However, I'm still using it here since it provides a simpler example.

It contains as data members the objects needed for the calculations—namely, the cash flows on the first and second leg and the yield term structure used to discount their amounts—and two variables used to store additional results. Furthermore, it declares methods implementing the `Instrument` interface and others returning the swap-specific results. The class diagram of `Swap` and the related classes is shown in the figure below.



Class diagram of the `Swap` class.

The fitting of the class to the `Instrument` framework is done in three steps, the third being optional depending on the derived class; the relevant methods are shown in the next listing.

Partial implementation of the `Swap` class.

```
Swap::Swap(const vector<shared_ptr<CashFlow> >& firstLeg,
           const vector<shared_ptr<CashFlow> >& secondLeg,
           const Handle<YieldTermStructure>& termStructure)
: firstLeg_(firstLeg), secondLeg_(secondLeg),
  termStructure_(termStructure) {
    registerWith(termStructure_);
    vector<shared_ptr<CashFlow> >::iterator i;
    for (i = firstLeg_.begin(); i!= firstLeg_.end(); ++i)
        registerWith(*i);
    for (i = secondLeg_.begin(); i!= secondLeg_.end(); ++i)
        registerWith(*i);
}

bool Swap::isExpired() const {
    Date settlement = termStructure_->referenceDate();
    vector<shared_ptr<CashFlow> >::const_iterator i;
    for (i = firstLeg_.begin(); i!= firstLeg_.end(); ++i)
        if (!(*i)->hasOccurred(settlement))
            return false;
    for (i = secondLeg_.begin(); i!= secondLeg_.end(); ++i)
        if (!(*i)->hasOccurred(settlement))
            return false;
    return true;
}

void Swap::setupExpired() const {
    Instrument::setupExpired();
    firstLegBPS_= secondLegBPS_ = 0.0;
}

void Swap::performCalculations() const {
    NPV_ = - Cashflows::npv(firstLeg_,**termStructure_)
           + Cashflows::npv(secondLeg_,**termStructure_);
    errorEstimate_ = Null<Real>();

    firstLegBPS_ = - Cashflows::bps(firstLeg_, **termStructure_);
    secondLegBPS_ = Cashflows::bps(secondLeg_, **termStructure_);
}

Real Swap::firstLegBPS() const {
    calculate();
    return firstLegBPS_;
}

Real Swap::secondLegBPS() const {
    calculate();
    return secondLegBPS_;
}
```

The first step is performed in the class constructor, which takes as arguments (and copies into the corresponding data members) the two sequences of cash flows to be exchanged and the yield term structure to be used for discounting their amounts. The step itself consists in registering the swap as an observer of both the cash flows and the term structure. As previously explained, this enables them to notify the swap and trigger its recalculation each time a change occurs.

The second step is the implementation of the required interface. The logic of the `isExpired` method is simple enough; its body loops over the stored cash flows checking their payment dates. As soon as it finds a payment which still has not occurred, it reports the swap as not expired. If none is found, the instrument has expired. In this case, the `setupExpired` method will be called. Its implementation calls the base-class one, thus taking care of the data members inherited from `Instrument`; it then sets to `0` the swap-specific results.

Aside: handles and shared pointers.

You might wonder why the `Swap` constructor accepts the discount curve as a handle and the cash flows as simple shared pointers. The reason is that we might decide to switch to a different curve (which can be done by means of the handle) whereas the cash flows are part of the definition of the swap and are thus immutable.

The last required method is `performCalculations`. The calculation is performed by calling two external functions from the `Cashflows` class.[6] The first one, namely, `npv`, is a straightforward translation of the algorithm outlined above: it cycles on a sequence of cash flows adding the discounted amount of its future cash flows. We set the `NPV_` variable to the difference of the results from the two legs. The second one, `bps`, calculates the basis-point sensitivity (BPS) of a sequence of cash flows. We call it once per leg and store the results in the corresponding data members. Since the result carries no numerical error, the `errorEstimate_` variable is set to `Null<Real>()`—a specific floating-point value which is used as a sentinel value indicating an invalid number.[7]

The third and final step only needs to be performed if—as in this case—the class defines additional

[6]If you happen to feel slightly cheated, consider that the point of this example is to show how to package calculations into a class—not to show how to implement the calculations. Your curiosity will be satisfied in a later chapter devoted to cash flows and related functions.

[7]`NaN` might be a better choice, but the means of detecting it are not portable. Another possibility still to be investigated would be to use `boost::optional`.

results. It consists in writing corresponding methods (here, `firstLegBPS` and `secondLegBPS`) which ensure that the calculations are (lazily) performed before returning the stored results.

The implementation is now complete. Having been written on top of the `Instrument` class, the `Swap` class will benefit from its code. Thus, it will automatically cache and recalculate results according to notifications from its inputs—even though no related code was written in `Swap` except for the registration calls.

2.1.4 Further developments

You might have noticed a shortcoming in my treatment of the previous example and of the `Instrument` class in general. Albeit generic, the `Swap` class we implemented cannot manage interest-rate swaps in which the two legs are paid in different currencies. A similar problem would arise if you wanted to add the values of two instruments whose values are not in the same currency; you would have to convert manually one of the values to the currency of the other before adding them together.

Such problems stem from a single weakness of the implementation: we used the `Real` type (i.e., a simple floating-point number) to represent the value of an instrument or a cash flow. Therefore, such results miss the currency information which is attached to them in the real world.

The weakness might be removed if we were to express such results by means of the `Money` class. Instances of such class contain currency information; moreover, depending on user settings, they are able to automatically perform conversion to a common currency upon addition or subtraction.

However, this would be a major change, affecting a large part of the code base in a number of ways. Therefore, it will need some serious thinking before we tackle it (if we do tackle it at all).

Another (and more subtle) shortcoming is that the `Swap` class fails to distinguish explicitly between two components of the abstraction it represents. Namely, there is no clear separation between the data specifying the contract (the cash-flow specification) and the market data used to price the instrument (the current discount curve).

The solution is to store in the instrument only the first group of data (i.e., those that would be in its term sheet) and keep the market data elsewhere.[8] The means to do this are the subject of the next section.

2.2 Pricing engines

We now turn to the second of the requirements I stated in the previous section. For any given instrument, it is not always the case that a unique pricing method exists; moreover, one might want to use multiple methods for different reasons. Let's take the classic textbook example—the European equity option. One might want to price it by means of the analytic Black-Scholes formula in order to

[8]Beside being conceptually clearer, this would prove useful to external functions implementing serialization and deserialization of the instrument—for instance, to and from the FpML format.

retrieve implied volatilities from market prices; by means of a stochastic volatility model in order to calibrate the latter and use it for more exotic options; by means of a finite-difference scheme in order to compare the results with the analytic ones and validate one's finite-difference implementation; or by means of a Monte Carlo model in order to use the European option as a control variate for a more exotic one.

Therefore, we want it to be possible for a single instrument to be priced in different ways. Of course, it is not desirable to give different implementations of the `performCalculations` method, as this would force one to use different classes for a single instrument type. In our example, we would end up with a base `EuropeanOption` class from which `AnalyticEuropeanOption`, `McEuropeanOption` and others would be derived. This is wrong in at least two ways. On a conceptual level, it would introduce different entities when a single one is needed: a European option is a European option is a European option, as Gertrude Stein said. On a usability level, it would make it impossible to switch pricing methods at run-time.

The solution is to use the Strategy pattern, i.e., to let the instrument take an object encapsulating the computation to be performed. We called such an object a *pricing engine*. A given instrument would be able to take any one of a number of available engines (of course corresponding to the instrument type), pass the chosen engine the needed arguments, have it calculate the value of the instrument and any other desired quantities, and fetch the results. Therefore, the `performCalculations` method would be implemented roughly as follows:

```
void SomeInstrument::performCalculations() const {
    NPV_ = engine_->calculate(arg1, arg2, ... , argN);
}
```

where we assumed that a virtual `calculate` method is defined in the engine interface and implemented in the concrete engines.

Unfortunately, the above approach won't work as such. The problem is, we want to implement the dispatching code just once, namely, in the `Instrument` class. However, that class doesn't know the number and type of arguments; different derived classes are likely to have data members differing wildly in both number and type. The same goes for the returned results; for instance, an interest-rate swap might return fair values for its fixed rate and floating spread, while the ubiquitous European option might return any number of Greeks.

An interface passing explicit arguments to the engine through a method, as the one outlined above, would thus lead to undesirable consequences. Pricing engines for different instruments would have different interfaces, which would prevent us from defining a single base class; therefore, the code for calling the engine would have to be replicated in each instrument class. This way madness lies.

The solution we chose was that arguments and results be passed and received from the engines by means of opaque structures aptly called `arguments` and `results`. Two structures derived from those and augmenting them with instrument-specific data will be stored in any pricing engine; an instrument will write and read such data in order to exchange information with the engine.

The listing below shows the interface of the resulting `PricingEngine` class, as well as its inner `argument` and `results` classes and a helper `GenericEngine` class template. The latter implements most of the `PricingEngine` interface, leaving only the implementation of the `calculate` method to developers of specific engines. The `arguments` and `results` classes were given methods which ease their use as drop boxes for data: `arguments::validate` is to be called after input data are written to ensure that their values lie in valid ranges, while `results::reset` is to be called before the engine starts calculating in order to clean previous results.

Interface of `PricingEngine` and of related classes.

```
    class PricingEngine : public Observable {
      public:
        class arguments;
        class results;
        virtual ~PricingEngine() {}
        virtual arguments* getArguments() const = 0;
        virtual const results* getResults() const = 0;
        virtual void reset() const = 0;
        virtual void calculate() const = 0;
    };

    class PricingEngine::arguments {
      public:
        virtual ~arguments() {}
        virtual void validate() const = 0;
    };

    class PricingEngine::results {
      public:
        virtual ~results() {}
        virtual void reset() = 0;
    };

    // ArgumentsType must inherit from arguments;
    // ResultType from results.
    template<class ArgumentsType, class ResultsType>
    class GenericEngine : public PricingEngine {
      public:
        PricingEngine::arguments* getArguments() const {
            return &arguments_;
        }
        const PricingEngine::results* getResults() const {
            return &results_;
        }
        void reset() const { results_.reset(); }
      protected:
        mutable ArgumentsType arguments_;
        mutable ResultsType results_;
    };
```

Armed with our new classes, we can now write a generic `performCalculation` method. Besides the already mentioned Strategy pattern, we will use the Template Method pattern to allow any given instrument to fill the missing bits. The resulting implementation is shown in the next listing. Note that an inner class `Instrument::result` was defined; it inherits from `PricingEngine::results` and contains the results that have to be provided for any instrument[9]

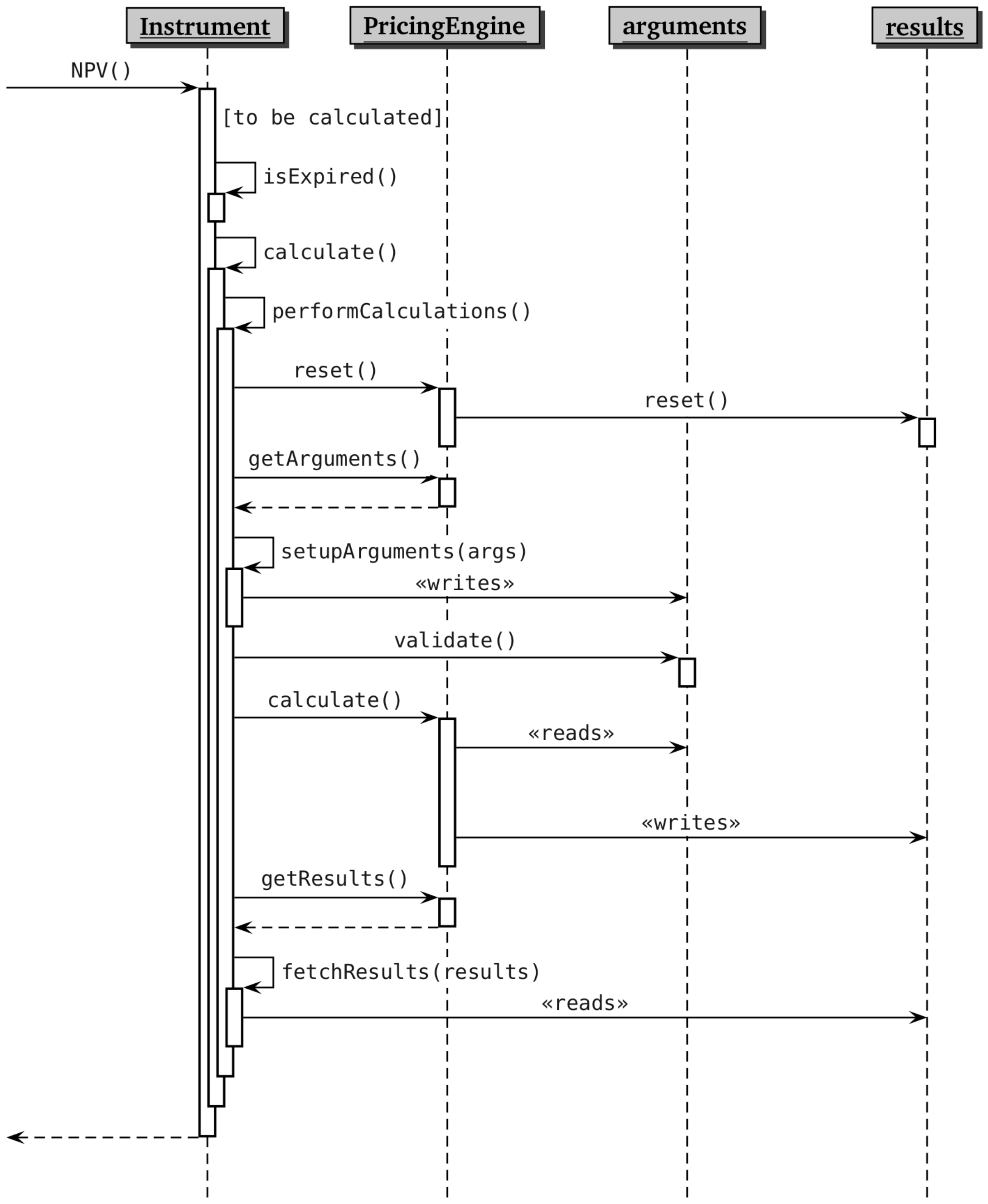
Excerpt of the `Instrument` class.

```
    class Instrument : public LazyObject {
      public:
       class results;
       virtual void performCalculations() const {
          QL_REQUIRE(engine_, "null pricing engine");
          engine_->reset();
          setupArguments(engine_->getArguments());
          engine_->getArguments()->validate();
          engine_->calculate();
          fetchResults(engine_->getResults());
       }
       virtual void setupArguments(
                         PricingEngine::arguments*) const {
          QL_FAIL("setupArguments() not implemented");
       }
       virtual void fetchResults(
                   const PricingEngine::results* r) const {
          const Instrument::results* results =
              dynamic_cast<const Value*>(r);
          QL_ENSURE(results != 0, "no results returned");
          NPV_ = results->value;
          errorEstimate_ = results->errorEstimate;
       }
       template <class T> T result(const string& tag) const;
      protected:
       shared_ptr<PricingEngine> engine_;
    };
```

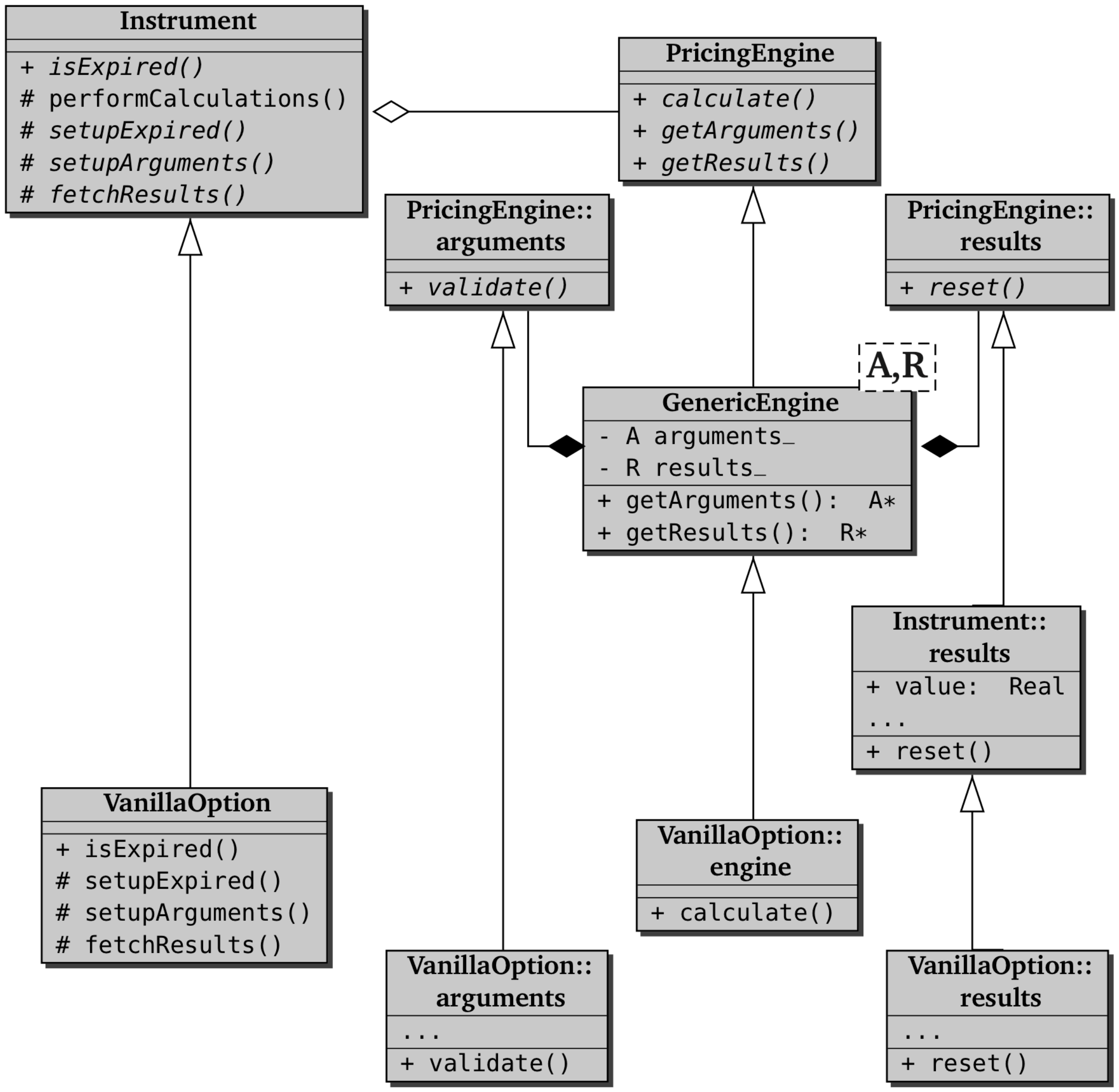
[9]The `Instrument::results` class also contains a `std::map` where pricing engines can store additional results. The relevant code is here omitted for clarity.

```
    class Instrument::results
        : public virtual PricingEngine::results {
      public:
       Value() { reset(); }
       void reset() {
           value = errorEstimate = Null<Real>();
       }
       Real value;
       Real errorEstimate;
    };
```

As for `performCalculation`, the actual work is split between a number of collaborating classes—the instrument, the pricing engine, and the arguments and results classes. The dynamics of such a collaboration (described in the following paragraphs) might be best understood with the help of the UML sequence diagram shown in the first of the next two figures; the static relationship between the classes (and a possible concrete instrument) is shown in the second.



