Computer Science 160
Translation of Programming Languages

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Code Generation

Overview

- Intermediate Representations
  - There is more that one way to represent code as it is being generated, analyzed, and optimized (we use ASTs)
- How code runs
  - The way code runs on a machine depends on if the code is compiled or interpreted, and if it is statically or dynamically linked
- Code Generation
  - Three-address code and stack code
  - Dealing with Boolean values and control (such as loops)
  - Arrays

Code Generation

- To generate actual code that can run on a processor (such as gcc) or on a virtual machine (such as javac) we need to understand what code for each of these machines looks like.

- Rather than worry about the exact syntax of a given assembly language, we instead use a type of pseudo-assembly that is close to the underlying machine.

- In this class, we need to worry about 2 different types of code
  - Stack-based code: Similar to the Java Virtual Machine
  - Three-address code (Register-based code): Similar to most processors (x86, Sparc, ARM, …)

Register-based vs. Stack-based Machines

A **register**-based machine has a number of registers used for calculations. 2 + 3 would work something like this:

- LOADI R4,#2; :Load immediate 2 into register 4
  LOADI R5,#3; :Load immediate 3 into register 5
  ADD R4,R5; :Add R4 and R5, storing result in R4

On a **stack**-based machine, computation would work like this

- PUSHI #2 ; :Push immediate 2 onto stack
  PUSHI #3; :Push immediate 3 onto stack
  ADD; :Pop top two numbers, add them, and push results to the top of the stack.

Three-Address Code (Register-based Code)

- Each instruction can have at most three operands
- We have to break large statements into little operations that use temporary variables
  - X=(2+3)+4 turns into to T1=2+3; X=T1+4;
- Temporary variables store the results at the internal nodes in the AST
- Assignments
  - x := y
  - x := y op z *op: binary arithmetic or logical operators*
  - x := op y *op: unary operators (minus, negation, integer to float)*
- Branch
  - goto L *execute the statement with labeled L next*
- Conditional Branch
  - if x relop y goto L relop: <, =, <=, >=, ==, !=
    - if the condition holds, we execute statement labeled L next
    - if the condition does not hold, we execute the statement following this statement next

Three-Address Code


```
if (x < y)
  x = 5*y + 5*y/3;
else
  y = 5;
x = x + y;
```

Variables can be represented with their locations in the symbol table

```
        if x < y goto L1
        goto L2
L1:     t1 := 5 * y
        t2 := 5 * y
        t3 := t2 / 3
        x := t1 + t3
        goto L3
L2:     y := 5
L3:     x := x + y
```

Temporaries: temporaries correspond to the internal nodes of the syntax tree

- Three-address code instructions can be represented as an array of

  quadruples: operation, argument1, argument2, result

  triples: operation, argument1, argument2

  (each triple implicitly corresponds to a temporary)

Stack Machine Code

- Stack based code uses the stack to store temporary variables

- When we evaluate an expression (E+E), it will take its arguments off the stack, add them together and put the result back on the stack.

- (2+3)+4 will push 2; push 3; add; push 4; add

- The machine code for this is a bit uglier, but the code is actually easier to generate because we do not need to handle temporary variables

Why is Code Easier to Generate?

- Each operation takes operands from the same place and puts results in the same place
  - Location of the operands is implicit
  - Always on the top of the stack
  - No need to specify operands explicitly
  - No need to specify the location of the result
  - Instruction “add” as opposed to “add r1, r2” ⇒ Smaller encoding of instructions ⇒ More **compact** programs

Stack Machine Code


```
if (x < y)
  x = 5*y + 5*y/3;
else
  y = 5;
x = x+y;
```

JVM: A stack machine

- JVM interpreter executes the bytecode on different machines
- JVM has an operand stack which we use to evaluate expressions
- JVM provides 65,535 local variables for each method The local variables are like registers so we do not have to worry about register allocation
- Each local variable in JVM is denoted by a number between 0 and 65535 (x and y in the example will be assigned unique numbers)

pushes the value at the location x to the stack

```
    load x
    load y
    iflt L1
    goto L2
L1: push 5
    load y
    multiply
    push 5
    load y
    multiply
    push 3
    divide
    add
    store x
    goto L3
L2: push 5
    store y
L3: load x
    load y
    add
    store x
```

pops the top two elements and compares them

pops the top two elements, multiplies them, and pushes the result back to the stack

stores the value at the top of the stack to the location x

Code

- Three-Address Code:
  - Good - Compact representation
  - Good - Statement is “self contained” in that it has the inputs, outputs, and operation all in one “instruction”
  - Bad - Requires lots of temporary variables
  - Bad - Temporary variables have to be handled explicitly
- Stack Based Code:
  - Good – No temporaries, everything is kept on the stack
  - Good – It is easy to generate code for this
  - Bad – Requires more instructions to do the same thing

