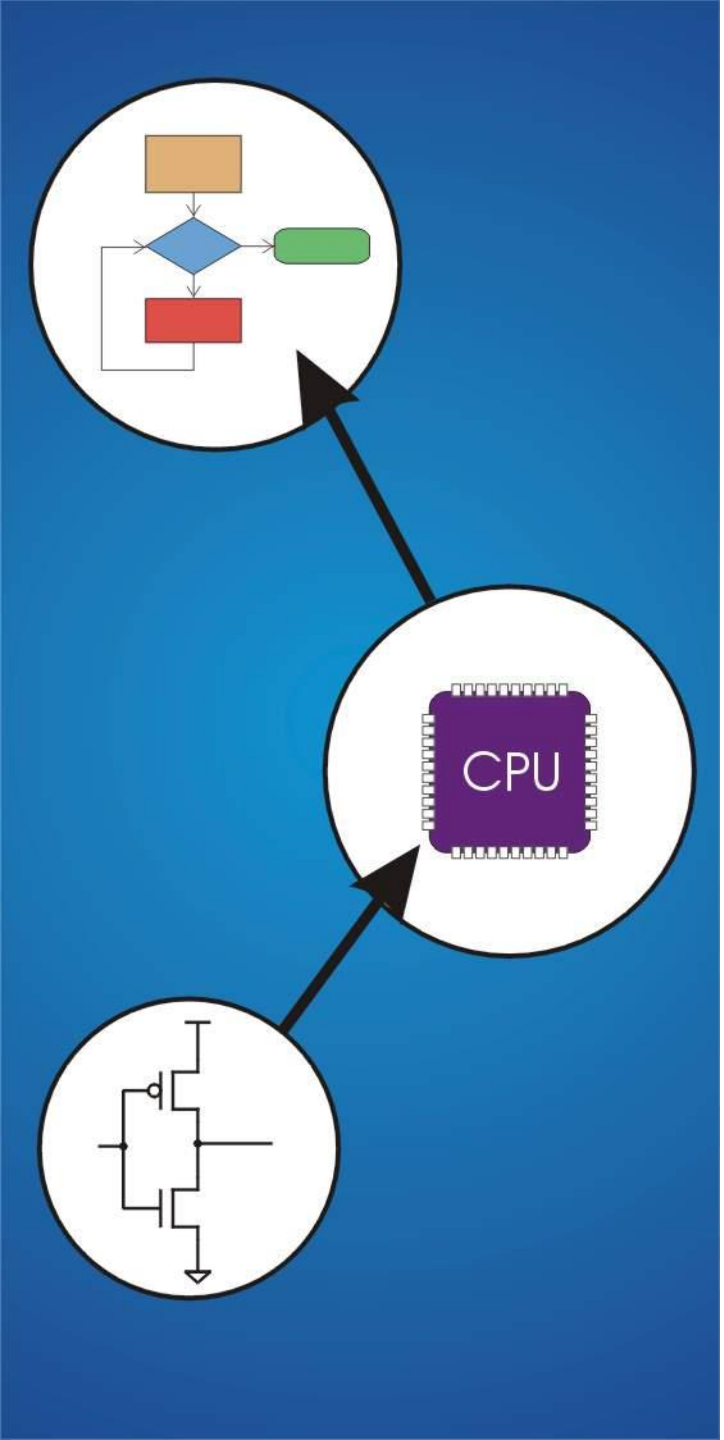


Chapter 12
Variables and Operators

Basic C Elements

Variables

- named, typed data items

Operators

- predefined actions performed on data items
- combined with variables to form expressions, statements

We will see

- Rules and usage
- Implementation using LC-3 (later)

Data Types

C has three basic data types

`int`	**integer (at least 16 bits)**
`double`	**floating point (at least 32 bits)**
`char`	**character (at least 8 bits)**

Exact size can vary, depending on processor

- **int was supposed to be "natural" integer size; for LC-3, that's 16 bits**
- **Int is 32 bits for most modern processors, double usually 64 bits**

Variable Names: Rules

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

Case matters

- **"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 used in older compilers

- **compiler dependent**

Variable Names: Customs

- **Separate words with underscores** (`big_dog`) **or CamelCase** (`bigDog`)
- **Lowercase for variables** (`buffer`)
- **All caps for constants** (`BUFFER_LENGTH`)**, whether via** **`#define`** **or** **`const`**
- **Capitalized for structures** (`struct Packet`)

next

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 in the program

- **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 variables are declared outside all blocks**

Example

```c
#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
```

Operators

Programmers manipulate variables using the operators provided by the high-level language.

