Chapter 11
Introduction to Programming in C

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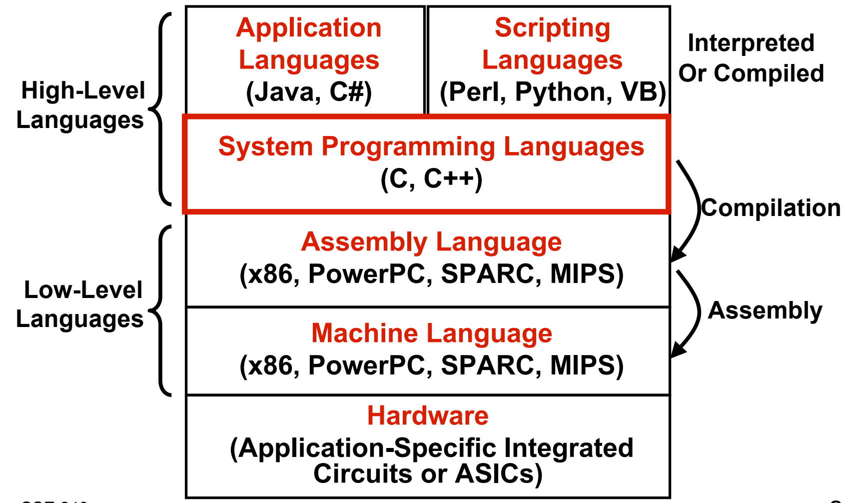
Programming Levels



The Course Thus Far…

We did digital logic
- Bits are bits
- Ultimately, to understand a simple processor

We did assembly language programming
- Programming the "raw metal" of the computer
- Ultimately, to understand C programming

Starting today: we're doing C programming
- C is still common for systems programming
- You'll need it for the operating systems class (CSE380)
- Ultimately, for a deeper understanding of any language (Java)

Why High-Level Languages?

Easier than assembly. Why?
- Less primitive constructs
- Variables
- Type checking

Portability
- Write program once, run it on the LC-3 or Intel's x86

Disadvantages
- Slower and larger programs (in most cases)
- Can't manipulate low-level hardware
  - All operating systems have some assembly in them

Verdict: assembly coding is rare today

Our Challenge

All of you already know Java

- We're going to try to cover the basics quickly
- We'll spend more time on pointers & other C-specific nastiness

Created two decades apart

- C: 1970s - AT&T Bell Labs
- C++: 1980s - AT&T Bell Labs
- Java: 1990s - Sun Microsystems

Java and C/C++

- Syntactically similar (Java uses C syntax)
- C lacks many of Java's features
- Subtly different semantics

C is Similar To Java Without:

Objects

- No classes, objects, methods, or inheritance

Exceptions

- Check all error codes explicitly

Standard class library

- C has only a small standard library

Garbage collection

- C requires explicit memory allocate and free

Safety

- Java has strong type checking, checks array bounds
- In C, anything goes

Portability

- Source: C code is less portable (but better than assembly)
- Binary: C compiles to specific machine code

More C vs Java differences

C has a "preprocessor"

- A separate pre-pass over the code
- Performs replacements

Include vs Import

- Java has import java.io.*;
- C has: #include <stdio.h>
- #include is part of the preprocessor

Boolean type

- Java has an explicit boolean type
- C just uses an "int" as zero or non-zero
- C's lack of boolean causes all sorts of trouble

More differences as we go along…

History of C and Unix

Unix is the most influential operating system

First developed in 1969 at AT&T Bell Labs

- By Ken Thompson and Dennis Ritchie
- Designed for "smaller" computers of the day
- Reject some of the complexity of MIT's Multics

They found writing in assembly tedious

- Dennis Ritchie invented the C language in 1973
- Based on BCPL and B, needed to be efficient (24KB of memory)

Unix introduced to UC-Berkeley (Cal) in 1974

- Bill Joy was an early Unix hacker as a PhD student at Cal
- Much of the early internet consisted of Unix systems Mid-80s
- Good, solid TCP/IP for BSD in 1984

Linux - Free (re)implementation of Unix (libre and gratuit)

- Announced by Linus Torvalds in 1991

Much more in CSE380!

Aside: The Unix Command Line

Text-based approach to give commands

- Commonly used before graphical displays
- Many advantages even today

Examples

- `mkdir cse240hw8` make a directory
- `cd cse240hw8` change to the directory
- `ls` list contents of directory
- `cp /mnt/eniac/home1/c/cse240/project/hw/hw8/* .`
  - Copy files from one location to current dir (".")
- `emacs foo.c &` run the command "emacs" with input "foo.c"
- `gcc -o foo foo.c` compile foo.c (create program called "foo")

Unix eventually developed graphical UIs (GUIs)

- X-windows (long before Microsoft Windows)

What is C++?

C++ is an extension of C

- Also done at AT&T Bell Labs (1983)
- Backward compatible (good and bad)
- That is, all C programs are legal C++ programs

C++ adds many features to C

- Classes, objects, inheritance
- Templates for polymorphism
- A large, cumbersome class library (using templates)
- Exceptions (not actually implemented for a long time)
- More safety (though still unsafe)
- Operator and function overloading
- Kitchen sink

Thus, many people uses it (to some extent)

- However, we're focusing on only C, not C++

Quotes on C/C++ vs Java

"C is to assembly language as Java is to C"

- Unknown

"With all due respect, saying Java is just a C++ subset is rather like saying that `Pride and Prejudice' is just a subset of the Encyclopedia Britanica. While it is true that one is shorter than the other, and that both have the same syntax, there are rather overwhelming differences."

- Sam Weber, on the ACM SIGSCE mailing list

"Java is C++ done right."

- Unknown

More quotes on C/C++

"The C programming language combines the power of assembly language with the ease-of-use of assembly language."

- Unknown

"It is my impression that it's possible to write good programs in C++, but nobody does."

- John Levine, moderator of comp.compilers

"C makes it easy to shoot yourself in the foot; C++ makes it harder, but when you do it, it blows your whole leg off."

- Bjarne Stroustrup, creator of C++

Program Execution: Compilation vs Interpretation

Different ways of executing high-level languages

Interpretation

- Interpreter: program that executes program statements
  - ➢ Directly interprets program (portable but slow)
  - ➢ Limited optimization
- Easy to debug, make changes, view intermediate results
- Languages: BASIC, LISP, Perl, Python, Matlab

Compilation

- Compiler: translates statements into machine language
  - ➢ Creates executable program (non-portable, but fast)
  - ➢ Performs optimization over multiple statements
- Harder to debug, change requires recompilation
- Languages: C, C++, Fortran, Pascal

Hybrid

- Java, has features of both interpreted and compiled languages

Compilation vs. Interpretation

Consider the following algorithm:

- `Get W from the keyboard.`
- `X = W + W`
- `Y = X + X`
- `Z = Y + Y`
- `Print Z to screen.`

If interpreting, how many arithmetic operations occur?

