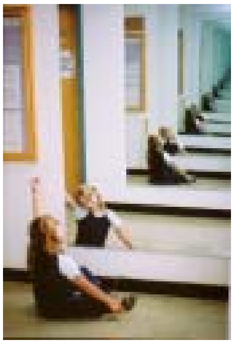


Writing a Design Document & How Recursive Functions are Implemented

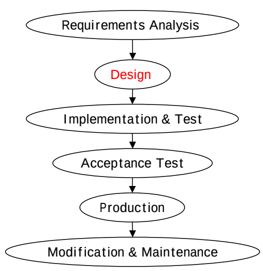
Week 8
CS 212 – Spring 2008

Announcements

- Project Part 3
  - Online by tomorrow afternoon for both Compiler & GBA
  - Design Document is due on Thursday, March 27
  - Part 3 code is due near Thursday, April 10

Software Life Cycle (Again)

- Problem specification
- Program design
- Choosing algorithms & data structures
- Coding & debugging
- Testing & verification
- Support & maintenance



Program Design

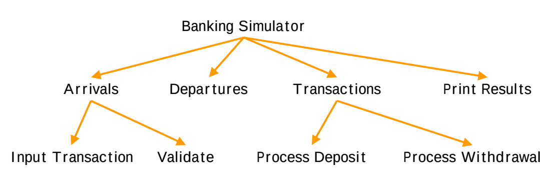
- Specify a set of *components* that will solve the specified problem
- *Component?*
  - Depends on the language we're using
  - Typically: function, procedure, class, template, package, or interface
- Design is a Divide & Conquer operation
  - Break problem into smaller and simpler subproblems

Specifying a Component

- Interface
  - How this component is invoked
- Preconditions
  - The conditions that must be true for this unit to work correctly
- Postconditions
  - The conditions that will be true when the component finishes (assuming the preconditions are met)

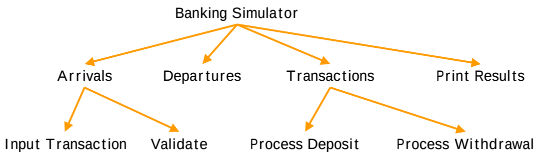
Top-Down Design

- Based on subdividing by *task* (i.e., by *function*)
  - Example is from "Modern Software Development using Java" by Tymann & Schneider



Criticism of Top-Down (Function-Oriented) Design

- What if we want to add a new type of transaction?
  - Say, *make-loan-payment*
  - Which components are affected?



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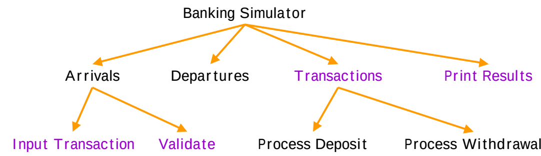


Object-Oriented Design

- Decompose problem via entities (i.e., objects) instead of by function
  - For the banking simulation, we might have
    - Customers
    - Waiting lines
    - Tellers
    - Transactions
- We then determine the methods for each class

Specifying Classes & Methods

Class WaitingLine

putAtEnd(c)	Put new customer at end of line
c = getFirstCustomer()	Remove & return 1st customer in line
isEmpty()	True iff line is empty
isFull()	True iff line is full

Class Teller

isBusy()	True iff teller is busy
serve(c)	Teller begins serving customer c

Class Customer

depart()	The customer leaves the bank
t = getTransaction()	Return customer's desired transaction

Class Transaction

t = transactionType()	Return the type of this transaction
a = transactionAmount()	Return dollar amount of transaction

What to Put in Your Design Document

- Specify each class
  - For each class, specify the class's methods
    - For each method, specify
      - Its arguments (i.e., its interface)
      - Its preconditions (if any)
      - Its postconditions (i.e., what the method does)
- Specify how the classes interact
  - Diagrams can be useful here, but aren't required
    - UML (Unified Modeling Language) can be used, but informal diagrams are OK, too
- Expected length of design document
  - One page ⇒ probably too short
  - Ten pages ⇒ definitely too long

Recursive Functions

Positive Integer Powers

- $a^n = a \cdot a \cdot a \cdots a$ (n times)
- Alternate description:
  - $a^0 = 1$
  - $a^{n+1} = a \cdot a^n$

```
static int power(int a, int n) {
   if (n == 0) return 1;
   else return a*power(a,n-1);
}
```

