BBM 101 – Introduction to Programming I

Fall 2014, Lecture 7

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Today

- **Functions**
  - Definitions
  - Invocation
  - Parameter Lists
  - Return Values
  - Prototypes
- **Variable Scopes**
  - Block Structure
  - Global and Local Variables
  - Static Variables
- **Recursion**
  - Recursion
  - Inductive reasoning
  - Divide and conquer

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Introduction

Structured Programming is a problem-solving strategy and a programming methodology that includes the following two guidelines:

- The flow of control in a program should be as simple as possible.
- The construction of a program should embody *top-down* design.

Top-down Design

Top-down design (*stepwise refinement*, or *divide and conquer)* consists of repeatedly decomposing a problem into smaller problems.

- A program is constructed from smaller pieces (components, modules)
- Each piece is more manageable than the original program

Functions

- Programs combine *user-defined* functions with *library* functions
  - C standard library has a wide variety of functions, e.g. several math functions are included in math.h
- Invoking functions
  - Provide function name and arguments
  - Function performs operations or manipulations
  - Function returns results
- Function call analogy
  - Boss asks worker to complete task
  - Worker gets information, does task, returns result
  - Information hiding: boss does not know details

Math Library Functions

- Math library functions
  - perform common mathematical calculations
  - **#include <math.h>**
- Format for calling functions
  - **FunctionName(** *argument* **);**
    - If multiple arguments, use comma-separated list
  - `y = sqrt( 900.0 );`
    - Calls function **sqrt**, which returns the square root of its argument
- Arguments may be any r-value (constants, variables, or expressions)

Math Library Functions

Function Header	Description
int abs(int num)	Returns the absolute value of an integer element
double fabs(double num)	Returns the absolute value of a double precision element.
double pow(double x,double y)	Returns x raised to the power of y.
int rand(void)	Returns a random number
double sin(double angle)	Returns the sine of an angle; the angle should be in Radius.
double cos(double angle)	Returns the cosine of an angle; the angle should be in Radius.
double sqrt(double num)	Returns the the square root of a double

Math Library Functions (Example)

- How to code square root of **$(x1 - x2)^2 + (y1 - y2)^2$** by using math.h library functions?

```
a = x1 - x2;
b = y1 - y2;
c = pow(a, 2) + pow(b, 2);
d = sqrt(c);
```


Functions

- We have already written/called some functions before.

```
/* Welcome to BBM 101 */
#include <stdio.h>

int main(void)
{
      printf("Hello world!\n");
      return 0;
}
```

- **main** is a function that must exist in every C program.
- **printf** is a library function which we have already used in our program.

Let's create and call our own functions now!

Function Definition

- Syntax

```
type name (parameters){
      variables;
      statements;
}
```

- ***name*** is the name of the function
- ***type*** is the type of the returned value by the function
  - *void* means the function returns nothing
  - Functions return *int* value if nothing is specified
- ***parameters*** specify the types and names of the parameters separated by comma

Function Returning a Value (Example)

- Let's define a function to compute the cube of a number:

```
int cube ( int num ) {
      int result;
      result = num * num * num;
      return result;
}
```

- This function can be called as:

```
n = cube(5);
```

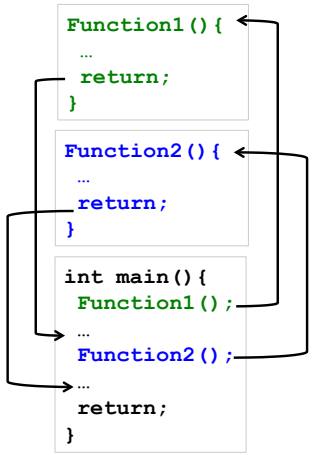
void Function (Example)

```
/* function definition */
void print_message(void){
      printf("A message for you:   ");
      printf("Have a nice day!\n");
}

int main(void){
      /* function invocation */
      print_message();
      return 0;
}
```


Function Invocation

- A program is made up of one or more functions, one of them being main( ).
- When a program encounters a function, the function is called or invoked.
- After the function does its work, program control is passed back to the calling environment, where program execution continues.



