Ve 280

Programming and Introductory Data Structures

Procedural Abstraction;

Recursion; Function Pointers;

Function Call Mechanism;

Outline

- Procedural Abstraction
- Recursion
- Function Pointers
- Function Call Mechanism

Procedural Abstraction

- Procedural abstractions, done properly, have two important properties:
  - Local: the **implementation** of an abstraction does not depend on any other abstraction **implementation**.
    - To realize an implementation, you only need to focus **locally**.
  - Substitutable: you can replace one (correct) **implementation** of an abstraction with another (correct) one, and no callers of that abstraction will need to be modified.

Implementation of square() does not depend on **how you implement** multi()

```
int square(int a)
{
  return multi(a,a);
}
```

We can **change** the implementation of multi(). It won't affect square() as long as it does multiplication

Procedural Abstraction

- Locality and substitutability only apply to **implementations** of abstractions, not the **abstractions** themselves.
  - If you change the **abstraction** that is offered, the change is not local.
- It is CRITICALLY IMPORTANT to get the **abstractions** right before you start writing code.

```
int square(int a)
{
  return multi(a,a);
}
```

We cannot change the abstraction of "multi" to 2*a*b.

Procedural Abstraction: Summary

- Abstraction and abstraction implementation are **<u>different</u>**!
  - Abstraction: tells **what**
  - Implementation: tells **how**
  - **Same** abstraction could have **different** implementations
- If you need to change what an **abstraction** itself, it can involve many different changes in the program.
- However, if you only change the **implementation** of an abstraction, then you are guaranteed that no other part of the project needs to change.
  - **This is vital for projects that involve many programmers.**

Procedural Abstraction and Function

- **Function** is a way of providing procedure abstractions.

- The **type signature** of a function can be considered as part of the abstraction
  - Recall: type signature includes return type, number of arguments and the type of each argument.
  - If you change type signature, callers must also change.

- Besides type signature, we need some way to describe **the abstraction (not implementation)** of the function.
  - We use **specifications** to do this.

Procedural Abstraction

Specifications

- We describe procedural abstraction by specification. It answers three questions:
  - What pre-conditions must hold to use the function?
  - Does the function change any inputs (even implicit ones, e.g., a global variable)? If so, how?
  - What does the procedure actually do?
- We answer each of these three questions in a **specification comment**, and we **always** include one with **function declaration** (or function definition in case we don' have declaration)

```
…
// SPECIFICATION COMMENT
int add(int a, int b);
```

Procedural Abstraction

Specification Comments

- There are three clauses to the specification:
  - **REQUIRES**: the pre-conditions that must hold, if any.
  - **MODIFIES**: how inputs are modified, if any.
  - **EFFECTS**: what the procedure computes given legal inputs.

- Note that the first two clauses have an "if any", which means they may be empty, in which case you may omit them.

Procedural Abstraction

Specification Comment Example

```
bool isEven(int n);
    // EFFECTS: returns true if n is even,
    // false otherwise
```

- This function returns true if and only if its argument is an even number.
- Since the function isEven is well-defined over all inputs (every possible integer is either even or odd) there need be no REQUIRES clause.
- Since isEven modifies no (implicit or explicit) arguments, there need be no MODIFIES clause.

Procedural Abstraction

Specification Comment Example

```
int factorial(int n);
    // REQUIRES: n >= 0
    // EFFECTS: returns n!
```

- The mathematical abstraction of factorial is only defined for non-negative integers. So, there is a **REQUIRE** clause.
- The **EFFECTS** clause is only valid for inputs satisfying the **REQUIRES** clause.
- Importantly, this means that the implementation of factorial DOES NOT HAVE TO CHECK if n < 0! The function specification tells the caller that s/he **must** pass a non-negative integer.