If compiling, we can analyze the entire program and possibly reduce the number of operations.

- Can we simplify the above algorithm to use a single arithmetic operation?

Compiling a C Program

Entire mechanism is usually called the "compiler"

Preprocessor

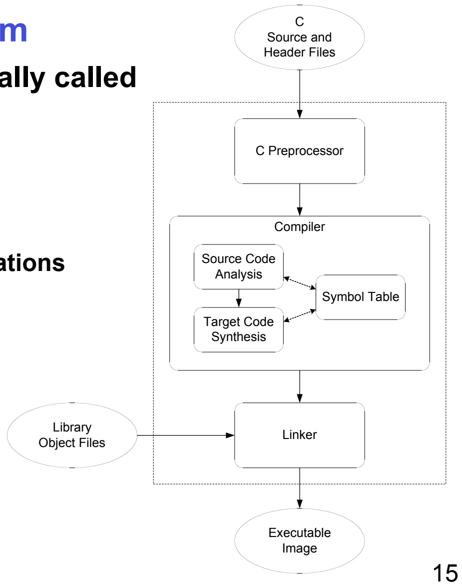
- Macro substitution
- Conditional compilation
- "Source-level" transformations
  - ➢ Output is still C

Compiler

- Generates object file
  - ➢ Machine instructions

Linker

- Combine object files (including libraries) into executable image



Compiler

Source Code Analysis

- "Front end"
- Parses programs to identify its pieces
  - ➢ Variables, expressions, statements, functions, etc.
- Depends on language (not on target machine)

Code Generation

- "Back end"
- Generates machine code from analyzed source
- May optimize machine code to make it run more efficiently
- Very dependent on target machine

Example Compiler: GCC

- The Free-Software Foundation's compiler
- Many front ends: C, C++, Fortran, Java
- Many back ends: Intel x86, PowerPC, SPARC, MIPS, Itanium

A Simple C Program

```
#include <stdio.h>
#define STOP 0

void main()
{
  /* variable declarations */
  int counter;  /* an integer to hold count values */
  int startPoint; /* starting point for countdown */

  /* prompt user for input */
  printf("Enter a positive number: ");
  scanf("%d", &startPoint); /* read into startPoint */

  /* count down and print count */
  for (counter=startPoint; counter >= STOP; counter--) {
    printf("%d\n", counter);
  }
}
```


Preprocessor Directives

`#include <stdio.h>`

- Before compiling, copy contents of header file (stdio.h) into source code.
- Header files typically contain descriptions of functions and variables needed by the program.
  - no restrictions -- could be any C source code

`#define STOP 0`

- Before compiling, replace all instances of the string "STOP" with the string "0"
- Called a *macro*
- Used for values that won't change during execution, but might change if the program is reused. (Must recompile.)

Comments

Begins with `/*` and ends with `*/`

- Can span multiple lines
- Comments are not recognized within a string
  - example: "my/*don't print this*/string"
    would be printed as: my/*don't print this*/string

Begins with // and ends with “end of line”

- Single-line comment
- Much like “;” in LC-3 assembly
- Introduced in C++, later back-ported to C

As before, use comments to help reader, not to confuse or to restate the obvious

`main` Function

Every C program must have a function called `main()`

- Starting point for every program
- Similar to Java’s main method
  - `public static void main(String[] args)`

The code for the function lives within brackets:

```
void main()
{
  /* code goes here */
}
```

Variable Declarations

Variables are used as names for data items

Each variable has a *type*, tells the compiler:

- How the data is to be interpreted
- How much space it needs, etc.

```
int counter;
int startPoint;
```

C has similar primitive types as Java

- int, char, long, float, double
- More later

Input and Output

Variety of I/O functions in *C Standard Library*

- Must include `<stdio.h>` to use them

```
printf("%d\n", counter);
```

- String contains characters to print and formatting directions for variables
- This call says to print the variable `counter` as a decimal integer, followed by a linefeed (`\n`)

```
scanf("%d", &startPoint);
```

- String contains formatting directions for looking at input
- This call says to read a decimal integer and assign it to the variable `startPoint` (Don't worry about the `&` yet)

More About Output

Can print arbitrary expressions, not just variables

```
printf("%d\n", startPoint - counter);
```

Print multiple expressions with a single statement

```
printf("%d %d\n", counter,
       startPoint - counter);
```

Different formatting options:

- `%d` decimal integer
- `%x` hexadecimal integer
- `%c` ASCII character
- `%f` floating-point number

Examples

This code:

```
printf("%d is a prime number.\n", 43);
printf("43 plus 59 in decimal is %d.\n", 43+59);
printf("43 plus 59 in hex is %x.\n", 43+59);
printf("43 plus 59 as a character is %c.\n", 43+59);
```

produces this output:

```
43 is a prime number.
43 plus 59 in decimal is 102.
43 plus 59 in hex is 66.
43 plus 59 as a character is f.
```

Examples of Input

Many of the same formatting characters are available for user input

```
scanf("%c", &nextChar);
```

- reads a single character and stores it in nextChar

```
scanf("%f", &radius);
```

- reads a floating point number and stores it in radius

```
scanf("%d %d", &length, &width);
```

- reads two decimal integers (separated by whitespace), stores the first one in length and the second in width

Must use ampersand (`&`) for variables being modified

(Explained in Chapter 16.)

Compiling and Linking

Various compilers available

- cc, gcc
- includes preprocessor, compiler, and linker

Lots and lots of options!

- level of optimization, debugging
- preprocessor, linker options
- intermediate files -- object (.o), assembler (.s), preprocessor (.i), etc.