Variables and operators combine to form expressions and statements which denote the work to be done by the program.

Each operator may correspond to many machine instructions.

- **Example: The multiply operator (*) typically requires multiple LC-3 ADD instructions.**

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 groups simple statements using 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.

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
+	add	`x + y`	7	l-to-r
-	subtract	`x - y`	7	l-to-r

All associate left to right.

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

Full precedence chart on page 602 of textbook

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.**

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 of a logcial operation is always either TRUE (1) or FALSE (0).

Relational Operators

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

Result is 1 (TRUE) or 0 (FALSE).

Note: Don’t confuse equality (==) with assignment (=)!

Special Operators: ++ and --

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

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

- **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)

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);
```

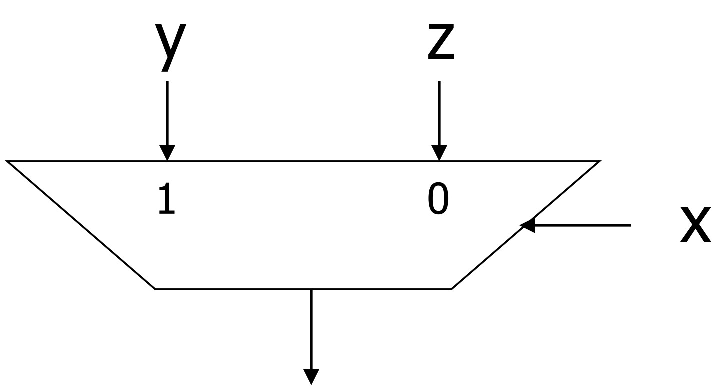
For long or confusing expressions, use parentheses, because reader might not have memorized precedence table.

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

Special Operator: Conditional

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

- **If x is TRUE (non-zero), result is y; else, result is z.**
- **Like a MUX, with x as the select signal.**



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.

Variable storage

Local variables: kept in the run-time stack. Kept during the duration of a function.

Global variables: Kept in Global Data area. For the entire duration of a program.

Dynamically allocated variables: Kept in the heap. Allocated and deallocated dynamically by the program.

Compiler keeps information about the exact location of the variables. It accesses them using pointers and offsets.

Storage management topics

We will skip the slides below. We will come back to them after we have seen the related LC-3 materials.

Symbol Table

Like assembler, compiler needs to know information associated with identifiers

- **in assembler, all identifiers were labels and information is address**

Compiler keeps more information

Name (identifier)

Type

Location in memory

Scope

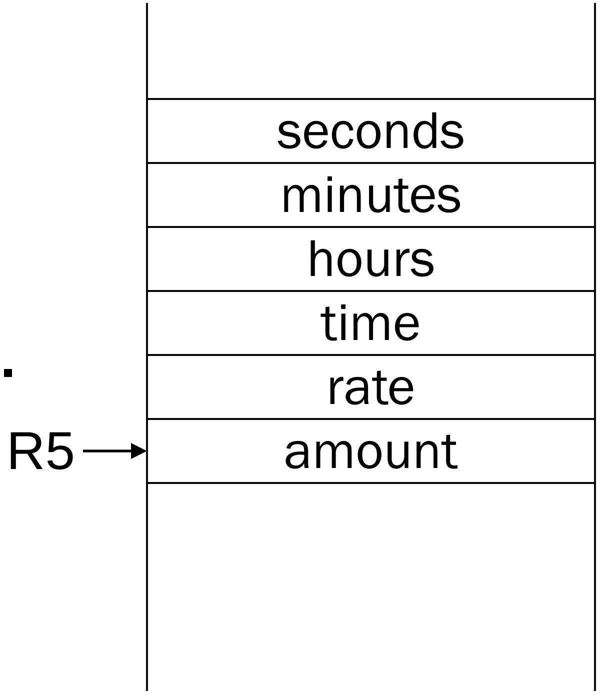
Name	Type	Offset	Scope
amount	int	0	main
