C 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

- Rules and usage
  Implementation using LC-3

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 -- 32 bits for most modern processors

Variable Names

- 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

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
```

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
+	addition	x + y	7	l-to-r
-	subtraction	x - y	7	l-to-r

All associate left to right.

* / % have higher precedence than + -.

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 is 1 (TRUE) or 0 (FALSE).

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).

Note: Don't confuse equality (==) with assignment (=).

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)

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.

Symbol Table

- Like assembler, compiler needs to know information associated with identifiers
  - in assembler, all identifiers were labels and information is address

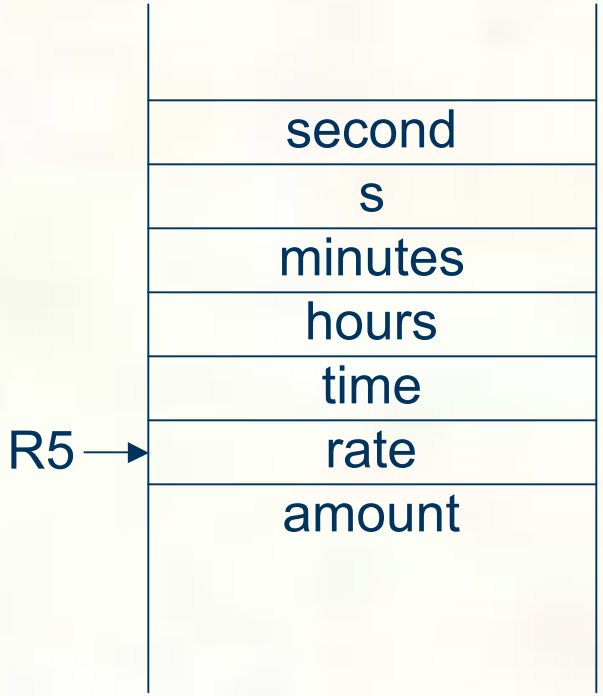
- Compiler keeps more information
  - Name (identifier)
  - Type
  - Location in memory
  - Scope

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

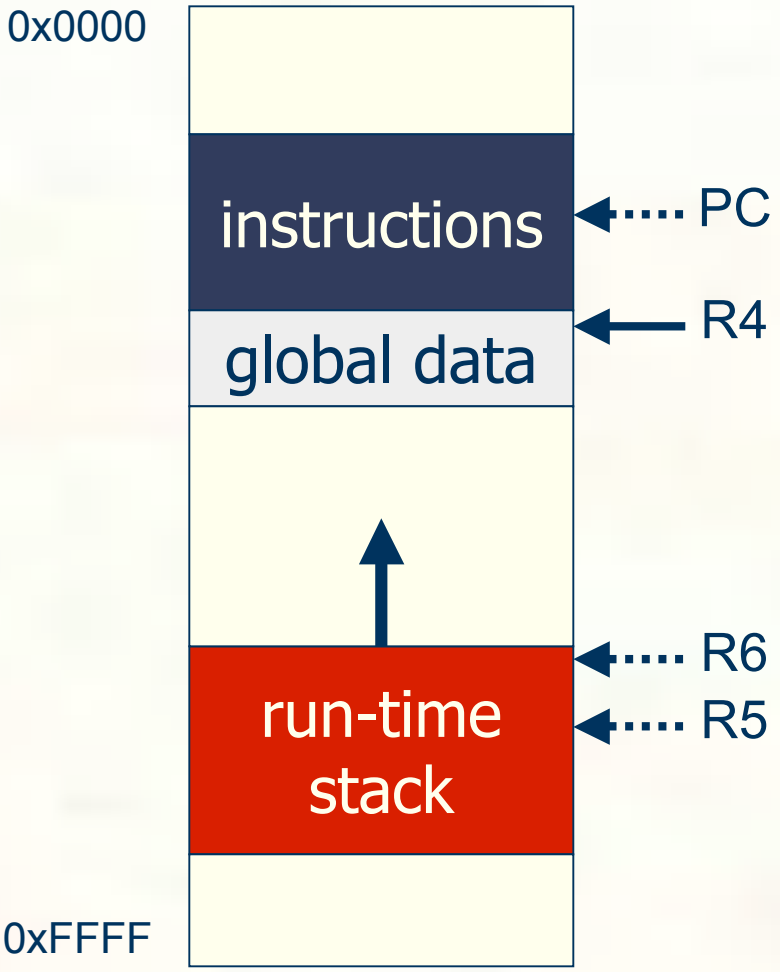
- Local variables are stored in an *activation record*, also known as a *stack frame*.

- 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 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)
```

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

If x is TRUE (non-zero), result is y;
else, result is z.

Like a MUX, with x as the select signal.