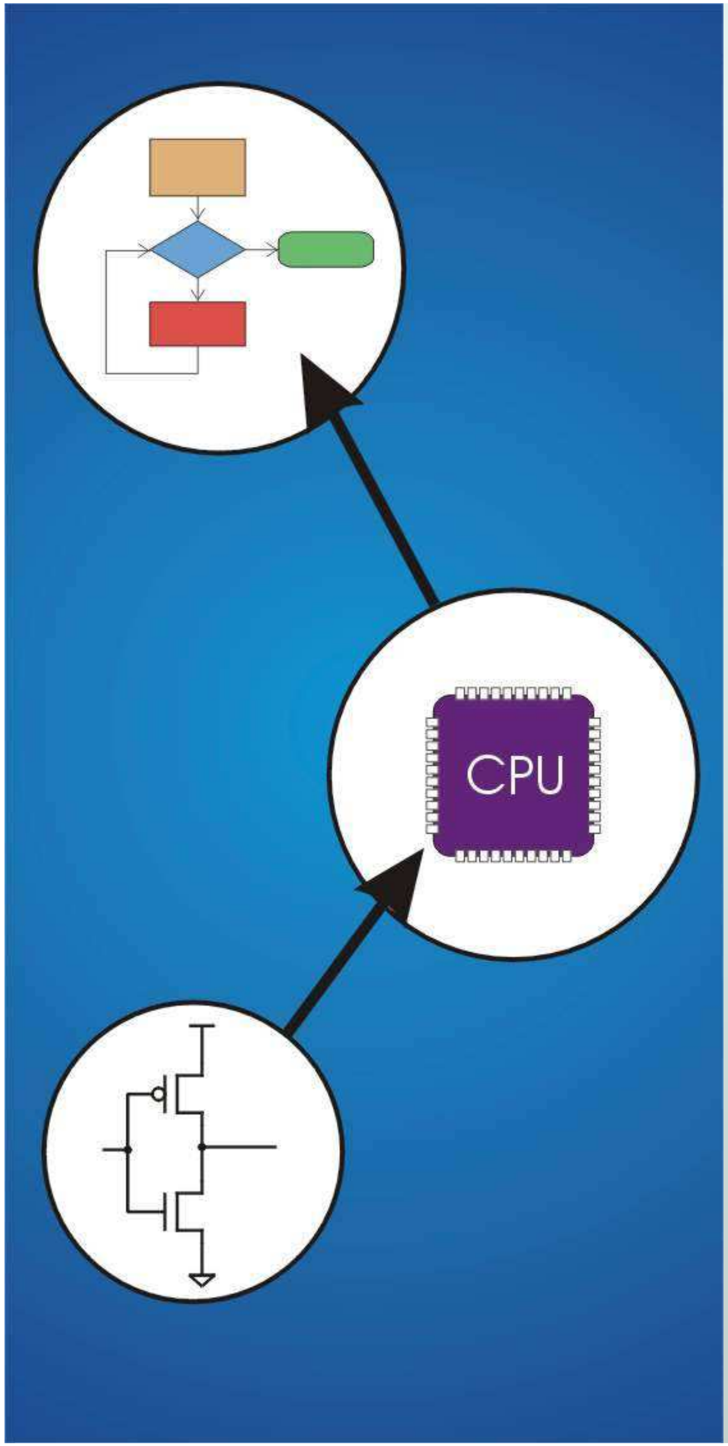

Chapter 12
Variables and Operators

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Basic C Elements

- Variables
  - named, typed data items
- Operators
  - predefined actions performed on data items
  - combined with variables to form expressions, statements
- Rules and usage
- Implementation using LC-3 instructions

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** is supposed to be "natural" integer size, for LC-3 that's 16 bits, LC-3 does not have **double**
  - **int** on a modern processor is usually 32 bits, **double** is usually 64 bits

Variable Names

- Any combination of letters, numbers, and underscore (_)
- Case matters
  - "sum" is different than "Sum“, this is also true of function names
- Cannot begin with a number
  - usually variables beginning with underscore are used only in special library routines
- Only first 31 characters are used
  - actually that’s compiler dependent, so be careful not to create ambiguous variables!

Examples

- *Legal*

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

same identifier (aReally_longName_moreThan31chars, aReally_longName_moreThan31characters)

- *Illegal*

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

reserved keyword (double)