A Smarter Version

- Power computation:
  - $a^0 = 1$
  - If n is nonzero and even, $a^n = (a^{n/2})^2$
  - If n is odd, $a^n = a \cdot (a^{n/2})^2$
    - Java note: If x and y are integers, "x/y" returns the integer part of the quotient
- Example:
  $a^5 = a \cdot (a^{5/2})^2 = a \cdot (a^2)^2 = a \cdot ((a^{2/2})^2)^2 = a \cdot (a^2)^2$
  Note: this requires 3 multiplications rather than 5
- What if n were larger?
  - Savings would be more significant
- This is much faster than the straightforward computation
  - Straightforward computation: n multiplications
  - Smarter computation: log(n) multiplications

Smarter Version in Java

- n = 0: $a^0 = 1$
- n nonzero and even: $a^n = (a^{n/2})^2$
- n nonzero and odd: $a^n = a \cdot (a^{n/2})^2$

local variable   parameters

```
static int power(int a, int n) {
   if (n == 0) return 1;
   int halfPower = power(a,n/2);
   if (n%2 == 0) return halfPower*halfPower;
   return halfPower*halfPower*a;
}
```

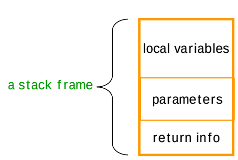
- The method has two parameters and a local variable
- Why aren't these overwritten on recursive calls?

Implementation of Recursive Methods

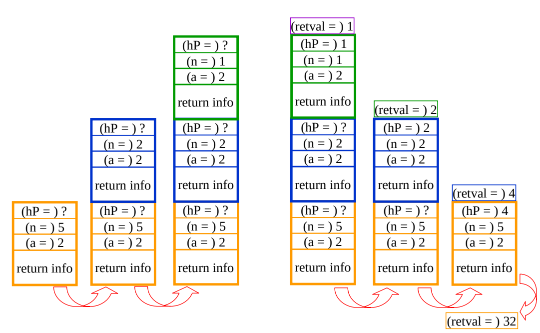
- Key idea:
  - Use a stack to remember parameters and local variables across recursive calls
  - Each method invocation gets its own stack frame
- A stack frame contains storage for
  - Local variables of method
  - Parameters of method
  - Return info (return address and return value)
  - Other bookkeeping info

Stack Frame

- A new stack frame is pushed with each recursive call
- The stack frame is popped when the method returns
  - Leaving a return value (if there is one) on top of the Stack



Example: power(2, 5)

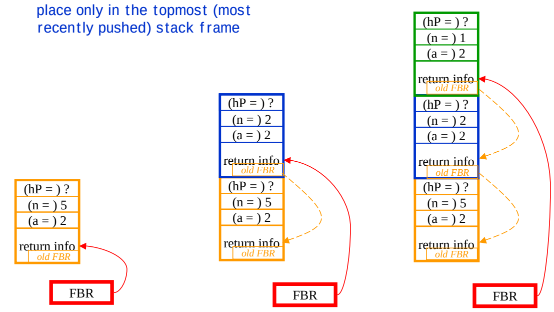


How Do We Keep Track?

- At any point in execution, many invocations of *power* may be in existence
  - Many stack frames (all for *power*) may be in Stack
  - Thus there may be several different versions of the variables *a* and *n*
- How does processor know which location is relevant at a given point in the computation?
- Answer:
  Frame Base Register
  - When a method is invoked, a frame is created for that method invocation, and FBR is set to point to that frame
  - When the invocation returns, FBR is restored to what it was before the invocation
- How does machine know what value to restore in the FBR?
  - This is part of the return info in the stack frame

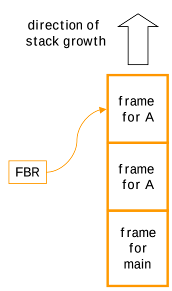
FBR

- Computational activity takes place only in the topmost (most recently pushed) stack frame



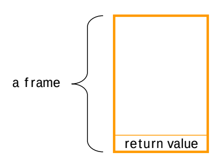
Basic Idea for Functions

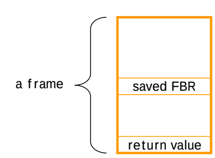
- A new *frame* (on the stack) is created for each function call
  - We use the FBR (Frame Base Register) to indicate the current frame
  - When a function returns it should "clean up" its frame



What's Kept in a Frame?

