Run-time organization

Lecture 23

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
  - The term *virtual machine* refers to the compiler's target
  - Can be just a bare hardware architecture (small embedded systems)
  - Can be an interpreter, as for Java, or an interpreter that does additional compilation, as in modern Java JITs
  - For now, we'll stick to hardware + *conventions* for using it ("API") + some *runtime-support library*

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

Outline

- Management of run-time resources

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

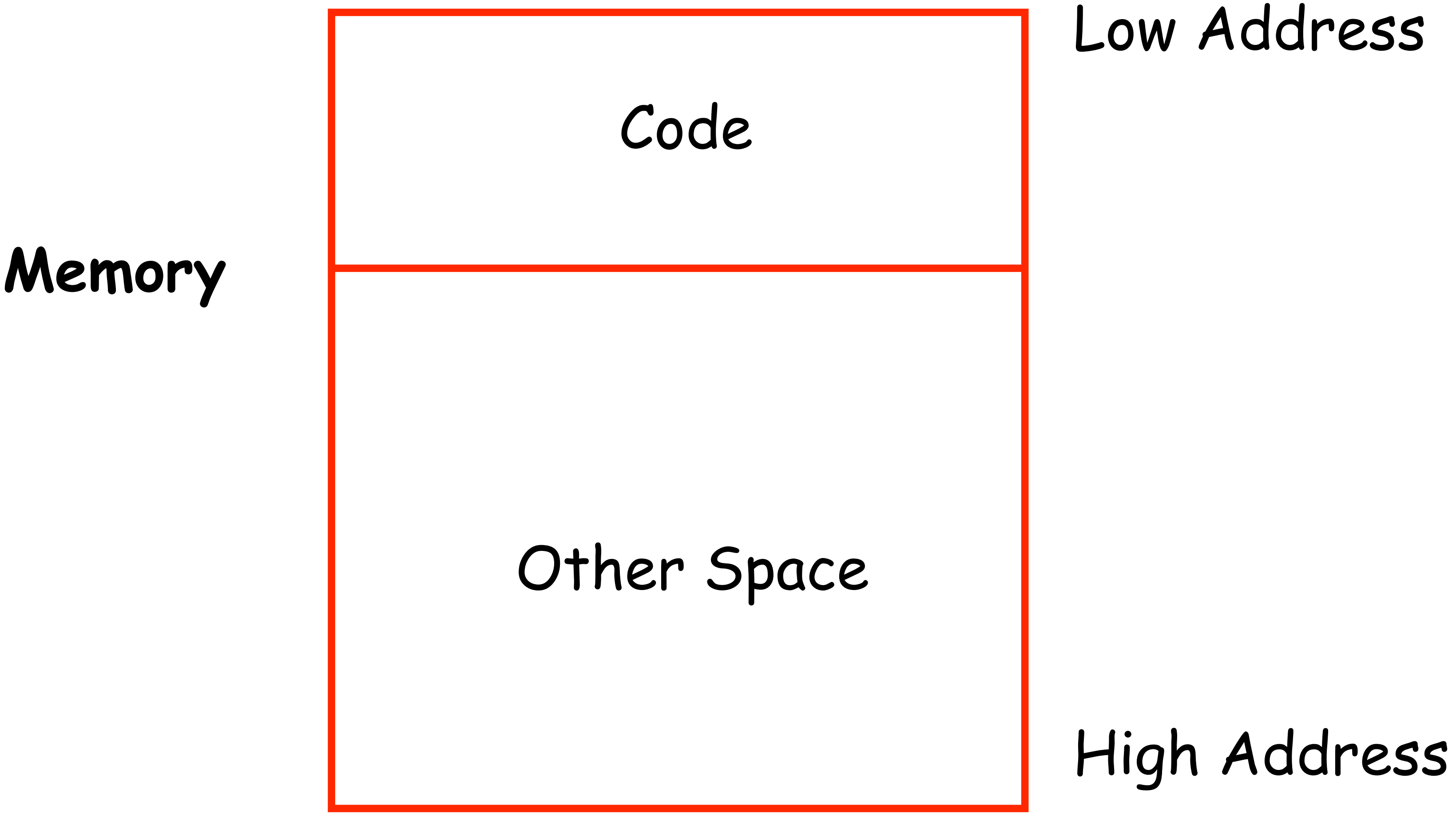
- Storage organization

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



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
- Lifetime is a dynamic (run-time) concept
- … As opposed to scope, which is a static concept

