Imperative Programming

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Reading Assignment

- Mitchell, Chapter 5.1-2
- C Reference Manual, Chapter 8

Imperative Programming

- Oldest and most popular paradigm
  - Fortran, Algol, C, Java ...
- Mirrors computer architecture
  - In a von Neumann machine, memory holds instructions and data
- Key operation: assignment
  - Side effect: updating state (i.e., memory) of the machine
- Control-flow statements
  - Conditional and unconditional (GO TO) branches, loops

Elements of Imperative Programs

- Data type definitions
- Variable declarations (usually typed)
- Expressions and assignment statements
- Control flow statements (usually structured)
- Lexical scopes and blocks
  - Goal: provide locality of reference
- Declarations and definitions of procedures and functions (i.e., parameterized blocks)

Variable Declarations

- Typed variable declarations restrict the values that a variable may assume during program execution
  - Built-in types (int, char ...) or user-defined
  - Initialization: Java integers to 0. What about C?
- Variable size
  - How much space needed to hold values of this variable?
    - C on a 32-bit machine: sizeof(char) = 1 byte, sizeof(short) = 2 bytes, sizeof(int) = 4 bytes, sizeof(char*) = 4 bytes (why?)
    - What about this user-defined datatype:

```
typedef struct TreeNode {
      int x;
      TreeNode *front, *back;
};
```

Variables: Locations and Values

- When a variable is declared, it is bound to some <u>memory location</u> and becomes its identifier
  - Location could be in global, heap, or stack storage
- l-value: memory location (address)
- r-value: value stored at the memory location identified by l-value
- Assignment: A (target) = B (expression)
  - Destructive update: overwrites the memory <u>location</u> identified by A with a <u>value</u> of expression B
    - What if a variable appears on both sides of assignment?

Copy vs. Reference Semantics

- **Copy semantics:** expression is evaluated to a value, which is copied to the target
  - Used by imperative languages
- **Reference semantics:** expression is evaluated to an object, whose pointer is copied to the target
  - Used by object-oriented languages

Variables and Assignment

- On the RHS of an assignment, use the variable's r-value; on the LHS, use its l-value
  - Example: x = x+1
  - Meaning: "get r-value of x, add 1, store the result into the l-value of x"
- An expression that does not have an l-value cannot appear on the LHS of an assignment
  - What expressions don't have l-values?
    - Examples: 1=x+1, ++x++ (why?)
    - What about a[1] = x+1, where a is an array? Why?

l-Values and r-Values (1)

- Any expression or assignment statement in an imperative language can be understood in terms of l-values and r-values of variables involved
  - In C, also helps with complex pointer dereferencing and pointer arithmetic
- Literal constants
  - Have r-values, but not l-values
- Variables
  - Have both r-values and l-values
  - Example: x=x*y means "compute rval(x)*rval(y) and store it in lval(x)"

l-Values and r-Values (2)

- Pointer variables
  - Their r-values are l-values of another variable
    - Intuition: the value of a pointer is an address
- Overriding r-value and l-value computation in C
  - &x always returns l-value of x
  - *p always return r-value of p
    - If p is a pointer, this is an l-value of another variable

```
int x = 5;  // lval(x) is some (stack) address, rval(x) == 5
int *p = &x // rval(p) == lval(x)
*p = 2 * x; // rval(p) <- rval(2) * rval(x)
```

What are the values of p and x at this point?

l-Values and r-Values (3)

- Declared functions and procedures
  - Have l-values, but no r-values

```
int f(int y); // lval(f) is some global address
typedef int (*IFP)(int); // pointer to an int function that takes an int argument
IFP g = &f; // lval(g) <- lval(f)
(*g)(5);    // (rval(g))== lval(f), so *g invokes f with argument rval(5)
            // the function call operator () has higher precedence than * so
            // we have to write (*g)(5) to deference g to invoke f(5)
```