The return Statement

- When a return statement is executed, the execution of the function is terminated and the program control is immediately passed back to the calling environment.
- If an expression follows the keyword return, the value of the expression is returned to the calling environment as well.
- A return statement can be one of the following two forms:

```
return;
return expression;
```

Examples:

```
return;
return 1.5;
return result;
return a+b*c;
return x < y ? x : y;
```


The return Statement (Example)

- Define a function to check if asked year is a leap year

```
int IsLeapYear(int year){
      return ( ((year % 4 == 0) && (year % 100 != 0))
                  || (year % 400 == 0) );
}
```

- This function may be called as:

```
if (IsLeapYear(2005))
      printf("29 days in February.\n");
else
      printf("28 days in February.\n");
```

Example: Find minimum of two integers

```
#include  <stdio.h>
int min(int a, int b){
   if (a < b)
      return a;
   else
      return b;
}

int main (void){
   int j, k, m;

   printf("Input two integers: ");
   scanf("%d %d", &j, &k);

   m = min(j, k);

   printf("\nThe minimum is %d.\n", m);
   return 0;
}
```

```
Input two integers: 11 3
The mininum is 3.
```


Function Parameters

- A function can have zero or more parameters.
- The *formal parameter list* in declaration header

```
int f (int x, double y, char c);
```

Parameter variables and their types are declared here.

- The *actual parameter list* in function calling:

```
value = f(age, 100*score, initial);
```

Cannot be told what their types are from here.

Rules for Parameter Lists

- The number of parameters in the actual and formal parameter lists must be *consistent.*
- Parameter association is *positional:* the first *actual* parameter matches the first *formal* parameter, the second matches the second, and so on.
- *Actual* parameters and *formal* parameters must be of compatible *data types.*
- *Actual* parameters may be a variable, constant, any expression matching the type of the corresponding formal parameter.

Call-by-Value Invocation

- Each argument is evaluated, and its value is used locally in place of the corresponding formal parameter.
- If a variable is passed to a function, the stored value of that variable in the calling environment will not be changed.
- In C, **all** calls are call-by-value.

Function Call

- The type of a function-call expression is the same as the type function being called, and its value is the value returned by the function.

- Function calls can be embedded in other function calls.

```
t = cubesum(i);
j = cubesum(t);
```

is equivalent to

```
j = cubesum(cubesum(i));
```


Function Call (Example)

```
#include  <stdio.h>
int compute_sum (int n){
   int  sum = 0;

   for ( ; n > 0; --n)
      sum += n;

   printf("%d ", n);

   return sum;
}
```

```
int main (void){
   int n = 3, sum;

   printf("%d ", n);

   sum = compute_sum(n);

   printf("%d ", n);
   printf("%d", sum);

   return 0;
}
```

```
3 0 3 6
```


Example: Find maximum of three integers

```
#include  <stdio.h>
int maximum(int a, int b, int c){
   int max = a;

   if (b > max)
      max = b;
   if (c > max)
      max = c;

   return max;
}

int main (void){
   int j, k, l, m;

   printf("Input three integers: ");
   scanf("%d %d %d", &j, &k, &l);

   printf("\nThe maximum is %d.\n", maximum(j, k, l));
   return 0;
}
```

```
Input three integers: 11 3 7
The maxinum is 11.
```


Function Prototypes

- General form for a function prototype declaration:

```
return_type function_name (parameter-type-list)
```

- Used to validate functions
  - Prototype only needed if function definition comes after use in program

- The function with the prototype

```
int maximum( int, int, int );
```

(Takes in 3 **int**s, returns an **int**)

Using Function Prototypes

```
#include <stdio.h>
int max (int a, int b){
  ...
}

int min (int a, int b){
  ...
}

int main(void){
  ...
  min(x,y);
  max(u,v);
  ...
}
```

=

```
#include <stdio.h>
int max(int,int);
int min(int,int);

int main(void){
  min(x,y);
  max(u,v);
  ...
}

int max (int a, int b){
  ...
}

int min (int a, int b){
 ...
}
```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  - Static Variables

Block Structure and Variable Scope

```
#include <stdio.h>

int total, count;

int main(int argc, const char * argv[]){
    total = count = 0;
    {
        int count = 0;
        while (1) {
            if (count > 10)
                break;
            total += count;
            count++;
        }
        printf("%d\n", count);
    }

    count++;
    printf("%d\n", count);
    return 0;
}
```

Global *count* variable is valid in the whole program.