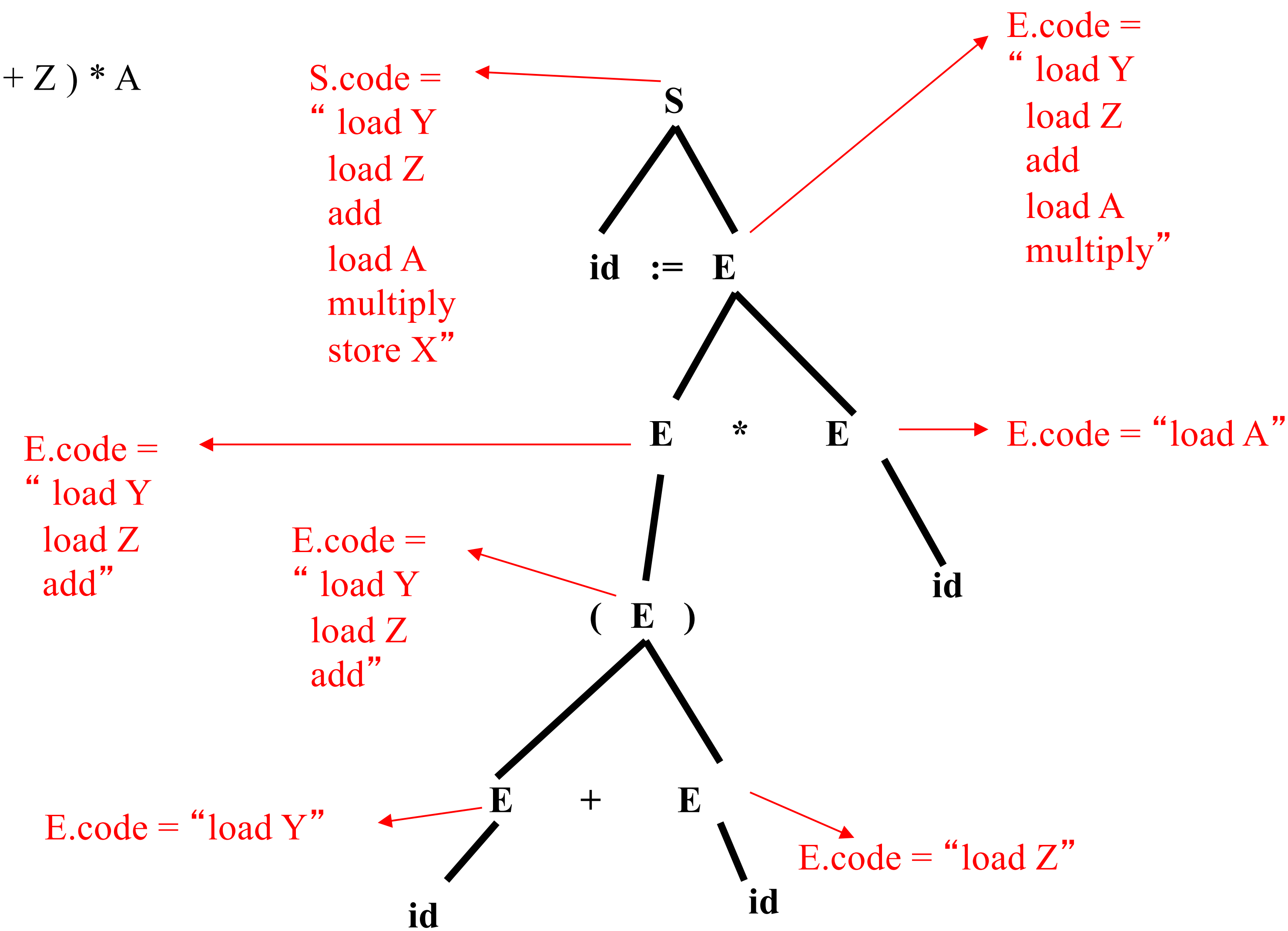
Stack-Based Code Generation

Attributes:	*E.code*: sequence of instructions that are generated for *E*
	(no place for an expression is needed since the result of an expression is stored in the operand stack)
Procedures:	newtemp(): Returns a new temporary each time it is called
	gen(): Generates instruction (have to call it with appropriate arguments)
	lookup(id.*name*): Returns the location of id from the symbol table

Productions	Semantic Rules
$S \rightarrow \text{id} := E$	id.*place* $\leftarrow$ lookup(id.*name*);
	S.code $\leftarrow$ *E.code* || gen('store' id.*place*);
$E \rightarrow E_1 + E_2$	*E.code* $\leftarrow$ E_1*.code* || E_2*.code* || gen('add');
	(*arguments for the add instruction are in the top of the stack*)
$E \rightarrow E_1 * E_2$	*E.code* $\leftarrow$ E_1*.code* || E_2*.code* || gen('multiply');
$E \rightarrow (E_1)$	*E.code* $\leftarrow$ E_1*.code*;
$E \rightarrow - E_1$	*E.code* $\leftarrow$ E_1*.code* || gen('negate ');
$E \rightarrow \text{id}$	*E.code* $\leftarrow$ gen('load' id.*place*)

Example

X := (Y + Z) * A



Three-Address Code

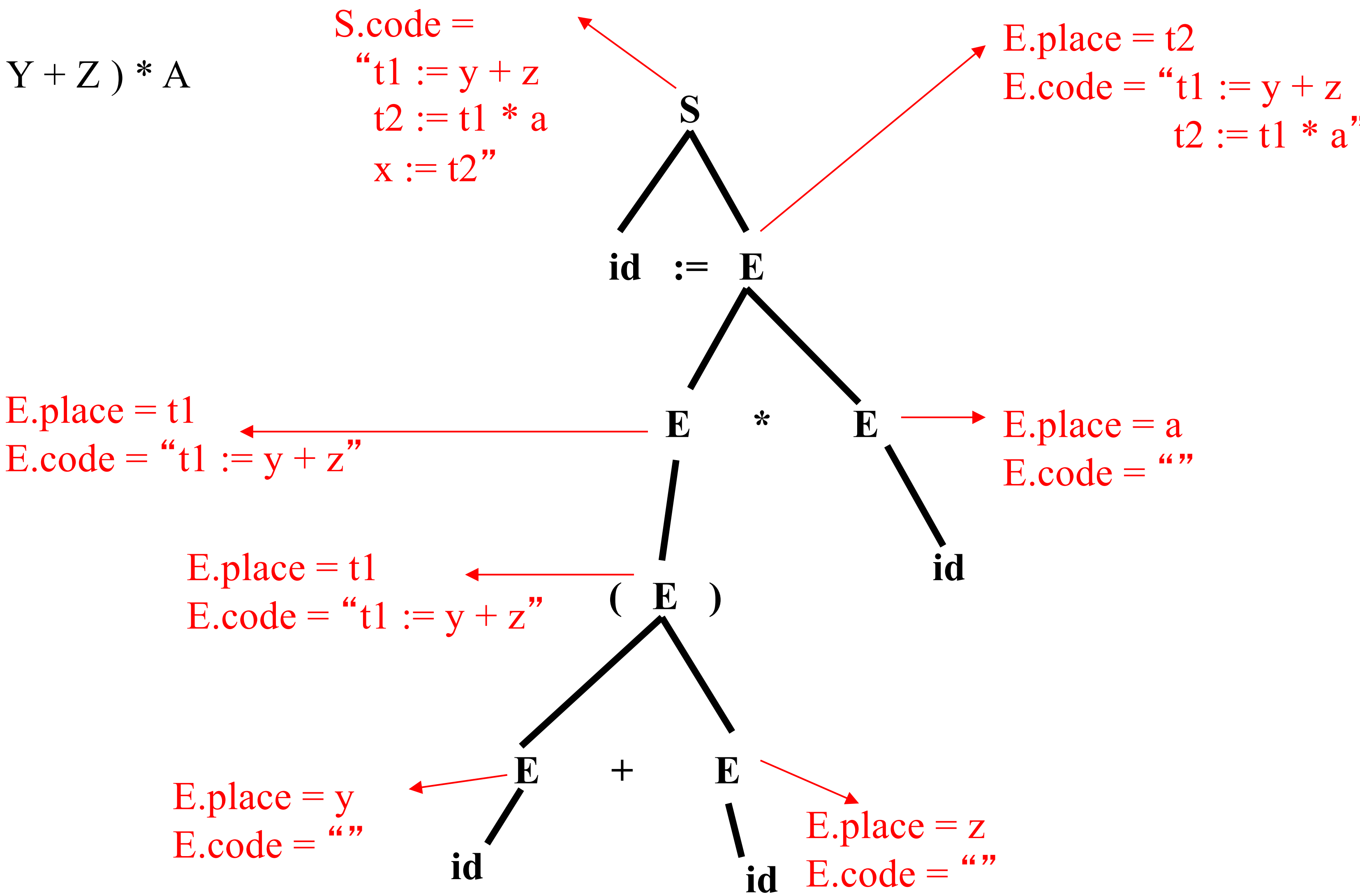
Attributes: $E.place$: location that holds the value of expression E
$E.code$: sequence of instructions that are generated for E

