Computing with functions

Overview

- Most programs that we have seen treat objects as abstract data types
  - they define both state and behavior
  - the state is primary
  - the behavior describes how to manipulate the state
- Sometimes, it is useful to treat behavior as more important than state

A classic example

- Many programming languages have sort functions as part of their libraries
- It is usually useful to be able to specify a comparison function as an argument to the sort function

Another example

- Suppose we want a generic linear-search function
- We have seen how to make the function independent of the data structure being searched
- What about making it independent of the search criterion as well?

Searching for a particular value

- The `find` function looks for the first element with a given value:

```
template<class It, class X>
It find(It begin, It end, const X& x)
{
    while (begin != end && *begin != x)
        ++begin;
    return begin;
}
```

- How can we generalize the search criterion?

Generalizing the search criterion

- We want something to which we can hand a sequence element and get an answer: yes or no
- It seems to make sense for that something to be a function whose input is an `X` and output is a `bool`

Rewriting the search function

```
template<class It, class X>
It find2(It begin, It end, bool (*f)(X))
{
    while (begin != end && !f(*begin))
        ++begin;
    return begin;
}
```

- Can we generalize it even more?

Further generalization

- We need not insist that `f` be a function. It can be any appropriate type:

```
template<class It, class F>
It find_if(It begin, It end, F f)
{
    while (begin != end && !f(*begin))
        ++begin;
}
```

- How might `f` be anything other than a function?

Function objects

- In C++, we can call any object as if it were a function, provided that the object has `operator()` defined
- In other words, if `obj` is an object, then `obj(x)` means `obj.operator()(x)`
- Of course, `obj` has to be of a type with `operator()` defined
- We call such objects *function objects*

In other words...

- The `find_if` function will accept any function or function object as its third argument
- It will call the function (or call the `operator()` member of the object) to test each element of the sequence

Example

- Find the first white-space character in a string:

```
find(s.begin(), s.end(), isspace)
```

A more interesting example

- Suppose that `b` and `e` are iterators that delimit a sequence, and we want to find the first element that is >10
- We might write a function

```
bool gt10(int x) { return x > 10; }
```

- and then call

```
find(b, e, gt10)
```

- But what if we want to find the first element that is >n?

Doing it the hard way

```
int xx;
bool gtxx(int x) { return x > xx; }
```

- and then, we might say

```
xx = n;
  … find_if(b, e, gtxx) …
```

- This approach is ugly!
- Why?

Why the approach is ugly

- It relies on a global variable
- To use it, you must
  - set the state explicitly (by assigning to the variable), and then
  - call the function
- In effect, the function relies on hidden state

How to clean it up

- Bind the state and the function together into a function object:

```
class gt_n {
public:
  gt_n(int n0): n(n0) { }
  bool operator()(int x)
    { return x > n; }
private:
  int n;
};
```

Using class `gt_n`

- To find the first element >10:
  `find_if(b, e, gt_n(10))`
- To find the first element >x:
  `find_if(b, e, gt_n(x))`
- In both cases, global variables are unnecessary

It might be nice if...

- Another way to get rid of the global variable would be to make it local:

```
{
  int n;
  bool gt_n(int x) { return x > n; }
  … find_if(b, e, gt_n) …
}
```

- But C++ doesn't allow this technique
- Why not?

Nested functions

- Programming languages of the Algol and Pascal family generally allow nested functions
- C and C++ do not
- The reason has to do with ease of implementation: While a function is executing, it sees only its own local variables and all global variables

Function objects simulate nested functions

- If a function could be nested inside another, you would be able to get at the inner function's local variables, or those of the outer function(s), or global variables
- A member function can get at its local variables, or its object's members, or global variables

Generating function objects

- Our gt_n type lets us create function objects that encapsulate comparison with a particular value
- It would be tricky to do that even with nested functions (because it needs GC):

```
bool (*gt_n(int n))(int)
{
    bool f(int x) { return x > n; }
    return f;
}
```

Two problems

- Allowing nested functions in a language potentially complicates the calling sequence for all functions
- Allowing functions to return nested functions as values causes trouble unless the language supports garbage collection
- C++ pushes the complexity into objects

How do other languages do it?