Remaining Chapters

A more detailed look at many C features

- Variables and declarations
- Operators
- Control Structures
- Functions
- Pointers and Data Structures
- I/O

Emphasis on how C is converted to assembly language

Also see "C Reference" in Appendix D

Chapter 12
Variables and Operators

Basic C Elements

Variables

- Named, typed data items

Operators

- Predefined actions performed on data items
- Combined with variables to form expressions, statements

Statements and Functions

- Group together operations

Data Types

C has several basic data types

`int`	integer (at least 16 bits, commonly 32 bits)
`long`	integer (at least 32 bits)
`float`	floating point (at least 32 bits)
`double`	floating point (commonly 64 bits)
`char`	character (at least 8 bits)

Exact size can vary, depending on processor

- int is supposed to be "natural" integer size;
  for LC-3, that's 16 bits -- 32 bits for most modern processors

Signed vs unsigned:

- Default is 2's complement signed integers
- Use "`unsigned`" keyword for unsigned numbers

Variable Names

Any combination of letters, numbers, and underscore (_)

Case sensitive

- "sum" is different than "Sum"

Cannot begin with a number

- Usually, variables beginning with underscore
  are used only in special library routines

Only first 31 characters are definitely used

- Implementations can consider more characters if they like

Examples

Legal

```
i
wordsPerSecond
words_per_second
_green
aReally_longName_moreThan31chars
aReally_longName_moreThan31characters
```

same identifier

Illegal

```
10sdigit
ten'sdigit
done?
double
```

reserved keyword

Literals

Integer

```
123   /* decimal */
-123
0x123 /* hexadecimal */
```

Floating point

```
6.023
6.023e23  /* 6.023 x 10^23 */
5E12      /* 5.0 x 10^12 */
```

Character

```
'c'
'\n'  /* newline */
'\xA' /* ASCII 10 (0xA) */
```


Scope: Global and Local

Where is the variable accessible?

Global: accessed anywhere in program

Local: only accessible in a particular region

Compiler infers scope from where variable is declared

- Programmer doesn't have to explicitly state

Variable is local to the block in which it is declared

- Block defined by open and closed braces { }
- Can access variable declared in any "containing" block

Global variable is declared outside all blocks

Example

```
#include <stdio.h>
int itsGlobal = 0;

main()
{
  int itsLocal = 1;   /* local to main */
  printf("Global %d Local %d\n", itsGlobal, itsLocal);
  {
    int itsLocal = 2;   /* local to this block */
    itsGlobal = 4;      /* change global variable */
    printf("Global %d Local %d\n", itsGlobal, itsLocal);
  }
  printf("Global %d Local %d\n", itsGlobal, itsLocal);
}
```

Output

```
Global 0 Local 1
Global 4 Local 2
Global 4 Local 1
```


Expression

Any combination of variables, constants, operators, and function calls

- Every expression has a type, derived from the types of its components (according to C typing rules)

Examples:

```
counter >= STOP
x + sqrt(y)
x & z + 3 || 9 - w-- % 6
```

Statement

Expresses a complete unit of work

- **Executed in sequential order**

Simple statement ends with semicolon

```
z = x * y; /* assign product to z */
y = y + 1; /* after multiplication */
;  /* null statement */
```

Compound statement formed with braces

- **Syntactically equivalent to a simple statement**

```
{ z = x * y; y = y + 1; }
```


Operators

Three things to know about each operator

(1) Function

- **What does it do?**

(2) Precedence

- **In which order are operators combined?**
- **Example:**
  "a * b + c * d" is the same as "(a * b) + (c * d)"
  because multiply (*) has a higher precedence than addition (+)

(3) Associativity

- **In which order are operators of the same precedence combined?**
- **Example:**
  "a - b - c" is the same as "(a - b) - c"
  because add/sub associate left-to-right

Assignment Operator

Changes the value of a variable

```
x = x + 4;
```

1. Evaluate right-hand side.

2. Set value of left-hand side variable to result.

Assignment Operator

All expressions evaluate to a value,even ones with the assignment operator

For assignment, the result is the value assigned

- **Usually (but not always) the value of the right-hand side**
  - **Type conversion might make assigned value different than computed value**

Assignment associates right to left.

```
y = x = 3;
```

y gets the value 3, because (x = 3) evaluates to the value 3

```
y = (x = 3);
```

Arithmetic Operators

Symbol	Operation	Usage	Precedence	Assoc
*	multiply	`x * y`	6	l-to-r
/	divide	`x / y`	6	l-to-r
%	modulo	`x % y`	6	l-to-r
+	addition	`x + y`	7	l-to-r
-	subtraction	`x - y`	7	l-to-r

All associate left to right

`* / %` have higher precedence than `+ -`

Example

- 2 + 3 * 4 versus
- (2 + 3) * 4

Arithmetic Expressions

If mixed types, smaller type is "promoted" to larger

`x + 4.3`

if x is int, converted to double and result is double

Integer division -- fraction is dropped

`x / 3`

if x is int and x=5, result is 1 (not 1.666666...)

Modulo -- result is remainder

`x % 3`

if x is int and x=5, result is 2

Bitwise Operators

Symbol	Operation	Usage	Precedence	Assoc
~	bitwise NOT	`~x`	4	r-to-l
<<	left shift	`x << y`	8	l-to-r
>>	right shift	`x >> y`	8	l-to-r
&	bitwise AND	`x & y`	11	l-to-r
^	bitwise XOR	`x ^ y`	12	l-to-r
|	bitwise OR	`x | y`	13	l-to-r

Operate on variables bit-by-bit

- Like LC-3 AND and NOT instructions

Shift operations are logical (not arithmetic)

- Operate on *values* -- neither operand is changed
- `x = y << 1` same as `x = y+y`

Logical Operators

Symbol	Operation	Usage	Precedence	Assoc
!	logical NOT	`!x`	4	r-to-l
&&	logical AND	`x && y`	14	l-to-r
||	logical OR	`x || y`	15	l-to-r

Treats entire variable (or value) as

- TRUE (non-zero), or
- FALSE (zero).

Result is 1 (TRUE) or 0 (FALSE)

- `x = 15; y = 0; printf("%d", x || y);`

Bit-wise vs Logical

- 1 & 8 = 0 (000001 AND 001000 = 000000)
- 1 && 8 = 1 (True & True = True)

Relational Operators

Symbol	Operation	Usage	Precedence	Assoc
>	greater than	`x > y`	9	l-to-r
>=	greater than or equal	`x >= y`	9	l-to-r
<	less than	`x < y`	9	l-to-r
<=	less than or equal	`x <= y`	9	l-to-r
==	equal	`x == y`	10	l-to-r
!=	not equal	`x != y`	10	l-to-r

Result is 1 (TRUE) or 0 (FALSE)

Assignment vs Equality

Don't confuse equality (==) with assignment (=)

```
int x = 9;
int y = 10;
if (x == y) {
  printf("not executed\n");
}
if (x = y) {
  printf("%d %d", x, y);
}
```

Result: "10 10" is printed. Why?

Compiler will not stop you! (What happens in Java?)