Local *count* variable is only valid in the red block here.

```
11
1
```


External Variables

- Local variables can only be accessed in the function in which they are defined.
- If a variable is defined outside any function at the same level as function definitions, it is available to all the functions defined below in the same source file

  → external variable
- **Global variables** are external variables defined before any function definition
  - Their scope will be the whole program

Local Variables

```
#include  <stdio.h>

void func1 (void){
      int i = 5;
      printf("%d\n", i);
      i++;
      printf("%d\n", i);
}

int main (void){
      int i = 5;
      printf("%d \n", i);
      func1();
      printf("%d \n",i);
      return 0;
}
```

```
5
5
6
5
```


Static Variables

- A variable is said to be **static** if it is allocated storage at the beginning of the program execution and the storage remains allocated until the program execution terminates.
- External variables are always static.
- Within a block, a variable can be specified to be static by using the keyword static before its type declaration:

```
static type variable-name;
```

- Variable declared static can be initialized only with constant expressions **(if not, its default value is zero)**.

Static Variables (Example)

```
#include <stdio.h>
void incr(void);

int main(void){
   int i;
   void incr(void);

   for (i=0; i<3; i++)
       incr();
   return 0;
}

void incr(void){
   static int static_i = 0;
   printf("static_i = %d\n", static_i++);
}
```

A static variable inside a function keeps its value between invocations.

```
Output:
static_i = 0
static_i = 1
static_i = 2
```


Static Variables (Example-Initial Value)

```
#include <stdio.h>

void put_stars(int n){
  static int static_n;
  int i;

  for (i=0; i<static_n; i++)
       printf(" ");
  for (i=0; i<n; i++)
       printf("*");

  printf("\n");
  static_n+= n;
}

int main(void){
   put_stars(3);
   put_stars(2);
   put_stars(3);
   return 0;
}
```

```
Output:
***
  **
    ***
```

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Recursion

- ***Recursion*** is the process whereby a construct operates on itself.
- In C, a function may directly or indirectly call itself in the course of execution.
  - **direct:** The call to a function occurs inside the function itself
  - **indirect:** A function calls another function, which in turn makes a call to the first one
- Recursion is a programming technique that naturally implements the divide-and-conquer problem solving methodology.

Iterative Algorithms

- Looping constructs (e.g. while or for loops) lead naturally to **iterative** algorithms
- Can conceptualize as capturing computation in a set of "state variables" which update on each iteration through the loop

Iterative multiplication by successive additions

- Imagine we want to perform multiplication by successive additions:
  - To multiply a by b, add a to itself b times
- State variables:
  - i – iteration number; starts at b
  - result – current value of computation; starts at 0
- Update rules
  - i←i -1; stop when 0
  - result←result + a

```
int iterMul(int a, int b)
{
  int result = 0;
  while (b > 0) {
    result += a!
     b--;
  }
  return result;
}
```

Recursive version

- An alternative is to think of this computation as:

$$a * b = \underbrace{a + a + \ldots + a}_{\text{b copies}}$$

$$= \underbrace{a + a + \ldots + a}_{\text{b-1 copies}}$$

$$= a + a * (b - 1)$$

Recursion

- This is an instance of a **recursive** algorithm
  - Reduce a problem to a simpler (or smaller) version of the same problem, plus some simple computations
- **Recursive step**
  - Keep reducing until reach a simple case that can be solved directly
- **Base case**
  - a*b=a; if b=1 (Basecase)
  - a * b = a + a * (b-1); otherwise (Recursive case)

```
int recurMul(int a, int b)
{
  if (b==1)
      return a;
  else
      return a + recurMul(a,b-1);
}
```


Inductive reasoning

- How do we know that our recursive code will work?
- **`iterMul`** terminates because b is initially positive, and decrease by 1 each time around loop; thus must eventually become less than 1
- **`recurMul`** called with b = 1 has no recursive call and stops
- **`recurMul`** called with b > 1 makes a recursive call with a smaller version of b; must eventually reach call with b = 1

Mathematical Induction

- To prove a statement indexed on integers is true for all values of n:
  - Prove it is true when n is smallest value (e.g. n = 0 or n = 1)
  - Then prove that if it is true for an arbitrary value of n, one can show that it must be true for n+1

Example

- 0+1+2+3+...+n=(n(n+1))/2

- Proof
  - If n = 0, then LHS is 0 and RHS is 0*1/2 = 0, so true
  - Assume true for some k, then need to show that
    - 0 + 1 + 2 + ... + k + (k+1) = ((k+1)(k+2))/2
    - LHS is k(k+1)/2 + (k+1) by assumption that property holds for problem of size k
    - This becomes, by algebra, ((k+1)(k+2))/2
  - Hence expression holds for all n >= 0

What does this have to do with code?