Procedural Abstraction

More Function Details

- Functions without REQUIRES clauses are considered **complete**; they are valid for all input.
- Functions with REQUIRES clauses are considered **partial**
  - Some arguments that are "legal" with respect to the type (e.g., int) are not legal with respect to the function.
- Whenever possible, it is much better to write complete functions than partial ones.
- When we discuss **exceptions**, we will see a way to convert partial functions to complete ones.

Procedural Abstraction

More Function Details

- What about the MODIFIES clause?

- A MODIFIES clause identifies any function argument or global state that **might** change if this function is called.
  - For example, it can happen with call-by-reference as opposed to call-by-value inputs.

Procedural Abstraction

Specification Comment Example

```
void swap(int &x, int &y);
  // MODIFIES: x, y
  // EFFECTS: exchanges the values of
  // x and y
```

- NOTE: If the function **could** change a reference argument, the argument must go in the MODIFIES clause. Leave it out only if the function can **never** change it.

Outline

- Procedural Abstraction
- Recursion
- Function Pointers
- Function Call Mechanism

Recursion

- Recursion is a nice way to solve problems
  - "Recursive" just means "refers to itself".
  - There is (at least) one "trivial" base or "stopping" case.
  - All other cases can be solved by first solving one smaller case, and then combining the solution with a simple step.
- Example: calculate factorial $n!$

$$n! = \begin{cases} 1 & n = 0 \\ n \cdot (n-1)! & n > 0 \end{cases}$$

```
int factorial (int n) {
// REQUIRES: n >= 0
// EFFECTS:  computes n!
  if (n == 0) return 1; // base case
  else return n*factorial(n-1); // recursive step
}
```

Recursive Helper Function

- Sometimes it is easier to find a recursive solution to a problem if you change the original problem slightly, and then solve that problem using a **recursive helper function**.

```
soln()
{
   …
   soln_helper();
   …
}
```

```
soln_helper()
{
   …
   soln_helper();
   …
}
```

Recursive Helper Function

Example

- A palindrome is a string that is equal to itself when you reverse all characters.
  - For example: rotor, racecar

- Write a function to test if a string is a palindrome.

```
bool is_palindrome(string s);
// EFFECTS: return true if s is
// a palindrome.
```

Palindrome Example

- If a string is empty, it is a palindrome.
- If a string is of length one, it is a palindrome.
- Given a string of length more than one, it is a palindrome, if
  - its first character equals its last one, **and**
  - the substring without the first and the last characters is a palindrome.
- In order to test whether a substring is a palindrome, we define a **helper** function

```
bool is_palindrome_helper(string s,
  int begin, int end);
// EFFECTS: return true if the subtring
// of s starting at begin and ending at
// end is a palindrome.
```

Palindrome Example

```
bool is_palindrome_helper(string s,
  int begin, int end)
// EFFECTS: return true if the subtring
// of s starting at begin and ending at
// end is a palindrome.
{
  if(begin >= end) return true;
  if(s[begin] == s[end])
    return is_palindrome_helper(s,
      begin+1, end-1);
  else return false;
}
```

Palindrome Example

- With the helper function, `is_palindrome()` can be realized as

```
bool is_palindrome(string s)
// EFFECTS: return true if s is
// a palindrome.
{
  return is_palindrome_helper(s, 0,
    s.length()-1);
}
```

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Function Pointers

Motivation

- If you were asked to write a function to add all the elements in a list, and another to multiply all the elements in a list, your functions would be almost exactly **the same**.

- Writing almost the exact same function twice is a bad idea! Why?
  1. It's wasteful of your time!!
  2. If you find a better way to implement some common parts, you have to change **many different** places; this is prone to error.