Procedures: newtemp(): Returns a new temporary each time it is called
gen(): Generates instruction (have to call it with appropriate arguments)
lookup(id.*name*): Returns the location of id from the symbol table

Productions	Semantic Rules
$S \rightarrow \text{id} := E$	id.*place* $\leftarrow$ lookup(id.*name*); $S.code \leftarrow E.code$ || gen(id.*place* ':=' $E.place$);
$E \rightarrow E_1 + E_2$	$E.place \leftarrow$ newtemp(); $E.code \leftarrow E_1.code$ || $E_2.code$ || gen($E.place$ ':=' $E_1.place$ '+' $E_2.place$);
$E \rightarrow E_1 * E_2$	$E.place \leftarrow$ newtemp(); $E.code \leftarrow E_1.code$ || $E_2.code$ || gen($E.place$ ':=' $E_1.place$ '*' $E_2.place$);
$E \rightarrow (E_1)$	$E.code \leftarrow E_1.code$; $E.place \leftarrow E_1.place;$
$E \rightarrow - E_1$	$E.place \leftarrow$ newtemp(); $E.code \leftarrow E_1.code$ || gen($E.place$ ':=' 'uminus' $E_1.place$);
$E \rightarrow \text{id}$	$E.place \leftarrow$ lookup(id.*name*); $E.code \leftarrow$ '' (*empty string*)

Example

X := (Y + Z) * A



x86 Architecture

- Complex Instruction Set Computer (CISC)
- Significantly larger opcode set : 400-odd compared to 40-odd in RISC
- Opcodes often can operate on both registers and/or memory
  - Do not necessarily need separate load/store instructions
- 8 general purpose registers (32 bits each)
  - We will use %esp, %eax, and %ecx
  - Intel engineers felt that it is better to provide more opcodes and less registers. Use on-chip real-estate for more functional units and logic (by saving space through a shorter register file and its connections).

(A few) x86 Opcodes

- movl %reg1/(memaddr1)/$imm, %reg2/(memaddr2)
  - Move 32-bit word from register reg1 (or address memaddr1 or the immediate value itself) into reg2 or to memory address memaddr2
  - Captures several opcodes in one mnemonic (load, store, li, move-register, etc.). More powerful than RISC, e.g., MIPS cannot move immediate value directly to memory
- add %reg1/(memaddr1)/$imm, %reg2/(memaddr2)
  - %reg2/(memaddr2) <-- reg1/(memaddr1)/imm + %reg2/(memaddr2)
  - Overflow is always computed for both signed/unsigned arithmetic. Happens in parallel so not in critical performance path, but switches more transistors (more power)
- push %reg/(memaddr)/$imm
  - (%esp-4) <-- reg/(memaddr)/imm; %esp <-- %esp-4
- pop %reg/(memaddr)/$imm
  - reg/(memaddr)/imm <-- (%esp); %esp <-- %esp+4

Expression Code for x86

- The stack-machine code for 7+5 in x86

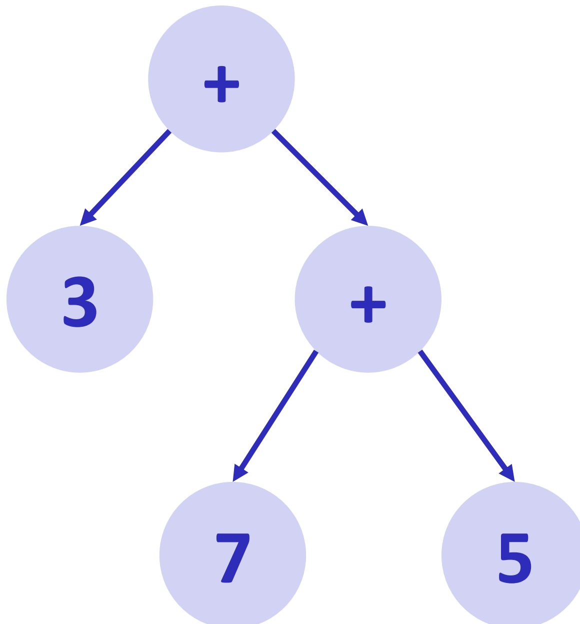
```
pushl  $0x7          ; push first expression (argument) on the stack
pushl  $0x5          ; push second expression (argument) on the stack

                     ; do the add operation
popl   %ebx          ; load first argument into temporary register
popl   %eax          ; load second arg. into accumulator
addl   %ebx, %eax    ; add result together and store in accumulator
pushl  %eax          ; push result back on the stack
```