Special Operators: ++ and --

Changes value of variable before (or after) its value is used in an expression

Symbol	Operation	Usage	Precedence	Assoc
++	postincrement	`x++`	2	r-to-l
--	postdecrement	`x--`	2	r-to-l
++	preincrement	`++x`	3	r-to-l
--	predecrement	`--x`	3	r-to-l

Pre: Increment/decrement variable before using its value

Post: Increment/decrement variable after using its value

Using ++ and --

```
x = 4;
y = x++;
```

Results: x = 5, y = 4
(because x is incremented after assignment)

```
x = 4;
y = ++x;
```

Results: x = 5, y = 5
(because x is incremented before assignment)

Please, don't combine ++ and =. Really. Just don't!

Special Operators: +=, *=, etc.

Arithmetic and bitwise operators can be combined with assignment operator

Statement	Equivalent assignment
`x += y;`	`x = x + y;`
`x -= y;`	`x = x - y;`
`x *= y;`	`x = x * y;`
`x /= y;`	`x = x / y;`
`x %= y;`	`x = x % y;`
`x &= y;`	`x = x & y;`
`x |= y;`	`x = x | y;`
`x ^= y;`	`x = x ^ y;`
`x <<= y;`	`x = x << y;`
`x >>= y;`	`x = x >> y;`

All have same precedence and associativity as = and associate right-to-left.

Special Operator: Conditional

Symbol	Operation	Usage	Precedence	Assoc
? :	conditional	`x?y:z`	16	l-to-r

x ? y : z

- If x is non-zero, result is y
- If x is zero, result is z

Seems useful, but I don't use it

- A normal "if" is almost always more clear
- You don't need to use every language feature
- Really, don't use it (you don't have to show how clever you are)

Practice with Precedence

Assume a=1, b=2, c=3, d=4

```
x = a * b + c * d / 2;  /* x = 8 */
```

same as:

```
x = (a * b) + ((c * d) / 2);
```

For long or confusing expressions, use parentheses, because reader might not have memorized precedence table

Note: Assignment operator has lowest precedence, so all the arithmetic operations on the right-hand side are evaluated first

Practice with Operators

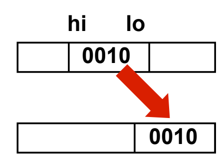
In preparation for our dis-assembler (HW#8):

```
int opcode(int ir)
{
   /* code to extract bits 15 through 12 of ir */
}

int get_field(int bits, int hi_bit, int lo_bit)
{
   /* code to extract hi_bit through lo_bit of bits */
}
```

For example, body of `opcode` function is now just

- `get_field(ir, 15, 12);`

What about a "signed-extended" version?



Practice with Operators (Solution 1)

```
int opcode(int ir)
{
  ir = ir >> 12;
  ir = ir & 0xf;
  return ir;
}
```

OR

```
int opcode(int ir)
{
  ir = ir & 0xf000;
  ir = ir >> 12;
  return ir;
}
```


Practice with Operators (Solution 2)

```
int get_field(int bits, int hi_bit, int lo_bit)
{
  int inv_mask = ~0 << (hi_bit+1)
  int mask = ~inv_mask;
  bits = bits & mask;  // Mask off high-order bits
  bits = bits >> lo_bit;  // Shift away low-order bits
  return bits;
}
```

OR

```
int get_field(int bits, int hi_bit, int lo_bit)
{
  bits = ~(~0 << (hi_bit+1)) & bits; // Mask high bits
  bits = bits >> lo_bit;  // Shift away low-order bits
  return bits;
}
```


Sign Extended Version

```
int get_sext_field(int bits, int hi_bit, int lo_bit)
{
  int most_significant_bit = bits & (1 << hi_bit);
  if (most_significant_bit != 0) {
    bits = (~0 << hi_bit) | bits;  // One extend
  } else {
    bits = ~(~0 << (hi_bit+1)) & bits;  // Zero extend
  }

  bits = bits >> lo_bit;  // Shift away low-order bits
  return bits;
}
```


Chapter 13
Control Structures

Control Structures

Conditional

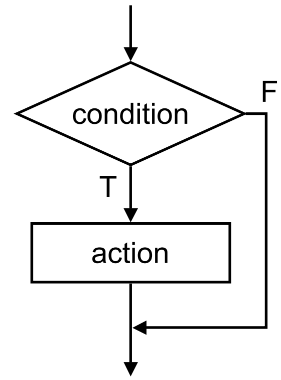
- **Making decision about which code to execute, based on evaluated expression**
- `if`
- `if-else`
- `switch`

Iteration

- **Executing code multiple times, ending based on evaluated expression**
- `while`
- `for`
- `do-while`

If

```
if (condition)
  action;
```



Condition is a C expression,
which evaluates to TRUE (non-zero) or FALSE (zero).
Action is a C statement,
which may be simple or compound (a block).

Example If Statements

```
if (x <= 10)
  y = x * x + 5;
```

Style: avoid singleton if statements (I **really** dislike them)

```
if (x <= 10) {
  y = x * x + 5;
  z = (2 * y) / 3;
}
```

compound statement; both executed if x <= 10

```
if (x <= 10)
  y = x * x + 5;
  z = (2 * y) / 3;
```

only first statement is conditional; second statement is ***always*** executed

More If Examples

```
if (0 <= age && age <= 11) {
  kids = kids + 1;
}
if (month == 4 || month == 6 ||
     month == 9 || month == 11) {
  printf("The month has 30 days.\n");
}
if (x = 2) {
  y = 5;
}
```

Common C error, assignment (=) Versus equality (==)

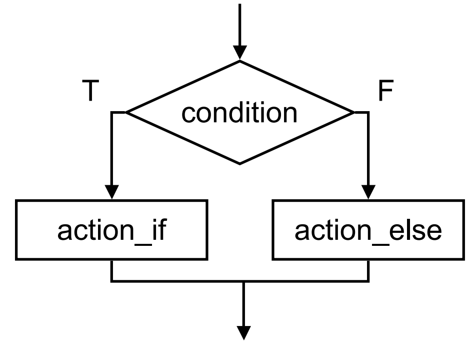
This is a common programming error (= instead of ==), not caught by compiler because it's syntactically correct.

Generating Code for If Statement

```
if (x == 2) {
  y = 5;
}
      LDR  R0, R6, #0   ; load x into R0
      ADD  R0, R0, #-2  ; subtract 2
      BRnp NOT_TRUE     ; if non-zero, x is not 2
      AND  R1, R1, #0   ; store 5 to y
      ADD  R1, R1, #5
      STR  R1, R6, #1
NOT_TRUE ...              ; next statement
```


If-else

```
if (condition)
  action_if;
else
  action_else;
```



Else allows choice between two mutually exclusive actions without re-testing condition.