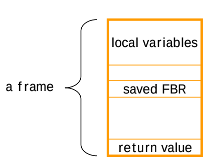
- We already have this principle:
  - When an expression is evaluated, the result is left on top of the stack
- What should be left on the stack after a function call?
- We know we have to change the FBR for each new frame
  - What do we do with the old FBR?

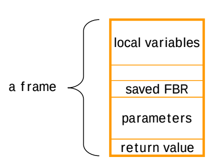




What Else is Kept in a Frame?

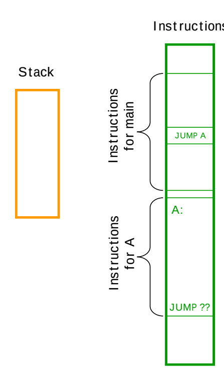
- Another principle:
  - Every time a function is called, it has its own local variables
- Thus it makes sense to keep a function's local variables in its frame
- The parameters of a function are also "local variables"
  - They can be kept in the frame, too





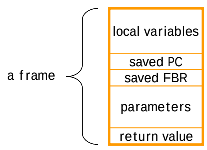
Is That It? Nothing Else in a Frame?

- Well, no; there's one more thing…
- We're using assembly language
  - If we want to jump somewhere and then come back then we must *remember* where to come back to



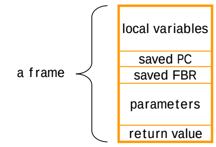
How Do We Jump Back?

- We can store the *return address* (i.e., a saved PC value) in the frame, too
- We have provided SAM instructions to store and restore the PC
  - JSR *address*
    - push PC+1 onto stack; set PC to *address*
    - Jump to SubRoutine
  - JUMPIND
    - set PC to value on top of stack
    - JUMP INDirect
- We also have instructions to save and restore the FBR
  - LINK
    - push value of FBR onto stack; set FBR to SP-1
  - UNLINK
    - set value of FBR to value on top of stack



Creating a Frame

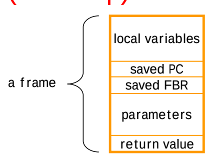
- Responsibility for creating a frame is shared by the *caller* (calling code) and the *callee* (the function's code)



- Caller's responsibilities
  - Push space for return value
  - Push arguments
  - Create new frame (use LINK = push current FBR and set FBR to SP–1)
  - JSR to callee (push PC+1 and jump to callee)
- Callee's responsibilities
  - Reserve space for local variables
  - Continue with callee's code

Clearing a Frame (Clean-up)

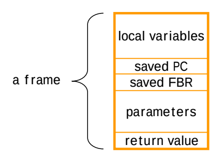
- Responsibility for clearing a frame is shared by the *callee* (the function's code) and the *caller* (calling code)



- Callee's responsibilities
  - Clear local variables from stack
  - JUMPIND to caller (clear the saved PC and jump back to calling code)
- Caller's responsibilities
  - Restore the FBR (UNLINK)
  - Clear the arguments from stack
  - Note: return value *remains on stack*

Access to Frame's Data

- Data stored in the frame are accessed via offset from the FBR
  - Let p be the number of parameters



The first local variable
- STOREOFF 2

The second local variable
- STOREOFF 3

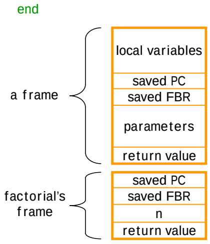
The first parameter
- STOREOFF –p

The second parameter
- STOREOFF –p + 1

The return value
- STOREOFF –p – 1

An Example

```
int factorial (int n) : :
  if n < 2 then return 1;
  else return n * factorial(n-1);
  endif
end
```




```
factorial: PUSHOFF -1
PUSHIMM 2
LESS
JUMPC true
JUMP false
true: PUSHIMM 1
STOREOFF -2        // Store return value
JUMPIND            // Return
false: PUSHOFF -1
ADDSP 1            // Space for return value
PUSHOFF -1
PUSHIMM 1
SUB                // Argument is now on stack
LINK               // Create new stack frame
JSR factorial      // Call the function
UNLINK             // Restore FBR
ADDSP -1           // Clear the argument
TIMES
STOREOFF -2        // Store return value
JUMPIND            // Return
```

Example Calling Code

```
program:
ADDSP 1            // Space for return value
PUSHIMM 5          // The argument
LINK               // Create new stack frame
JSR factorial      // Call the function
UNLINK             // Restore FBR
ADDSP -1           // Clear the argument
WRITE              // Write result
STOP
```

- We need this "calling code" to help create factorial's initial frame