- Functional languages treat functions as first-class values:

```
find_if(b, e, (fn x => x > n))
```

- Pure object-oriented languages (Smalltalk, Java) don't have functions as separate entities at all

Function objects are objects

- Because function objects are objects, we can perform computations on them
- It is possible to write functions (and the C++ standard library includes some such functions) that make it unnecessary to define classes such as `gt_n` at all

Some sample library functions

- Template class `greater` is defined so that `greater<T>()(x, y)` has the same value as `x>y` (and similarly for `less`, `equal_to`, ...)
- If `f` is a function object, then template function `bind1st(f, x)(y)` has the same value as `f(x, y)` (and similarly for `bind2nd`)

Using `greater` and `bind2nd`

- To find the first element `>n`:
```
find(b, e, bind2nd(greater<T>(), n))
```

Making binders work

- C++ binders are a nice example of making a high-level abstraction work in a language that wasn't designed in advance to support it
- Binders and function objects rely on a mixture of code and conventions

Function object conventions

- Every function object has a member called `result_type` that names the type of its result
- In addition,
  - if it has a single argument, it has a member named `argument_type`
  - if it has two arguments, it has members named `first_argument_type` and `second_argument_type`

Abbreviation base classes

```
template<class A, class R>
struct unary_function {
  typedef A argument_type;
  typedef R result_type;
};
template<class A1, class A2, class R>
struct binary_function {
  typedef A1 first_argument_type;
  typedef A2 second_argument_type;
  typedef R result_type;
};
```

Definition of `greater`

```
template<class T> class greater:
    public binary_function<T, T, bool>: {
public:
    bool operator()
        (const T& x, const T& y) const
    {
        return x > y;
    }
};
```

Making `bind2nd` work

- The result of `bind2nd(f, x)` has to include the values of `f` and `x`
- Therefore, it has to have a type that includes the types of `f` and `x`
- We need an auxiliary type, which we will call `binder2nd`, to do the work

Definition of `binder2nd`

```
template<class Op> class binder2nd:
 public unary_function<
  typename Op::first_argument_type,
  typename Op::result_type> {
public:
 binder2nd(const Op&,
  const typename Op::second_argument_type&);
 result_type operator()
  (const typename Op::first_argument_type&)
   const;
private:
 Op op;
 typename Op::second_argument_type value;
};
```

Member functions of `binder2nd`

```
template<class Op>
binder2nd::binder2nd(
  const Op& o,
  const typename Op::second_argument_type& v):
    op(o), value(v) { }
template<class Op>
binder2nd::result_type operator()
  (const typename Op::first_argument_type& arg)
   const
{
  return op(arg, value);
}
```

Definition of `bind2nd`

```
template<class Op, class T>
binder2nd<Op> bind2nd(const Op& op, const T& t)
{
  return binder2nd<Op>(op,
    typename Op::second_argument_type(t));
}
```

The point of all this code

- Although the types are somewhat messy,
  - the classes themselves are small
  - they can be combined in useful ways
  - the techniques used to build them can be used in other contexts
- Objects can be abstractions of behavior, not just of data structures

Other relevant library functions

- If `f` is a (pointer to a) function, `ptr_fun(f)` is the corresponding function object
- If `pred` is a unary (function object) predicate, `not1(pred)` is a predicate that yields the inverse result

Using `ptr_fun` and `not1`

- Find the first non-space character in the `string s`:

```
find_if(s.begin(), s.end(),
        not1(ptr_fun(isspace)));
```

A few more examples

- Flip the sign of every element of x:

```
transform(x.begin(), x.end(), x.begin(),
          negate<x::value_type>());
```

- Replace every pointer to a null-terminated string that compares equal to “C” by a pointer to “C++”

```
replace_if(x.begin(), x.end(),
  not1(bind2nd(ptr_fun(strcmp), “C”)),
  “C++”);
```

Projects

- Each team will be expected to demonstrate its project
  - be prepared to answer design and process related questions
- Each team has to find appropriate computing facilities for the demonstration and schedule a mutually agreeable time
- All demonstrations during exam week

Project scheduling

- If we heard from you by ~~5~~ 10:30 PM, April 20 (well beyond the original deadline), we accommodated your requests
- If not, it is now your problem! Either pick an open slot or trade with another project

Project reviews for Monday, 5/17

- All 4 slots still open
  - 10:30 - 11:30
  - 1:30 - 2:30
  - 3:00 - 4:00
  - 4:30 - 5:30

Project reviews for Tuesday, 5/18

- 10:30 Campus Calendar
- 1:30 Direct Chat
- 3:00 AT 5000
- 4:30 Sound Images

Project reviews for Wednesday 5/19

- 10:30 *This space available*
- 1:30 Space Dust
- 3:00 Redemption
- 5:15 Clipbook

Project reviews for Thursday, 5/20

- 10:30 *This space available*
- 1:30 Online Trading
- 3:00 Project Vulcan
- 4:30 Logic Studio