Expression Code for x86

- The stack-machine code for 3+(7+5) in x86

```
pushl  $0x3
pushl  $0x7
pushl  $0x5
popl   %ebx
popl   %eax
addl   %ebx, %eax
pushl  %eax
popl   %ebx
popl   %eax
addl   %ebx, %eax
pushl  %eax
```



Code Generation for Boolean Expressions

- Two approaches
  - Numerical representation
  - Implicit representation
- Numerical representation
  - Use 1 to represent true, use 0 to represent false
  - For three-address code, store this result in a temporary
  - For stack machine code, store this result on the stack
- Implicit representation
  - For the Boolean expressions that are used in flow-of-control statements (such as if-statements, while-statements etc.) Boolean expressions do not have to explicitly compute a value, they just need to branch to the right instruction
  - Generate code for Boolean expressions that branch to the appropriate instruction based on the result of the Boolean expression

Boolean Expressions: Numerical Representation

Attributes : *E.place*: location that holds the value of expression *E*
E.code: sequence of instructions that are generated for *E*
id.*place*: location for id
relop.*func*: the type of relational function

If there are instructions in the architecture that support operations on Boolean data (like "logical and" or "logical or"), then the easiest way to implement Boolean data is to just treat it like normal data

Productions	Semantic Rules
$E \rightarrow \text{id}_1 \ \text{relop} \ \text{id}_2$	$E.place \leftarrow$ newtemp();
	$E.code \leftarrow$ gen($E.place$ ':=' $id_1.place$ relop.$func$ $id_1.place$)
$E \rightarrow E_1 \ \text{and} \ E_2$	$E.place \leftarrow$ newtemp();
	$E.code \leftarrow E_1.code$
	$\|\| \ E_2.code$
	$\|\|$ gen($E.place$ ':=' $E_1.place$ 'and' $E_2.place$);

Boolean Expressions: Implicit Representation

Attributes :

E.code: sequence of instructions that are generated for *E*
E.false: instruction to branch to if *E* evaluates to false
E.true: instruction to branch to if *E* evaluates to true
(*E.code* is synthesized whereas *E.true* and *E.false* are inherited)
id.*place*: location for id

can be any relational operator: ==, <=, >= !=

Productions	Semantic Rules
$E \rightarrow \text{id}_1 \ \text{relop} \ \text{id}_2$	$E.code \leftarrow$ gen('if' $\text{id}_1.place$ relop.op $\text{id}_2.place$ 'goto' $E.true$) || gen('goto' $E.false$);
$E_0 \rightarrow E_1$ and E_2	$E_1.false \leftarrow E_0.false$; (*short-circuiting*) $E_2.false \leftarrow E_0.false$; $E_1.true \leftarrow$ newlabel(); $E_2.true \leftarrow E_0.true$; $E.code \leftarrow E_1.code$ || gen($E_1.true$ ':') || $E_2.code$;

These places will be filled with labels later on when they become available

This generated label will be inserted to the place for $E_1.true$ in the code generated for E_1

Example

These are the locations of three-address code instructions, they are not labels

Numerical representation:

```
100     t1 := x < y
101     t2 := a == b
102     t3 := t1 and t2
```

Input Boolean expression:
x < y and a == b

Implicit representation:

```
        if x < y goto L1
        goto LFalse
 L1:    if a == b goto LTrue
        goto LFalse
        ...
LTrue:

LFalse:
```

These labels will be generated later on, and will be inserted to the corresponding places

Flow-of-Control Statements

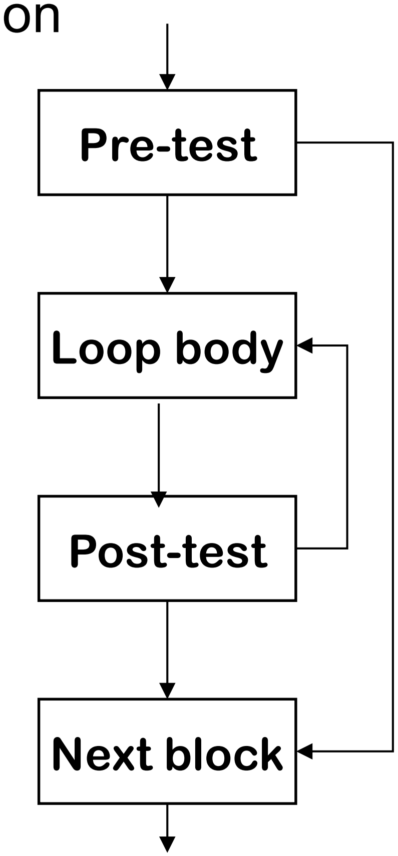
If-then-else

- Branch based on the result of Boolean expression

Loops

- Evaluate condition before loop (if needed)
- Evaluate condition after loop
- Branch back to the top if condition holds

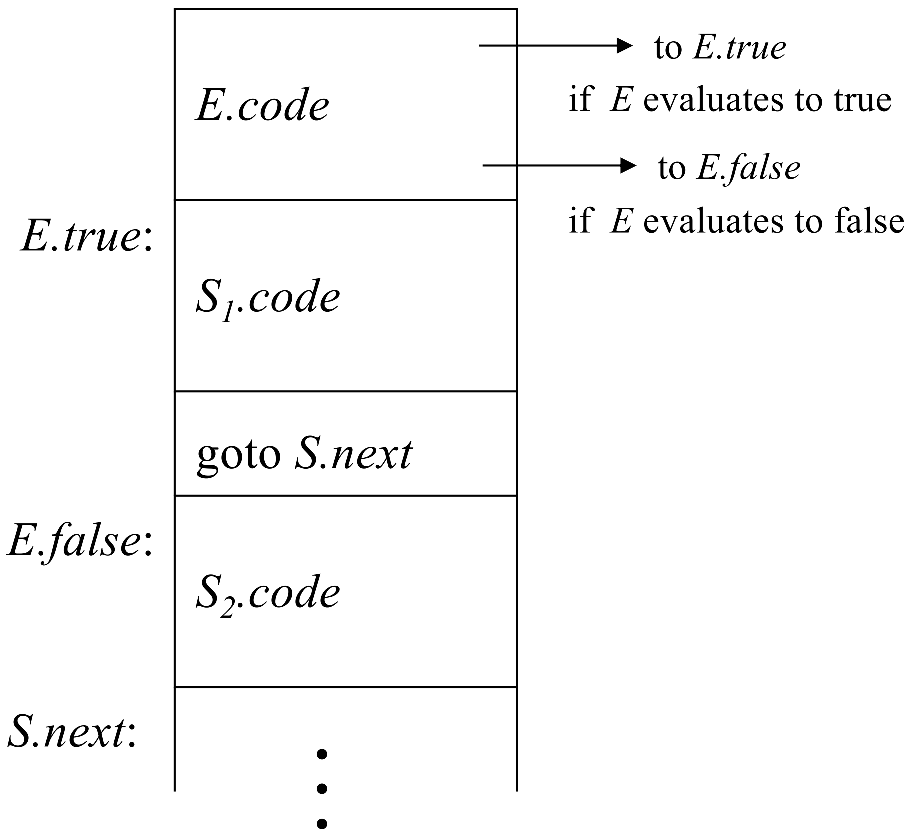
  Merges test with last block of loop body



