Runtime Environments

CS143

Lecture 11

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Status

- We have covered the front-end phases
  - Lexical analysis
  - Parsing
  - Semantic analysis
- Next are the back-end phases
  - Optimization
  - Code generation
- We'll do code generation first . . .

Run-time environments

- Before discussing code generation, we need to understand what we are trying to generate

- There are a number of standard techniques for structuring executable code that are widely used

Outline

- Management of run-time resources

- Correspondence between
  - static (compile-time) and
  - dynamic (run-time) structures

- Storage organization

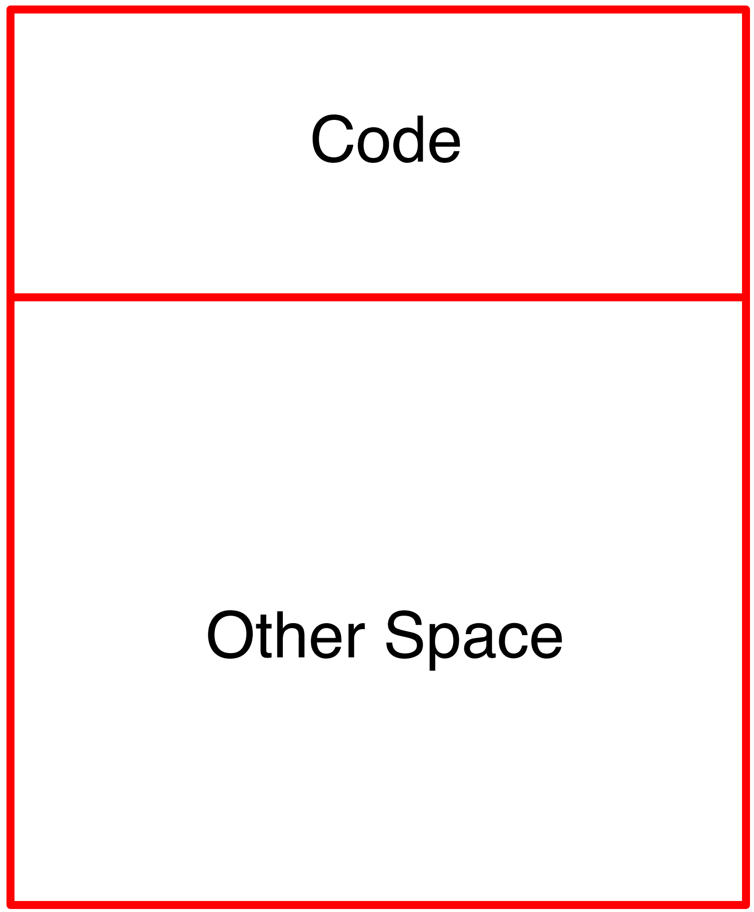
Run-time Resources

- Execution of a program is initially under the control of the operating system

- When a program is invoked:
  - The OS allocates space for the program
  - The code is loaded into part of the space
  - The OS jumps to the entry point (i.e., “main”)

Memory Layout

Memory



Low Address

High Address

Notes

- By tradition, pictures of machine organization have:
  - Low address at the top
  - High address at the bottom
  - Lines delimiting areas for different kinds of data
- These pictures are simplifications
  - E.g., not all memory need be contiguous

What is Other Space?

- Holds all data for the program
- Other Space = Data Space

- Compiler is responsible for:
  - Generating code
  - Orchestrating use of the data area

Code Generation Goals

- Two goals:
  - Correctness
  - Speed
- Most complications in code generation come from trying to be fast as well as correct

Assumptions about Execution

1. Execution is sequential; control moves from one point in a program to another in a well-defined order

2. When a procedure is called, control eventually returns to the point immediately after the call

Do these assumptions always hold?