- Same logic applies

```
int recurMul(int a, int b)
{
  if (b==1)
      return a;
  else
      return a + recurMul(a,b-1);
}
```

- Base case, we can show that **`recurMul`** must return correct answer
- For recursive case, we can assume that **`recurMul`** correctly returns an answer for problems of size smaller than b, then by the addition step, it must also return a correct answer for problem of size b
- Thus by induction, code correctly returns answer

Factorial Function – *Iterative Definition*

n! = n * (n-1) * (n-2) * … * 2 * 1 *for any integer n > 0*
0! = 1

Iterative Definition in C:

```
fval = 1;
for (i = n; i >= 1; i--)
        fval = fval * i;
```


Factorial Function – *Recursive Definition*

- To define ***n!*** recursively, ***n!*** must be defined in terms of the factorial of a smaller number.
- Observation (problem size is reduced):
  n! = n * (n-1)!
- Base case → **0! = 1**
- We can reach the base case, by subtracting **1** from **n** if **n** is a positive integer.

Recursive Definition:

n! = 1 if *n = 0*
n! = n(n-1)!* if *n > 0*

Recursive Factorial Function Definition in C

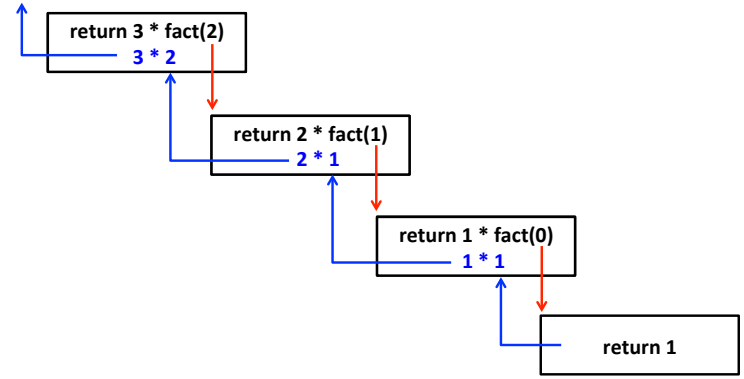
```
/* Computes the factorial of a nonnegative integer.
   Precondition: n must be greater than or equal to 0.
   Postcondition: Returns the factorial of n; n is unchanged.*/

int fact(int n)
{
        if (n == 0)
                return (1);
        else
                return (n * fact(n-1));
}
```

This ***fact*** function satisfies the four criteria of a recursive solution.

How does it Compute?

```
printf("%d", fact (3));
```

6



Tracing a Recursive Function

- A **stack** is used to keep track of function calls.
- Whenever a new function is called
  - For each function call, an ***activation record (AR)*** is created on the stack.
  - AR consists of the function's parameters and local variables are pushed onto the stack along with the memory address of the calling statement (return point).
- To trace a recursive function, the ***box method*** can be used.
  - The box method is a systematic way to trace the actions of a recursive function.
  - The box method illustrates how compilers implement recursion.
  - Each box in the box method roughly corresponds to an activation record.

The Box Method

- Label each recursive call in the body of the recursive function.
  - These labels help us to keep track of the correct place to which we must return after a function call completes.
  - After each recursive call, we return to the labeled location, and substitute that recursive call with returned value.

```
if (n ==0)
        return (1);
else
        return (n * fact(n-1) )
                    A
```

The Box Method (cont'd.)

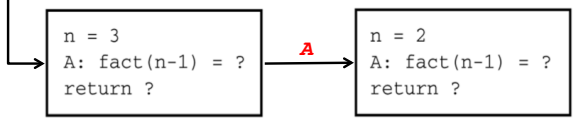
- Every time a function is called, a new box is created to represent its local environment.
- Each box contains:
  - The values of the arguments
  - The function's local variables
  - A placeholder for the value returned from each recursive call from the current box (label in the previous step).
  - The value of the function itself.

```
n = 3
A: fact(n-1) = ?
return ?
```


The Box Method (cont'd.)

- Draw an arrow from the statement that initiates the recursive process to the first box.
  - Then draw an arrow to a new box created after a recursive call, put a label on that arrow.

```
printf("%d", fact (3));
```



The Box Method (cont'd.)