Sequence diagram of the interplay between instruments and pricing engines.



Class diagram of `Instrument`, `PricingEngine`, and related classes including a derived instrument class.

A call to the `NPV` method of the instrument eventually triggers (if the instrument is not expired and the relevant quantities need to be calculated) a call to its `performCalculations` method. Here is where the interplay between instrument and pricing engine begins. First of all, the instrument verifies that an engine is available, aborting the calculation if this is not the case. If one is found, the instrument prompts it to reset itself. The message is forwarded to the instrument-specific result structure by means of its `reset` method; after it executes, the structure is a clean slate ready for writing the new results.

At this point, the Template Method pattern enters the scene. The instrument asks the pricing engine for its argument structure, which is returned as a pointer to `arguments`. The pointer is then passed to the instrument's `setupArguments` method, which acts as the variable part in the pattern. Depending on the specific instrument, such method verifies that the passed argument is of the correct type and proceeds to fill its data members with the correct values. Finally, the arguments are asked to perform any needed checks on the newly-written values by calling the `validate` method.

The stage is now ready for the Strategy pattern. Its arguments set, the chosen engine is asked to perform its specific calculations, implemented in its `calculate` method. During the processing, the engine will read the inputs it needs from its argument structure and write the corresponding outputs into its results structure.

After the engine completes its work, the control returns to the `Instrument` instance and the Template Method pattern continues unfolding. The called method, `fetchResults`, must now ask the engine for the results, downcast them to gain access to the contained data, and copy such values into its own data members. The `Instrument` class defines a default implementation which fetches the results common to all instruments; derived classes might extend it to read specific results.

Aside: impure virtual methods.

Upon looking at the final implementation of the `Instrument` class, you might wonder why the `setupArguments` method is defined as throwing an exception rather than declared as a pure virtual method. The reason is not to force developers of new instruments to implement a meaningless method, were they to decide that some of their classes should simply override the `performCalculation` method.

2.2.1 Example: plain-vanilla option

At this point, an example is necessary. A word of warning, though: although a class exists in QuantLib which implements plain-vanilla options—i.e., simple call and put equity options with either European, American or Bermudan exercise—such class is actually the lowermost leaf of a deep class hierarchy. Having the `Instrument` class at its root, such hierarchy specializes it first with an `Option` class, then again with a `OneAssetOption` class generalizing options on a single underlying, passing through another class or two until it finally defines the `VanillaOption` class we are interested in.

There are good reasons for this; for instance, the code in the `OneAssetOption` class can naturally be reused for, say, Asian options, while that in the `Option` class lends itself for reuse when implementing all kinds of basket options. Unfortunately, this causes the code for pricing a plain option to be spread among all the members of the described inheritance chain, which would not make for an extremely clear example. Therefore, I will describe a simplified `VanillaOption` class with the same implementation as the one in the library, but inheriting directly from the `Instrument` class; all code implemented in the intermediate classes will be shown as if it were implemented in the example class rather than inherited.

The listing below shows the interface of our vanilla-option class. It declares the required methods from the `Instrument` interface, as well as accessors for additional results, namely, the greeks of the options; as pointed out in the previous section, the corresponding data members are declared as `mutable` so that their values can be set in the logically constant `calculate` method.

Interface of the `VanillaOption` class.

```
class VanillaOption : public Instrument {
  public:
    // accessory classes
    class arguments;
    class results;
    class engine;
    // constructor
    VanillaOption(const shared_ptr<Payoff>&,
                  const shared_ptr<Exercise>&);
    // implementation of instrument method
    bool isExpired() const;
    void setupArguments(Arguments*) const;
    void fetchResults(const Results*) const;
    // accessors for option-specific results
    Real delta() const;
    Real gamma() const;
    Real theta() const;
    // ...more greeks
  protected:
    void setupExpired() const;
    // option data
    shared_ptr<Payoff> payoff_;
    shared_ptr<Exercise> exercise_;
    // specific results
    mutable Real delta_;
    mutable Real gamma_;
    mutable Real theta_;
    // ...more
};
```

Besides its own data and methods, `VanillaOption` declares a number of accessory classes: that is, the specific argument and result structures and a base pricing engine. They are defined as inner classes to highlight the relationship between them and the option class; their interface is shown in the next listing.

Interface of the `VanillaOption` inner classes.

```
class VanillaOption::arguments
    : public PricingEngine::arguments {
  public:
    // constructor
    arguments();
    void validate() const;
    shared_ptr<Payoff> payoff;
    shared_ptr<Exercise> exercise;
};

class Greeks : public virtual PricingEngine::results {
  public:
    Greeks();
    Real delta, gamma;
    Real theta;
    Real vega;
    Real rho, dividendRho;
};

class VanillaOption::results : public Instrument::results,
                               public Greeks {
  public:
    void reset();
};

class VanillaOption::engine
    : public GenericEngine<VanillaOption::arguments,
                           VanillaOption::results> {};
```

Two comments can be made on such accessory classes. The first is that, making an exception to what I said in my introduction to the example, I didn't declare all data members into the `results` class. This was done in order to point out an implementation detail. One might want to define structures holding a few related and commonly used results; such structures can then be reused by means of inheritance, as exemplified by the `Greeks` structure that is here composed with `Instrument::results` to obtain the final structure. In this case, virtual inheritance from `PricingEngine::results` must be used to avoid the infamous inheritance diamond (see, for instance, Stroustrup, 2013; the name is in the index).

The second comment is that, as shown, it is sufficient to inherit from the class template `GenericEngine` (instantiated with the right argument and result types) to provide a base class for instrument-specific pricing engines. We will see that derived classes only need to implement their `calculate` method.

We now turn to the implementation of the `VanillaOption` class, shown in the following listing.

Implementation of the `VanillaOption` class.

```
VanillaOption::VanillaOption(
    const shared_ptr<StrikedTypePayoff>& payoff,
    const shared_ptr<Exercise>& exercise)
: payoff_(payoff), exercise_(exercise) {}

bool VanillaOption::isExpired() const {
    Date today = Settings::instance().evaluationDate();
    return exercise_->lastDate() < today;
}

void VanillaOption::setupExpired() const {
    Instrument::setupExpired();
    delta_ = gamma_ = theta_ = ... = 0.0;
}

void VanillaOption::setupArguments(
                   PricingEngine::arguments* args) const {
    VanillaOption::arguments* arguments =
        dynamic_cast<VanillaOption::arguments*>(args);
    QL_REQUIRE(arguments != 0, "wrong argument type");
    arguments->exercise = exercise_;
    arguments->payoff = payoff_;
}

void VanillaOption::fetchResults(
                  const PricingEngine::results* r) const {
    Instrument::fetchResults(r);
    const VanillaOption::results* results =
        dynamic_cast<const VanillaOption::results*>(r);
    QL_ENSURE(results != 0, "wrong result type");
    delta_ = results->delta;
    ... // other Greeks
}

Real VanillaOption::delta() const {
    calculate();
    QL_ENSURE(delta_ != Null<Real>(), "delta not given");
    return delta_;
}
```

Its constructor takes a few objects defining the instrument. Most of them will be described in later chapters or in appendix A. For the time being, suffice to say that the payoff contains the strike and type (i.e., call or put) of the option, and the exercise contains information on the exercise dates and variety (i.e., European, American, or Bermudan). The passed arguments are stored in the corresponding data members. Also, note that they do not include market data; those will be passed elsewhere.

The methods related to expiration are straightforward; `isExpired` checks whether the latest exercise date is passed, while `setupExpired` calls the base-class implementation and sets the instrument-specific data to `0`.

The `setupArguments` and `fetchResults` methods are a bit more interesting. The former starts by downcasting the generic `argument` pointer to the actual type required, raising an exception if another type was passed; it then turns to the actual work. In some cases, the data members are just copied verbatim into the corresponding argument slots. However, it might be the case that the same calculations (say, converting dates into times) will be needed by a number of engines; `setupArguments` provides a place to write them just once.

The `fetchResults` method is the dual of `setupArguments`. It also starts by downcasting the passed `results` pointer; after verifying its actual type, it copies the results into his own data members.

Any method that returns additional results, such as `delta`, will do as `NPV` does: it will call `calculate`, check that the corresponding result was cached (because any given engine might or might not be able to calculate it) and return it.

The above implementation is everything we needed to have a working instrument—working, that is, once it is set an engine which will perform the required calculations. Such an engine is sketched in the listing below and implements the analytic Black-Scholes-Merton formula for European options.

Sketch of an engine for the `VanillaOption` class.

```
    class AnalyticEuropeanEngine
        : public VanillaOption::engine {
      public:
        AnalyticEuropeanEngine(
          const shared_ptr<GeneralizedBlackScholesProcess>&
                                                       process)
        : process_(process) {
            registerWith(process);
        }
        void calculate() const {
          QL_REQUIRE(
              arguments_.exercise->type() == Exercise::European,
              "not an European option");
          shared_ptr<PlainVanillaPayoff> payoff =
             dynamic_pointer_cast<PlainVanillaPayoff>(
                                             arguments_.payoff);
          QL_REQUIRE(process, "Black-Scholes process needed");
          ... // other requirements

          Real spot = process_->stateVariable()->value();
          ... // other needed quantities

          BlackCalculator black(payoff, forwardPrice,
                                stdDev, discount);

          results_.value = black.value();
          results_.delta = black.delta(spot);
          ... // other greeks
        }
      private:
        shared_ptr<GeneralizedBlackScholesProcess> process_;
    };
```

Its constructor takes (and registers itself with) a Black-Scholes stochastic process that contains market-data information about the underlying including present value, risk-free rate, dividend yield, and volatility. Once again, the actual calculations are hidden behind the interface of another class, namely, the `BlackCalculator` class. However, the code has enough detail to show a few relevant features.

The method starts by verifying a few preconditions. This might come as a surprise, since the arguments of the calculations were already validated by the time the `calculate` method is called. However, any given engine can have further requirements to be fulfilled before its calculations can be performed. In the case of our engine, one such requirement is that the option is European and that the payoff is a plain call/put one, which also means that the payoff will be cast down to the needed class.[10]

In the middle section of the method, the engine extracts from the passed arguments any information not already presented in digested form. Shown here is the retrieval of the spot price of the underlying; other quantities needed by the engine, e.g., the forward price of the underlying and the risk-free discount factor at maturity, are also extracted.[11]

Finally, the calculation is performed and the results are stored in the corresponding slots of the results structure. This concludes both the `calculate` method and the example.

[10]`dynamic_pointer_cast` is the equivalent of `dynamic_cast` for shared pointers.
[11]You can find the full code of the engine in the QuantLib sources.

A. Odds and ends

A number of basic issues with the usage of QuantLib have been glossed over in the previous chapters, in order not to undermine their readability (if any) with an accumulation of technical details; as pointed out by Douglas Adams in the fourth book of its *Hitchhiker* trilogy,[12]

> [An excessive amount of detail] is guff. It doesn't advance the action. It makes for nice fat books such as the American market thrives on, but it doesn't actually get you anywhere.

This appendix provides a quick reference to some such issues. It is not meant to be exhaustive nor systematic;[13] if you need that kind of documentation, check the QuantLib reference manual, available at the QuantLib web site.

Basic types

The library interfaces don't use built-in types; instead, a number of typedefs are provided such as `Time`, `Rate`, `Integer`, or `Size`. They are all mapped to basic types (we talked about using full-featured types, possibly with range checking, but we dumped the idea). Furthermore, all floating-point types are defined as `Real`, which in turn is defined as `double`. This makes it possible to change all of them consistently by just changing `Real`.

In principle, this would allow one to choose the desired level of accuracy; but to this, the test-suite answers "Fiddlesticks!" since it shows a few failures when `Real` is defined as `float` or `long double`. The value of the typedefs is really in making the code more clear—and in allowing dimensional analysis for those who, like me, were used to it in a previous life as a physicist; for instance, expressions such as `exp(r)` or `r+s*t` can be immediately flagged as fishy if they are preceded by `Rate r`, `Spread s`, and `Time t`.

Of course, all those fancy types are only aliases to `double` and the compiler doesn't really distinguish between them. It would nice if they had stronger typing; so that, for instance, one could overload a method based on whether it is passed a price or a volatility.

One possibility would be the `BOOST_STRONG_TYPEDEF` macro, which is one of the bazillion utilities provided by Boost. It is used as, say,

[12]No, it's not a mistake. It is an inaccurately-named trilogy of five books. It's a long story.
[13]Nor automatic, nor hydromatic. That would be the Grease Lightning.

```
BOOST_STRONG_TYPEDEF(double, Time)
BOOST_STRONG_TYPEDEF(double, Rate)
```

and creates a corresponding proper class with appropriate conversions to and from the underlying type. This would allow overloading methods, but has the drawbacks that not all conversions are explicit. This would break backward compatibility and make things generally awkward.[14]

Also, the classes defined by the macro overload all operators: you can happily add a time to a rate, even though it doesn't make sense (yes, dimensional analysis again). It would be nice if the type system prevented this from compiling, while still allowing, for instance, to add a spread to a rate yielding another rate or to multiply a rate by a time yielding a pure number.

How to do this in a generic way, and ideally with no run-time costs, was shown first by Barton and Nackman, 1995; a variation of their idea is implemented in the Boost.Units library, and a simpler one was implemented once by yours truly while still working in Physics.[15] However, that might be overkill here; we don't have to deal with all possible combinations of length, mass, time and so on.

The ideal compromise for a future library might be to implement wrapper classes (à la Boost strong typedef) and to define explicitly which operators are allowed for which types. As usual, we're not the first ones to have this problem: the idea has been floating around for a while, and at some point a proposal was put forward (Brown, 2013) to add to C++ a new feature, called *opaque typedefs*, which would have made it easier to define this kind of types.

A final note: among these types, there is at least one which is not determined on its own (like `Rate` or `Time`) but depends on other types. The volatility of a price and the volatility of a rate have different dimensions, and thus should have different types. In short, `Volatility` should be a template type.

Date calculations

Date calculations are among the basic tools of quantitative finance. As can be expected, QuantLib provides a number of facilities for this task; I briefly describe some of them in the following subsections.

Dates and periods

An instance of the `Date` class represents a specific day such as November 15th, 2014. This class provides a number of methods for retrieving basic information such as the weekday, the day of the month, or the year; static information such as the minimum and maximum date allowed (at this time, January 1st, 1901 and December 31st, 2199, respectively) or whether or not a given year is a leap year; or other information such as a date's Excel-compatible serial number or whether or not a given date is the last date of the month. The complete list of available methods and their interface

[14]For instance, a simple expression like `Time t = 2.0;` wouldn't compile. You'd also have to write `f(Time(1.5))` instead of just `f(1.5)`, even if `f` wasn't overloaded.

[15]I won't explain it here, but go read it. It's almost insanely cool.

is documented in the reference manual. No time information is included (unless you enable an experimental compilation switch).