Activations

- An invocation of procedure P is an activation of P

- The lifetime of an activation of P is
  - All the steps to execute P
  - Including all the steps in procedures P calls

Lifetimes of Variables

- The lifetime of a variable x is the portion of execution in which x is defined

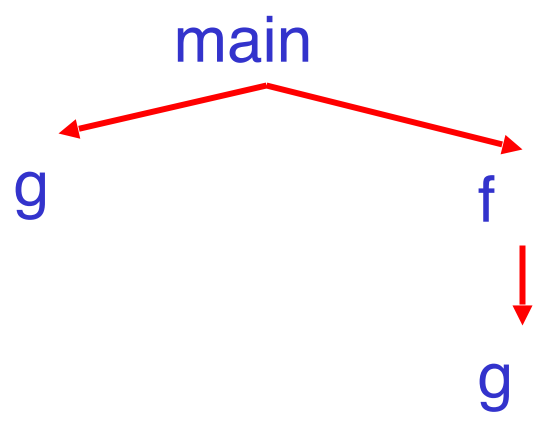
- Note that
  - Lifetime is a dynamic (run-time) concept
  - Scope is a static concept

Activation Trees

- Assumption (2) requires that when P calls Q, then Q returns before P does
- Lifetimes of procedure activations are properly nested
- Activation lifetimes can be depicted as a tree

Example

```
Class Main {
    g() : Int { 1 };
    f():  Int { g() };
    main(): Int {{ g(); f(); }};
}
```



Example 2

```
Class Main {
   g() : Int { 1 };
   f(x:Int):  Int { if x = 0 then g() else f(x - 1) fi };
   main(): Int { f(3) };
}
```

What is the activation tree for this example?

Notes

- The activation tree depends on run-time behavior
- The activation tree may be different for every program input
- Since activations are properly nested, a stack can track currently active procedures

Example

```
Class Main {
   g() : Int { 1 };
   f():  Int { g() };
   main(): Int {{ g(); f(); }};
}
```

main

Stack

main

Example

```
Class Main {
   g() : Int { 1 };
   f():  Int { g() };
   main(): Int {{ g(); f(); }};
}
```

main

g

Stack

main

g

Example

```
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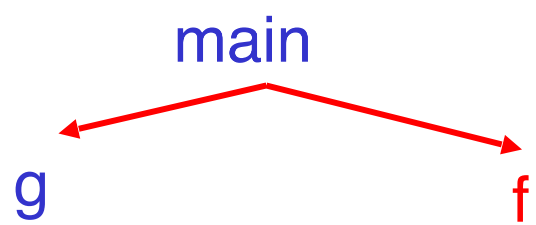

Stack

main

f

Example