Generating Code for If-Else

```
if (x) {
  y++;
  z--;
} else {
  y--;
  z++;
}
```

```
        LDR  R0, R6, #0
        BRz  ELSE
        ; x is not zero
        LDR  R1, R6, #1   ; incr y
        ADD  R1, R1, #1
        STR  R1, R6, #1
        LDR  R1, R6, #2   ; decr z
        ADD  R1, R1, #-1
        STR  R1, R6, #2
        BR   DONE    ; skip else code
        ; x is zero
ELSE    LDR  R1, R6, #1   ; decr y
        ADD  R1, R1, #-1
        STR  R1, R6, #1
        LDR  R1, R6, #2   ; incr z
        ADD  R1, R1, #1
        STR  R1, R6, #2
DONE    ...    ; next statement
```


Matching Else with If

Else is always associated with *closest* unassociated if

```
if (x != 10)
  if (y > 3)
    z = z / 2;
  else
    z = z * 2;
```

is the same as...

```
if (x != 10) {
  if (y > 3)
    z = z / 2;
  else
    z = z * 2;
}
```

is NOT the same as...

```
if (x != 10) {
  if (y > 3)
    z = z / 2;
}
else
    z = z * 2;
```

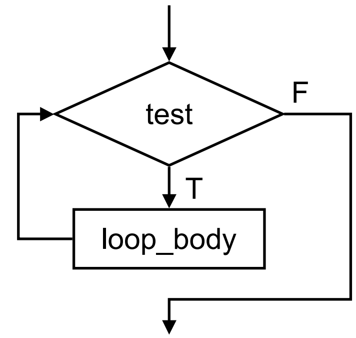
Solution: *always* use braces (avoids the problem entirely)

Chaining If's and Else's

```
if (month == 4 || month == 6 || month == 9 ||
    month == 11) {
  printf("Month has 30 days.\n");
} else if (month == 1 || month == 3 ||
           month == 5 || month == 7 ||
           month == 8 || month == 10 ||
           month == 12) {
  printf("Month has 31 days.\n");
} else if (month == 2) {
  printf("Month has 28 or 29 days.\n");
} else {
  printf("Don't know that month.\n");
}
```


While

```
while (test)
  loop_body;
```



Executes loop body as long as test evaluates to TRUE (non-zero)

*Note: Test is evaluated **before** executing loop body*

Generating Code for While

```
x = 0;
while (x < 10) {
  printf("%d ", x);
  x = x + 1;
}
```

```
      AND  R0, R0, #0
      STR  R0, R6, #0  ; x = 0
      ; test
LOOP  LDR  R0, R6, #0  ; load x
      ADD  R0, R0, #-10
      BRzp DONE
      ; loop body
      LDR  R0, R6, #0  ; load x
      ...
      <printf>
      ...
      ADD  R0, R0, #1  ; incr x
      STR  R0, R6, #0
      BR   LOOP        ; test again

DONE  ; next statement
```


Infinite Loops

The following loop will never terminate:

```
x = 0;
while (x < 10) {
  printf("%d ", x);
}
```

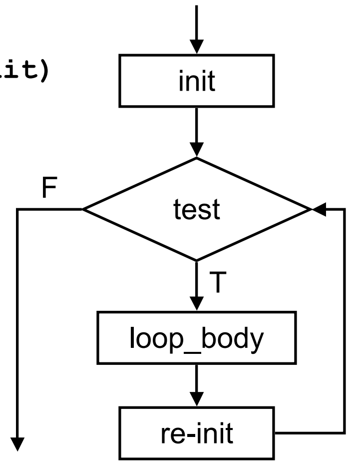
Loop body does not change condition...

- **...so test is never false**

Common programming error that can be difficult to find

For

```
for (init; end-test; re-init)
  statement
```



Executes loop body as long as test evaluates to TRUE (non-zero). Initialization and re-initialization code included in loop statement.

Note: Test is evaluated ***before*** *executing loop body*

Generating Code for For

```
for (i = 0; i < 10; i++) {
  printf("%d ", i);
}
```

This is the same as the while example!

```
        ; init
        AND  R0, R0, #0
        STR  R0, R6, #0  ; i = 0
        ; test
LOOP    LDR  R0, R6, #0  ; load i
        ADD  R0, R0, #-10
        BRzp DONE
        ; loop body
        LDR  R0, R6, #0  ; load i
        ...
        <printf>
        ...
        ; re-init
        ADD  R0, R0, #1  ; incr i
        STR  R0, R6, #0
        BR   LOOP        ; test again

DONE    ; next statement
```


Example For Loops

```
/* -- what is the output of this loop? -- */
for (i = 0; i <= 10; i++) {
  printf("%d ", i);
}
/* -- what does this one output? -- */
letter = 'a';
for (c = 0; c < 26; c++) {
  printf("%c ", letter+c);
}
/* -- what does this loop do? -- */
numberOfOnes = 0;
for (bitNum = 0; bitNum < 16; bitNum++) {
  if (inputValue & (1 << bitNum)) {
    numberOfOnes++;
  }
}
```


Nested Loops

Loop body can (of course) be another loop

```
/* print a multiplication table */
for (mp1 = 0; mp1 < 10; mp1++) {
  for (mp2 = 0; mp2 < 10; mp2++) {
    printf("%d\t", mp1*mp2);
  }
  printf("\n");
}
```

Another Nested Loop

Here, test for the inner loop depends on counter variable of outer loop

```
for (outer = 1; outer <= input; outer++) {
  for (inner = 0; inner < outer; inner++) {
    sum += inner;
  }
}
```


For vs. While

In general:

For loop is preferred for counter-based loops

- **Explicit counter variable**
- **Easy to see how counter is modified each loop**

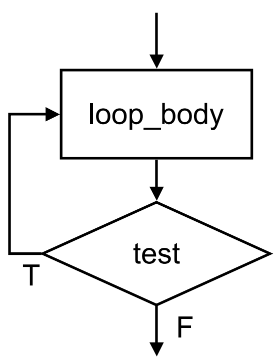
While loop is preferred for sentinel-based loops

- **Test checks for sentinel value.**

Either kind of loop can be expressed as other, so really a matter of style and readability

Do-While

```
do
  loop_body;
while (test);
```



Executes loop body as long as test evaluates to TRUE (non-zero).