Turing-Complete Mini-Language

- Integer variables, values, operations
- Assignment
- If
- Go To

Structured Control Flow

- Control flow in imperative languages is most often designed to be sequential
  - Instructions executed in order they are written
  - Some also support concurrent execution (Java)
- Program is structured if control flow is evident from syntactic (static) structure of program text
  - Big idea: programmers can reason about dynamic execution of a program by just analyzing program text
  - Eliminate complexity by creating language constructs for common control-flow "patterns"
    - Iteration, selection, procedures/functions

Fortran Control Structure

```
10 IF (X .GT. 0.000001) GO TO 20
11 X = -X
   IF (X .LT. 0.000001) GO TO 50
20 IF (X*Y .LT. 0.00001) GO TO 30
   X = X-Y-Y
30  X = X+Y
   ...
50 CONTINUE
   X = A
   Y = B-A
   GO TO 11
   ...
```

Similar structure may occur in assembly code

Historical Debate

- Dijkstra, “GO TO Statement Considered Harmful”
  - Letter to Editor, Comm. ACM, March 1968
  - Linked from the course website
- Knuth, “Structured Prog. with Go To Statements”
  - You can use goto, but do so in structured way ...
- Continued discussion
  - Welch, “GOTO (Considered Harmful)^n, n is Odd”
- General questions
  - Do syntactic rules force good programming style?
  - Can they help?

Modern Style

- Standard constructs that structure jumps
  - if ... then ... else ... end
  - while ... do ... end
  - for ... { ... }
  - case ...
- Group code in logical blocks
- Avoid explicit jumps (except function return)
- Cannot jump <u>into</u> the middle of a block or function body

Iteration

◆ Definite

```
for (int i = 0; i < 10; i++) {
    a[i] = 0;  // intialize each array element to zero
}
```

◆ Indefinite

- Termination depends on a dynamically computed value

```
int m = 0;
while (n > 0) {
    m = m * n;
    n = n - 1;
}
```

How do we know statically (i.e., before we run the program) that **the loop will terminate**, i.e., that n will eventually become less than or equal to 0?

Iteration Constructs in C

- while (condition) stmt;
  while (condition) { stmt; stmt; ...; }
- do stmt while (condition);
  do { stmt; stmt; ...; } while (condition);
- for (<initialize>; <test>; <step>) stmt;
  - Restricted form of “while” loop – same as
    <initialize>; while (<test>) { stmt; <step> }

  for (<initialize>; <test>; <step>) { stmt; stmt; ...; }

“Breaking Out” Of A Loop in C

```
int y;  // y is in the "outer" scope
...
while (cond == true) {
     int x;  // x is local to the while blocks scope (its extent and lifetime)
     ...
     if (x < y) { // special case...
       break;   // leave while loop
     }
     ... // normal case
}


while (cond1 == true) {
     while (cond2 == true) {
       if (x < y) // special case
         break; // leave inner loop, but not outer loop
       ...
     }
     ... // control resumes here after a break from the inner loop
}
```

Forced Loop Re-Entry in C

```
while (cond-expr == true) {
      ... // do something while cond is true
      if (a == b) {
         ... // do something special
         continue; // transfer to start of while and re-evaluate cond
      }
      ... // remaining statements of while loop
}
```