Capitalizing on C++ features, the `Date` class also overloads a number of operators so that date algebra can be written in a natural way; for example, one can write expressions such as `++d`, which advances the date `d` by one day; `d + 2`, which yields the date two days after the given date; `d2 - d1`, which yields the number of days between the two dates; `d - 3*Weeks`, which yields the date three weeks before the given date (and incidentally, features a member of the available `TimeUnit` enumeration, the other members being `Days`, `Months`, and `Years`); or `d1 < d2`, which yields `true` if the first date is earlier than the second one. The algebra implemented in the `Date` class works on calendar days; neither bank holidays nor business-day conventions are taken into account.

The `Period` class models lengths of time such as two days, three weeks, or five years by storing a `TimeUnit` and an integer. It provides a limited algebra and a partial ordering. For the non mathematically inclined, this means that two `Period` instances might or might not be compared to see which is the shorter; while it is clear that, say, 11 months are less than one year, it is not possible to determine whether 60 days are more or less than two months without knowing *which* two months. When the comparison cannot be decided, an exception is thrown.

And of course, even when the comparison seems obvious, we managed to sneak in a few surprises. For instance, the comparison

```
    Period(7,Days) == Period(1,Weeks)
```

returns `true`. It seems correct, right? Hold that thought.

Calendars

Holidays and business days are the domain of the `Calendar` class. Several derived classes exist which define holidays for a number of markets; the base class defines simple methods for determining whether or not a date corresponds to a holiday or a business day, as well as more complex ones for performing tasks such as adjusting a holiday to the nearest business day (where “nearest” can be defined according to a number of business-day conventions, listed in the `BusinessDayConvention` enumeration) or advancing a date by a given period or number of business days.

It might be interesting to see how the behavior of a calendar changes depending on the market it describes. One way would have been to store in the `Calendar` instance the list of holidays for the corresponding market; however, for maintainability we wanted to code the actual calendar rules (such as “the fourth Thursday in November” or “December 25th of every year”) rather than enumerating the resulting dates for a couple of centuries. Another obvious way would have been to use polymorphism and the Template Method pattern; derived calendars would override the `isBusinessDay` method, from which all others could be implemented. This is fine, but it has the shortcoming that calendars would need to be passed and stored in `shared_ptr`s. The class is conceptually simple, though, and is used frequently enough that we wanted users to instantiate it and pass it around more easily—that is, without the added verbosity of dynamic allocation.

The final solution was the one shown in the listing below. It is a variation of the *pimpl* idiom, also reminiscent of the Strategy or Bridge patterns; these days, the cool kids might call it *type erasure*, too (Becker,2007).

Outline of the `Calendar` class.

```
class Calendar {
  protected:
    class Impl {
      public:
        virtual ~Impl() {}
        virtual bool isBusinessDay(const Date&) const = 0;
    };
    shared_ptr<Impl> impl_;
  public:
    bool isBusinessDay(const Date& d) const {
        return impl_->isBusinessDay(d);
    }
    bool isHoliday(const Date& d) const {
        return !isBusinessDay(d);
    }
    Date adjust(const Date& d,
                BusinessDayConvention c = Following) const {
        // uses isBusinessDay() plus some logic
    }
    Date advance(const Date& d,
                 const Period& period,
                 BusinessDayConvention c = Following,
                 bool endOfMonth = false) const {
        // uses isBusinessDay() and possibly adjust()
    }
    // more methods
};
```

Long story short: `Calendar` declares a polymorphic inner class `Impl` to which the implementation of the business-day rules is delegated and stores a pointer to one of its instances. The non-virtual `isBusinessDay` method of the `Calendar` class forwards to the corresponding method in `Calendar::Impl`; following somewhat the Template Method pattern, the other `Calendar` methods are also non-virtual and implemented (directly or indirectly) in terms of `isBusinessDay`.[16]

Coming back to this after all these years, though, I'm thinking that we might have implemented all public methods in terms of `isHoliday` instead. Why? Because all calendars are defined by stating which days are holidays (e.g., Christmas on December 25th in a lot of places, or MLK Day on the

[16]The same technique is used in a number of other classes, such as `DayCounter` in the next section or `Parameter` from chapter 5.

third Monday in January in the United States). Having `isBusinessDay` in the `Impl` interface instead forces all derived classes to negate that logic instead of implementing it directly. It's like having them implement `isNotHoliday`.

Derived calendar classes can provide specialized behavior by defining an inner class derived from `Calendar::Impl`; their constructor will create a shared pointer to an `Impl` instance and store it in the `impl_` data member of the base class. The resulting calendar can be safely copied by any class that need to store a `Calendar` instance; even when sliced, it will maintain the correct behavior thanks to the contained pointer to the polymorphic `Impl` class. Finally, we can note that instances of the same derived calendar class can share the same `Impl` instance. This can be seen as an implementation of the Flyweight pattern—bringing the grand total to about two and a half patterns for one deceptively simple class.

Enough with the implementation of `Calendar`, and back to its behavior. Here's the surprise I mentioned in the previous section. Remember `Period(1,Weeks)` being equal to `Period(7,Days)`? Except that for the `advance` method of a calendar, 7 days means 7 *business* days. Thus, we have a situation in which two periods `p1` and `p2` are equal (that is, `p1 == p2` returns `true`) but `calendar.advance(p1)` differs from `calendar.advance(p2)`. Yay, us.

I'm not sure I have a good idea for a solution here. Since we want backwards compatibility, the current uses of `Days` must keep working in the same way; so it's not possible, say, to start interpreting `calendar.advance(7, Days)` as 7 calendar days. One way out might be to keep the current situation, introduce two new enumeration cases `BusinessDays` and `CalendarDays` that remove the ambiguity, and deprecate `Days`. Another is to just remove the inconsistency by dictating that a 7-days period do not, in fact, equal one week; I'm not overly happy about this one.

As I said, no obvious solution. If you have any other suggestions, I'm all ears.

Day-count conventions

The `DayCounter` class provides the means to calculate the distance between two dates, either as a number of days or a fraction of an year, according to different conventions. Derived classes such as `Actual360` or `Thirty360` exist; they implement polymorphic behavior by means of the same technique used by the `Calendar` class and described in the previous section.

Unfortunately, the interface has a bit of a rough edge. Instead of just taking two dates, the `yearFraction` method is declared as

```
Time yearFraction(const Date&,
                  const Date&,
                  const Date& refPeriodStart = Date(),
                  const Date& refPeriodEnd = Date()) const;
```

The two optional dates are required by one specific day-count convention (namely, the ISMA actual/actual convention) that requires a reference period to be specified besides the two input dates.

To keep a common interface, we had to add the two additional dates to the signature of the method for all day counters (most of which happily ignore them). This is not the only mischief caused by this day counter; you'll see another in the next section.

Schedules

The `Schedule` class, shown in the next listing, is used to generate sequences of coupon dates.

Interface of the `Schedule` class.

```
class Schedule {
  public:
    Schedule(const Date& effectiveDate,
             const Date& terminationDate,
             const Period& tenor,
             const Calendar& calendar,
             BusinessDayConvention convention,
             BusinessDayConvention terminationDateConvention,
             DateGeneration::Rule rule,
             bool endOfMonth,
             const Date& firstDate = Date(),
             const Date& nextToLastDate = Date());
    Schedule(const std::vector<Date>&,
             const Calendar& calendar = NullCalendar(),
             BusinessDayConvention convention = Unadjusted,
             ... /* `other optional parameters` */);

    Size size() const;
    bool empty() const;
    const Date& operator[](Size i) const;
    const Date& at(Size i) const;
    const_iterator begin() const;
    const_iterator end() const;

    const Calendar& calendar() const;
    const Period& tenor() const;
    bool isRegular(Size i) const;
    Date previousDate(const Date& refDate) const;
    Date nextDate(const Date& refDate) const;
    ... // other inspectors and utilities
};
```

Following practice and ISDA conventions, this class has to accept a lot of parameters; you can see them as the argument list of its constructor. (Oh, and you'll forgive me if I don't go and explain all of them. I'm sure you can guess what they mean.) They're probably too many, which is why the library uses the Named Parameter Idiom (already described in chapter 4) to provide a less unwieldy factory class. With its help, a schedule can be instantiated as

```
Schedule s = MakeSchedule().from(startDate).to(endDate)
             .withFrequency(Semiannual)
             .withCalendar(TARGET())
             .withNextToLastDate(stubDate)
             .backwards();
```

Other methods include on the one hand, inspectors for the stored data; and on the other hand, methods to give the class a sequence interface, e.g., `size`, `operator[]`, `begin`, and `end`.

The `Schedule` class has a second constructor, taking a precomputed vector of dates and a number of optional parameters, which might be passed to help the library use the resulting schedule correctly. Such information includes the date generation rule or whether the dates are aligned to the end of the month, but mainly, you'll probably need to pass the `tenor` and an `isRegular` vector of bools, about which I need to spend a couple of words.

What does "regular" mean? The boolean `isRegular(i)` doesn't refer to the `i`-th date, but to the `i`-th interval; that is, the one between the `i`-th and `(i+1)`-th dates. When a schedule is built based on a tenor, most intervals correspond to the passed tenor (and thus are regular) but the first and last intervals might be shorter or longer depending on whether we passed an explicit first or next-to-last date. We might do this, e.g., when we want to specify a short first coupon.

If we build the schedule with a precomputed set of dates, we don't have the tenor information and we can't tell if a given interval is regular unless those pieces of information are passed to the schedule.[17] In turn, this means that using that schedule to build a sequence of coupons (by passing it, say, to the constructor of a fixed-rate bond) might give us the wrong result. And why, oh, why does the bond needs this missing info in order to build the coupons? Again, because the day-count convention of the bond might be ISMA actual/actual, which needs a reference period; and in order to calculate the reference period, we need to know the coupon tenor. In absence of this information, all the bond can do is assume that the coupon is regular, that is, that the distance between the passed start and end dates of the coupon also corresponds to its tenor.

Finance-related classes

Given our domain, it is only to be expected that a number of classes directly model financial concepts. A few such classes are described in this section.

[17]Well, we could use heuristics, but it could get ugly fast.

Market quotes

There are at least two possibilities to model quoted values. One is to model quotes as a sequence of static values, each with an associated timestamp, with the current value being the latest; the other is to model the current value as a quoted value that changes dynamically.

Both views are useful; and in fact, both were implemented in the library. The first model corresponds to the `TimeSeries` class, which I won't describe in detail here; it is basically a map between dates and values, with methods to retrieve values at given dates and to iterate on the existing values, and it was never really used in other parts of the library. The second resulted in the `Quote` class, shown in the following listing.

Interface of the `Quote` class.

```
class Quote : public virtual Observable {
  public:
    virtual ~Quote() {}
    virtual Real value() const = 0;
    virtual bool isValid() const = 0;
};
```

Its interface is slim enough. The class inherits from the `Observable` class, so that it can notify its dependent objects when its value change. It declares the `isValid` method, that tells whether or not the quote contains a valid value (as opposed to, say, no value, or maybe an expired value) and the `value` method, which returns the current value.

These two methods are enough to provide the needed behavior. Any other object whose behavior or value depends on market values (for example, the bootstrap helpers of chapter 2) can store handles to the corresponding quotes and register with them as an observer. From that point onwards, it will be able to access the current values at any time.

The library defines a number of quotes—that is, of implementations of the `Quote` interface. Some of them return values which are derived from others; for instance, `ImpliedStdDevQuote` turns option prices into implied-volatility values. Others adapt other objects; `ForwardValueQuote` returns forward index fixings as the underlying term structures change, while `LastFixingQuote` returns the latest value in a time series.

At this time, only one implementation is an genuine source of external values; that would be the `SimpleQuote` class, shown in the next listing.

Implementation of the `SimpleQuote` class.

```
class SimpleQuote : public Quote {
  public:
    SimpleQuote(Real value = Null<Real>())
    : value_(value) {}

    Real value() const {
        QL_REQUIRE(isValid(), "invalid SimpleQuote");
        return value_;
    }

    bool isValid() const {
        return value_!=Null<Real>();
    }

    Real setValue(Real value) {
        Real diff = value-value_;
        if (diff != 0.0) {
            value_ = value;
            notifyObservers();
        }
        return diff;
    }

  private:
    Real value_;
};
```

It is simple in the sense that it doesn't implement any particular data-feed interface: new values are set manually by calling the appropriate method. The latest value (possibly equal to `Null<Real>()` to indicate no value) is stored in a data member. The `Quote` interface is implemented by having the `value` method return the stored value, and the `isValid` method checking whether it's null. The method used to feed new values is `setValue`; it takes the new value, notifies its observers if it differs from the latest stored one, and returns the increment between the old and new values.[18]

I'll conclude this post with a few short notes. The first is that the type of the quoted values is constrained to `Real`. This has not been a limitation so far, and besides, it's now too late to define `Quote` as a class template; so it's unlikely that this will ever change.

The second is that the original idea was that the `Quote` interface would act as an adapter to actual data feeds, with different implementations calling the different API and allowing QuantLib to use

[18]The choice to return the latest increment is kind of unusual; the idiomatic choice in C and C++ would be to return the old value.

them in a uniform way. So far, however, nobody provided such implementations; the closer we got was to use data feeds in Excel and set their values to instances of `SimpleQuote`.

The last (and a bit longer) note is that the interface of `SimpleQuote` might be modified in future to allow more advanced uses. When setting new values to a group of related quotes (say, the quotes interest rates used for bootstrapping a curve) it would be better to only trigger a single notification after all values are set, instead of having each quote send a notification when it's updated. This behavior would be both faster, since chains of notifications turn out to be quite the time sink, and safer, since no observer would risk to recalculate after only a subset of the quotes are updated. The change (namely, an additional `silent` parameter to `setValue` that would mute notifications when equal to `true`) has already been implemented in a fork of the library, and could be added to QuantLib too.

Interest rates

The `InterestRate` class (shown in the listing that follows) encapsulates general interest-rate calculations. Instances of this class are built from a rate, a day-count convention, a compounding convention, and a compounding frequency (note, though, that the value of the rate is always annualized, whatever the frequency). This allows one to specify rates such as "5%, actual/365, continuously compounded" or "2.5%, actual/360, semiannually compounded." As can be seen, the frequency is not always needed. I'll return to this later.

Outline of the `InterestRate` class.

```
enum Compounding { Simple,              // 1+rT
                   Compounded,          // (1+r)^T
                   Continuous,          // e^{rT}
                   SimpleThenCompounded
};

class InterestRate {
  public:
    InterestRate(Rate r,
                 const DayCounter&,
                 Compounding,
                 Frequency);
    // inspectors
    Rate rate() const;
    const DayCounter& dayCounter();
    Compounding compounding() const;
    Frequency frequency() const;
    // automatic conversion
    operator Rate() const;
    // implied discount factor and compounding after a given time
```

```
        // (or between two given dates)
        DiscountFactor discountFactor(Time t) const;
        DiscountFactor discountFactor(const Date& d1,
                                      const Date& d2) const;
        Real compoundFactor(Time t) const;
        Real compoundFactor(const Date& d1,
                            const Date& d2) const;
        // other calculations
        static InterestRate impliedRate(Real compound,
                                        const DayCounter&,
                                        Compounding,
                                        Frequency,
                                        Time t);
        ... // same with dates
        InterestRate equivalentRate(Compounding,
                                    Frequency,
                                    Time t) const;
        ... // same with dates
    };
```

Besides the obvious inspectors, the class provides a number of methods. One is the conversion operator to `Rate`, i.e., to `double`. On afterthought, this is kind of risky, as the converted value loses any day-count and compounding information; this might allow, say, a simply-compounded rate to slip undetected where a continuously-compounded one was expected. The conversion was added for backward compatibility when the `InterestRate` class was first introduced; it might be removed in a future revision of the library, dependent on the level of safety we want to force on users.[19]

Other methods complete a basic set of calculations. The `compoundFactor` returns the unit amount compounded for a time t (or equivalently, between two dates d_1 and d_2) according to the given interest rate; the `discountFactor` method returns the discount factor between two dates or for a time, i.e., the reciprocal of the compound factor; the `impliedRate` method returns a rate that, given a set of conventions, yields a given compound factor over a given time; and the `equivalentRate` method converts a rate to an equivalent one with different conventions (that is, one that results in the same compounded amount).

Like the `InterestRate` constructor, some of these methods take a compounding frequency. As I mentioned, this doesn't always make sense; and in fact, the `Frequency` enumeration has a `NoFrequency` item just to cover this case.

Obviously, this is a bit of a smell. Ideally, the frequency should be associated only with those compounding conventions that need it, and left out entirely for those (such as `Simple` and `Continuous`) that don't. If C++ supported it, we would write something like

[19]There are different views on safety among the core developers, ranging from "babysit the user and don't let him hurt himself" to "give him his part of the inheritance, pat him on his back, and send him to find his place in the world."

```
    enum Compounding { Simple,
                       Compounded(Frequency),
                       Continuous,
                       SimpleThenCompounded(Frequency)
    };
```

which would be similar to algebraic data types in functional languages, or case classes in Scala;[20] but unfortunately that's not an option. To have something of this kind, we'd have to go for a full-featured Strategy pattern and turn `Compounding` into a class hierarchy. That would probably be overkill for the needs of this class, so we're keeping both the enumeration and the smell.