*Note: Test is evaluated **after** executing loop body*

Break and Continue

`break;`

- **used *only* in switch statement or iteration statement**
- **passes control out of the “nearest” (loop or switch) statement containing it to the statement immediately following**
- **usually used to exit a loop before terminating condition occurs (or to exit switch statement when case is done)**

`continue;`

- **used only in iteration statement**
- **terminates the execution of the loop body for this iteration**
- **loop expression is evaluated to see whether another iteration should be performed**
- **if `for` loop, also executes the re-initializer**

Example

What does the following loop do?

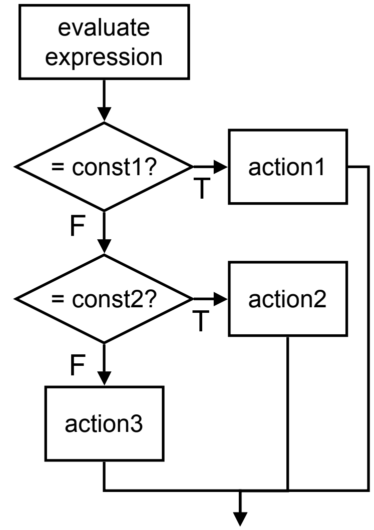
```
for (i = 0; i <= 20; i++) {
  if (i%2 == 0) {
    continue;
  }
  printf("%d ", i);
}
```

What would be an easier way to write this?

What happens if `break` instead of `continue`?

Switch

```
switch (expression) {
 case const1:
   action1;
   break;
 case const2:
   action2;
   break;
 default:
   action3;
 }
```



Alternative to long if-else chain.
If break is not used, then
case "falls through" to the next.

Switch Example

```
/* same as month example for if-else */
switch (month) {
 case 4:
 case 6:
 case 9:
 case 11:
   printf("Month has 30 days.\n");
   break;
 case 1:
 case 3:
 /* some cases omitted for brevity...*/
   printf("Month has 31 days.\n");
   break;
 case 2:
   printf("Month has 28 or 29 days.\n");
   break;
 default:
   printf("Don't know that month.\n");
}
```


More About Switch

Case expressions must be constant

```
case i:   /* illegal if i is a variable */
```

If no break, then next case is also executed

```
switch (a) {
  case 1:
    printf("A");
  case 2:
    printf("B");
  default:
    printf("C");
}
```

If a is 1, prints "ABC".
If a is 2, prints "BC".
Otherwise, prints "C".

Enumerations

Keyword `enum` declares a new type

- enum colors { RED, GREEN, BLUE, GREEN, YELLOW, MAUVE };
- RED is now 0, GREEN is 1, etc.
- Gives meaning to constants, groups constants

```
enum colors house_color;
house_color = get_color();
switch (house_color) {
  case RED:
    /* code here */
    break;
  /* more here… */
}
```

Enums are just ints, but can provide more type checking

- Warning on assignment (example: house_color = 85;)
- Warning on "partial" switch statement
- C++ adds even more checking support

Example: Searching for Substring

Have user type in a line of text (ending with linefeed) and print the number of occurrences of *"the"*

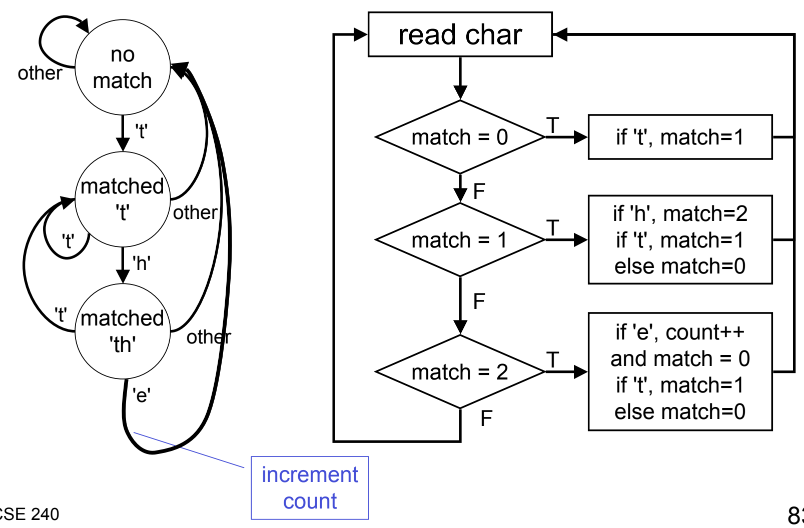
Reading characters one at a time

- Use the `getchar()` function -- returns a single character

Don't need to store input string; look for substring as characters are being typed

- Similar to state machine:
  based on characters seen, move toward success state
  or move back to start state
- Switch statement is a good match to state machine

Substring: State machine to flow chart



Substring: Code (Part 1)

```
#include <stdio.h>
enum state { NO_MATCH, ONE_MATCH, TWO_MATCHES };
main()
{
  char key;       /* input character from user */
  int match = NO_MATCH ; /* state of matching */
  int count = 0; /* number of substring matches */
  /* Read character until newline is typed */
  key = getchar();
  while (key != '\n') {
    /* Action depends on number of matches so far */
    switch (match) {
       See next two slides for
       contents of switch statement
    }
    key = getchar();
  }
  printf("Number of matches = %d\n", count);
}
```

Substring: Code (Part 2)

```
case NO_MATCH:  /* starting - no matches yet */
  if (key == 't') {
    match = ONE_MATCH;
  } else {
    match = NO_MATCH;
  }
  break;
case ONE_MATCH:  /* 't' has been matched */
  if (key == 'h') {
    match = TWO_MATCHES;
  } else if (key == 't') {
    match = ONE_MATCH;
  } else {
    match = NO_MATCH;
  }
  break;
```


Substring: Code (Part 3)

```
case TWO_MATCHES:  /* 'th' has been matched */
  if (key == 'e') {
    count++;    /* increment count */
    match = NO_MATCH; /* go to starting point */
  } else if (key == 't') {
    match = ONE_MATCH;
  } else {
    match = NO_MATCH;
  }
  break;
```


…C and the Right Shift Operator (>>)

Does right shift sign extend or not?

- **Answer: Yes and No**

Unsigned values: zero extend

- `unsigned int x = ~0;`
- **Then, `(x >> 10)` will have 10 leading zeros**

Signed values:

- **"Right shifting a *signed* quantity will fill with sign bits ("arithmetic shift") *on some machines* and with 0-bits ("logical shift") *on others*." - Kernighan and Ritchie**
- **In practice, it does sign extend**
  - `int x = ~0; /* signed */`
  - **Then, `(x >> 10)` will still be all 1s**

Chapter 14
Functions

Function

Smaller, simpler, subcomponent of program

Provides abstraction

- Hide low-level details
- Give high-level structure to program, easier to understand overall program flow
- Enables separable, independent development

C functions

- Zero or multiple **arguments (or parameters)** passed in
- Single result returned (optional)
- Return value is always a particular type

In other languages, called procedures, subroutines, ...