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

```
#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.
- These constructs denote the work to be done by the program.
- An 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`

Try to make them more readable

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 the operator do?
- (2) Precedence
  - in which order are operators combined?
  - Ex: “a * b + c * d” is the same as "(a * b) + (c * d)“ since multiply has 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 and subtract 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 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

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

- Operate on variables bit-by-bit.
  - Like LC-3 AND and NOT instructions.
- Shift left operations are logical. Shift right: implementation dependent. 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:

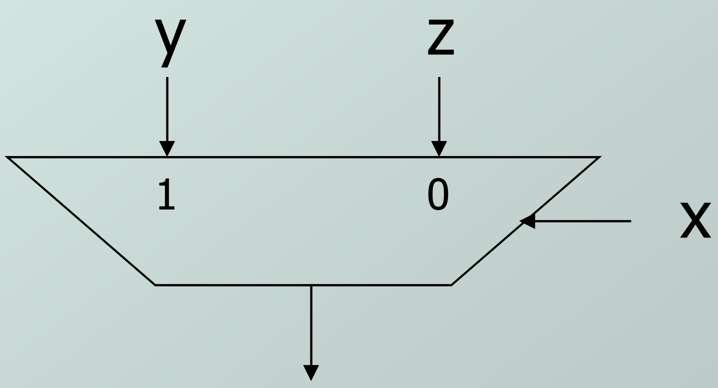
```
x = (a * b) + ((c * d) / 2);
```

- For long or confusing expressions, use parentheses, because reader might not have memorized precedence table.
- Note: Assignment operator has lowest precedence, so operations on the right-hand side are evaluated before assignment.

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.

Variables: LC-3 Implementation

- We will later see how these are implemented in LC-3:
  - Symbol table
  - Memory space allocation
  - How local and global variables are stored.
- We will return to the following slides later.

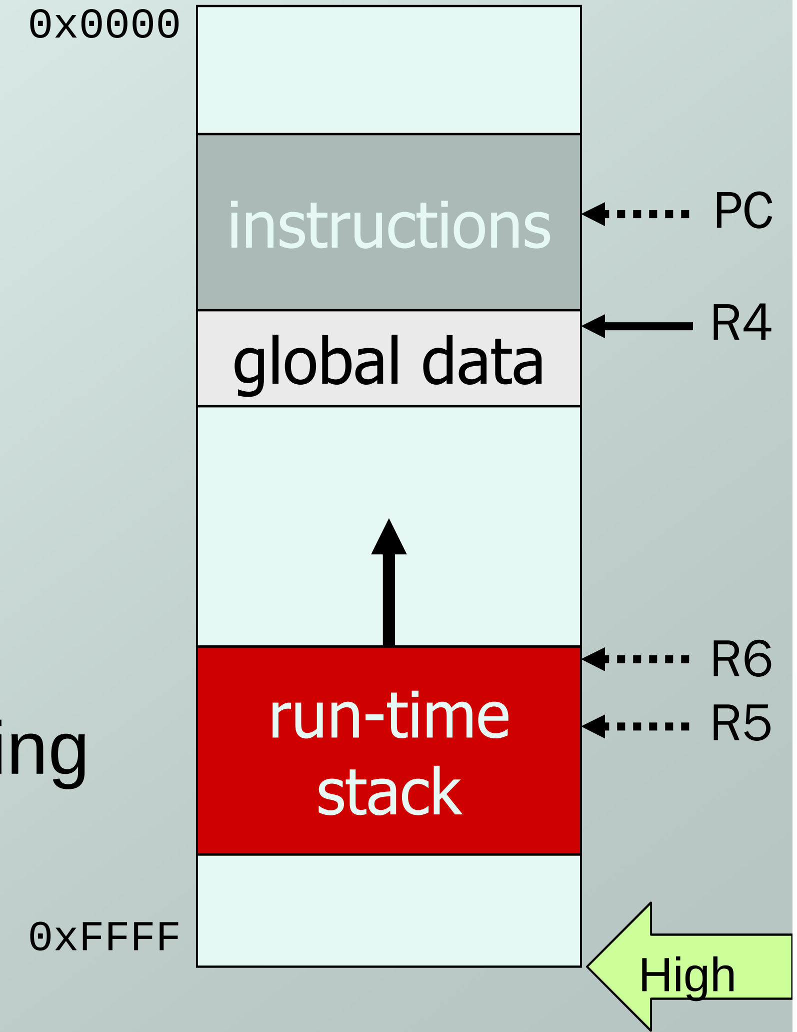
Symbol Table

- Like assembler, compiler needs to know information associated with identifiers
  - in assembler, all identifiers are 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

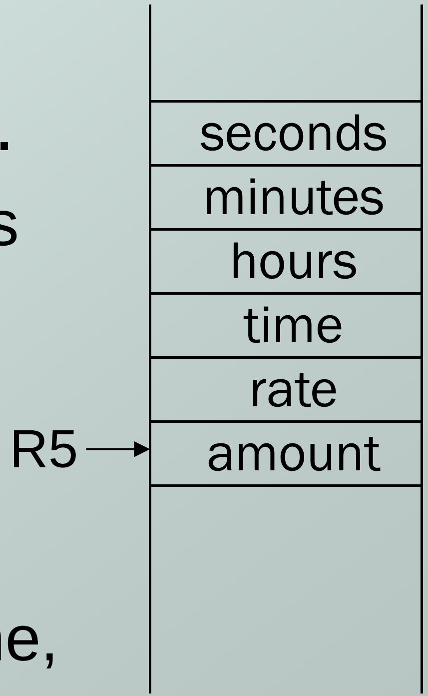
Allocating Space for Variables

- Global data section
  - All global variables stored here 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`



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.



Variables and Memory Locations

- In our examples, a variable is always stored in memory.
- When assigning to a variable, must store 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)
```