```
Class Main {
   g() : Int { 1 };
   f():  Int { g() };
   main(): Int {{ g(); f(); }};
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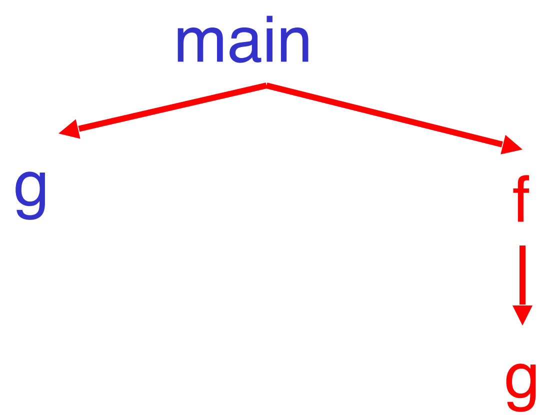
```



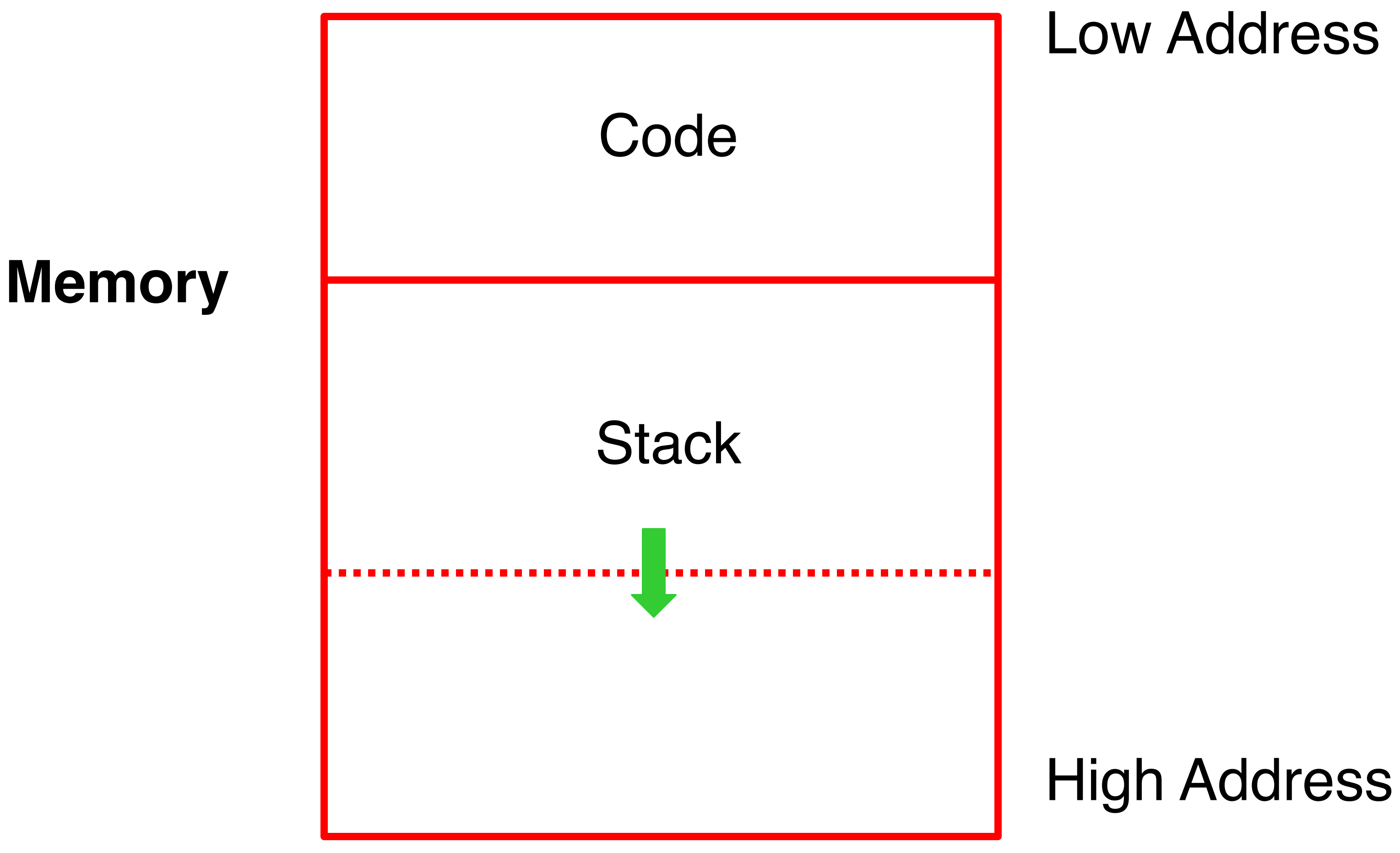
Stack

main

f

g

Revised Memory Layout



Activation Records

- The information needed to manage one procedure activation is called an activation record (AR) or a stack frame

- If procedure F calls G, then G's activation record contains a mix of info about F and G.

What is in G’s AR when F calls G?