hours	int	-3	main
minutes	int	-4	main
rate	int	-1	main
seconds	int	-5	main
time	int	-2	main

Local Variable Storage

Local variables are stored in an *activation record*, also known as a *stack frame*.

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

- **R5 is the frame pointer – holds address of the base of the current frame.**
- **A new frame is pushed on the run-time stack each time a block is entered.**
- **Because stack grows downward, base is the highest address of the frame, and variable offsets are <= 0.**



Allocating Space for Variables

Global data section

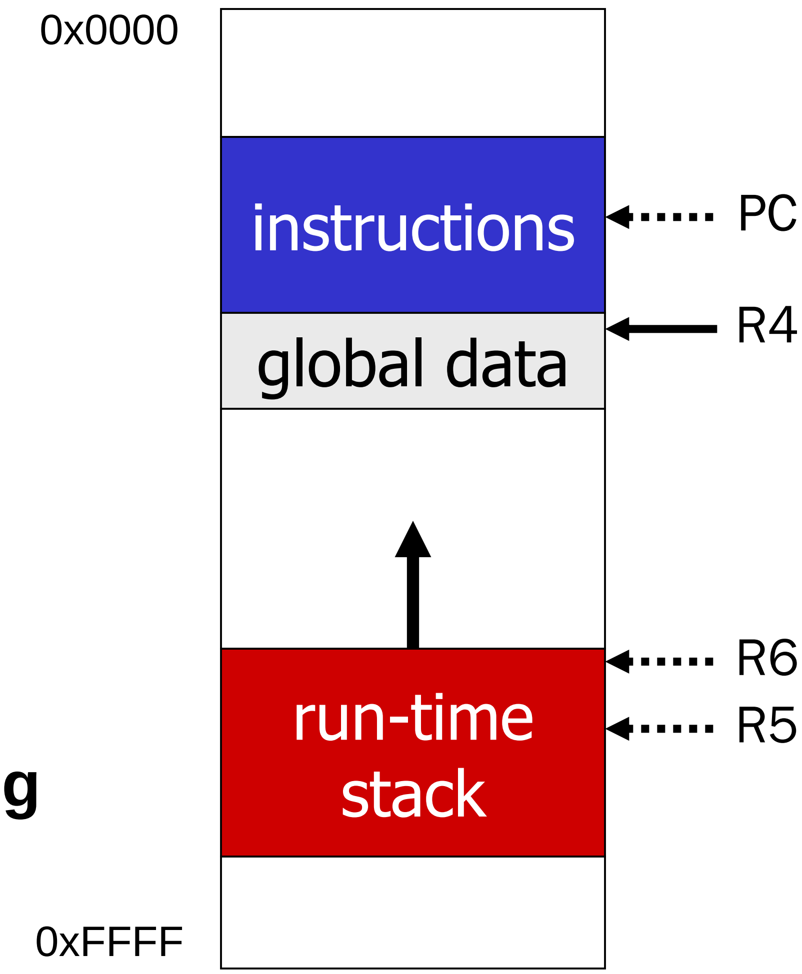
- **All global variables stored here (actually all static variables)**
- **R4 points to beginning**

Run-time stack

- **Used for local variables**
- **R6 points to top of stack**
- **R5 points to top frame on 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, R5, #-3`



Variables and Memory Locations

In our examples,
a variable is always stored in memory.

When assigning to a variable,
must <u>store</u> to memory location.

A real compiler would perform code optimizations
that try to keep variables allocated in registers.

Why?

Example: Compiling to LC-3

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

main()
{
  int inLocal;    /* local to main */
  int outLocalA;
  int outLocalB;

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

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

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

Example: Symbol Table

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

Example: Code Generation

```
; main
; initialize variables
        AND R0, R0, #0
        ADD R0, R0, #5   ; inLocal = 5
        STR R0, R5, #0   ; (offset = 0)

        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, R5, #0   ; get inLocal
      ADD R1, R0, #1   ; increment
      STR R1, R5, #0   ; store

      LDR R1, R4, #0   ; get inGlobal
      NOT R1, R1       ; ~inGlobal
      AND R2, R0, R1   ; inLocal & ~inGlobal
      STR R2, R5, #-1  ; store in outLocalA
                       ; (offset = -1)
```

Example (continued)

```
; next statement:
; outLocalB = (inLocal + inGlobal)
;              - (inLocal - inGlobal);
      LDR R0, R5, #0   ; inLocal
      LDR R1, R4, #0   ; inGlobal
      ADD R0, R0, R1   ; R0 is sum
      LDR R2, R5, #0   ; inLocal
      LDR R3, R5, #0   ; inGlobal
      NOT R3, R3
      ADD R3, R3, #1
      ADD R2, R2, R3   ; R2 is difference
      NOT R2, R2       ; negate
      ADD R2, R2, #1
      ADD R0, R0, R2   ; R0 = R0 - R2
      STR R0, R5, #-2 ; outLocalB (offset = -2)
```