Example of High-Level Structure

```
void main()
{
  setup_board();  /* place pieces on board */

  determine_sides(); /* choose black/white */

  /* Play game */
  while (no_outcome_yet()){
    whites_turn();
    blacks_turn();
  }
}
```

Structure of program is evident, even without knowing implementation.

Functions in C

Definition

type of return value

name of function

```
int factorial(int n)
{
  int i;
  int result = 1;
  for (i = 1; i <= n; i++) {
    result = result * i;
  }
  return result;
}
```

types of all arguments

exits function with specified return value

Function call -- used in expression

```
a = x + factorial(f + g);
```

1. evaluate arguments

2. execute function

3. use return value in expression

Implementing Functions and Variables in LC-3

We've talked about...

- **Variables**
  - Local
  - Global
- **Functions**
  - Parameter passing
  - Return values

What does the assembly code look like for these idioms?

Important notes

- Different compilers for different ISAs do things differently
- As long as a compiler is consistent
- We're straying from the book's version to simplify things
  - Leaving out the R5 "frame pointer"

Allocating Space for Variables

Global data section

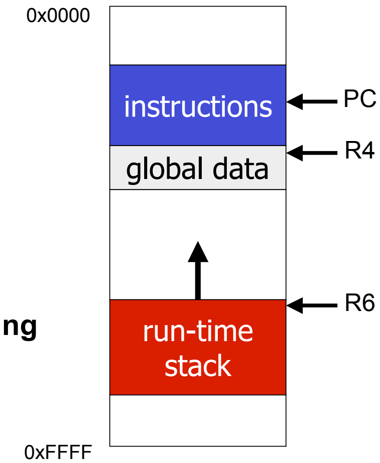
- All global variables stored here (actually all static variables)
- R4 points to beginning

Run-time stack

- Used for local variables
- R6 points to top of stack
- New frame for each block (goes away when block exited)

Offset = distance from beginning of storage area

- Global: `LDR R1, R4, #4`
- Local: `LDR R2, R6, #3`

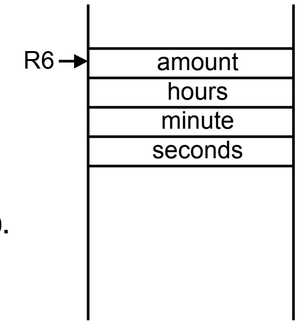


Local Variable Storage

Local variables stored in *activation record* (*stack frame*)

Symbol table "offset" gives the distance from the base of the frame

- A new frame is pushed on the run-time stack each time block is entered
- R6 is the stack pointer – holds address of current top of run-time stack
- Because stack grows downward, stack pointer is the smallest address of the frame, and variable offsets are >= 0.



Symbol Table

Compiler tracks each symbol (identifiers) and its location

- In assembler, all identifiers were labels
- In compiler, identifiers are variables

Compiler keeps more information

Name (identifier)

Type

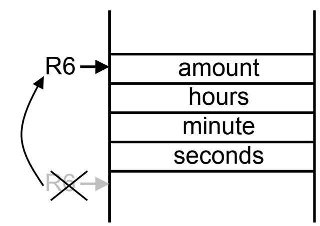
Location in memory

Scope

Name	Type	Offset	Scope
amount	double	0	main
hours	int	1	main
minutes	int	2	main
seconds	int	3	main

Symbol Table Example

```
int main()
{
  int seconds;
  int minutes;
  int hours;
  double amount;
  …
}
```



Name	Type	Offset	Scope
amount	double	0	main
hours	int	1	main
minutes	int	2	main
seconds	int	3	main

Example: Compiling to LC-3

```c
#include <stdio.h>
int inGlobal;

main()
{
  int inLocal;
  int outLocalA;
  int outLocalB;

  /* initialize */
  inLocal = 5;
  inGlobal = 3;

  /* perform calculations */
  outLocalA = inLocal & ~inGlobal;
  outLocalB = (inLocal + inGlobal) + outLocalB;

  /* print results */
  printf("The results are: outLocalA = %d, outLocalB = %d\n",
         outLocalA, outLocalB);
}
```

Name	Type	Offset	Scope
inGlobal	int	0	global
inLocal	int	2	main
outLocalA	int	1	main
outLocalB	int	0	main

Example: Code Generation

```
; main
; inLocal = 5
      AND R0, R0, #0
      ADD R0, R0, #5   ; inLocal = 5
      STR R0, R6, #2   ; (offset = 2)

; inGlobal = 3
      AND R0, R0, #0
      ADD R0, R0, #3   ; inGlobal = 3
      STR R0, R4, #0   ; (offset = 0)
```


Example (continued)

```
; first statement:
; outLocalA = inLocal & ~inGlobal;

   LDR R0, R6, #2   ; get inLocal(offset = 2)
   LDR R1, R4, #0   ; get inGlobal
   NOT R1, R1       ; ~inGlobal
   AND R2, R0, R1   ; inLocal & ~inGlobal
   STR R2, R6, #1   ; store in outLocalA
                    ; (offset = 1)
```

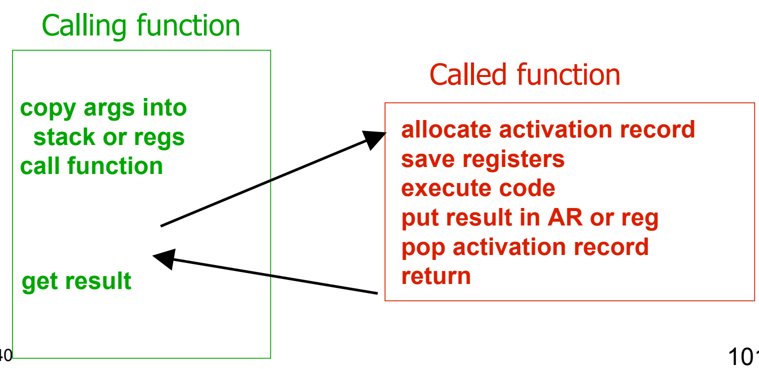

Example (continued)

```
                    R0
;outLocalB = (inLocal + inGlobal) + outLocalA;

      LDR R0, R6, #2   ; inLocal
      LDR R1, R4, #0   ; inGlobal
      ADD R0, R0, R1   ; R0 is sum

      LDR R1, R6, #1   ; outLocalA
      ADD R2, R0, R1   ; R2 is sum
      STR R2, R6, #0   ; outLocalB (offset = 0)
```