- F is “suspended” until G completes, at which point F resumes. G’s AR contains information needed to resume execution of F.

- G’s AR may also contain:
  - G’s return value (needed by F)
  - Actual parameters to G (supplied by F)
  - Space for G’s local variables

The Contents of a Typical AR for G

- Space for G's return value
- Actual parameters
- Pointer to the previous activation record
  - The control link; points to AR of caller of G
- Machine status prior to calling G
  - Contents of registers & program counter
  - Local variables
- Other temporary values

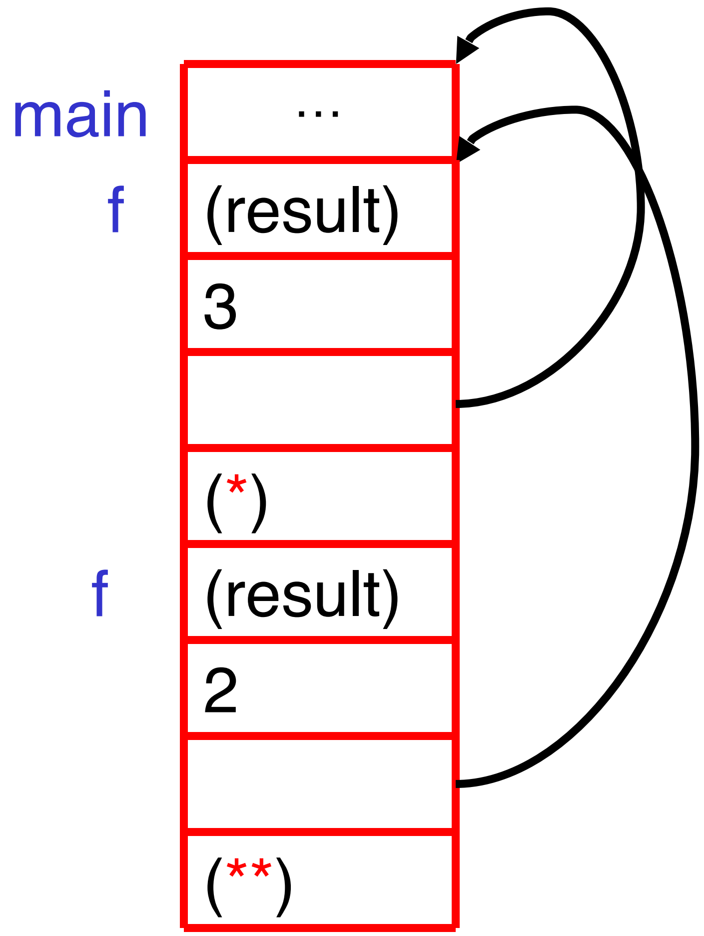
Example 2, Revisited