Block-Structured Languages

◆ Nested blocks with local variables

new variables declared in nested blocks

outer block

```
{ int x = 2;
    { int y = 3;
      x = y+2;
    }
}
```

inner block

local variable

global variable

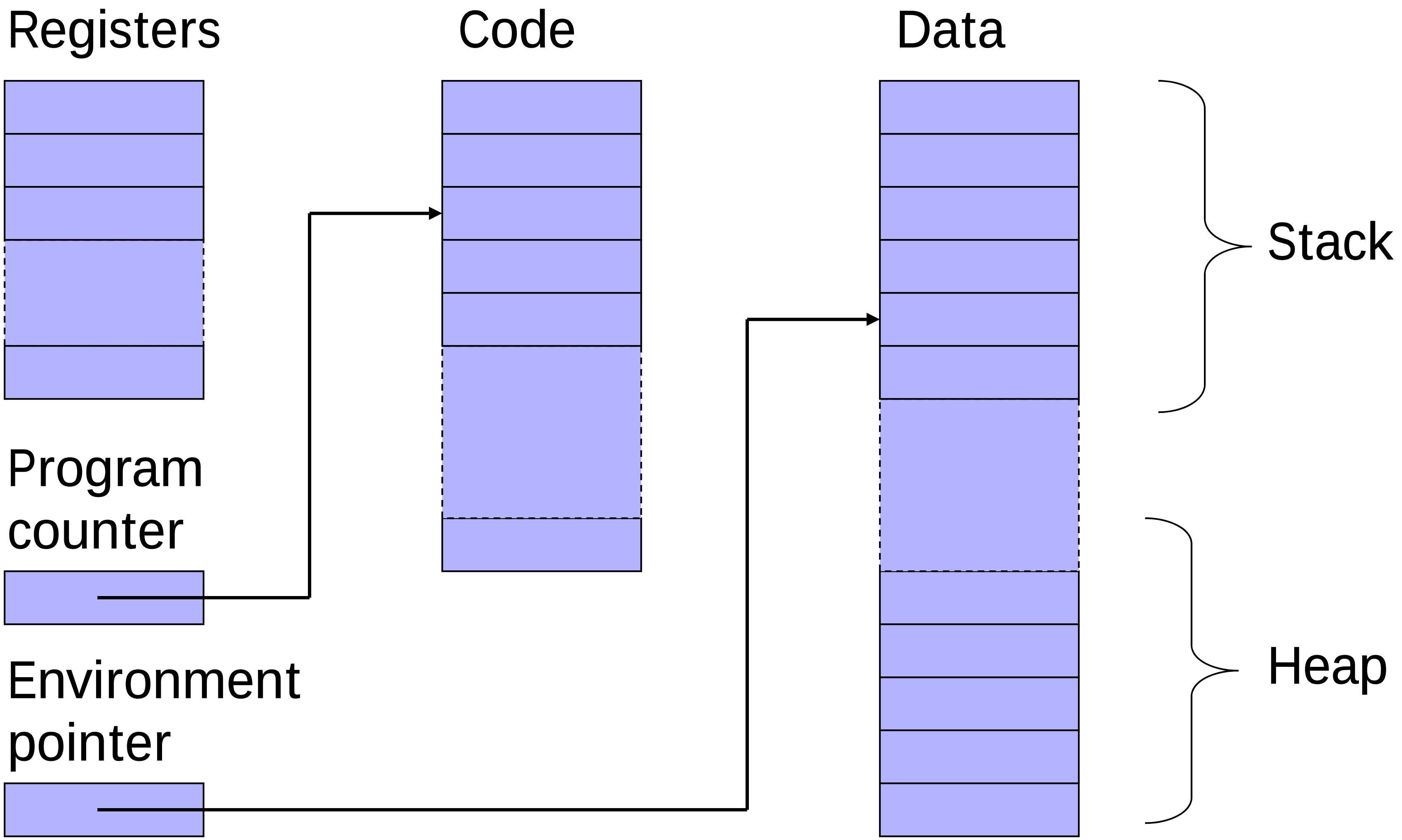
- Storage management
  - Enter block: allocate space for variables
  - Exit block: some or all space may be deallocated

Blocks in Common Languages

- Examples
  - C, ~~JavaScript~~ * { ... }
  - Algol begin ... end
  - ML let ... in ... end
- Two forms of blocks
  - Inline blocks
  - Blocks associated with functions or procedures
    - We'll talk about these later

* JavaScript functions provides blocks

Simplified Machine Model



Memory Management

- Registers, Code segment, Program counter
  - Ignore registers (for our purposes) and details of instruction set
- Data segment
  - Stack contains data related to block entry/exit
  - Heap contains data of varying lifetime
  - Environment pointer points to current stack position
    - Block entry: add new activation record to stack
    - Block exit: remove most recent activation record