Indexes

Like other classes such as `Instrument` and `TermStructure`, the `Index` class is a pretty wide umbrella: it covers concepts such as interest-rate indexes, inflation indexes, stock indexes—you get the drift.

Needless to say, the modeled entities are diverse enough that the `Index` class has very little interface to call its own. As shown in the following listing, all its methods have to do with index fixings.

Interface of the `Index` class.

```
    class Index : public Observable {
      public:
        virtual ~Index() {}
        virtual std::string name() const = 0;
        virtual Calendar fixingCalendar() const = 0;
        virtual bool isValidFixingDate(const Date& fixingDate)
                                                    const = 0;
        virtual Real fixing(const Date& fixingDate,
                            bool forecastTodaysFixing = false)
                                                    const = 0;
        virtual void addFixing(const Date& fixingDate,
                               Real fixing,
                               bool forceOverwrite = false);
        void clearFixings();
    };
```

The `isValidFixingDate` method tells us whether a fixing was (or will be made) on a given date; the `fixingCalendar` method returns the calendar used to determine the valid dates; and the `fixing` method retrieves a fixing for a past date or forecasts one for a future date. The remaining methods deal specifically with past fixings: the `name` method, which returns an identifier that must be unique

[20]Both support pattern matching on an object, which is like a neater `switch` on steroids. Go have a look when you have some time.

for each index, is used to index (pun not intended) into a map of stored fixings; the `addFixing` method stores a fixing (or many, in other overloads not shown here); and the `clearFixing` method clears all stored fixings for the given index.

Why the map, and where is it in the `Index` class? Well, we started from the requirement that past fixings should be shared rather than per-instance; if one stored, say, the 6-months Euribor fixing for a date, we wanted the fixing to be visible to all instances of the same index,[21] and not just the particular one whose `addFixing` method we called. This was done by defining and using an `IndexManager` singleton behind the curtains. Smelly? Sure, as all singletons. An alternative might have been to define static class variables in each derived class to store the fixings; but that would have forced us to duplicate them in each derived class with no real advantage (it would be as much against concurrency as the singleton).

Since the returned index fixings might change (either because their forecast values depend on other varying objects, or because a newly available fixing is added and replaces a forecast) the `Index` class inherits from `Observable` so that instruments can register with its instances and be notified of such changes.

At this time, `Index` doesn't inherit from `Observer`, although its derived classes do (not surprisingly, since forecast fixings will almost always depend on some observable market quote). This was not an explicit design choice, but rather an artifact of the evolution of the code and might change in future releases. However, even if we were to inherit `Index` from `Observer`, we would still be forced to have some code duplication in derived classes, for a reason which is probably worth describing in more detail.

I already mentioned that fixings can change for two reasons. One is that the index depends on other observables to forecast its fixings; in this case, it simply registers with them (this is done in each derived class, as each class has different observables). The other reason is that a new fixing might be made available, and that's more tricky to handle. The fixing is stored by a call to `addFixing` on a particular index instance, so it seems like no external notification would be necessary, and that the index can just call the `notifyObservers` method to notify its observers; but that's not the case. As I said, the fixings is shared; if we store today's 3-months Euribor fixing, it will be available to all instances of such index, and thus we want all of them to be aware of the change. Moreover, instruments and curves might have registered with any of those `Index` instances, so all of them must send in turn a notification.

The solution is to have all instances of the same index communicate by means of a shared object; namely, we used the same `IndexManager` singleton that stores all index fixings. As I said, `IndexManager` maps unique index tags to sets of fixings; also, by making the sets instances of the `ObservableValue` class, it provides the means to register and receive notification when one or more fixings are added for a specific tag (this class is described later in this appendix. You don't need the details here).

All pieces are now in place. Upon construction, any `Index` instance will ask `IndexManager` for the

[21]Note that by "instances of the same index" I mean here instances of the same specific index, not of the same class (which might group different indexes); for instance, `USDLibor(3*Months)` and `USDLibor(6*Months)` are *not* instances of the same index; two different `USDLibor(3*Months)` are.

shared observable corresponding to the tag returned by its `name` method. When we call `addFixings` on, say, some particular 6-months Euribor index, the fixing will be stored into `IndexManager`; the observable will send a notification to all 6-months Euribor indexes alive at that time; and all will be well with the world.

However, C++ still throws a small wrench in our gears. Given the above, it would be tempting to call

```
    registerWith(IndexManager::instance().notifier(name()));
```

in the `Index` constructor and be done with it. However, it wouldn't work; for the reason that in the constructor of the base class, the call to the virtual method `name` wouldn't be polymorphic.[22] From here stems the code duplication I mentioned a few paragraphs earlier; in order to work, the above method call must be added to the constructor of each derived index class which implements or overrides the `name` method. The `Index` class itself doesn't have a constructor (apart from the default one that the compiler provides).

As an example of a concrete class derived from `Index`, the next listing sketches the `InterestRateIndex` class.

Sketch of the `InterestRateIndex` class.

```
    class InterestRateIndex : public Index, public Observer {
      public:
        InterestRateIndex(const std::string& familyName,
                          const Period& tenor,
                          Natural settlementDays,
                          const Currency& currency,
                          const Calendar& fixingCalendar,
                          const DayCounter& dayCounter);
        : familyName_(familyName), tenor_(tenor), ... {
            registerWith(Settings::instance().evaluationDate());
            registerWith(
                     IndexManager::instance().notifier(name()));
        }

        std::string name() const;
        Calendar fixingCalendar() const;
        bool isValidFixingDate(const Date& fixingDate) const {
            return fixingCalendar().isBusinessDay(fixingDate);
        }
        Rate fixing(const Date& fixingDate,
```

[22] If you're not familiar with the darker corners of C++: when the constructor of a base class is executed, any data members defined in derived classes are not yet built. Since any behavior specific to the derived class is likely to depend on such yet-not-existing data, C++ bails out and uses the base-class implementation of any virtual method called in the base-class constructor body.

```
                        bool forecastTodaysFixing = false) const;
        void update() { notifyObservers(); }

        std::string familyName() const;
        Period tenor() const;
        ... // other inspectors

        Date fixingDate(const Date& valueDate) const;
        virtual Date valueDate(const Date& fixingDate) const;
        virtual Date maturityDate(const Date& valueDate) const = 0;
      protected:
        virtual Rate forecastFixing(const Date& fixingDate)
                                                      const = 0;
        std::string familyName_;
        Period tenor_;
        Natural fixingDays_;
        Calendar fixingCalendar_;
        Currency currency_;
        DayCounter dayCounter_;
    };

    std::string InterestRateIndex::name() const {
        std::ostringstream out;
        out << familyName_;
        if (tenor_ == 1*Days) {
            if (fixingDays_==0) out << "ON";
            else if (fixingDays_==1) out << "TN";
            else if (fixingDays_==2) out << "SN";
            else out << io::short_period(tenor_);
        } else {
            out << io::short_period(tenor_);
        }
        out << " " << dayCounter_.name();
        return out.str();
    }

    Rate InterestRateIndex::fixing(
                           const Date& d,
                           bool forecastTodaysFixing) const {
        QL_REQUIRE(isValidFixingDate(d), ...);
        Date today = Settings::instance().evaluationDate();
        if (d < today) {
            Rate pastFixing =
                IndexManager::instance().getHistory(name())[d];
            QL_REQUIRE(pastFixing != Null<Real>(), ...);
            return pastFixing;
        }
        if (d == today && !forecastTodaysFixing) {
            Rate pastFixing = ...;
            if (pastFixing != Null<Real>())
                return pastFixing;
        }
        return forecastFixing(d);
    }

    Date InterestRateIndex::valueDate(const Date& d) const {
        QL_REQUIRE(isValidFixingDate(d) ...);
        return fixingCalendar().advance(d, fixingDays_, Days);
    }
```

As you might expect, such class defines a good deal of specific behavior besides what it inherits from `Index`. To begin with, it inherits from `Observer`, too, since `Index` doesn't. The `InterestRateIndex` constructor takes the data needed to specify the index: a family name, as in "Euribor", common to different indexes of the same family such as, say, 3-months and 6-months Euribor; a tenor that specifies a particular index in the family; and additional information such as the number of settlement days, the index currency, the fixing calendar, and the day-count convention used for accrual.

The passed data are, of course, copied into the corresponding data members; then the index registers with a couple of observables. The first is the global evaluation date; this is needed because, as I'll explain shortly, there's a bit of date-specific behavior in the class that is triggered when an instance is asked for today's fixing. The second observable is the one which is contained inside `IndexManager` and provides notifications when new fixings are stored. We can identify this observable here: the `InterestRateIndex` class has all the information needed to determine the index, so it can implement the `name` method and call it. However, this also means that classes deriving from `InterestRateIndex` must not override `name`; since the overridden method would not be called in the body of this constructor (as explained earlier), they would register with the wrong notifier. Unfortunately, this can't be enforced in C++, which doesn't have a keyword like `final` in Java or `sealed` in C#; but the alternative would be to require that all classes derived from `InterestRateIndex` register with `IndexManager`, which is equally not enforceable, probably more error-prone, and certainly less convenient.

The other methods defined in `InterestRateIndex` have different purposes. A few implement the required `Index` and `Observer` interfaces; the simplest are `update`, which simply forwards any notification, `fixingCalendar`, which returns a copy of the stored calendar instance, and `isValidFixingDate`, which checks the date against the fixing calendar.

The `name` method is a bit more complicated. It stitches together the family name, a short representation of the tenor, and the day-count convention to get an index name such as “Euribor 6M Act/360” or “USD Libor 3M Act/360”; special tenors such as overnight, tomorrow-next and spot-next are detected so that the corresponding acronyms are used.

The `fixing` method contains the most logic. First, the required fixing date is checked and an exception is raised if no fixing was supposed to take place on it. Then, the fixing date is checked against today’s date. If the fixing was in the past, it must be among those stored in the `IndexManager` singleton; if not, an exception is raised since there’s no way we can forecast a past fixing. If today’s fixing was requested, the index first tries looking for the fixing in the `IndexManager` and returns it if found; otherwise, the fixing is not yet available. In this case, as well as for a fixing date in the future, the index forecasts the value of the fixing; this is done by calling the `forecastFixing` method, which is declared as purely virtual in this class and implemented in derived ones. The logic in the `fixing` method is also the reason why, as I mentioned, the index registers with the evaluation date; the behavior of the index depends on the value of today’s date, so it need to be notified when it changes.

Finally, the `InterestRateIndex` class defines other methods that are not inherited from `Index`. Most of them are inspectors that return stored data such as the family name or the tenor; a few others deal with date calculations. The `valueDate` method takes a fixing date and returns the starting date for the instrument that underlies the rate (for instance, the deposit underlying a LIBOR, which for most currencies starts two business days after the fixing date); the `maturityDate` method takes a value date and returns the maturity of the underlying instrument (e.g., the maturity of the deposit); and the `fixingDate` method is the inverse of `valueDate`, taking a value date and returning the corresponding fixing date. Some of these methods are virtual, so that their behavior can be overridden; for instance, while the default behavior for `valueDate` is to advance the given number of fixing days on the given calendar, LIBOR index mandates first to advance on the London calendar, then to adjust the resulting date on the calendar corresponding to the index currency. For some reason, `fixingDate` is not virtual; this is probably an oversight that should be fixed in a future release.

Aside: how much generalization?

Some of the methods of the `InterestRateIndex` class were evidently designed with LIBOR in mind, since that was the first index of that kind implemented in the library. On the one hand, this makes the class less generic than one would like: for instance, if we were to decide that the 5–10 years swap-rate spread were to be considered an interest-rate index in its own right, we would be hard-pressed to fit it to the interface of the base class and its single `tenor` method. But on the other hand, it is seldom wise to generalize an interface without having a couple of examples of classes that should implement it; and a spread between two indexes (being just that; a spread, not an index) is probably not one such class.

Exercises and payoffs

I'll close this section with a couple of domain-related classes used in the definitions of a few instruments.

First, the `Exercise` class, shown in the listing below.

Interface of the `Exercise` class and its derived classes.

```
class Exercise {
  public:
    enum Type {
        American, Bermudan, European
    };
    explicit Exercise(Type type);
    virtual ~Exercise();
    Type type() const;
    Date date(Size index) const;
    const std::vector<Date>& dates() const;
    Date lastDate() const;
  protected:
    std::vector<Date> dates_;
    Type type_;
};

class EarlyExercise : public Exercise {
  public:
    EarlyExercise(Type type,
                  bool payoffAtExpiry = false);
    bool payoffAtExpiry() const;
};

class AmericanExercise : public EarlyExercise {
  public:
    AmericanExercise(const Date& earliestDate,
                     const Date& latestDate,
                     bool payoffAtExpiry = false);
};

class BermudanExercise : public EarlyExercise {
  public:
    BermudanExercise(const std::vector<Date>& dates,
                     bool payoffAtExpiry = false);
};
```

```
class EuropeanExercise : public Exercise {
  public:
    EuropeanExercise(const Date& date);
};
```

As you would expect, the base class declares methods to retrieve information on the date, or dates, of the exercise. Quite a few of them, actually. There's a `dates` method that returns the set of exercise dates, a `date` method that returns the one at a particular index, and a convenience method `lastDate` that, as you might have guessed, returns the last one; so there's some redundancy there.[23] Also, there's a `type` method that is leaving me scratching my head as I look at the code again.

The `type` method returns the kind of exercise, picking its value from a set (European, Bermudan, or American) declared in an inner enumeration `Exercise::Type`. This is not puzzling *per se*, but it goes somewhat against what we did next, which is to use inheritance to declare `AmericanExercise`, `BermudanExercise`, and `EuropeanExercise` classes. On the one hand, the use of a virtual destructor in the base `Exercise` class seems to suggest that inheritance is the way to go if one wants to define new kind of exercises. On the other hand, enumerating the kind of exercises in the base class seems to go against this kind of extension, since inheriting a new exercise class would also require one to add a new case to the enumeration. For inheritance, one can also argue that the established idiom around the library is to pass around smart pointers to the `Exercise` class; and against inheritance, that the class doesn't define any virtual method except the destructor, and the behavior of an instance of any derived class is only given by the value of the data members stored in the base class. In short: it seems that, when we wrote this, we were even more confused than I am now.

Were I to write it now, I'd probably keep the enumeration and make it a concrete class: the derived classes might either create objects that can be safely sliced to become `Exercise` instances when passed around, or they could be turned into functions returning `Exercise` instances directly. As much as this might irk object-oriented purists, there are a number of places in the code where the type of the exercise need to be checked, and having an enumeration is probably the pragmatic choice when compared to using casts or some kind of visitor pattern. The absence of specific behavior in derived classes seems another hint to me.

As I wrote this, it occurred to me that an exercise might also be an `Event`, as described in chapter 4. However, this doesn't always match what the `Exercise` class models. In the case of a European exercise, we could also model it as an `Event` instance; in the case of a Bermudan exercise, the `Exercise` instance would probably correspond to a set of `Event` instances; and in the case of an American exercise, what we're really modeling here is an exercise range—and as a matter of fact, the meaning of the interface also changes in this case, since the `dates` method no longer returns the set of all possible exercise dates, but just the first and last date in the range. As often happens, the small things that seem obvious turn out to be difficult to model soundly when looked up close.

* * *

[23]Lovers of encapsulation will probably prefer the version taking an index to the one returning a vector, since the latter reveals more than necessary about the internal storage of the class.

Onwards to the `Payoff` class, shown in the next listing together with a few of its derived classes.

Interface of the `Payoff` class and a few derived classes.

```
class Payoff : std::unary_function<Real,Real> {
  public:
    virtual ~Payoff() {}
    virtual std::string name() const = 0;
    virtual std::string description() const = 0;
    virtual Real operator()(Real price) const = 0;
    virtual void accept(AcyclicVisitor&);
};

class TypePayoff : public Payoff {
  public:
    Option::Type optionType() const;
  protected:
    TypePayoff(Option::Type type);
};

class FloatingTypePayoff : public TypePayoff {
  public:
    FloatingTypePayoff(Option::Type type);
    Real operator()(Real price) const;
    // more Payoff interface
};

class StrikedTypePayoff : public TypePayoff {
  public:
    Real strike() const;
    // more Payoff interface
  protected:
    StrikedTypePayoff(Option::Type type,
                      Real strike);
};

class PlainVanillaPayoff : public StrikedTypePayoff {
  public:
    PlainVanillaPayoff(Option::Type type,
                       Real strike);
    Real operator()(Real price) const;
    // more Payoff interface
};
```

Its interface includes an `operator()`, returning the value of the payoff given the value of the underlying, an `accept` method to support the Visitor pattern, and a couple of inspectors (`name` and `description`) which can be used for reporting—and are probably one too many.

In hindsight, we tried to model the class before having a grasp of enough use cases. Unfortunately, the resulting interface stuck. The biggest problem is the dependency of `operator()` on a single underlying, which excludes payoffs based on multiple underlying values.[24] Another one is the over-reliance on inheritance. For instance, we have a `TypePayoff` class that adds a type (`Call` or `Put`, which again might be restrictive) and the corresponding inspector; a `StrikedTypePayoff` which adds a strike; and, finally, `PlainVanillaPayoff`, which models a simple call or put payoff and ends up removed from the `Payoff` class by three levels of inheritance: probably too many, considering that this is used to implement a textbook option and will be looked up by people just starting with the library.