```
Class Main {
    g() : Int { 1 };
    f(x:Int):Int { if x=0 then g() else f(x - 1)(**) fi };
    main(): Int { f(3)(*) };
}
```

AR for f:

result
argument
control link
return address

Stack After Two Calls to f



Notes

- main has no argument or local variables and its result is never used; its AR is uninteresting
- (*) and (**) are return addresses of the invocations of f
  - The return address is where execution resumes after a procedure call finishes
- This is only one of many possible AR designs
  - Would also work for C, Pascal, FORTRAN, etc.

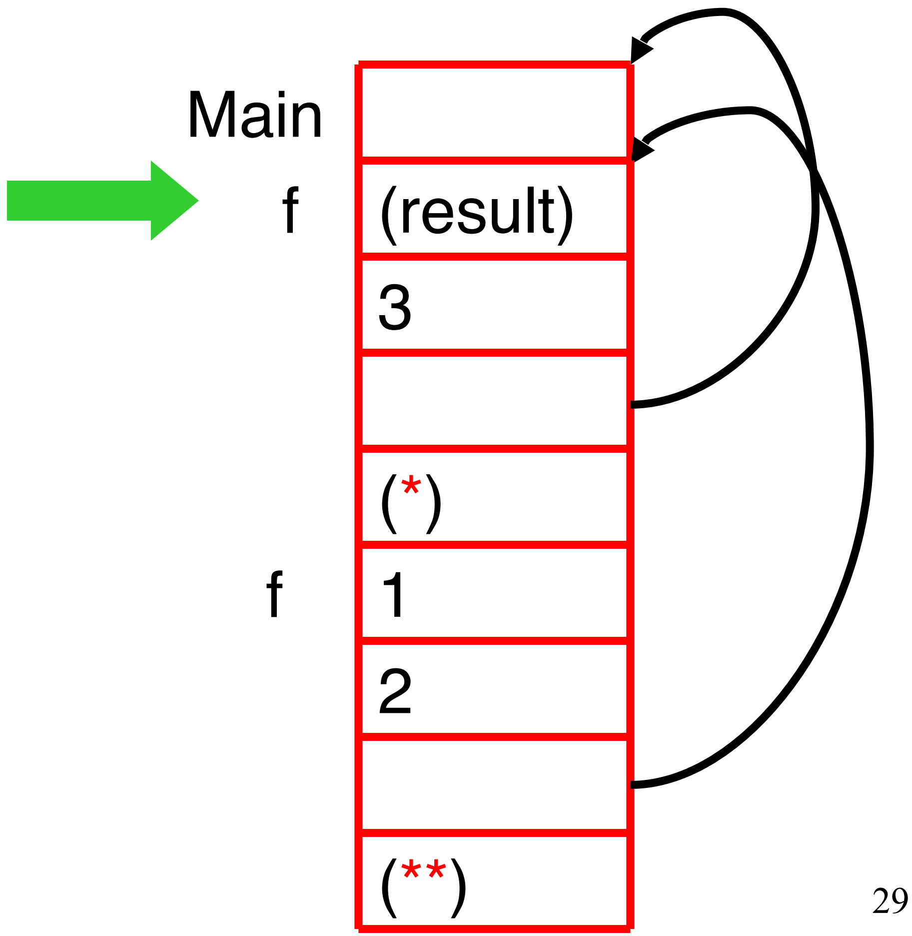
The Main Point

The compiler must determine, at compile-time, the layout of activation records and generate code that correctly accesses locations in the activation record

Thus, the AR layout and the code generator must be designed together!

Example

The picture shows the state after the call to the 2nd invocation of f returns



Discussion

- The advantage of placing the return value 1st in a frame is that the caller can find it at a fixed offset from its own frame

- There is nothing magic about this organization
  - Can rearrange order of frame elements
  - Can divide caller/callee responsibilities differently
  - An organization is better if it improves execution speed or simplifies code generation

Discussion (Cont.)

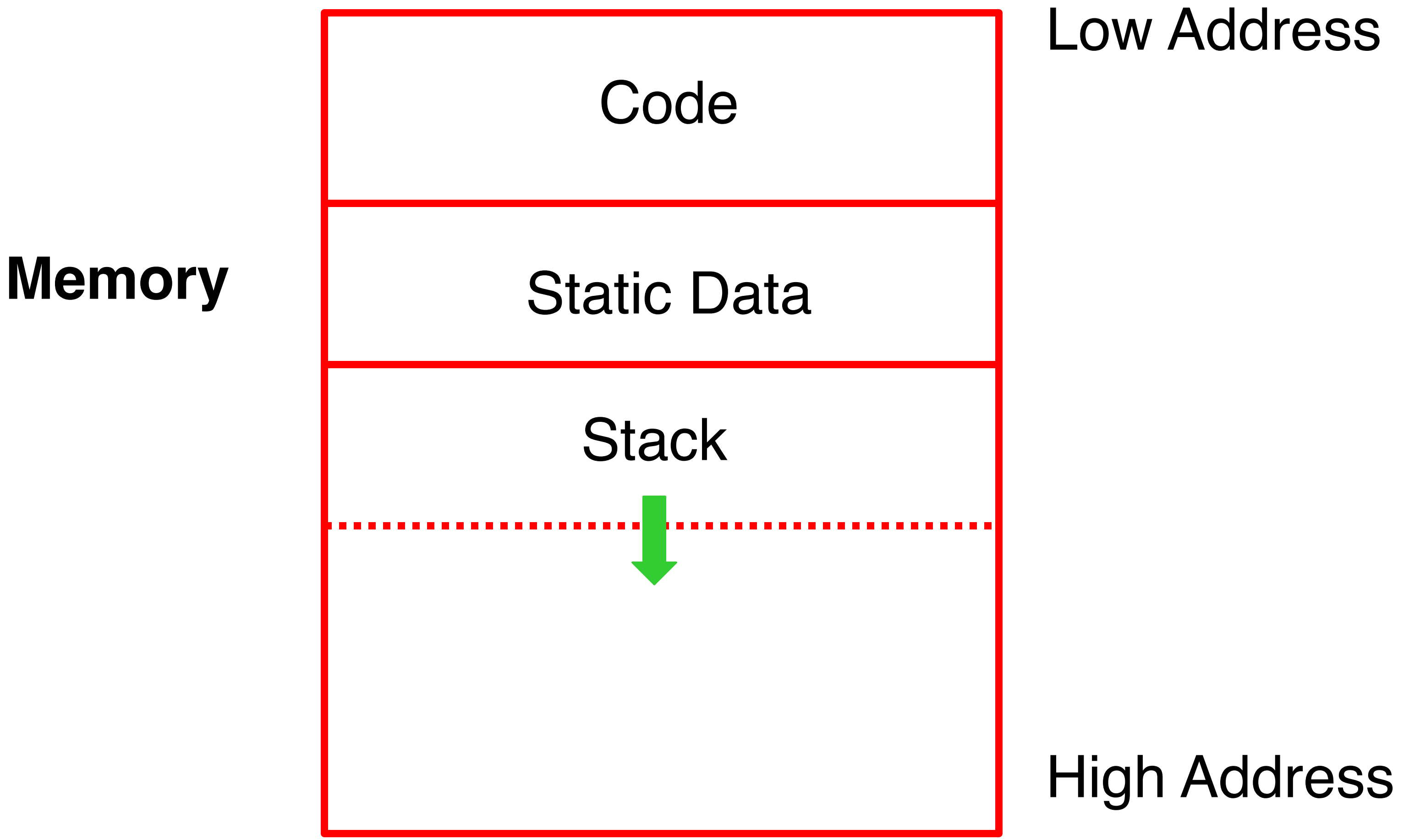