Scope and Lifetime

- **Scope**
  - Region of program text where declaration is visible
- **Lifetime**
  - Period of time when location is allocated to program

```
{ int x = ... ;
    {  int y = ... ;
        {  int x = ... ;
            ....
        };
    };
};
```

- Inner declaration of x hides outer one ("hole in scope")
- Lifetime of outer x includes time when inner block is executed
- Lifetime $\neq$ scope

Inline Blocks

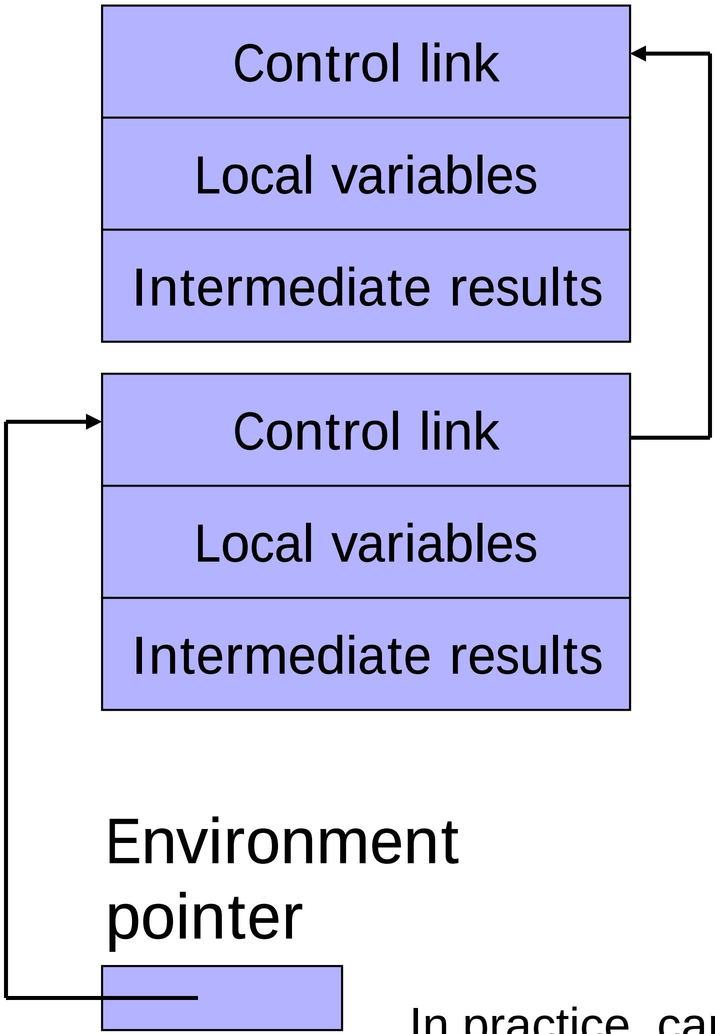
- Activation record
  - Data structure stored on run-time stack
  - Contains space for local variables

```
{ int x=0;
  int y=x+1;
    { int z=(x+y)*(x-y);
    };
};
```

Push record with space for x, y
Set values of x, y
  Push record for inner block
  Set value of z
  Pop record for inner block
Pop record for outer block

May need space for variables and intermediate results like (x+y), (x-y)

Activation Record For Inline Block



- Control link
  - Pointer to previous record on stack
- Push record on stack
  - Set new control link to point to old env ptr
  - Set env ptr to new record
- Pop record off stack
  - Follow control link of current record to reset environment pointer

In practice, can be optimized away

Example

```
{ int x=0;
  int y=x+1;
    {  int z=(x+y)*(x-y);
    };
};
```

Push record with space for x, y

Set values of x, y

- Push record for inner block
- Set value of z
- Pop record for inner block

Pop record for outer block