Another misstep we might have made is to add a pointer to a `Payoff` instance to the `Option` class as a data member, with the intent that it should contain the information about the payoff. This led us to classes such as `FloatingTypePayoff`, also shown in the listing. It's used in the implementation of floating lookback options, and stores the information about the type (as in, call or put); but since the strike is fixed at the maturity of the option, it can't specify it and can't implement the payoff with the interface we specified. Its `operator()` throws an exception if invoked. In this case, we might as well do without the payoff and just pass the type to the lookback option; that is, if its base `Option` class didn't expect a payoff.

Math-related classes

The library also needs some mathematical tools, besides those provided by the C++ standard library. Here is a brief overview of some of them.

Interpolations

Interpolations belong to a kind of class which is not common in QuantLib: namely, the kind that might be unsafe to use.

The base class, `Interpolation`, is shown in the listing below. It interpolates two underlying random-access sequences of x and y values, and provides an `operator()` that returns the interpolated values as well as a few other convenience methods. Like the `Calendar` class we saw in a previous section, it implements polymorphic behavior by means of the pimpl idiom: it declares an inner `Impl` class whose derived classes will implement specific interpolations and to which the `Interpolation` class forwards its own method calls. Another inner class template, `templateImpl`, implements the common machinery and stores the underlying data.

[24]This also constrains how we model payoffs based on multiple fixings of an underlying; for instance, Asian options are passed the payoff for a plain option and the average of the fixings is done externally, before passing it to the payoff. One might want the whole process to be described as "the payoff".

Sketch of the **`Interpolation`** class.

```
class Interpolation : public Extrapolator {
  protected:
    class Impl {
      public:
        virtual ~Impl() {}
        virtual void update() = 0;
        virtual Real xMin() const = 0;
        virtual Real xMax() const = 0;
        virtual Real value(Real) const = 0;
        virtual Real primitive(Real) const = 0;
        virtual Real derivative(Real) const = 0;
    };
    template <class I1, class I2>
    class templateImpl : public Impl {
      public:
        templateImpl(const I1& xBegin, const I1& xEnd,
                     const I2& yBegin);
        Real xMin() const;
        Real xMax() const;
      protected:
        Size locate(Real x) const;
        I1 xBegin_, xEnd_;
        I2 yBegin_;
    };
    shared_ptr<Impl> impl_;
  public:
    typedef Real argument_type;
    typedef Real result_type;
    bool empty() const { return !impl_; }
    Real operator()(Real x, bool extrapolate = false) const {
        checkRange(x,extrapolate);
        return impl_->value(x);
    }
    Real primitive(Real x, bool extrapolate = false) const;
    Real derivative(Real x, bool extrapolate = false) const;
    Real xMin() const;
    Real xMax() const;
    void update();
  protected:
    void checkRange(Real x, bool extrapolate) const;
};
```

As you can see, `templateImpl` doesn't copy the x and y values; instead, it just provides a kind of view over them by storing iterators into the two sequences. This is what makes interpolations unsafe: on the one hand, we have to make sure that the lifetime of an `Interpolation` instance doesn't exceed that of the underlying sequences, to avoid pointing into a destroyed object; and on the other hand, any class that stores an `interpolation` instance will have to take special care of copying.

The first requirement is not a big problem. An interpolation is seldom used on its own; it is usually stored as a data member of some other class, together with its underlying data. This takes care of the lifetime issues, as the interpolation and the data live and die together.

The second is not a big problem, either: but whereas the first issue is usually taken care of automatically, this one requires some action on the part of the developer. As I said, the usual case is to have an `Interpolation` instance stored in some class together with its data. The compiler-generated copy constructor for the container class would make new copies of the underlying data, which is correct; but it would also make a new copy of the interpolation that would still be pointing at the original data (since it would store copies of the original iterators). This is, of course, not correct.

To avoid this, the developer of the host class needs to write a user-defined copy constructor that not only copies the data, but also regenerates the interpolation so that it points to the new sequences—which might not be so simple. An object holding an `Interpolation` instance can't know its exact type (which is hidden in the `Impl` class) and thus can't just rebuild it to point somewhere else.

One way out of this would have been to give interpolations some kind of virtual `clone` method to return a new one of the same type, or a virtual `rebind` method to change the underlying iterators once copied. However, that wasn't necessary, as most of the times we already have interpolation traits laying around.

What's that, you say? Well, it's those `Linear` or `LogLinear` classes I've been throwing around while I was explaining interpolated term structures in chapter 3. An example is in the following listing, together with its corresponding interpolation class.

Sketch of the `LinearInterpolation` class and of its traits class.

```
template <class I1, class I2>
class LinearInterpolationImpl
    : public Interpolation::templateImpl<I1,I2> {
  public:
    LinearInterpolationImpl(const I1& xBegin, const I1& xEnd,
                            const I2& yBegin)
    : Interpolation::templateImpl<I1,I2>(xBegin, xEnd, yBegin),
      primitiveConst_(xEnd-xBegin), s_(xEnd-xBegin) {}
    void update();
    Real value(Real x) const {
        Size i = this->locate(x);
        return this->yBegin_[i] + (x-this->xBegin_[i])*s_[i];
    }
```

```
        Real primitive(Real x) const;
        Real derivative(Real x) const;
      private:
        std::vector<Real> primitiveConst_, s_;
    };

    class LinearInterpolation : public Interpolation {
      public:
        template <class I1, class I2>
        LinearInterpolation(const I1& xBegin, const I1& xEnd,
                            const I2& yBegin) {
            impl_ = shared_ptr<Interpolation::Impl>(
                new LinearInterpolationImpl<I1,I2>(xBegin, xEnd,
                                                   yBegin));
            impl_->update();
        }
    };

    class Linear {
      public:
        template <class I1, class I2>
        Interpolation interpolate(const I1& xBegin, const I1& xEnd,
                                  const I2& yBegin) const {
            return LinearInterpolation(xBegin, xEnd, yBegin);
        }
        static const bool global = false;
        static const Size requiredPoints = 2;
    };
```

The `LinearInterpolation` class doesn't have a lot of logic: its only method is a template constructor (the class itself is not a template) that instantiates an inner implementation class. The latter inherits from `templateImpl` and is the one that does the heavy lifting, implementing the actual interpolation formulas (with the help of methods, such as `locate`, defined in its base class).

The `Linear` traits class defines some static information, namely, that we need at least two points for a linear interpolation, and that changing a point only affects the interpolation locally; and also defines an `interpolate` method that can create an interpolation of a specific type from a set of iterators into x and y. The latter method is implemented with the same interface by all traits (when an interpolation, such as splines, needs more parameters, they are passed to the traits constructor and stored) and is the one that's going to help in our copying problem. If you look, for instance, at the listing of the `InterpolatedZeroCurve` class back in chapter 3, you'll see that we're storing an instance of the traits class (it's called `interpolator_` there) together with the interpolation and the underlying data. If we do the same in any class that stores an interpolation, we'll be able to use the traits to create a new one in the copy constructor.

Unfortunately, though, we have no way at this time to enforce writing a copy constructor in a class that stores an interpolation, so its developer will have to remember it. We have no way, that is, without making the `Interpolation` class non-copyable and thus also preventing useful idioms (like returning an interpolation from a method, as traits do). In C++11, we'd solve this by making it non-copyable and movable.

Aside: gordian knots

When implementing a class that stores an interpolation, an alternative to writing a copy constructor would be to cut right through the problem and make the class non-copyable. It might be less of a problem than it seems: such classes are usually term structures, and more often than not they're passed around inside `shared_ptr`s, which don't require copying.

(True story: most curves have been non-copyable for a while before release 1.0, and nobody complained much about it. Eventually, we reintroduced copying as a convenience, but I'm still not sure it was necessary.)

A final note: the interpolation stores iterators into the original data, but this is not enough to keep it up to date when any of the data changes. When this happens, its `update` method must be called so that the interpolation can refresh its state; this is the responsibility of the class that contains the interpolation and the data (and which, probably, is registered as an observer with whatever may change.) This holds also for those interpolations, such as linear, that might just read the data directly: depending on the implementation, they might precalculate some results and store them as state to be kept updated. (The current `LinearInterpolation` implementation does this for the slopes between the points, as well as the values of its primitive at the nodes.[25] Depending on how frequently the data are updated, this might be either an optimization or a pessimization.)

One-dimensional solvers

Solvers were used in the bootstrap routines described in chapter 3, the yield calculations mentioned in chapter 4, and any code that needs a calculated value to match a target; i.e, that needs, given a function f, to find the x such that $f(x) = \xi$ within a given accuracy.

The existing solvers will find the x such that $f(x) = 0$; of course, this doesn't make them any less generic, but it requires you to define the additional helper function $g(x) \equiv f(x) - \xi$. There are a few of them, all based on algorithms which were taken from *Numerical Recipes in C* (Press *et al*, 1992) and duly reimplemented.[26]

[25] The presence of the `primitive` and `derivative` methods is a bit of implementation leak. They were required by interpolated interest-rate curves in order to pass from zero rates to forwards and back.

[26] This also goes for a few multi-dimensional optimizers. In that case, apart from the obvious copyright issues, we also rewrote them in order to use idiomatic C++ and start indexing arrays from 0.

The following listing shows the interface of the class template `Solver1D`, used as a base by the available solvers.

Interface of the `Solver1D` class template and of a few derived classes.

```
template <class Impl>
class Solver1D : public CuriouslyRecurringTemplate<Impl> {
  public:
    template <class F>
    Real solve(const F& f,
               Real accuracy,
               Real guess,
               Real step) const;
    template <class F>
    Real solve(const F& f,
               Real accuracy,
               Real guess,
               Real xMin,
               Real xMax) const;
    void setMaxEvaluations(Size evaluations);
    void setLowerBound(Real lowerBound);
    void setUpperBound(Real upperBound);
};

class Brent : public Solver1D<Brent> {
  public:
    template <class F>
    Real solveImpl(const F& f,
                   Real xAccuracy) const;
};

class Newton : public Solver1D<Newton> {
  public:
    template <class F>
    Real solveImpl(const F& f,
                   Real xAccuracy) const;
};
```

It provides some boilerplate code, common to all of them: one overload of the `solve` method looks for lower and upper values of x that bracket the solution, while the other checks that the solution is actually bracketed by the passed minimum and maximum values. In both cases, the actual calculation is delegated to the `solveImpl` method defined by the derived class and implementing a specific algorithm. Other methods allow you to set constraints on the explored range, or the number of function evaluations.

The forwarding to `solveImpl` is implemented using the Curiously Recurring Template Pattern, already described in chapter 7. When we wrote these classes, we were at the height of our template craze (did I mention we even had an implementation of expression templates? (Veldhuizen, 2000)) so you might suspect that the choice was dictated by the fashion of that time. However, it wouldn't have been possible to use dynamic polymorphism. We wanted the solvers to work with any function pointer or function object, and `boost::function` wasn't around yet, which forced us to use a template method. Since the latter couldn't be virtual, CRTP was the only way to put the boilerplate code in the base class and let it call a method defined in derived ones.

A few notes to close this subsection. First: if you want to write a function that takes a solver, the use of CRTP forces you to make it a template, which might be awkward. To be honest, most of the times we didn't bother and just hard-coded an explicit choice of solver. I won't blame you if you do the same. Second: most solvers only use the passed `f` by calling `f(x)`, so they work with anything that can be called as a function, but `Newton` and `NewtonSafe` also require that `f.derivative(x)` be defined. This, too, might have been awkward if we used dynamic polymorphism. Third, and last: the `Solver1D` interface doesn't specify if the passed accuracy ϵ should apply to x (that is, if the returned $\tilde{x}$ should be within ϵ of the true root) or to $f(x)$ (that is, if $f(\tilde{x})$ should be within ϵ of 0). However, all existing solvers treat it as the accuracy on x.

Optimizers

Multi-dimensional optimizers are more complex than 1-D solvers. In a nutshell, they find the set of variables $\tilde{\mathbf{x}}$ for which the cost function $f(\mathbf{x})$ returns its minimum value; but of course, there's a bit more to it.

Unlike solvers, optimizers don't use templates. They inherit from the base class `OptimizationMethod`, shown in the next listing.

Interface of the `OptimizationMethod` class.

```
    class OptimizationMethod {
      public:
        virtual ~OptimizationMethod() {}
        virtual EndCriteria::Type minimize(
                                Problem& P,
                                const EndCriteria& endCriteria) = 0;
    };
```

Its only method, apart from the virtual destructor, is `minimize`. The method takes a reference to a `Problem` instance, which in turn contains references to the function to minimize and to any constraints, and performs the calculations; at the end of which, it has the problem of having too many things to return. Besides the best-solution array $\tilde{\mathbf{x}}$, it must return the reason for exiting the calculation (did it converge, or are we returning our best guess after the maximum number of evaluations?) and it would be nice to return $f(\tilde{\mathbf{x}})$ as well, since it's likely that it was already calculated.

In the current implementation, the method returns the reason for exiting and stores the other results inside the `Problem` instance. This is also the reason for passing the problem as a non-`const` reference; an alternative solution might have been to leave the `Problem` instance alone and to return all required values in a structure, but I see how this might be seen as more cumbersome. On the other hand, I see no reason for `minimize` itself to be non-`const`: my guess is that it was an oversight on our part (I'll get back to this later).

Onward to the `Problem` class, shown in the listing below.

Interface of the `Problem` class.

```
class Problem {
  public:
    Problem(CostFunction& costFunction,
            Constraint& constraint,
            const Array& initialValue = Array());

    Real value(const Array& x);
    Disposable<Array> values(const Array& x);
    void gradient(Array& grad_f, const Array& x);
    // ... other calculations ...

    Constraint& constraint() const;
    // ... other inspectors ...

    const Array& currentValue();
    Real functionValue() const;
    void setCurrentValue(const Array& currentValue);
    Integer functionEvaluation() const;
    // ... other results ...
};
```

As I mentioned, it groups together arguments such as the cost function to minimize, the constraints, and an optional guess. It provides methods that call the underlying cost function while keeping track of the number of evaluation, and that I'll describe when talking about cost functions; a few inspectors for its components; and methods to retrieve the results (as well as to set them; the latter are used by the optimizers).

The problem (no pun intended) is that it takes and stores its components as non-`const` references. I'll talk later about whether they might be `const` instead. The fact that they're reference is an issue in itself, since it puts the responsibility on client code to make sure that their lifetimes last at least as much as that of the `Problem` instance.

In an alternative implementation in which the optimizer returned its results in a structure, the issue might be moot: we might do away with the `Problem` class and pass its components directly to the `minimize` method. This would sidestep the lifetime issue, since they wouldn't be stored. The disadvantage would be that each optimizer would have to keep track of the number of function evaluations, causing some duplication in the code base.

Also unlike for 1-D solvers, the cost function is not a template parameter for the minimization method. It needs to inherit from the `CostFunction` class, shown in the next listing.

Interface of the `CostFunction` class.

```
class CostFunction {
  public:
    virtual ~CostFunction() {}

    virtual Real value(const Array& x) const = 0;
    virtual Array values(const Array& x) const = 0;

    virtual void gradient(Array& grad, const Array& x) const;
    virtual Real valueAndGradient(Array& grad,
                                  const Array& x) const;
    virtual void jacobian(Matrix &jac, const Array &x) const;
    virtual Array valuesAndJacobian(Matrix &jac,
                                    const Array &x) const;
};
```

Unsurprisingly, its interface declares the `value` method, which returns, well, the value of the function for the given array of arguments;[27] but it also declares a `values` method returning an array, which is a bit more surprising until you remember that optimizers are often used for calibrating over a number of quotes. Whereas `value` returns the total error to minimize (let's say, the sum of the squares of the errors, or something like it), `values` returns the set of errors over each quote; there are algorithms that can make use of this information to converge more quickly.

Other methods return the derivatives of the value, or the values, for use by some specific algorithms: `gradient` calculates the derivative of `value` with respect to each variable and stores it in the array passed as first argument, `jacobian` does the same for `values` filling a matrix, and the `valueAndGradient` and `valuesAndJacobian` methods calculate both values and derivatives at the same time for efficiency. They have a default implementation that calculates numerical derivatives; but of course that's costly, and derivative-based algorithms should only be used if you can override the method with an analytic calculation.

A note: checking the interface of `CostFunction` shows that all its methods are declared as `const`, so passing it as non-{const} reference to the `Problem` constructor was probably a goof. Changing it to `const` would widen the contract of the constructor, so it should be possible without breaking backward compatibility.

Finally, the `Constraint` class, shown in the following listing.

[27]Although you might be a bit surprised that it doesn't declare `operator()` instead.

Interface of the `Constraint` class.

```
class Constraint {
  protected:
    class Impl;
  public:
    bool test(const Array& p) const;
    Array upperBound(const Array& params) const;
    Array lowerBound(const Array& params) const;
    Real update(Array& p,
                const Array& direction,
                Real beta);
    Constraint(const shared_ptr<Impl>& impl =
                                     shared_ptr<Impl>());
};
```

It works as a base class for constraints to be applied to the domain of the cost function; the library also defines a few predefined ones, not shown here, as well as a `CompositeConstraint` class that can be used to merge a number of them into a single one.

Its main method is `test`, which takes an array of variables and returns whether or not they satisfy the constraint; that is, if the array belongs to the domain we specified as valid. It also defines the `upperBound` and `lowerBound` methods, which in theory should specify the maximum and minimum value of the variables but in practice can't always specify them correctly; think of the case in which the domain is a circle, and you'll see that there are cases in which x and y are both between their upper and lower bounds but the resulting point is outside the domain.