Activation Trees

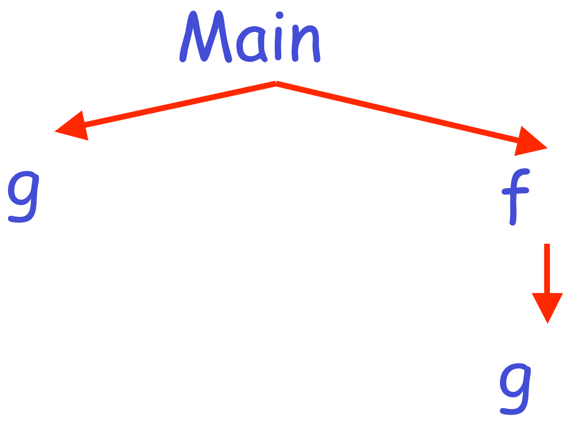
- Assumption (2) requires that when P calls Q, then Q returns before P does

- Lifetimes of procedure activations are properly nested

- Activation lifetimes can be depicted as a tree

Example (from Java)

```
class Main {
    int g() { return 1; }
    int f() {return g(); }
    void main() { g(); f(); }
}
```



Example 2

```
class Main {
    int g() { return 1; }
    int f(int x) {
        if (x == 0) { return g(); }
        else { return f(x - 1); }
    }
    void main() { f(2); }
}
```

What is the activation tree for this example?

Example 2

```
class Main {
    int g() { return 1; }
    int f(int x) {
        if (x == 0) { return g(); }
        else { return f(x - 1); }
    }
    void main() { f(2); }
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```
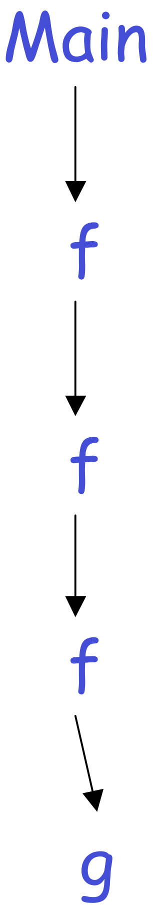



Notes

- 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 {
   int g() { return 1; }
   int f() { return g(); }
   void main() { g(); f(); }
}
```

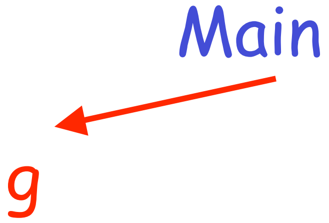
Main

Stack

Main

Example

```
class Main {
   int g() { return 1; }
   int f() { return g(); }
   void main() { g(); f(); }
}
```



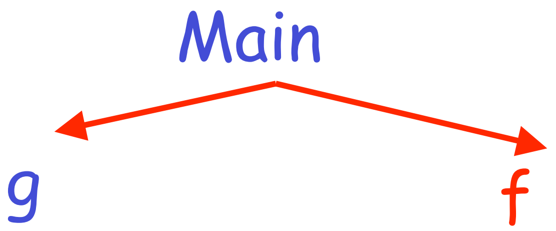
Stack

Main

g

Example

```
class Main {
   int g() { return 1; }
   int f() { return g(); }
   void main() { g(); f(); }
}
```