Our Example: list_t type

- A list can hold a sequence of zero or more integers.
- There is a recursive definition for the values that a list can take:
  - A valid list is:

either `an empty list`

or `an integer followed by another valid list`

Function Pointers

Background on lists

- Here are some examples of valid lists:

```
( 1 2 3 4 )  // a list of four elements
( 2 5 2 )    // a list of three elements
( )          // an empty list
```

- There are also several operations that can be applied to lists. We will use the following three:
  - list_first( ) takes a list, and returns the first element (an integer) from the list. **REQUIRES: non-empty list!**
  - list_rest( ) takes a list and returns the list comprising all but the first element. **REQUIRES: non-empty list!**
  - list_isEmpty( ) takes a list and returns the Boolean "true" if the argument is an empty list, and "false" otherwise.

Function Pointers

Using lists

- Suppose we want to write a **recursive** function to find the smallest element in a list.
  - The function requires the input list to be non-empty.

Question: how do you do it **recursively**?

- **Answer**:

```
smallest(list) =  the element (if list has
                  only a single element)
               or the minimum of the first
                  element and the smallest
                  element from the rest of
                  the list
```

Function Pointers

Using recursion to find the smallest element in a list

```
int smallest(list_t list)
  // REQUIRES: list is not empty
  // EFFECTS:  returns smallest element
  // in the list
{
   int first = list_first(list);
   list_t rest = list_rest(list);
   if(list_isEmpty(rest)) return first;
   int cand = smallest(rest);
   if(first <= cand) return first;
   return cand;
}
```

Function Pointers

Using lists

- Now suppose we want to write a recursive function to find the largest element in a list.
  - The function also requires the input list to be non-empty.

- Recursive definition:

```
largest(list) =  the element (if list has
                 only a single element)
              or the maximum of the first
                 element and the largest
                 element from the rest of
                 the list
```

Function Pointers

Using recursion to find the largest element in a list

```
int largest(list_t list)
  // REQUIRES: list is not empty
  // EFFECTS:  returns largest element
  // in the list
{
   int first = list_first(list);
   list_t rest = list_rest(list);
   if(list_isEmpty(rest)) return first;
   int cand = largest(rest);
   if(first >= cand) return first;
   return cand;
}
```

Function Pointers

More Motivation

- `largest` is almost identical to the definition of `smallest`.
- Unsurprisingly, the solution is almost identical, too.
- In fact, the **only** differences between smallest and largest are:
  1. The names of the function
  2. The comment in the EFFECTS list
  3. The polarity of the comparison: <= vs. >=
- It is silly to write almost the same function twice!

Function pointers to rescue!

Function Pointers

A first look

- So far, we've only defined functions as entities that can be called. However, functions can also be referred to by **variables**, and passed as **arguments** to functions.

- Suppose there are two functions we want to pick between: min() and max(). They are defined as follows:

```
int min(int a, int b);
  // EFFECTS: returns the smaller of a and b.
int max(int a, int b);
  // EFFECTS: returns the larger of a and b.
```

Function Pointers

A first look

```
int min(int a, int b);
  // EFFECTS: returns the smaller of a and b.
int max(int a, int b);
  // EFFECTS: returns the larger of a and b.
```

- These two functions have precisely the same type signature:
  - They both take two integers, and return an integer.
- Of course, they do completely different things:
  - One returns a min and one returns a max.
  - **However, from a syntactic point of view, you call either of them the same way.**

Function Pointers

The basic format

- How do you define a **variable** that points to a function taking two integers, and returns an integer?
- Here's how:

```
int  (*foo)(int, int);
```

- You read this from "inside out". In other words:

`foo`	"foo"
`(*foo)`	"is a pointer"
`(*foo)(         );`	"to a function"
`(*foo)(int, int);`	"that takes two integers"
`int  (*foo)(int, int);`	"and returns an integer"

Function Pointers

The basic format

```
int  (*foo)(int, int);
```

- Once we've declared foo, we can **assign** any function to it:

```
foo = min;
```

- Furthermore, after assigning min to foo, we can just call it as follows:

```
foo(3, 5)
```

- …and we'll get back 3!