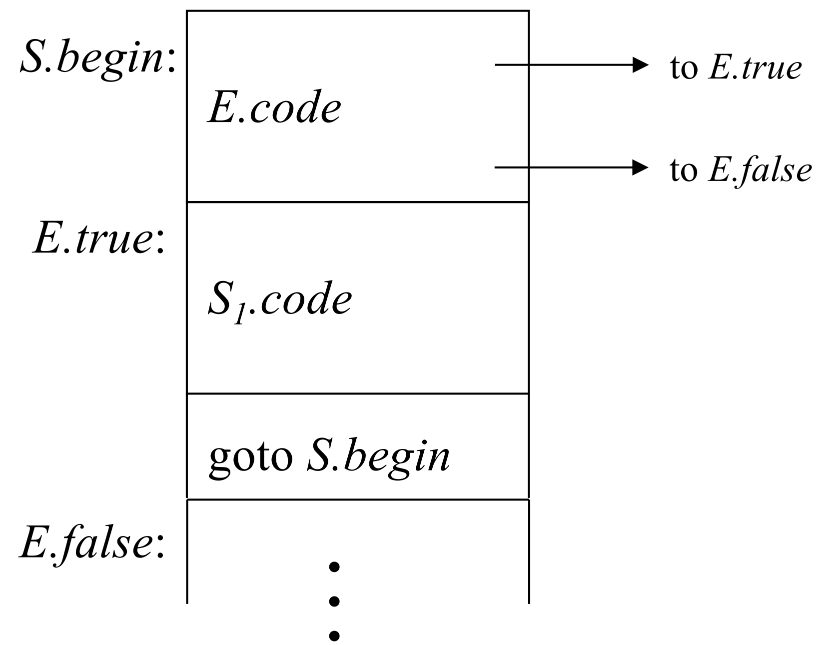
While, for, do, and until all fit this basic model

Flow-of-Control Statements: Code Structure

$S \rightarrow$ if E then S_1 else S_2



$S \rightarrow$ while E do S_1



Another approach is to place $E.code$ after $S_1.code$

Flow-of-Control Statements

Attributes : $S.code$: sequence of instructions that are generated for S
$S.next$: label of the instruction that will be executed immediately after S
($S.next$ is an inherited attribute)

Productions	Semantic Rules
$S \rightarrow$ if E then S_1 else S_2	$E.true \leftarrow$ newlabel(); $E.false \leftarrow$ newlabel(); $S_1.next \leftarrow S.next$; $S_2.next \leftarrow S.next$; $S.code \leftarrow E.code$ || gen($E.true$ ':') || $S_1.code$ || gen('goto' $S.next$) || gen($E.false$ ':') || $S_2.code$;
$S \rightarrow$ while E do S_1	$S.begin \leftarrow$ newlabel(); $E.true \leftarrow$ newlabel(); $E.false \leftarrow S.next$; $S_1.next \leftarrow S.begin$; $S.code \leftarrow$ gen($S.begin$ ':') || $E.code$ || gen($E.true$ ':') || $S_1.code$ || gen('goto' $S.begin$);
$S \rightarrow S_1 ; S_2$	$S_1.next \leftarrow$ newlabel(); $S_2.next \leftarrow S.next$; $S.code \leftarrow S_1.code$ || gen($S_1.next$ ':') || $S_2.code$

Example

Input code fragment:

```
while (a < b)  {
    if  (c < d)
        x = y + z;
    else
        x = y – z
}
```

```
L1:      if a < b goto L2
         goto LNext
L2:      if c < d goto L3
         goto L4
L3:      t1  := y + z
         x  := t1
         goto L1
L4:      t2  := y - z
         x  := t2
         goto L1
LNext:      ...
```

x86 Example

Input code fragment:

```
if (x != 2) {
  y = true;
}
else {
  y = false;
}
```

```
        movl    0xfffffffc(%ebp), %eax
        pushl   %eax
        pushl   $0x2
        popl    %ebx
        popl    %eax
        cmpl    %ebx, %eax
        jne     c_t_label_1
        pushl   $0x0
        jmp     c_f_label_1
c_t_label_1:
        pushl   $0x1
c_f_label_1:
        popl    %eax
        cmpl    $0x01, %eax
        jne     if_else_label_0
        pushl   $0x1
        popl    %eax
        movl    %eax, 0xfffffff8(%ebp)
        jmp     if_end_label_0
if_else_label_0:
        pushl   $0x0
        popl    %eax
        movl    %eax, 0xfffffff8(%ebp)
if_end_label_0:
```

Array Accesses

First, must agree on a storage scheme:

Row-major order (most languages)

Lay out as a sequence of consecutive rows

Rightmost subscript varies fastest

A[1,1], A[1,2], A[1,3], A[2,1], A[2,2], A[2,3]

Column-major order (Fortran)

Lay out as a sequence of columns

Leftmost subscript varies fastest

A[1,1], A[2,1], A[1,2], A[2,2], A[1,3], A[2,3]

Indirection vectors (Java)