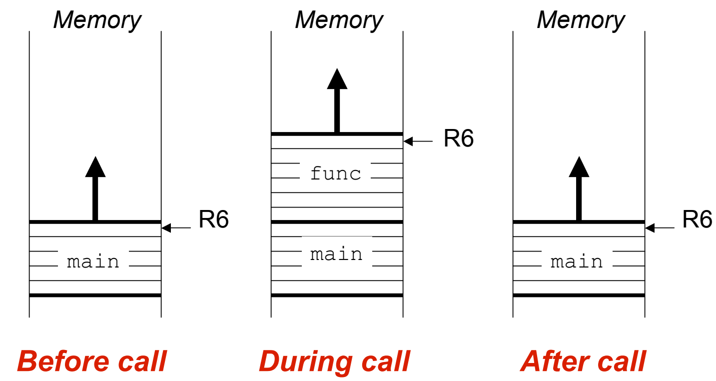
Implementing Functions

Activation record

- Information about each function, including arguments and local variables
- Also stored on run-time stack



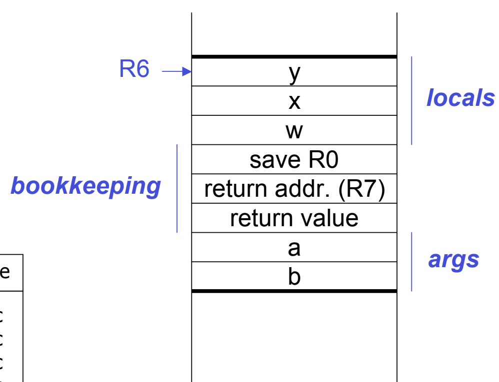
Run-Time Stack for Functions



Activation Record

```
int func(int a, int b)
{
  int w, x, y;
  .
  .
  .
  return y;
}
```

Name	Type	Offset	Scope
b	int	7	func
a	int	6	func
"ret. value"	int	5	func
w	int	2	func
x	int	1	func
y	int	0	func



Activation Record Bookkeeping

Return value

- Space for value returned by function
- Allocated even if function does not return a value

Return address

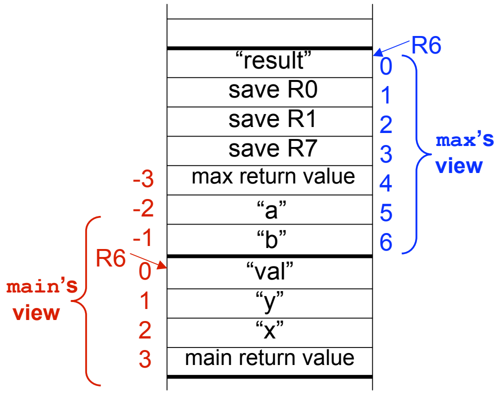
- Save pointer to next instruction in calling function
- Convenient location to store R7
  - in case another function (JSR) is called

Save registers

- Save all other registers used (but not R6, and often not R4)

Function Call Example

```
int main()
{
  int x, y, val;
  x = 10;
  y = 11;
  val = max(x + 10, y);
  return val;
}

int max(int a, int b)
{
  int result;
  result = a;
  if (b > a) {
    result = b;
  }
  return result;
}
```



Main Function (1 of 2)

```
MAIN    ADD R6, R6, #-4     ; allocate frame
        AND R0, R0, #0      ; x = 10
        ADD R0, R0, #10
        STR R0, R6, #2

        AND R0, R0, #0      ; y = 11
        ADD R0, R0, #11
        STR R0, R6, #1

        LDR R0, R6, #1      ; load y into R0
        STR R0, R6, #-1     ; 2nd argument

        LDR R1, R6, #2      ; load x into R1
        ADD R1, R1, #10     ; R1 = x + 10
        STR R1, R6, #-2     ; 1st argument

        JSR MAX             ; call max function

        … ; more here
```


Max Function

```
MAX     ADD R6, R6, #-7     ; allocate frame
        STR R7, R6, #3      ; save R7 (link register)
        STR R1, R6, #2      ; save R1
        STR R0, R6, #1      ; save R0

        LDR R0, R6, #5      ; load "a"
        STR R0, R6, #0      ; store "a" into "result"

        LDR R1, R6, #6      ; load "b"
        NOT R1, R1          ; calculate -b
        ADD R1, R1, 1
        LDR R0, R6, #5      ; load "a"
        ADD R0, R1, R0      ; compare

        BRp AFTER
        LDR R0, R6, #6      ; load "b"
        STR R0, R6, #0      ; store "b" into "result"

AFTER   LDR R0, R6, #0      ; load "result"
        STR R0, R6, #4      ; store "result" into return value

        LDR R0, R6, #1      ; restore R0
        LDR R1, R6, #2      ; restore R1
        LDR R7, R6, #3      ; restore R7 (link register)
        ADD R6, R6, #7      ; pop stack
        RET
```


Main Function (2 of 2)

```
; previous code here

JSR MAX             ; call max function

LDR R0, R6, #-3     ; read return value of max
STR R0, R6, #0      ; put value into local "val"

LDR R0, R6, #0      ; load "val"
STR R0, R6, #3      ; put "val" into main's
                    ; return value

ADD R6, R6, #4      ; pop stack
RET
```

Summary of LC-3 Function Call Implementation

1. Caller places arguments on stack (last to first)
2. Caller invokes subroutine (JSR)
3. Callee allocates frame
4. Callee saves R7 and other registers
5. Callee executes function code
6. Callee stores result into return value slot
7. Callee restores registers
8. Callee deallocates frame (local vars, other registers)
9. Callee returns (RET or JMP R7)
10. Caller loads return value
11. Caller resumes computation…

Callee versus Caller Saved Registers

Callee saved registers

- In our examples, the callee saved and restored registers
- Saves/restores any registers it modifies

What if a you wants R7 to be preserved across a call?

- Before call: caller saves it on the stack
- After call: caller restores it from the stack

Caller saved registers

- R7 is an example of a caller saved register
- Value assumed destroyed across calls
- Only needs to save R7 when it's in use

Which is better? Callee or Caller saved registers?

- Neither: many ISA calling conventions specify some of each

Compilers are Smart(er)

In our examples, variables always stored in memory

- Read from stack, written to stack

Compiler will perform code optimizations

- Keeps many variables in registers
- Avoids many save/restores of registers
- Why?

Passing parameter values in registers

- First few parameters in registers
- Return value in register
- Like in your homework projects
- Again, why?