Function Pointers v.s. Variable Pointers

- For function pointers, the compiler allows us to **ignore** the "address-of" and "dereference" operators.

```
int  (*foo)(int, int);
foo = min; // min() is predefined
foo(5,3);
```

We don't write:

```
foo = &min;
(*foo)(5, 3);
```

- In contrast, for variable pointers:

```
int  foo;
int *bar;
bar = &foo;
*bar = 2;
```

Function Pointers

Re-write `smallest` in terms of function pointers

```
int compare_help(list_t list, int (*fn)(int, int))
{
    int first = list_first(list);
    list_t rest = list_rest(list);
    if(list_isEmpty(rest)) return first;
    int cand = compare_help(rest, fn);
    return fn(first, cand);
}
int smallest(list_t list)
  // REQUIRES: list is not empty
  // EFFECTS: returns smallest element in list
{
  return compare_help(list, min);
}
```

```
int min(int a, int b);
    // EFFECTS: returns the
    // smaller of a and b.
```

Function Pointers

Re-write `largest` in terms of function pointers

```
int compare_help(list_t list, int (*fn)(int, int))
{
    int first = list_first(list);
    list_t rest = list_rest(list);
    if(list_isEmpty(rest)) return first;
    int cand = compare_help(rest, fn);
    return fn(first, cand);
}
int largest(list_t list)
  // REQUIRES: list is not empty
  // EFFECTS: returns largest element in list
{
  return compare_help(list, max);
}
```

```
int max(int a, int b);
    // EFFECTS: returns the
    // larger of a and b.
```

Outline

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Call Stacks

How a function call really works

- When we call a function, the program does following steps:

1. Evaluate the actual arguments to the function (order is not guaranteed).

   Example: y = add(4-1, 5);

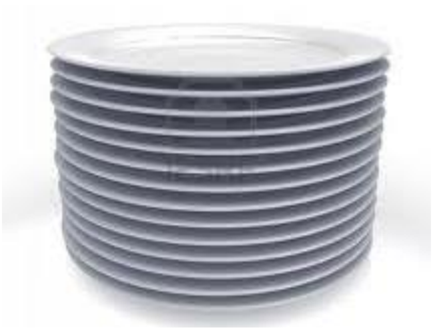
2. Create an "**activation record**" (sometimes called a "**stack frame**") to hold the function's formal parameters and local variables.
   - When call function `int add(int a, int b)`, system creates an activation record: a, b (formal), result (local)
3. Copy the actuals' values to the formals' storage space.

   a=3
   b=5
4. Evaluate the function in its local scope.
5. Replace the function call with the result. y=8
6. Destroy the activation record.

Call Stacks

How a function call really works

- It is typical to have multiple function calls. How the activation records are maintained?
  - Answer: stored as a **stack**.
- Stack: a set of objects which modifies as **last in first out**. Example: a stack of plates in a cafeteria
  - Each time you clean a plate, you add it to the top of the stack
  - Each time a new plate is needed, the one at the top is taken **first**



Call Stacks

How a function call really works

- When a function f() is called, its **activation record** is added to the "top" of the stack.
- When the function f() returns, its **activation record** is removed from the "top" of the stack.
- In the meantime, f() may have called other functions.
  - These functions create corresponding activation records.
  - These functions must return (and destroy their corresponding activation records) before f() can return.

Call Stacks

Example

- When a function is called, its **activation record** is added to the "top" of the stack.
- When that function returns, its **activation record** is removed from the "top" of the stack.

double add(double a, double b): a = 1, b = 0, result = 0
double sin(double x): x = 1, result = 0
int main(): x = 1, sinResult = 0

- Note: "top" is placed in quotes, because in reality, stack of activation records grows **down** rather than **up**.

Reference

- Procedural abstraction
  - Problem Solving with C++, 8th Edition, Chapter 4.4 and 5.3
- Recursion
  - Problem Solving with C++, 8th Edition, Chapter 14
- Function pointers
  - C++ Primer (4th Edision), Chapter 7.9