Vector of pointers to pointers to … to values

Takes more space

Locality may not be good

Laying Out Arrays

The Concept

A

1,1	**1,2**	**1,3**	**1,4**
2,1	**2,2**	**2,3**	**2,4**

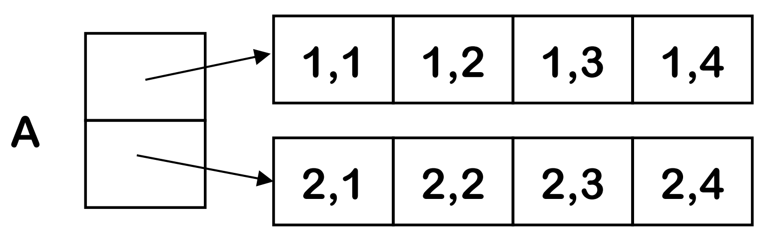
Row-major order

A

1,1	**2,1**	**1,2**	**2,2**	**1,3**	**2,3**	**1,4**	**2,4**

Column-major order

Indirection vectors



These have distinct & different cache behavior

The order of traversal of an array can effect the performance

How do we insert the calculation for arrays

- If I access element A[2,3], what address is storing my variable?

	0	1	2	3	4	5	6	7
A	**1,1**	**1,2**	**1,3**	**1,4**	**2,1**	**2,2**	**2,3**	**2,4**

Need to map i = 2, j = 3 to array element 6

- If i = 2, and we start at 1, we need to skip over one row (Row 1) worth of stuff. In general, we would skip over (*i – low)* rows (*low* is the number you start counting at for your arrays - in the example, it is 1)
- Each row is some number of elements in length (*high* – *low* + 1)
  = (4 – 1) + 1 = 4
- Once you get to the correct row, we just add *j* – *low* to get the right index
  = (3 – 1) = 2

Computing an Array Address

1-D array: A[i]

- $@A + (i - low) \times sizeof(A[1])$

Almost always a power of 2, known at compile-time ⇒ use a shift for speed

Base of A (starting address of the array)

int A[1:10] ⇒ low is 1
Make low 0 for faster access (save a subtraction)

Expensive computation!

Lots of +, -, x operations

Two-D array: $A[i_1,i_2]$

Row-major order, two dimensions

$$@A + ((i_1 - low_1) \times (high_2 - low_2 + 1) + i_2 - low_2) \times sizeof(A[1])$$

Column-major order, two dimensions

$$@A + ((i_2 - low_2) \times (high_1 - low_1 + 1) + i_1 - low_1) \times sizeof(A[1])$$

Indirection vectors, two dimensions

$*(A[i_1])[i_2]$ — where $A[i_1]$ is, itself, a 1-d array reference

Optimizing the Stack Machine

- The "**add**" instruction does 3 memory operations
  - Two reads and one write to the stack
  - The top of the stack is frequently accessed
  - Idea: keep the top of the stack in a register (called accumulator) Register accesses are faster
  - The "add" instruction is now acc ← acc + top_of_stack
  - Only one memory operation!

- Key: Now we have arithmetic instructions to support operands both in register and on stack. Previously, the operands must be on the stack.

Example

- Consider the expression: e1 + e2

- At a high level, the stack machine code will be:

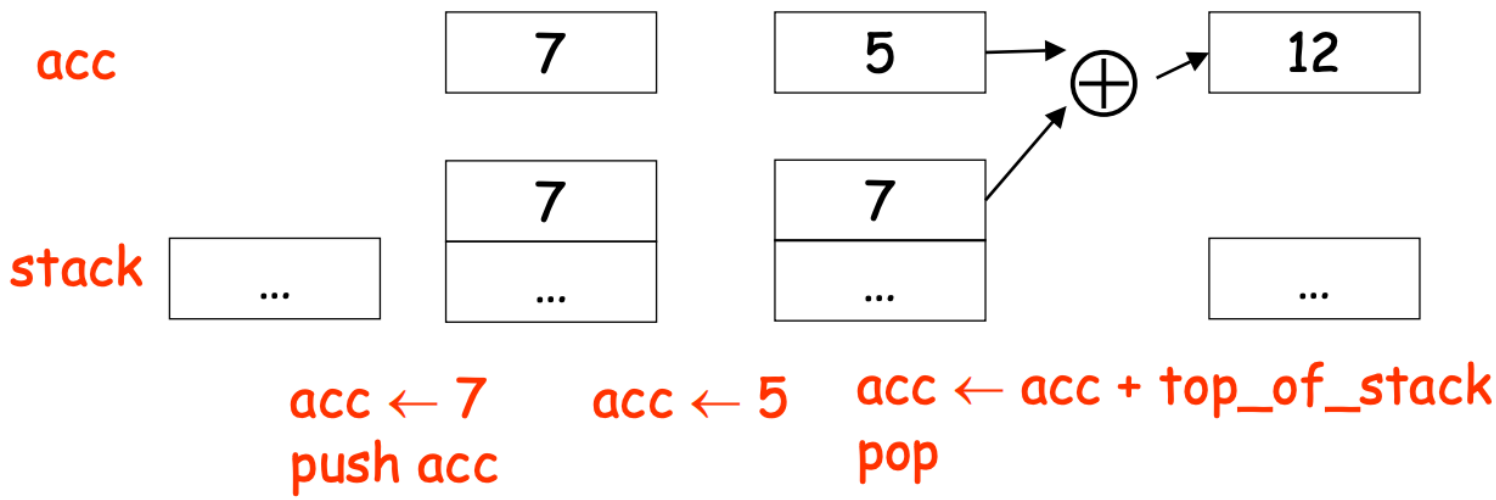
  <code to evaluate e1>
  push acc on the stack
  <code to evaluate e2>
  push acc on the stack
  add top two stack elements, store in acc
  pop two elements off the stack

- Observation: There is no need to push the result of e2 on the stack.