- Real compilers hold as much of the frame as possible in registers
  - Especially the method result and arguments

Globals

- All references to a global variable point to the same object
  – Can’t store a global in an activation record

- Globals are assigned a fixed address once
  – Variables with fixed address are “statically allocated”
- Depending on the language, there may be other statically allocated values

Memory Layout with Static Data



Heap Storage

- A value that outlives the procedure that creates it cannot be kept in the AR

  method foo() { new Bar }

  The Bar value must survive deallocation of foo's AR

- Languages with dynamically allocated data use a heap to store dynamic data

Notes

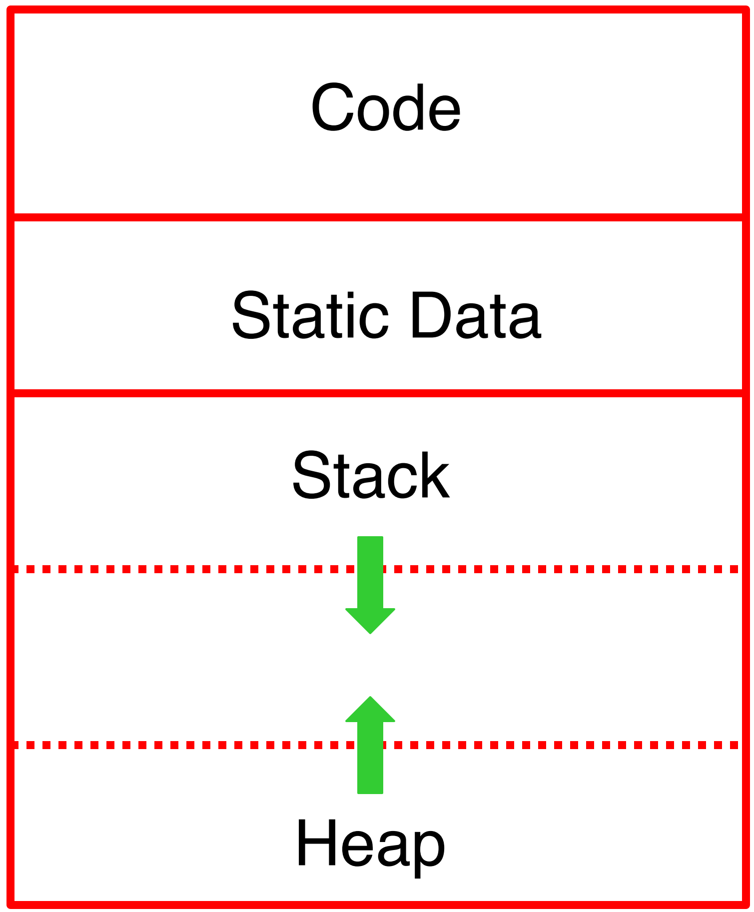
- The code area contains object code
  - For most languages, fixed size and read only
- The static area contains data (not code) with fixed addresses (e.g., global data)
  - Fixed size, may be readable or writable
- The stack contains an AR for each currently active procedure
  - Each AR usually fixed size, contains locals
- Heap contains all other data
  - In C, heap is managed by malloc and free

Notes (Cont.)

- Both the heap and the stack grow
- Must take care that they don't grow into each other
- Solution: start heap and stack at opposite ends of memory and let them grow towards each other

Memory Layout with Heap

Memory



Low Address