A couple more notes. First, the `Constraint` class also defines an `update` method. It's not `const`, which would make sense if it updated the constraint; except it doesn't. It takes an array of variables and a direction, and extends the original array in the given direction until it satisfies the constraint. It should have been `const`, it should have been named differently, and as the kids say I can't even. This might be fixed, though. Second, the class uses the pimpl idiom (see a previous section) and the default constructor also takes an optional pointer to the implementation. Were I to write the class today, I'd have a default constructor taking no arguments and an additional constructor taking the implementation and declared as protected and to be used by derived classes only.

Some short final thoughts on the `const`-correctness of these classes. In summary: it's not great, with some methods that can be fixed and some others that can't. For instance, changing the `minimize` method would break backwards compatibility (since it's a virtual method, and `const`ness is part of its signature) as well as a few optimizers, that call other methods from `minimize` and use data members as a way to transfer information between methods.[28] We could have avoided this if we had put some more effort in reviewing code before version 1.0. Let this be a lesson for you, young coders.

[28] Some of them declare those data members as `mutable`, suggesting the methods might have been `const` in the past. As I write this, I haven't investigated this further.

Statistics

The statistics classes were written mostly to collect samples from Monte Carlo simulations (you'll remember them from chapter 6). The full capabilities of the library are implemented as a series of decorators, each one adding a layer of methods, instead of a monolith; as far as I can guess, that's because you can choose one of two classes at the bottom of the whole thing. A layered design gives you the possibility to build more advanced capabilities just once, based on the common interface of the bottom layer.

The first class you can choose, shown below, is called `IncrementalStatistics`, and has the interface you would more or less expect: it can return the number of samples, their combined weight in case they were weighed, and a number of statistics results.

Interface of the **`IncrementalStatistics`**class.

```
class IncrementalStatistics {
  public:
    typedef Real value_type;
    IncrementalStatistics();

    Size samples() const;
    Real weightSum() const;
    Real mean() const;
    Real variance() const;
    Real standardDeviation() const;
    Real errorEstimate() const;
    // skewness, kurtosis, min, max...

    void add(Real value, Real weight = 1.0);
    template <class DataIterator>
    void addSequence(DataIterator begin, DataIterator end);
};
```

Samples can be added one by one or as a sequence delimited by two iterators. The shtick of this class is that it doesn't store the data it gets passed, but instead it updates the statistics on the fly; the idea was to save the memory that would be otherwise used for the storage, and in the year 2000 (when a computer might have 128 or 256 MB of RAM) it was a bigger concern than it is now. The implementation used to be homegrown; nowadays it's written in terms of the Boost accumulator library.

The second class, `GeneralStatistics`, implements the same interface and adds a few other methods, made possible by the fact that it stores (and thus can return) the passed data; for instance, it can return percentiles or sort its data. It also provides a template `expectationValue` method that can be used for bespoke calculations; if you're interested, there's more on that in the aside at the end of this section.

Interface of the **GeneralStatistics** class.

```
class GeneralStatistics {
  public:
    // ... same as IncrementalStatistics ...

    const std::vector<std::pair<Real,Real> >& data() const;

    template <class Func, class Predicate>
    std::pair<Real,Size>
    expectationValue(const Func& f,
                     const Predicate& inRange) const;

    Real percentile(Real y) const;
    // ... other inspectors ...

    void sort() const;
    void reserve(Size n) const;
};
```

Next, the outer layers. The first ones add statistics associated with risk, like expected shortfall or value at risk; the problem being that you usually need the whole set of samples for those. In the case of incremental statistics, therefore, we have to forgo the exact calculation and look for approximations. One possibility is to take the mean and variance of the samples, suppose they come from a Gaussian distribution with the same moments, and get analytic results based on this assumption; that's what the `GenericGaussianStatistics` class does.

Interface of the **GaussianStatistics** class.

```
template<class S>
class GenericGaussianStatistics : public S {
  public:
    typedef typename S::value_type value_type;
    GenericGaussianStatistics() {}
    GenericGaussianStatistics(const S& s) : S(s) {}

    Real gaussianDownsideVariance() const;
    Real gaussianDownsideDeviation() const;
    Real gaussianRegret(Real target) const;
    Real gaussianPercentile(Real percentile) const;
    Real gaussianValueAtRisk(Real percentile) const;
    Real gaussianExpectedShortfall(Real percentile) const;
    // ... other measures ...
};
```

```
    typedef GenericGaussianStatistics<GeneralStatistics>
                                              GaussianStatistics;
```

As I mentioned, and as you can see, it's implemented as a decorator; it takes the class to decorate as a template parameter, inherits from it so that it still has all the methods of its base class, and adds the new methods. The library provides a default instantiation, `GaussianStatistics`, in which the template parameter is `GeneralStatistics`. Yes, I would have expected the incremental version, too, but there's a reason for this; bear with me for a minute.

When the base class stores the full set of samples, we can write a decorator that calculates the actual risk measures; that would be the `GenericRiskStatistics` class. As for the Gaussian statistics, I won't discuss the implementation (you can look them up in the library).

Interface of the `RiskStatistics` class.

```
    template <class S>
    class GenericRiskStatistics : public S {
      public:
        typedef typename S::value_type value_type;

        Real downsideVariance() const;
        Real downsideDeviation() const;
        Real regret(Real target) const;
        Real valueAtRisk(Real percentile) const;
        Real expectedShortfall(Real percentile) const;
        // ... other measures ...
    };

    typedef GenericRiskStatistics<GaussianStatistics>
                                                  RiskStatistics;
```

As you can see, the layers can be combined; the default instantiation provided by the library, `RiskStatistics`, takes `GaussianStatistics` as its base and thus provides both Gaussian and actual measures. This was also the reason why `GeneralStatistics` was used as the base for the latter.

On top of it all, it's possible to have other decorators; the library provides a few, but I won't show their code here. One is `SequenceStatistics`, that can be used when a sample is an array instead of a single number, uses internally a vector of instances of scalar statistics classes, and also adds the calculation of the correlation and covariance between the elements of the samples; it is used, for instance, in the LIBOR market model, where each sample usually collects cash flows at different times. Other two are `ConvergenceStatistics` and `DiscrepancyStatistics`; they provide information on the properties of the sequence of samples, aren't used anywhere else in the library, but at least we had the decency of writing unit tests for both of them.

Aside: extreme expectations.

Looking back at the `GeneralStatistics` class, I'm not sure if I should be proud or ashamed of it, because—oh boy, I really went to town with generalization there.

It might have been the mathematics. It started with a straightforward implementation; but looking at the formulas for the mean, the variance, and even some more complex one defined in other layers, I saw that they all could be written (give or take some later adjustments) as

$$\frac{\sum_{x_i \in \mathcal{R}} f(x_i) w_i}{\sum_{x_i \in \mathcal{R}} w_i},$$

that is, the expected value of $f(x)$ over some range $\mathcal{R}$. For the mean, $f(x)$ would be the identity and $\mathcal{R}$ would be the full domain of the samples; for the variance, $f(x)$ would be $(x - \bar{x})^2$ over the same range; and so on. The result was a template `expectationValue` method that would take the function f and the range $\mathcal{R}$ and return the corresponding result and the number of samples in the range; most other methods are implemented by calling it with the relevant inputs. If you're a bit confused at first about the mean being implemented as

```
return expectationValue(identity<Real>(),
                        everywhere()).first;
```

then I can't blame you. By the way, I must have been learning about functional programming at the time; the range is passed as a function that takes a sample and return `true` or `false` depending on whether it's in the range, and `everywhere` above is one of a few small predefined helper functions I added to write this kind of code. It's all fun and games until someone writes $(x - \bar{x})^2$ as

```
compose(square<Real>(),
        std::bind2nd(std::minus<Real>(), mean()))
```

Self-snark aside: the above is very general and allows client code to create new calculations, but probably caters a bit too much to the math-inclined and can make for cryptic code, so I'm not sure that I stroke the right balance here. Replacing binds with lambdas in C++11 might certainly help; we'll see how this code turns out when we start using them. On the other hand, performance shouldn't be a problem: `expectationValue` is a template, and so are the functions like `compose` and `everywhere` above, so the compiler can see their implementation and can probably inline them. In that case, the result would be the simpler loop we might have written in a direct implementation of the mean or variance formulas.

Linear algebra

I don't have a lot to write about the current implementation of the `Array` and `Matrix` classes, shown in the following listing.

Sketch of the **Array** and **Matrix** classes.

```
class Array {
  public:
    explicit Array(Size size = 0);
    // ... other constructors ...
    Array(const Array&);
    Array(const Disposable<Array>&);
    Array& operator=(const Array&);
    Array& operator=(const Disposable<Array>&);

    const Array& operator+=(const Array&);
    const Array& operator+=(Real);
    // ... other operators ...

    Real operator[](Size) const;
    Real& operator[](Size);

    void swap(Array&);
    // ... iterators and other utilities ...
  private:
    boost::scoped_array<Real> data_;
    Size n_;
};

Disposable<Array> operator+(const Array&, const Array&);
Disposable<Array> operator+(const Array&, Real);
// ... other operators and functions ...

class Matrix {
  public:
    Matrix(Size rows, Size columns);
    // ... other constructors, assignment operators etc. ...

    const_row_iterator operator[](Size) const;
    row_iterator operator[](Size);
    Real& operator()(Size i, Size j) const;

    // ... iterators and other utilities ...
};

Disposable<Matrix> operator+(const Matrix&, const Matrix&);
// ... other operators and functions ...
```

Their interface is what you would expect: constructors and assignment operators, element access (the `Array` class provides the `a[i]` syntax; the `Matrix` class provides both `m[i][j]` and `m(i,j)`, because we aim to please), a bunch of arithmetic operators, all working element by element as usual,[29] and a few utilities. There are no methods for resizing, or for other operations suited for containers, because this classes are not meant to be used as such; they're mathematical utilities. Storage is provided by a `scoped_ptr`, which manages the lifetime of the underlying memory.

In the case of `Array`, we also provide a few functions such as `Abs`, `Log` and their like; being good citizens, we're not overloading the corresponding functions in namespace `std` because that's forbidden by the standard. More complex functionality (such as matricial square root, or various decompositions) can be found in separate modules.

In short, a more or less straightforward implementation of arrays and matrices. The one thing which is not obvious is the presence of the `Disposable` class template, which I'll describe in more detail in a further section of this appendix; for the time being, let me just say that it's a pre-C++11 attempt at move semantics.

The idea was to try and reduce the abstraction penalty. Operator overloading is very convenient—after all, `c = a+b` is much easier to read than understand than `add(a,b,c)`—but doesn't come for free: declaring addition as

```
Array operator+(const Array& a, const Array& b);
```

means that the operator must create and return a new `Array` instance, that is, must allocate and possibly copy its memory. When the number of operations increases, so does the overhead.

In the first versions of the library, we tried to mitigate the problem by using expression templates. The idea (that I will only describe very roughly, so I suggest you read (Veldhuizen, 2000) for details) is that operators don't return an array, but some kind of parse tree holding references to the terms of the expression; so, for instance, `2*a+b` won't actually perform any calculation but only create a small structure with the relevant information. It is only when assigned that the expression is unfolded; and at that point, the compiler would examine the whole thing and generate a single loop that both calculates the result and copies it into the array being assigned.

The technique is still relevant today (possibly even more so, given the progress in compiler technology) but we abandoned it after a few years. Not all compilers were able to process it, forcing us to maintain both expression templates and the simpler implementation, and it was difficult to read and maintain (compare the current declaration of `operator+` with

```
VectorialExpression<
    BinaryVectorialExpression<
        Array::const_iterator, Array::const_iterator, Add> >
operator+(const Array& v1, const Array& v2);
```

[29]It always bothered me that `a*b` returns the element-wise product and not the dot product, but I seem to be alone among programmers.

for a taste of what the code was like); therefore, when the C++ community started talking of move semantics and some ideas for implementations began to appear, we took the hint and switched to `Disposable`.

As I said, compilers progressed a lot during these years; nowadays, I'm guessing that all of them would support an expression-template implementation, and the technique itself has probably improved. However, if I were to write the code today (or if I started to change things) the question might be whether to write classes such as `Array` or `Matrix` at all. At the very least, I'd consider implementing them in terms of `std::valarray`, which is supposed to provide facilities for just such a task. In the end, though, I'd probably go for some existing library such as uBLAS: it is available in Boost, it's written by actual experts in numerical code, and we already use it in some parts of the library for specialized calculations.

Global settings

The `Settings` class, outlined in the listing below, is a singleton (see later) that holds information global to the whole library.

Outline of the `Settings` class.

```
class Settings : public Singleton<Settings> {
  private:
    class DateProxy : public ObservableValue<Date> {
        DateProxy();
        operator Date() const;
        ...
    };
    ... // more implementation details
  public:
    DateProxy& evaluationDate();
    const DateProxy& evaluationDate() const;
    boost::optional<bool>& includeTodaysCashFlows();
    boost::optional<bool> includeTodaysCashFlows() const;
    ...
};
```

Most of its data are flags that you can look up in the official documentation, or that you can simply live without; the one piece of information that you'll need to manage is the evaluation date, which defaults to today's date and is used for the pricing of instruments and the fixing of any other quantity.

This poses a challenge: instruments whose value can depend on the evaluation date must be notified when the latter changes. This is done by returning the corresponding information indirectly, namely, wrapped inside a proxy class; this can be seen from the signature of the relevant methods. The proxy inherits from the `ObservableValue` class template (outlined in the next listing) which is implicitly convertible to `Observable` and overloads the assignment operator in order to notify any changes. Finally, it allows automatic conversion of the proxy class to the wrapped value.

Outline of the `ObservableValue` class template.

```
template <class T>
class ObservableValue {
  public:
    // initialization and assignment
    ObservableValue(const T& t)
    : value(t), observable_(new Observable) {}
    ObservableValue<T>& operator=(const T& t)  {
      value_ = t;
      observable_->notifyObservers();
      return *this;
    }
    // implicit conversions
    operator T() const { return value_; }
    operator shared_ptr<Observable>() const {
      return observable_;
    }
  private:
    T value_;
    shared_ptr<Observable> observable_;
};
```

This allows one to use the facility with a natural syntax. On the one hand, it is possible for an observer to register with the evaluation date, as in:

```
registerWith(Settings::instance().evaluationDate());
```

on the other hand, it is possible to use the returned value just like a `Date` instance, as in:

```
Date d2 =
    calendar.adjust(Settings::instance().evaluationDate());
```

which triggers an automatic conversion; and on the gripping hand, an assignment can be used for setting the evaluation date, as in:

```
Settings::instance().evaluationDate() = d;
```

which will cause all observers to be notified of the date change.

* * *

Of course, the elephant in the room is the fact that we have a global evaluation date at all. The obvious drawback is that one can't perform two parallel calculations with two different evaluation dates, at least in the default library configuration; but while this is true, it is also not the whole story. On the one hand, there's a compilation flag that allows a program to have one distinct `Settings` instance per thread (with a bit of work on the part of the user) but as we'll see, this doesn't solve all the issues. On the other hand, the global data may cause unpleasantness even in a single-threaded program: even if one wanted to evaluate just an instrument on a different date, the change will trigger recalculation for every other instrument in the system when the evaluation date is set back to its original value.

This clearly points (that is, quite a few smart people had the same idea when we talked about it) to some kind of context class that should replace the global settings. But how would one select a context for any given calculation?

It would be appealing to add a `setContext` method to the `Instrument` class, and to arrange things so that during calculation the instrument propagates the context to its engine and in turn to any term structures that need it. However, I don't think this can be implemented easily.

First, the instrument and its engine are not always aware of all the term structures that are involved in the calculation. For instance, a swap contains a number of coupons, any of which might or might not reference a forecast curve. We're not going to reach them unless we add the relevant machinery to all the classes involved. I'm not sure that we want to set a context to a coupon.

Second, and more important, setting the context for an engine would be a mutating operation. Leaving it to the instrument during calculations would execute it at some point during the call to its `NPV` method, which is supposed to be `const`. This would make it way too easy to trigger a race condition; for instance with a harmless-looking operation such as using the same discount curve for two instruments and evaluating them at different dates. If you have a minimum of experience in parallel programming, you wouldn't dream of, say, relinking the same handle in two concurrent threads; but when the mutation is hidden inside a `const` method, you might not be aware of it. (But wait, you say. Aren't there other mutating operations possibly being done during the call to `NPV`? Good catch: see the aside at the end of this section.)

So it seems that we have to set up the context before starting the calculation. This rules out driving the whole thing from the instrument (because, again, we would be hiding the fact that setting a context to an instrument could undo the work done by another that shared a term structure with the first) and suggests that we'd have to set the context explicitly on the several term structures. On the plus side, we no longer run the risk of a race in which we unknowingly try to set the same context to the same object. The drawbacks are that our setup just got more complex, and that we'd have to duplicate curves if we want to use them concurrently in different contexts: two parallel calculations on different dates would mean, for instance, two copies of the overnight curve for discounting. And if we have to do this, we might as well manage with per-thread singletons.