Main

g

f

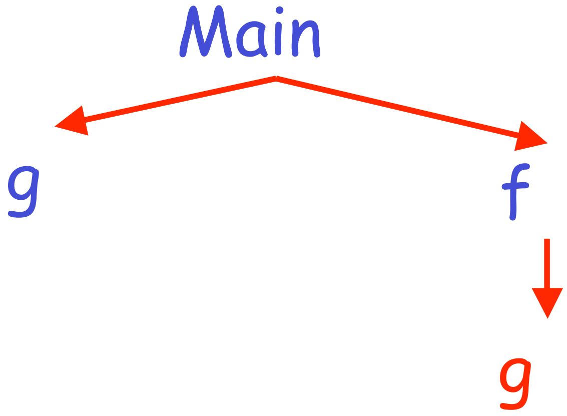
Stack

Main

f

Example

```
class Main {
    int g() { return 1; }
    int f() { return g(); }
    void main() { g(); f(); }
}
```



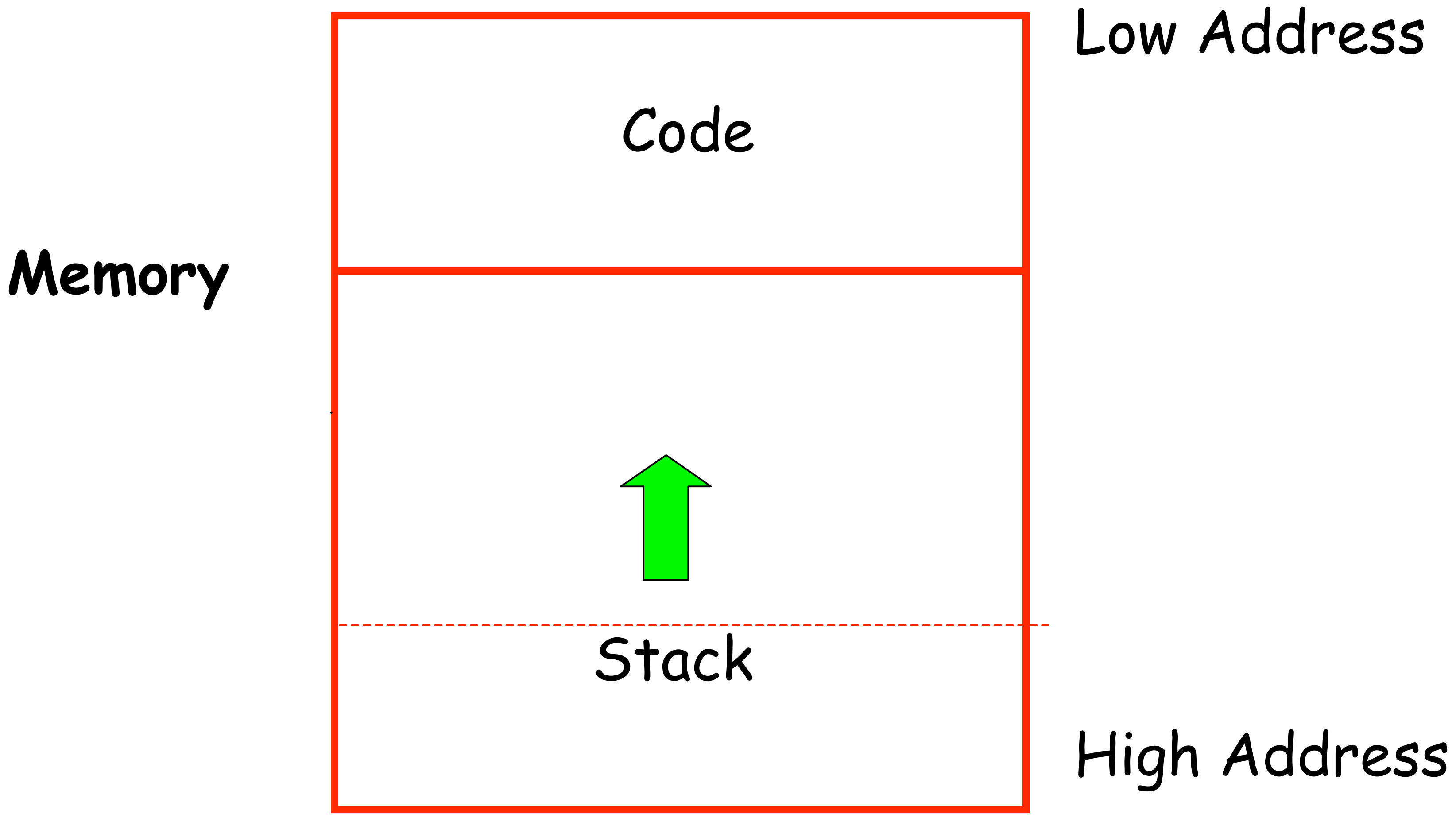
Stack

Main

f

g

Revised Memory Layout



Activation Records

- The information needed to manage one procedure activation is called an *activation record (AR)* or *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 *dynamic link* points to AR of caller of G