High Address

Data Layout

- Low-level details of machine architecture are important in laying out data for correct code and maximum performance

- Chief among these concerns is alignment

Alignment

- Most machines are 32 or 64 bit
  – 8 bits in a byte
  – 4 bytes in a word
  – Machines are either byte or word addressable
- Data is word aligned if it begins at a word boundary
- Most machines have some alignment restrictions
  – Or performance penalties for poor alignment

Alignment (Cont.)

- Example: A string

“Hello”

Takes 5 characters (without a terminating \0)

- To word align next datum, add 3 “padding” characters to the string

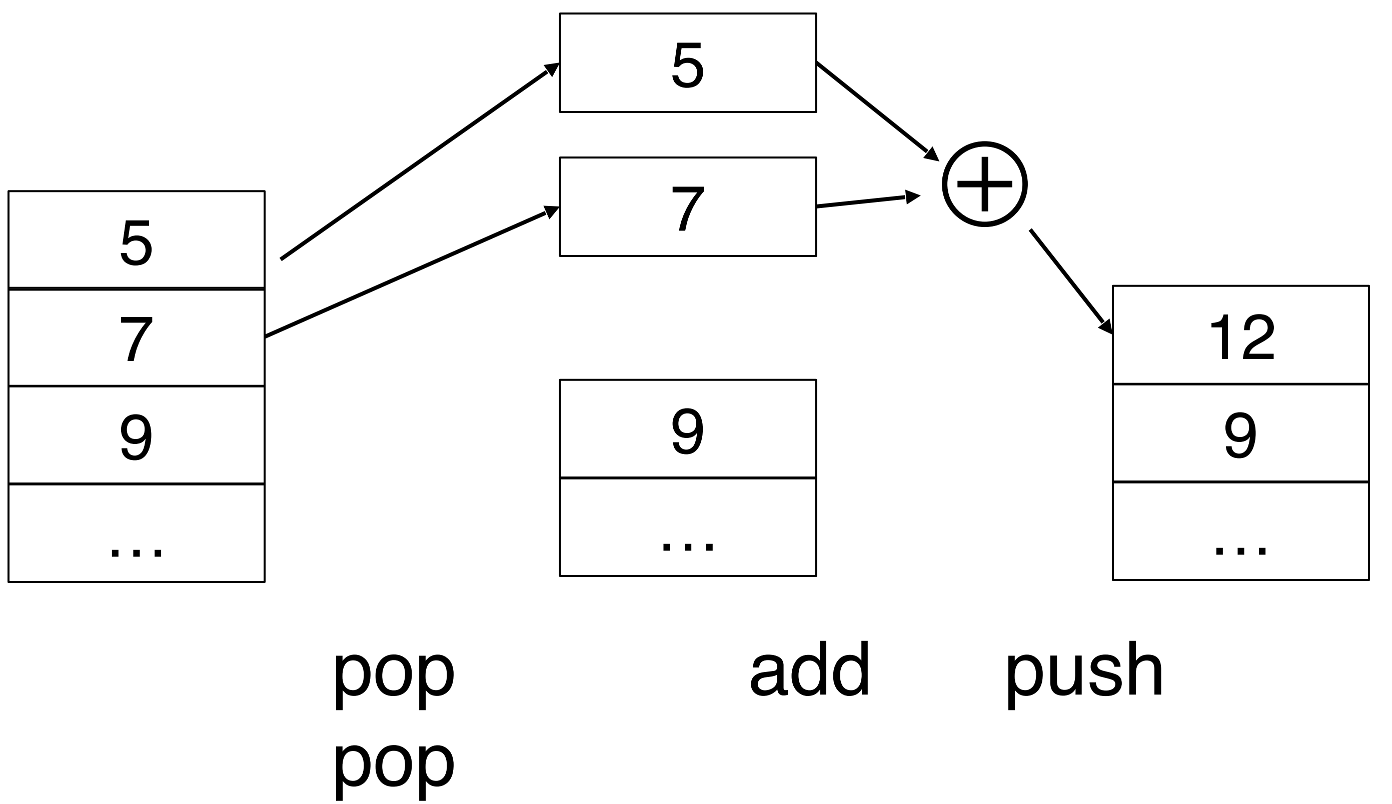
- The padding is not part of the string, it’s just unused memory

Next Topic: Stack Machines

- A simple evaluation model for expressions
- No variables or registers
- A stack of values for intermediate results
- Each instruction:
  - Takes its operands from the top of the stack
  - Removes those operands from the stack
  - Computes the required operation on them
  - Pushes the result on the stack

Example of Stack Machine Operation

- The addition operation on a stack machine



Example of a Stack Machine Program

- Consider two instructions
  - push i - place the integer i on top of the stack
  - add - pop two elements, add them and put the result back on the stack
- A program to compute 7 + 5:

```
push 7
push 5
add
```

Why Use a Stack Machine?

- Each operation takes operands from the same place and puts results in the same place
- This means a uniform compilation scheme
- And therefore a simpler compiler

Why Use a Stack Machine?

- 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 r_1, r_2”

  ⇒ Smaller encoding of instructions

  ⇒ More compact programs
- This is one reason why Java Bytecodes and WebAssembly use a stack evaluation model

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!

Stack Machine with Accumulator

Invariants

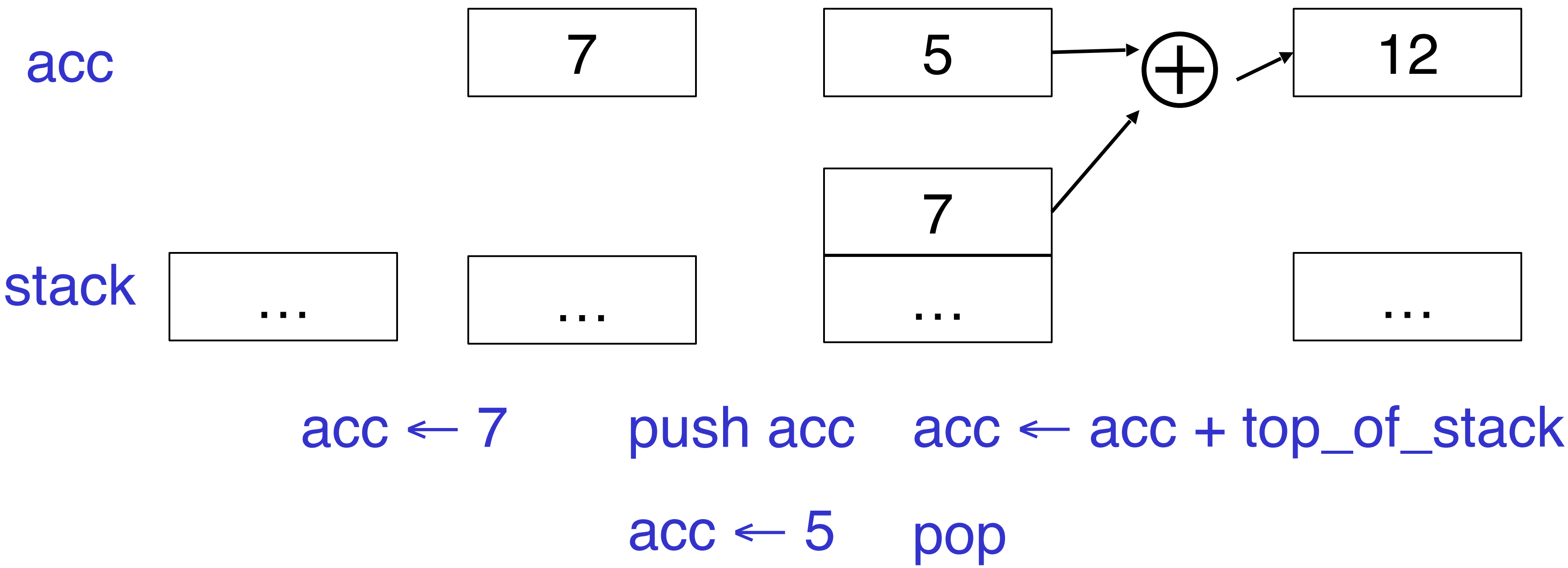
- The result of an expression is in the accumulator

- For $op(e_1,\ldots,e_n)$
  - Evaluate each of $e_1,\ldots,e_{n-1}$ and push results on the stack
  - Evaluating e_n leaves the result in the accumulator
  - Evaluating op pops n-1 values from the stack and updates the accumulator

- Expression evaluation preserves the stack

Stack Machine with Accumulator. Example

- Compute 7 + 5 using an accumulator



A 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>

Notes

- It is very important evaluation of a subexpression preserves the stack
  - Stack before the evaluation of 7 + 5 is 3, <init>
  - Stack after the evaluation of 7 + 5 is 3, <init>
  - The first operand is on top of the stack