  <code to evaluate e1>
  push acc on the stack
  <code to evaluate e2>
  add top stack element and acc, store in acc
  pop one elements off the stack

Stack Machine with Accumulator

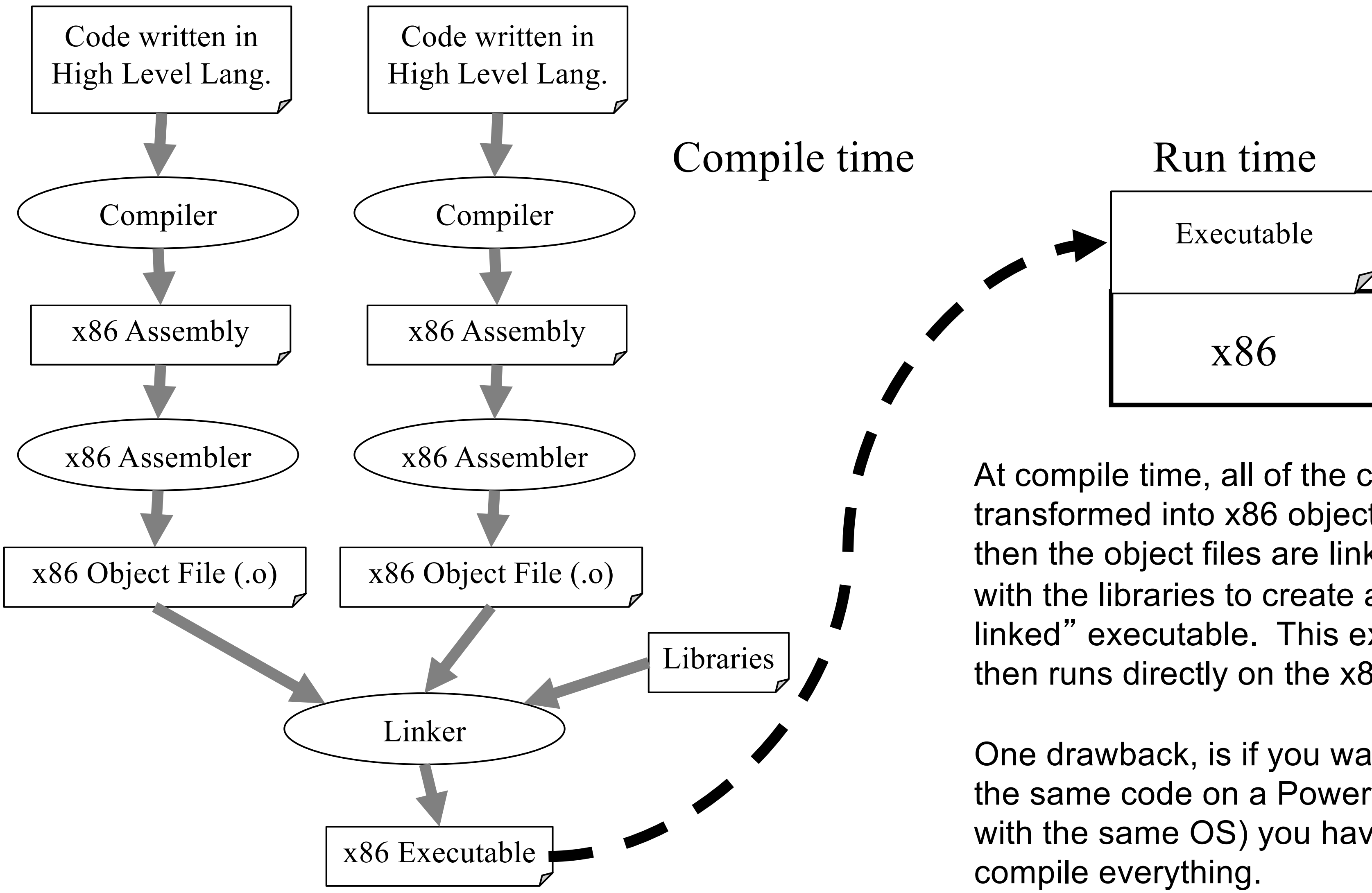
- Compute 7 + 5 using an accumulator



A (Slightly) Bigger Example: 3 + (7 + 5)

Code	Acc	Stack
acc ← 3	3	<init>
push acc	3	3, <init>
acc ← 7	7	3, <init>
push acc	7	7, 3, <init>
acc ← 5	5	7, 3, <init>
acc ← acc + top_of_stack	12	7, 3, <init>
pop	12	3, <init>
acc ← acc + top_of_stack	15	3, <init>
pop	15	<init>