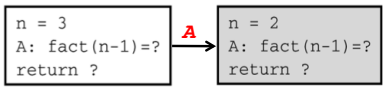
- After a new box is created, we start to execute the body of the function.
- On exiting a function, cross off the current box an follow its arrow back to the box that called the function.
  - This box becomes the current box.
  - Substitute the value returned by the just-terminated function call into the appropriate item in the current box.
  - Continue the execution from the returned point.

Box Trace of *fact(3)*

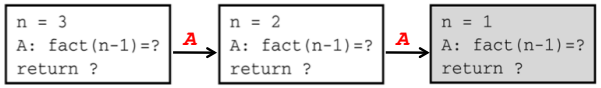
- The initial call is made, and the function *fact* begins execution.

```
n = 3
A: fact(n-1)=?
return ?
```

- At point A, a recursive call is made, and the new invocation of fact begins execution.

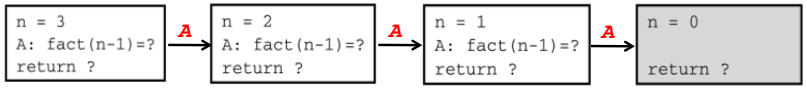


- At point A, a recursive call is made, and the new invocation of fact begins execution.

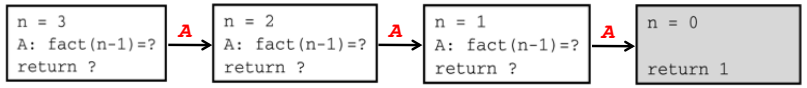


Box Trace of *fact(3)* (cont'd.)

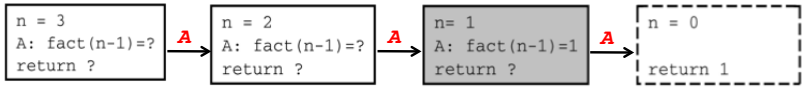
- At point A, a recursive call is made, and the new invocation of fact begins execution.



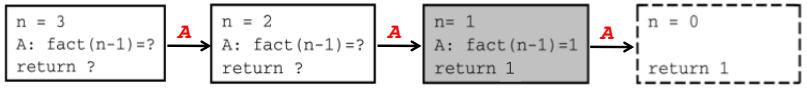
- This is the base case, so this invocation of fact completes.



- The function value is returned to the calling box, which continues the execution.



- The current invocation of fact completes.



Box Trace of *fact(3)* (cont'd.)

- The function value is returned to the calling box, which continues the execution.

- The current invocation of fact completes.

- The function value is returned to the calling box, which continues the execution.

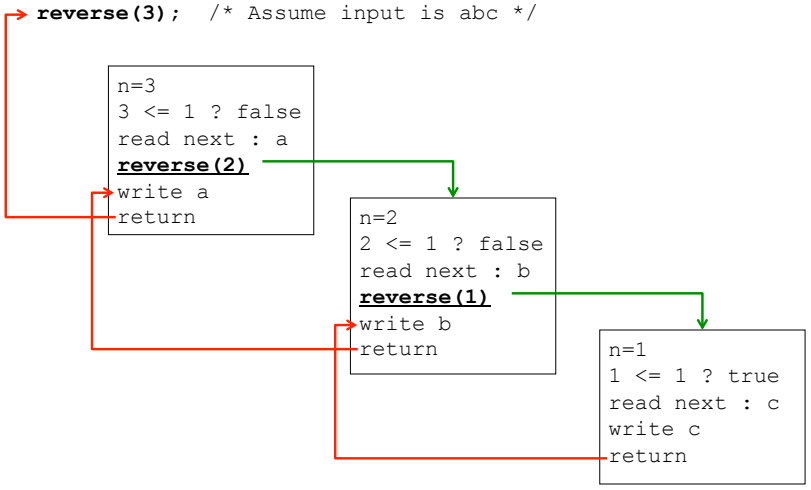
- The current invocation of fact completes.

- The value **6** is returned to the initial call.

Example: Find the reverse of an input string

```
/* reads n characters and prints them in reverse order. */
void reverse(int n){
        char next;
        if (n == 1) {                          /* stopping case */
                scanf("%c", &next);
                printf("%c", next);
        } else {
                scanf("%c", &next);
                reverse(n-1);
                printf("%c", next);
        }
        return;
}

int main(){
   printf("Enter a string: ");
   reverse(3);
   printf("\n");
}
```


Trace of *reverse(3)*



Recursion with multiple base cases

- Fibonacci numbers
  - Leonardo of Pisa (aka Fibonacci) modeled the following challenge
    - Newborn pair of rabbits (one female, one male) are put in a pen
    - Rabbits mate at age of one month
    - Rabbits have a one month gestation period
    - Assume rabbits never die, that female always produces one new pair (one male, one female) every month from its second month on.
    - How many female rabbits are there at the end of one year?