Finally, I'm skipping over the scenario in which the context is passed but not saved. It would lead to method calls like

```
termStructure->discount(t, context);
```

which would completely break caching, would cause discomfort to all parties involved, and if we wanted stuff like this we'd write in Haskell.

To summarize: I hate to close the section on a gloomy note, but all is not well. The global settings are a limitation, but I don't have a solution; and what's worse, the possible changes increase complexity. We would not only tell first-time users looking for the Black-Scholes formula that they needs term structures, quotes, an instrument and an engine: we'd also put contexts in the mix. A little help here?

Aside: more mutations than in a B-movie.

Unfortunately, there are already a number of things that change during a call to the supposedly `const` method `Instrument::NPV`.

To begin with, there are the `arguments` and `results` structures inside the engine, which are read and written during calculation and thus prevent the same engine to be used concurrently for different instruments. This might be fixed by adding a lock to the engine (which would serialize the calculations) or by changing the interface so that the engine's `calculate` method takes the `arguments` structure as a parameter and returns the `results` structure.

Then, there are the `mutable` data members of the instrument itself, which are written at the end of the calculation. Whether this is a problem depends on the kind of calculations one's doing. I suppose that calculating the value of the instrument twice in concurrent threads might just result in the same values being written twice.

The last one that comes to mind is a hidden mutation, and it's probably the most dangerous. Trying to use a term structure during the calculation might trigger its bootstrap, and two concurrent ones would trash each other's calculations. Due to the recursive nature of the bootstrap, I'm not even sure how we could add a lock around it. So if you do decide to perform concurrent calculations (being careful, setting up everything beforehand and using the same evaluation date) be sure to trigger a full bootstrap of your curves before starting.

Utilities

In QuantLib, there are a number of classes and functions which don't model a financial concept. They are nuts and bolts, used to build some of the scaffolding for the rest of the library. This section is devoted to some of these facilities.

Smart pointers and handles

The use of run-time polymorphism dictates that many, if not most, objects be allocated on the heap. This raises the problem of memory management—a problem solved in other languages by built-in garbage collection, but left in C++ to the care of the developer.

I will not dwell on the many issues in memory management, especially since they are now mostly a thing of the past. The difficulty of the task (especially in the presence of exceptions) was enough to discourage manual management; therefore, ways were found to automate the process.

The weapons of choice in the C++ community came to be smart pointers: classes that act like built-in pointers but that can take care of the survival of the pointed objects while they are still needed and of their destruction when this is no longer the case. Several implementations of such classes exist which use different techniques; we chose the smart pointers from the Boost libraries (most notably `shared_ptr`, now included in the ANSI/ISO C++ standard). Don't look for `boost::shared_ptr` in the library, though: the relevant classes are imported in an internal QuantLib namespace and used, e.g., as `ext::shared_ptr`. This will allow us to switch to the C++11 implementation painlessly when the time comes.

I won't go into details on shared pointers; you can browse the Boost site for documentation. Here, I'll just mention that their use in QuantLib completely automated memory management. Objects are dynamically allocated all over the place; however, there is not one single `delete` statement in all the tens of thousands of lines of which the library consists.

Pointers to pointers (if you need a quick refresher, see the aside at the end of the section for their purpose and semantics) were also replaced by smart equivalents. We chose not to just use smart pointers to smart pointers; on the one hand, because having to write

```
ext::shared_ptr<ext::shared_ptr<YieldTermStructure> >
```

gets tiresome very quickly—even in Emacs; on the other hand, because the inner `shared_ptr` would have to be allocated dynamically, which just didn't felt right; and on the gripping hand, because it would make it difficult to implement observability. Instead, a class template called `Handle` was provided for this purpose. Its implementation, shown in the listing that follows, relies on an intermediate inner class called `Link` which stores a smart pointer. In turn, the `Handle` class stores a smart pointer to a `Link` instance, decorated with methods that make it easier to use it. Since all copies of a given handle share the same link, they are all given access to the new pointee when any one of them is linked to a new object.

Outline of the `Handle` class template.

```
template <class Type>
class Handle {
  protected:
    class Link : public Observable, public Observer {
      public:
        explicit Link(const shared_ptr<Type>& h =
                                         shared_ptr<Type>());
        void linkTo(const shared_ptr<Type>&);
        bool empty() const;
        void update() { notifyObservers(); }
      private:
        shared_ptr<Type> h_;
    };
    shared_ptr<Link<Type> > link_;
  public:
    explicit Handle(const shared_ptr<Type>& h =
                                         shared_ptr<Type>());
    const shared_ptr<Type>& operator->() const;
    const shared_ptr<Type>& operator*() const;
    bool empty() const;
    operator shared_ptr<Observable>() const;
};

template <class Type>
class RelinkableHandle : public Handle<Type> {
  public:
    explicit RelinkableHandle(const shared_ptr<Type>& h =
                                         shared_ptr<Type>());
    void linkTo(const shared_ptr<Type>&);
};
```

The contained `shared_ptr<Link>` also gives the handle the means to be observed by other classes. The `Link` class is both an observer and an observable; it receives notifications from its pointee and forwards them to its own observers, as well as sending its own notification each time it is made to point to a different pointee. Handles take advantage of this behavior by defining an automatic conversion to `shared_ptr<Observable>` which simply returns the contained link. Thus, the statement

```
    registerWith(h);
```

is legal and works as expected; the registered observer will receive notifications from both the link and (indirectly) the pointed object.

You might have noted that the means of relinking a handle (i.e., to have all its copies point to a different object) were not given to the `Handle` class itself, but to a derived `RelinkableHandle` class. The rationale for this is to provide control over which handle can be used for relinking—and especially over which handle can't. In the typical use case, a `Handle` instance will be instantiated (say, to store a yield curve) and passed to a number of instruments, pricing engines, or other objects that will store a copy of the handle and use it when needed. The point is that an object (or client code getting hold of the handle, if the object exposes it via an inspector) must not be allowed to relink the handle it stores, whatever the reason; doing so would affect a number of other object.[30]

The link should only be changed from the original handle—the main handle, if you like.

Given the frailty of human beings, we wanted this to be enforced by the compiler. Making the `linkTo` method a `const` one and returning `const` handles from our inspectors wouldn't work; client code could simply make a copy to obtain a non-`const` handle. Therefore, we removed `linkTo` from the `Handle` interface and added it to a derived class. The type system works nicely to our advantage. On the one hand, we can instantiate the main handle as a `RelinkableHandle` and pass it to any object expecting a `Handle`; automatic conversion from derived to base class will occur, leaving the object with a sliced but fully functional handle. On the other hand, when a copy of a `Handle` instance is returned from an inspector, there's no way to downcast it to `RelinkableHandle`.

Aside: pointer semantics.

Storing a copy of a pointer in a class instance gives the holder access to the present value of the pointee, as in the following code:

```
class Foo {
    int* p;
  public:
    Foo(int* p) : p(p) {}
    int value() { return *p; }
};

int i=42;
int *p = &i;
Foo f(p);
cout << f.value(); // will print 42
i++;
cout << f.value(); // will print 43
```

However, the stored pointer (which is a copy of the original one) is not modified when the external one is.

```
int i=42, j=0;
int *p = &i;
```

[30]This is not as far-fetched as it might seem; we've been bitten by it.

```
Foo f(p);
cout << f.value(); // will print 42
p = &j;
cout << f.value(); // will still print 42
```

As usual, the solution is to add another level of indirection. Modifying `Foo` so that it stores a pointer to pointer gives the class both possibilities.

```
int i=42, j=0;
int *p = &i;
int **pp = &p;
Foo f(pp);
cout << f.value(); // will print 42
i++;
cout << f.value(); // will print 43
p = &j;
cout << f.value(); // will print 0
```

Error reporting

There are a great many places in the library where some condition must be checked. Rather than doing it as

```
if (i >= v.size())
    throw Error("index out of range");
```

we wanted to express the intent more clearly, i.e., with a syntax like

```
require(i < v.size(), "index out of range");
```

where on the one hand, we write the condition to be satisfied and not its opposite; and on the other hand, terms such as `require`, `ensure`, or `assert`—which have a somewhat canonical meaning in programming—would tell whether we're checking a precondition, a postcondition, or a programmer error.

We provided the desired syntax with macros. "Get behind thee," I hear you say. True, macros have a bad name, and in fact they caused us a problem or two, as we'll see below. But in this case, functions had a big disadvantage: they evaluate all their arguments. Many times, we want to create a moderately complex error message, such as

```
    require(i < v.size(),
            "index " + to_string(i) + " out of range");
```

If `require` were a function, the message would be built whether or not the condition is satisfied, causing a performance hit that would not be acceptable. With a macro, the above is textually replaced by something like

```
    if (!(i < v.size()))
        throw Error("index " + to_string(i) + " out of range");
```

which builds the message only if the condition is violated.

The next listing shows the current version of one of the macros, namely, `QL_REQUIRE`; the other macros are defined in a similar way.

Definition of the `QL_REQUIRE` macro.

```
    #define QL_REQUIRE(condition,message) \
    if (!(condition)) { \
        std::ostringstream _ql_msg_stream; \
        _ql_msg_stream << message; \
        throw QuantLib::Error(__FILE__,__LINE__, \
                              BOOST_CURRENT_FUNCTION, \
                              _ql_msg_stream.str()); \
    } else
```

Its definition has a few more bells and whistles that might be expected. Firstly, we use an `ostringstream` to build the message string. This allows one to use a syntax like

```
    QL_REQUIRE(i < v.size(),
               "index " << i << " out of range");
```

to build the message (you can see how that works by replacing the pieces in the macro body). Secondly, the `Error` instance is passed the name of the current function as well as the line and file where the error is thrown. Depending on a compilation flag, this information can be included in the error message to help developers; the default behavior is to not include it, since it’s of little utility for users. Lastly, you might be wondering why we added an `else` at the end of the macro. That is due to a common macro pitfall, namely, its lack of a lexical scope. The `else` is needed by code such as

```
    if (someCondition())
        QL_REQUIRE(i < v.size(), "index out of bounds");
    else
        doSomethingElse();
```

Without the `else` in the macro, the above would not work as expected. Instead, the `else` in the code would pair with the `if` in the macro and the code would translate into

```
    if (someCondition()) {
        if (!(i < v.size()))
            throw Error("index out of bounds");
        else
            doSomethingElse();
    }
```

which has a different behavior.

As a final note, I have to describe a disadvantage of these macros. As they are now, they throw exceptions that can only return their contained message; no inspector is defined for any other relevant data. For instance, although an out-of-bounds message might include the passed index, no other method in the exception returns the index as an integer. Therefore, the information can be displayed to the user but would be unavailable to recovery code in catch clauses—unless one parses the message, that is; but that is hardly worth the effort. There's no planned solution at this time, so drop us a line if you have one.

Disposable objects

The `Disposable` class template was an attempt to implement move semantics in C++03 code. To give credit where it's due, we took the idea and technique from an article by Andrei Alexandrescu (Alexandrescu, 2003) in which he described how to avoid copies when returning temporaries.

The basic idea is the one that was starting to float around in those years and that was given its final form in C++11: when passing a temporary object, copying it into another one is often less efficient than swapping its contents with those of the target. You want to move a temporary vector? Copy into the new object the pointer to its storage, instead of allocating a new one and copying the elements. In modern C++, the language itself supports move semantics with the concept of rvalue reference (Hinnant *et al*, 2006); the compiler knows when it's dealing with a temporary, and we can use `std::move` in the few cases when we want to turn an object into one. In our implementation, shown in the following listing, we don't have such support; you'll see the consequences of this in a minute.

Implementation of the `Disposable` class template.

```
template <class T>
class Disposable : public T {
  public:
    Disposable(T& t) {
        this->swap(t);
    }
    Disposable(const Disposable<T>& t) : T() {
        this->swap(const_cast<Disposable<T>&>(t));
    }
    Disposable<T>& operator=(const Disposable<T>& t) {
        this->swap(const_cast<Disposable<T>&>(t));
        return *this;
    }
};
```

The class itself is not much to look at. It relies on the template argument implementing a `swap` method; this is where any resource contained inside the class are swapped (hopefully in a cheap way) instead of copied. The constructors and the assignment operator all use this to move stuff around without copies—with a difference, depending on what is passed. When building a `Disposable` from another one, we take it by `const` reference because we want the argument to bind to temporaries; that's what most disposables will be. This forces us to use a `const_cast` in the body, when it's time to call `swap` and take the resources from the disposable. When building a `Disposable` from a non-disposable object, instead, we take is as a non-`const` reference; this is to prevent ourselves from triggering unwanted destructive conversions and from finding ourselves with the empty husk of an object when we thought to have a usable one. This, however, has a disadvantage; I'll get to it in a minute.

The next listing shows how to retrofit `Disposable` to a class; `Array`, in this case.

Use of the `Disposable` class template in the `Array` class.

```
Array::Array(const Disposable<Array>& from)
: data_((Real*)(0)), n_(0) {
    swap(const_cast<Disposable<Array>&>(from));
}

Array& Array::operator=(const Disposable<Array>& from) {
    swap(const_cast<Disposable<Array>&>(from));
    return *this;
}

void Array::swap(Array& from) {
    data_.swap(from.data_);
    std::swap(n_,from.n_);
}
```

As you see, we need to add a constructor and an assignment operator taking a `Disposable` (in C++11, they would be a move constructor and a move assignment operators taking an rvalue reference) as well as the `swap` method that will be used in all of them. Again, the constructors take the `Disposable` by `const` reference and cast it later, in order to bind to temporaries—although now that I think of it, they could take it by copy, adding another cheap swap.

Finally, the way `Disposable` is used is by returning it from function, like in the following code:

```
    Disposable<Array> ones(Size n) {
        Array result(n, 1.0);
        return result;
    }

    Array a = ones(10);
```

Returning the array causes it to be converted to `Disposable`, and assigning the returned object causes its contents to be swapped into `a`.

Now, you might remember that I talked about a disadvantage when I showed you the `Disposable` constructor being safe and taking an object by non-`const` reference. It's that it can't bind to temporaries; therefore, the function above can't be written more simply as:

```
    Disposable<Array> ones(Size n) {
        return Array(n, 1.0);
    }
```

because that wouldn't compile. This forces us to take the more verbose route and give the array a name.[31]

Nowadays, of course, we'd use rvalue references and move constructors and forget all about the above. To tell the truth, I've a nagging suspicion that `Disposable` might be getting in the way of the compiler and doing more harm than good. Do you know the best way to write code like the above and avoid abstraction penalty in modern C++? It's this one:

[31]Well, it doesn't actually *force* us, but writing `return Disposable<Array>(Array(n, 10))` is even uglier than the alternative.

```
Array ones(Size n) {
    return Array(n, 1.0);
}

Array a = ones(10);
```

In C++17, the copies that might have been done when returning the array and when assigning it are guaranteed to be elided (that is, the compiler will generate code that builds the returned array directly inside the one we're assigning); most recent compilers have been doing that for a while, without waiting for the standard to bind them. It's called RVO, for Return Value Optimization, and using `Disposable` prevents it and thus might make the code slower instead of faster.

Design patterns

A few design patterns were implemented in QuantLib. You can refer to the Gang of Four book (Gamma *et al*, 1995) for a description of such patterns; so why do I write about them? Well, as once noted by G. K. Chesterton,

> [p]oets have been mysteriously silent on the subject of cheese

and the Gang was just as silent on a number of issues that come up when you write actual implementations—through no fault of them, mind you. The variations are almost limitless, and they were only four.

Thus, I will use this final section to point out a few ways in which our implementations were tailored to the requirements of the library.

The Observer pattern

The use of the Observer pattern in the QuantLib library is widespread; you've seen it used in chapter 2 and chapter 3 to let financial instruments and term structures keep track of changes and recalculate when needed.

Our version of the pattern (sketched in the next listing) is close enough to that described in the Gang of Four book; but as I mentioned, there are questions and problems that weren't discussed there.

Sketch of the **Observable** and **Observer** classes.

```
class Observable {
    friend class Observer;
  public:
    void notifyObservers() {
        for (iterator i=observers_.begin();
                        i!=observers_.end(); ++i) {
            try {
                (*i)->update();
            } catch (std::exception& e) {
                // store information for later
            }
        }
    }
  private:
    void registerObserver(Observer* o) {
        observers_.insert(o);
    }
    void unregisterObserver(Observer*);
    list<Observer*> observers_;
};

class Observer {
  public:
    virtual ~Observer() {
        for (iterator i=observables_.begin();
                      i!=observables_.end(); ++i)
            (*i)->unregisterObserver(this);
    }
    void registerWith(const shared_ptr<Observable>& o) {
        o->registerObserver(this);
        observables_.insert(o);
    }
    void unregisterWith(const shared_ptr<Observable>&);
    virtual void update() = 0;
  private:
    list<shared_ptr<Observable> > observables_;
};
```

For instance: what information should we include in the notification? In our implementation, we went for minimalism—all that an observer gets to know is that something changed. It would have been possible to provide more information (e.g., by having the `update` method take the notifying observable as an argument) so that observers could select what to recalculate and save a few cycles; but I don't think that this feature was worth the added complexity.

Another question: what happens if an observer raises an exception from its `update` method? This would happen when an observable is sending a notification, i.e., while the observable is iterating over its observers, calling `update` on each one. If the exception were to propagate, the loop would be aborted and a number of observers would not receive the notification—bad. Our solution was to catch any such exception, complete the loop, and raise an exception at the end if anything went wrong. This causes the original exceptions to be lost, which is not good either; however, we felt this to be the lesser of the two evils.