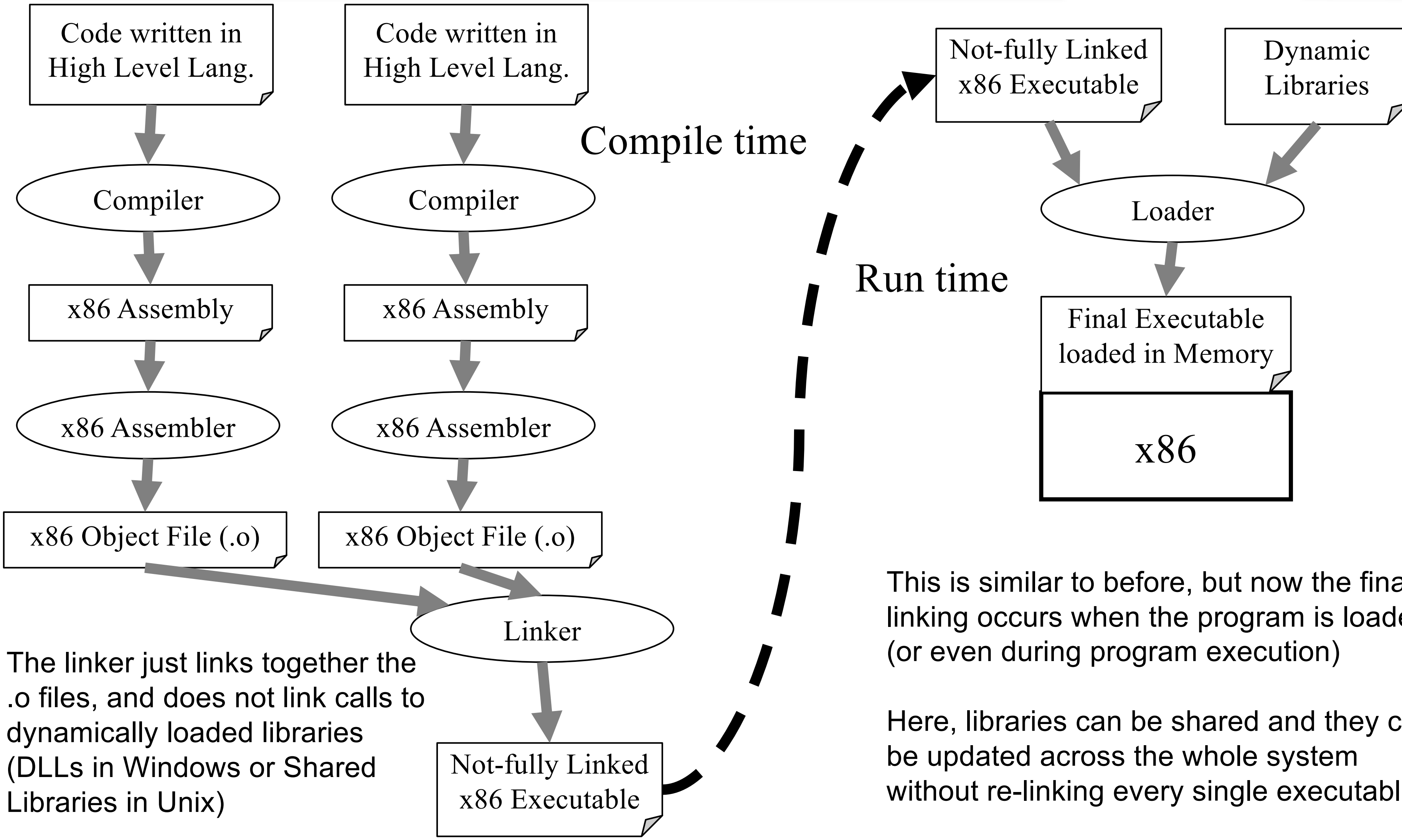
x86 C Compiler with Static Linking



At compile time, all of the code is transformed into x86 object files and then the object files are linked together with the libraries to create a "statically linked" executable. This executable then runs directly on the x86 hardware.

One drawback, is if you wanted to run the same code on a Power-PC (even with the same OS) you have to re-compile everything.

x86 C Compiler with Dynamic Linking

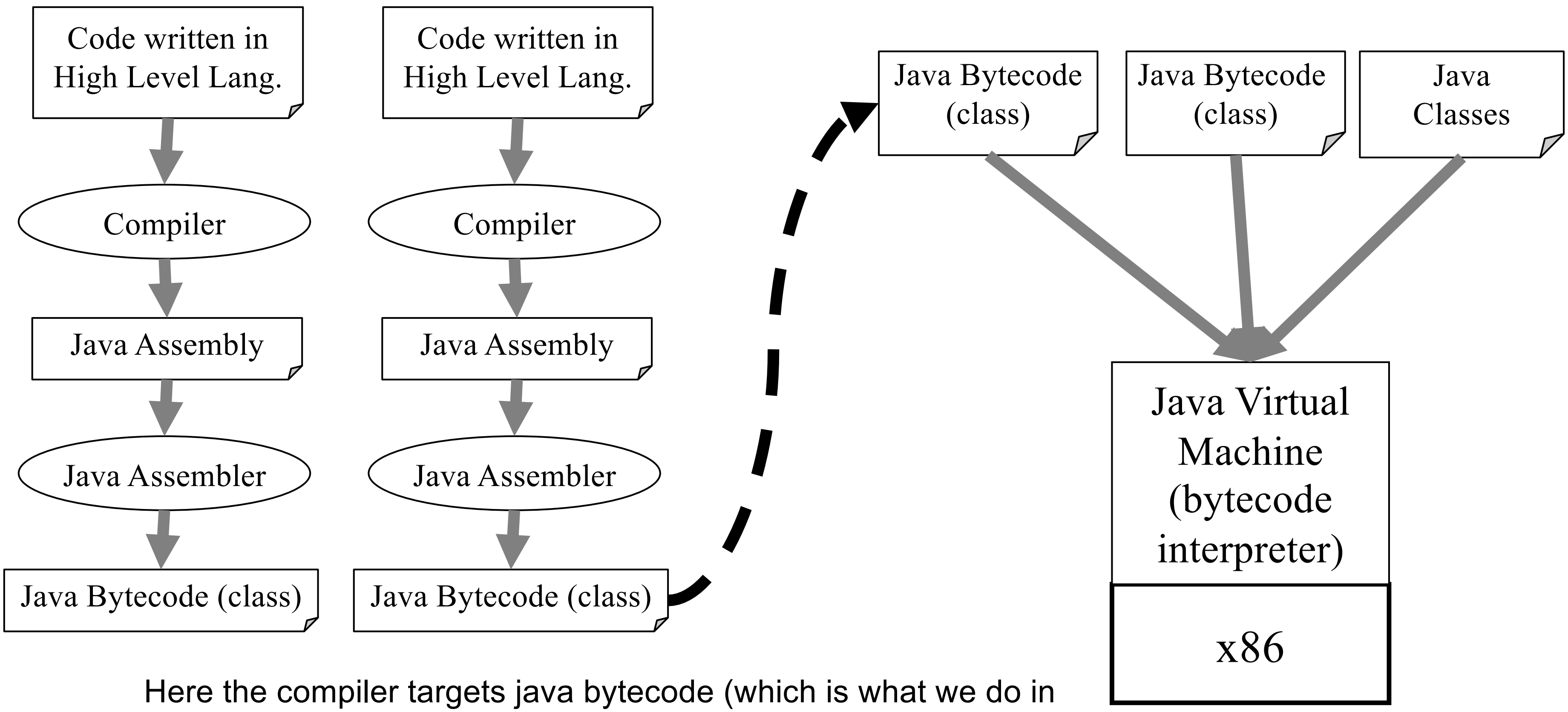


The linker just links together the .o files, and does not link calls to dynamically loaded libraries (DLLs in Windows or Shared Libraries in Unix)

This is similar to before, but now the final linking occurs when the program is loaded (or even during program execution)

Here, libraries can be shared and they can be updated across the whole system without re-linking every single executable

Java Compiler



Here the compiler targets java bytecode (which is what we do in this class) and the bytecode is then run on top of the Java Virtual Machine (JVM). The JVM really just interprets (simulates) the bytecode like any scripting language. Because of this, any java program compiled to bytecode is portable to any machine that someone has already ported the JVM too. No need to recompile.