Fibonacci Sequence

- After one month (call it 0) – 1 female
- After second month – still 1 female (now pregnant)
- After third month – two females, one pregnant, one not
- In general, females(n) = females(n-1) + females(n-2)
  - Every female alive at month n-2 will produce one female in month n;
  - These can be added those alive in month n-1 to get total alive in month n

Month	Females
0	1
1	1
2	2
3	3
4	5
5	8
6	13

Fibonacci Sequence

- Base cases:
  – Females(0) = 1
  – Females(1) = 1
- Recursive case
  – Females(n) = Females(n-1) + Females(n-2)

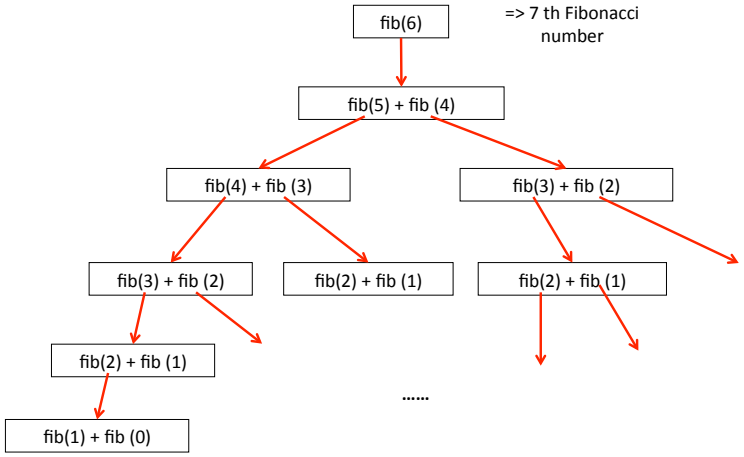
```
/* assumes x an int >= 0 and returns Fibonacci of x */
int fib(int n){
        if (n < 2)
                return n;
        else
                return(fib(n-2) + fib(n-1));
}
```


Fibonacci Sequence

```
/* assumes x an int >= 0 and returns Fibonacci of x */
int fib(int n){
        if (n < 2)
                return n;
        else
                return(fib(n-2) + fib(n-1));
}
```

- This is an example of *non-linear* recursion. Because total number of recursive calls grows exponentially.
- *fib(n-1)* expression must be evaluated completely before its value can be added to the expression *fib(n-2)* which must also be evaluated completely
- Recursion tree is useful in tracing the values of variables during non-linear recursion.

Recursion Tree for Fibonacci Sequence



Example: Fibonacci Sequence (Iterative Version)

```
int Fib(int n)
{
   int Prev1, Prev2, Temp, j;

   if (n==0 || n== 1)
      return n;
   else {
      Prev1=0;
      Prev2 = 1;
      for (j=1; j <= n; j++){
         Temp = Prev1 + Prev2;
         Prev2 = Prev1;
         Prev1 = Temp;
      }
      return Prev1;
   }
}
```


Recursion vs. Iteration

- In general, an iterative version of a program will execute more efficiently in terms of time and space than a recursive version.
  - This is because the overhead involved in entering and exiting a function is avoided in iterative version.
- However, a recursive solution can be sometimes the most natural and logical way of solving a problem.
  - Conflict: machine efficiency versus programmer efficiency.
- It is always true that recursion can be replaced with iteration and a stack (and vice versa).

Summary

- **Functions**
  - Definitions
  - Invocation
  - Parameter Lists
  - Return Values
  - Prototypes
- **Variable Scopes**
  - Block Structure
  - Global and Local Variables
  - Static Variables
- **Recursion**
  - Recursion
  - Inductive reasoning
  - Divide and conquer

Next week

- **Debugging**
  - Testing and debugging
  - Black box testing
  - Glass box testing
  - Integration testing and unit testing
  - Debugging approaches
- **Arrays**
  - Declaring Arrays
  - Examples
  - Passing Arrays to Functions
  - Sorting Arrays
  - Multi-Dimensional Arrays
  - Command Line Input