Onwards to the third issue: that is, copy behavior. It is not very clear what should happen when an observer or an observable are copied. Currently, what seemed a sensible choice is implemented: on the one hand, copying an observable results in the copy not having any observer; on the other hand, copying an observer results in the copy being registered with the same observables as the original. However, other behaviors might be considered; as a matter of fact, the right choice might be to inhibit copying altogether.

The big problems, however, were two. First: we obviously had to make sure that the lifetimes of the observer and observables were managed properly, meaning that no notification should be sent to an already deleted object. To do so, we had observers store shared pointers to their observables, which ensures that no observable is deleted before an observer is done with it. The observers will unregister with any observable before being deleted, which in turn makes it safe for observables to store a list of raw pointers to their observers.

This, however, is only guaranteed to work in a single-threaded setting; and we are exporting QuantLib bindings to C# and Java, where unfortunately there is always another thread where the garbage collector is busy deleting stuff. Every once in a while, this caused random crashes as a notification was sent to a half-deleted object. Once the problem was understood, it was fixed (hi, Klaus); however, the fix slows down the code, so it's inactive by default and can be enabled by a compilation switch. Use it if you need the C# or Java bindings.

The second big problem is[32] that, like in the Jerry Lee Lewis' song, there's a whole lotta notifyin' going on. A change of date can easily trigger tens or hundreds of notifications; and even if most of the `update` methods only set a flag and forward the call, the time adds up.

People using QuantLib in applications where calculation time is paramount, such as CVA/XVA (hi, Peter) have worked around the problem by disabling notifications and recalculating explicitly. A step towards reducing notification time would be to remove the middlemen, and shorten the chains of notifications; however, this is not possible due to the ubiquitous presence of the `Handle` class in the chains. Handles can be relinked, and thus chains of dependencies can change even after objects are built.

In short, the problem is still not solved. You know where to find us if you have any bright ideas.

[32]Notice that I didn't say *was*.

The Singleton pattern

The Gang of Four devoted the first part of their book to creational patterns. While logically sound, this choice turned out to have an unfortunate side effect: all too often, overzealous programmers would start to read the book and duly proceed to sprinkle their code with abstract factories and singletons. Needless to say, this does less than intended for the clarity of the code.

You might suspect the same reason for the presence of a `Singleton` class template in QuantLib. (Quite maliciously, I might add. Shame on you.) Fortunately, we can base our defense on version-control logs; such class was added to the library later than, say, Observer (a behavioral pattern) or Composite (a structural one).

Our default implementation is shown in the following listing.

Interface of the `Singleton` class template.

```
template <class T>
class Singleton : private noncopyable {
  public:
    static T& instance();
  protected:
    Singleton();
};

#if defined(QL_ENABLE_SESSIONS)
// the definition must be provided by the user
Integer sessionId();
#endif

template <class T>
T& Singleton<T>::instance() {
    static map<Integer, shared_ptr<T> > instances_;
    #if defined(QL_ENABLE_SESSIONS)
    Integer id = sessionId();
    #else
    Integer id = 0;
    #endif
    shared_ptr<T>& instance = instances_[id];
    if (!instance)
        instance = shared_ptr<T>(new T);
    return *instance;
}
```

It's based on the Curiously Recurring Template Pattern, that I described in chapter 7; to be a singleton, a class `C` needs to inherit from `Singleton<C>`, to provide a private constructor taking on arguments, and to make `Singleton<C>` a friend so that it can use it. You can see an example in the `Settings` class.

As suggested by Scott Meyers (Meyers, 2005), the map holding the instances (bear with me) is defined as a static variable inside the `instance` method. This prevents the so-called static initialization order fiasco, in which the variable is used before being defined, and in C++11 it has the additional guarantee that the initialization is thread-safe (even though that's not the whole story, as we'll see).

Now, you might have a few questions; e.g., why a map of instances if this is supposed to be a singleton? Well, that's because having a single instance might be limiting; for instance—no pun intended—you might want to perform simultaneous calculations on different evaluation dates. Thus, we tried to mitigate the problem by allowing one `Singleton` instance per thread. This is enabled by a compilation flag, and causes the `instance` method to use the `#if` branch in which it gets an id from a `sessionId` function and uses it to index into the map. If you enable per-thread singletons, you must also provide the latter function; it will probably be something like

```
Integer sessionId() {
    return /* `some unique thread id from your system API` */ ;
}
```

in which you will identify the thread using the functions made available by your operating system (or some threading library), turn the identifier into a unique integer, and return it. In turn, this will cause the `instance` method to return a unique instance per each thread. If you don't enable the feature, instead, the id will always ever be `0` and you'll always get the same instance. In this case, you probably don't want to use threads at all—and in the other case, you obviously do, but you have to be careful anyway: see the discussion in the section on global settings.

You might also be asking yourself why I said that this is our *default* implementation. Nice catch. There are others, which I won't show here and which are enabled by a number of compilation flags. On the one hand, it turned out that the static-variable implementation didn't work when compiled as managed C++ code under .NET (at least with older Visual Studio compilers), so in that case we switch it with one in which the map is a static class variable. On the other hand, if you want to use a global `Singleton` instance in a multi-threaded setting, you want to make sure that the initialization of the `Singleton` instance is thread-safe (I'm talking about the instance itself, not the map containing it; it's where the `new T` is executed). This requires locks, mutexes and stuff, and we don't want to go near any of that in the default single-threaded setting; therefore, that code is behind yet another compilation flag. You can look at it in the library, if you're interested.

Your last question might be whether we should have a `Singleton` class at all—and it's a tough one. Again, I refer you to the previous discussion of global settings. At this time, much like democracy according to Winston Churchill, it seems to be the worst solution except for all the others.

The Visitor pattern

Our implementation, shown in the next listing, follows the Acyclic Visitor pattern (Martin, 1997) rather than the one in the Gang of Four book: we defined a degenerate `AcyclicVisitor` class, to be used in the interfaces, and a class template `Visitor` which defines the pure virtual `visit` method for its template argument.

Interface of the `AcyclicVisitor` class and of the `Visitor` class template.

```
    class AcyclicVisitor {
      public:
        virtual ~AcyclicVisitor() {}
    };

    template <class T>
    class Visitor {
      public:
        virtual ~Visitor() {}
        virtual void visit(T&) = 0;
    };
```

The pattern also needs support from any class hierarchy that we want to be visitable; an example is shown in the listing that follows.

Implementation of the Visitor pattern in a class hierarchy.

```
    void Event::accept(AcyclicVisitor& v) {
        Visitor<Event>* v1 = dynamic_cast<Visitor<Event>*>(&v);
        if (v1 != 0)
            v1->visit(*this);
        else
            QL_FAIL("not an event visitor");
    }

    void CashFlow::accept(AcyclicVisitor& v) {
        Visitor<CashFlow>* v1 =
            dynamic_cast<Visitor<CashFlow>*>(&v);
        if (v1 != 0)
            v1->visit(*this);
        else
            Event::accept(v);
    }

    void Coupon::accept(AcyclicVisitor& v) {
        Visitor<Coupon>* v1 = dynamic_cast<Visitor<Coupon>*>(&v);
        if (v1 != 0)
            v1->visit(*this);
        else
```

```
            CashFlow::accept(v);
    }
```

Each of the classes in the hierarchy (or at least, those that we want to be specifically visitable) need to define an `accept` method that takes a reference to `AcyclicVisitor`. Each of the methods tries to cast the passed visitor to the specific `Visitor` instantiation for the corresponding class. A successful cast means that the visitor defines a `visit` method taking this specific class, so we invoke it. A failed cast means that we have to look for an fallback. If the class is not the root of the hierarchy (like `CashFlow` or `Coupon` in the listing) we can call the base-class implementation of `accept`, which in turn will try the cast. If we're at the root, like the `Event` class, we have no further fallback and we raise an exception.[33]

Finally, a visitor is implemented as the `BPSCalculator` class in chapter 4. It inherits from `AcyclicVisitor`, so that it can be passed to the various `accept` methods, as well as from an instantiation of the `Visitor` template for each class for which it will provide a `visit` method. It will be passed to the `accept` method of some instance, which will eventually call one of the `visit` methods or raise an exception.

I already discussed the usefulness of the Visitor pattern in chapter 4, so I refer you to it (the unsurprising summary: it depends). Therefore, I will only spend a couple of words on why we chose Acyclic Visitor.

In short, the Gang-of-Four version of Visitor might be a bit faster, but it's a lot more intrusive; in particular, every time you add a new class to the visitable hierarchy you're also forced to go and add the corresponding `visit` method to each existing visitor (where by "forced" I mean that your code wouldn't compile if you didn't). With Acyclic Visitor, you don't need to do it; the `accept` method in your new class will fail the cast and fallback to its base class.[34] Mind you, this is convenient but not necessarily a good thing (like a lot of things in life, I might add): you should review existing visitors anyway, check whether the fallback implementation makes sense for your class, and add a specific one if it doesn't. But I think that the disadvantage of not having the compiler warn you is more than balanced by the advantage of not having to write a `visit` method for each cash-flow class when, as in `BPSCalculator`, a couple will suffice.

[33]Another alternative would be to do nothing, but we preferred not to fail silently.

[34]In fact, you're not even required to define an `accept` method; you could just inherit it. However, this would prevent visitors to target this specific class.

B. Code conventions

Every programmer team has a number of conventions to be used while writing code. Whatever the conventions (several exist, which provides a convenient *casus belli* for countless wars) adhering to them helps all developers working on the same project,[35] as they make it easier to understand the code; a reader familiar with their use can distinguish at a glance between a macro and a function, or between a variable and a type name.

The following listing briefly illustrates the conventions used throughout the QuantLib library. Following the advice in Sutter and Alexandrescu, 2004, we tried to reduce their number at a minimum, enforcing only those conventions which enhance readability.

Illustration of QuantLib code conventions.

```
#define SOME_MACRO

typedef double SomeType;

class SomeClass {
  public:
    typedef Real* iterator;
    typedef const Real* const_iterator;
};

class AnotherClass {
  public:
    void method();
    Real anotherMethod(Real x, Real y) const;
    Real member() const;   // getter, no "get"
    void setMember(Real);  // setter
  private:
    Real member_;
    Integer anotherMember_;
};

struct SomeStruct {
    Real foo;
    Integer bar;
};
```

[35]However, the QuantLib developers are human. As such, they sometimes fail to follow the rules I am describing.

```
Size someFunction(Real parameter,
                  Real anotherParameter) {
    Real localVariable = 0.0;
    if (condition) {
        localVariable += 3.14159;
    } else {
        localVariable -= 2.71828;
    }
    return 42;
}
```

Macros are in all uppercase, with words separated by underscores. Type names start with a capital and are in the so-called camel case; words are joined together and the first letter of each word is capitalized. This applies to both type declarations such as `SomeType` and class names such as `SomeClass` and `AnotherClass`. However, an exception is made for type declarations that mimic those found in the C++ standard library; this can be seen in the declaration of the two iterator types in `SomeClass`. The same exception might be made for inner classes.

About everything else (variables, function and method names, and parameters) are in camel case and start with a lowercase character. Data members of a class follow the same convention, but are given a trailing underscore; this makes it easier to distinguish them from local variables in the body of a method (an exception is often made for public data members, especially in structs or struct-like classes). Among methods, a further convention is used for getters and setters. Setter names are created by adding a leading `set` to the member name and removing the trailing underscore. Getter names equal the name of the returned data member without the trailing underscore; no leading `get` is added. These conventions are exemplified in `AnotherClass` and `SomeStruct`.

A much less strict convention is that the opening brace after a function declaration or after an `if`, `else`, `for`, `while`, or `do` keyword are on the same line as the preceding declaration or keyword; this is shown in `someFunction`. Moreover, `else` keywords are on the same line as the preceding closing brace; the same applies to the `while` ending a `do` statement. However, this is more a matter of taste than of readability; therefore, developers are free to use their own conventions if they cannot stand this one. The shown function exemplifies another convention aimed at improving readability, namely, that function and method arguments should be aligned vertically if they do not fit a single line.

QuantLib license

QuantLib is

Bibliography

D. Abrahams, *Want Speed? Pass by Value*. In *C++ Next*, 2009.

D. Adams, *So Long, and Thanks for all the Fish*. 1984.

A. Alexandrescu, *Move Constructors*. In *C/C++ Users Journal*, February 2003.

F. Ametrano and M. Bianchetti, *Everything You Always Wanted to Know About Multiple Interest Rate Curve Bootstrapping but Were Afraid to Ask*. SSRN working papers series n.2219548, 2013.

J. Barton and L.R. Nackman, *Dimensional Analysis*. In *C++ Report*, January 1995.

T. Becker, *On the Tension Between Object-Oriented and Generic Programming in C++*. 2007.

Boost C++ libraries. http://boost.org.

M. K. Bowen and R. Smith, Derivative formulae and errors for non-uniformly spaced points. In *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, volume 461, pages 1975–1997. The Royal Society, 2005.

D. Brigo and F. Mercurio, *Interest Rate Models —— Theory and Practice*, 2nd edition. Springer, 2006.

Mel Brooks (director), *Young Frankenstein*. Twentieth Century Fox, 1974.

W.E. Brown, *Toward Opaque Typedefs for C++1Y, v2*. C++ Standards Committee Paper N3741, 2013.

L. Carroll, *The Hunting of the Snark*. 1876.

G.K. Chesterton, *Alarms and Discursions*. 1910.

M.P. Cline, G. Lomow and M. Girou, *C++ FAQs*, 2nd edition. Addison-Wesley, 1998.

J.O. Coplien, *A Curiously Recurring Template Pattern*. In S.B. Lippman, editor, *C++ Gems*. Cambridge University Press, 1996.

C.S.L. de Graaf. *Finite Difference Methods in Derivatives Pricing under Stochastic Volatility Models*. Master's thesis, Mathematisch Instituut, Universiteit Leiden, 2012.

C. Dickens, *Great Expectations*. 1860.

P. Dimov, H.E. Hinnant and D. Abrahams, *The Forwarding Problem: Arguments*. C++ Standards Committee Paper N1385, 2002.

M. Dindal (director), *The Emperor's New Groove*. Walt Disney Pictures, 2000.

D.J. Duffy, *Finite Difference Methods in Financial Engineering: A Partial Differential Equation Approach*. John Wiley and Sons, 2006.

M. Fowler, *UML Distilled: A Brief Guide to the Standard Object Modeling Language*, 3rd edition.

Addison-Wesley, 2003.

M. Fowler, *Fluent Interface*. 2005.

M. Fowler, K. Beck, J. Brant, W. Opdyke and D. Roberts, *Refactoring: Improving the Design of Existing Code*. Addison-Wesley, 1999.

E. Gamma, R. Helm, R. Johnson and J. Vlissides, *Design Patterns: Element of Reusable Object-Oriented Software*. Addison-Wesley, 1995.

P. Glasserman, *Monte Carlo Methods in Financial Engineering*. Springer, 2003.

D. Gregor, *A Brief Introduction to Variadic Templates*. C++ Standards Committee Paper N2087, 2006.

H.E. Hinnant, B. Stroustrup and B. Kozicki, *A Brief Introduction to Rvalue References*. C++ Standards Committee Paper N2027, 2006.

A. Hunt and D. Thomas, *The Pragmatic Programmer: From Journeyman to Master*. Addison-Wesley, 1999.

International Standards Organization, *Programming Languages — C++*. International Standard ISO/IEC 14882:2014.

International Swaps and Derivatives Associations, *Financial products Markup Language*.

P. Jäckel, *Monte Carlo Methods in Finance*. John Wiley and Sons, 2002.

J. Kerievsky, *Refactoring to Patterns*. Addison-Wesley, 2004.

R. Kleiser (director), *Grease*. Paramount Pictures, 1978.

H.P. Lovecraft, *The Call of Cthulhu*. 1928.

R.C. Martin, *Acyclic Visitor*. In *Pattern Languages of Program Design 3*. Addison-Wesley, 1997.

S. Meyers, *Effective C++*, 3rd edition. Addison-Wesley, 2005.

N.C. Myers, *Traits: a new and useful template technique*. In The C++ Report, June 1995.

G. Orwell, *Animal Farm*. 1945.

W.H. Press, S.A. Teukolsky, W.T. Vetterling and B.P. Flannery, *Numerical Recipes in C*, 2nd edition. Cambridge University Press, 1992.

QuantLib. http://quantlib.org.

E. Queen, *The Roman Hat Mystery*. 1929.

V. Simonis and R. Weiss, *Exploring Template Template Parameters*. In *Perspectives of System Informatics*, number 2244 in Lecture Notes in Computer Science. Springer Berlin / Heidelberg, 2001.

B. Stroustrup, *The C++ Programming Language*, 4th edition. Addison-Wesley, 2013.

H. Sutter, *You don't know const and mutable*. In Sutter's Mill, 2013.

H. Sutter and A. Alexandrescu, *C++ Coding Standards*. Addison-Wesley, 2004.

T. Veldhuizen, *Techniques for Scientific C++*. Indiana University Computer Science Technical Report

TR542, 2000.

H.G. Wells, *The Shape of Things to Come*. 1933.

P.G. Wodehouse, *My Man Jeeves*. 1919.