- Machine status prior to calling *G*
  - Contents of registers & program counter
  - Local variables
- Other temporary values

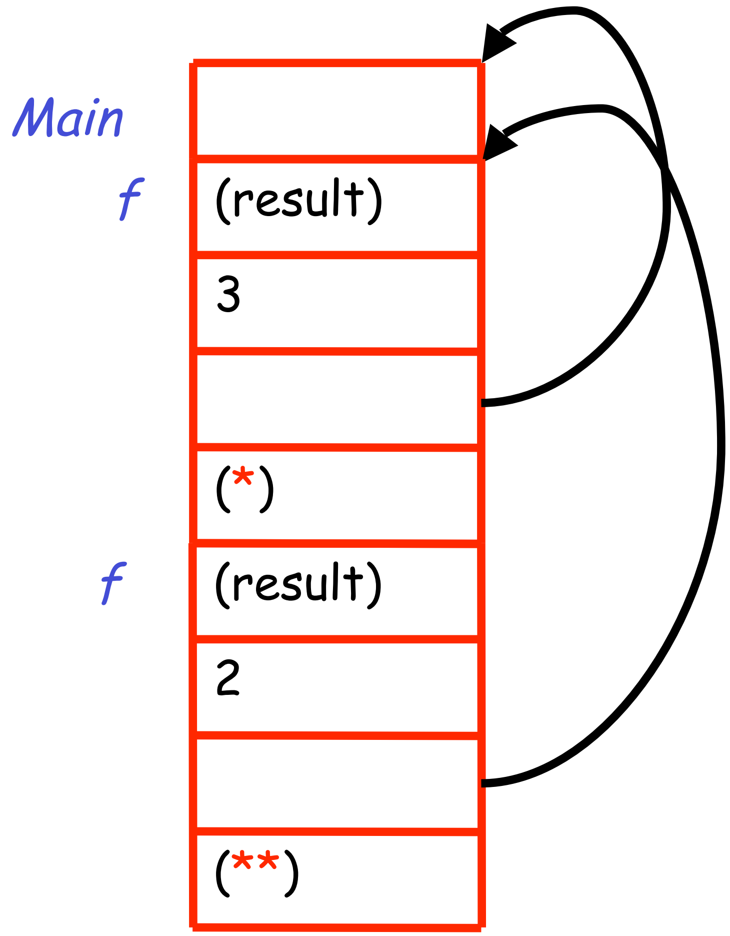
Example 2, Revisited

```
class Main {
    int g() { return 1; }
    int f(int x) {
        if (x == 0) { return g(); }
        else { return f(x - 1); (**) }
    }
    void main() { f(3); (*) }
}
```

AR for f:

result
argument
dynamic link
return address

Stack After Two Calls to *f*



Notes

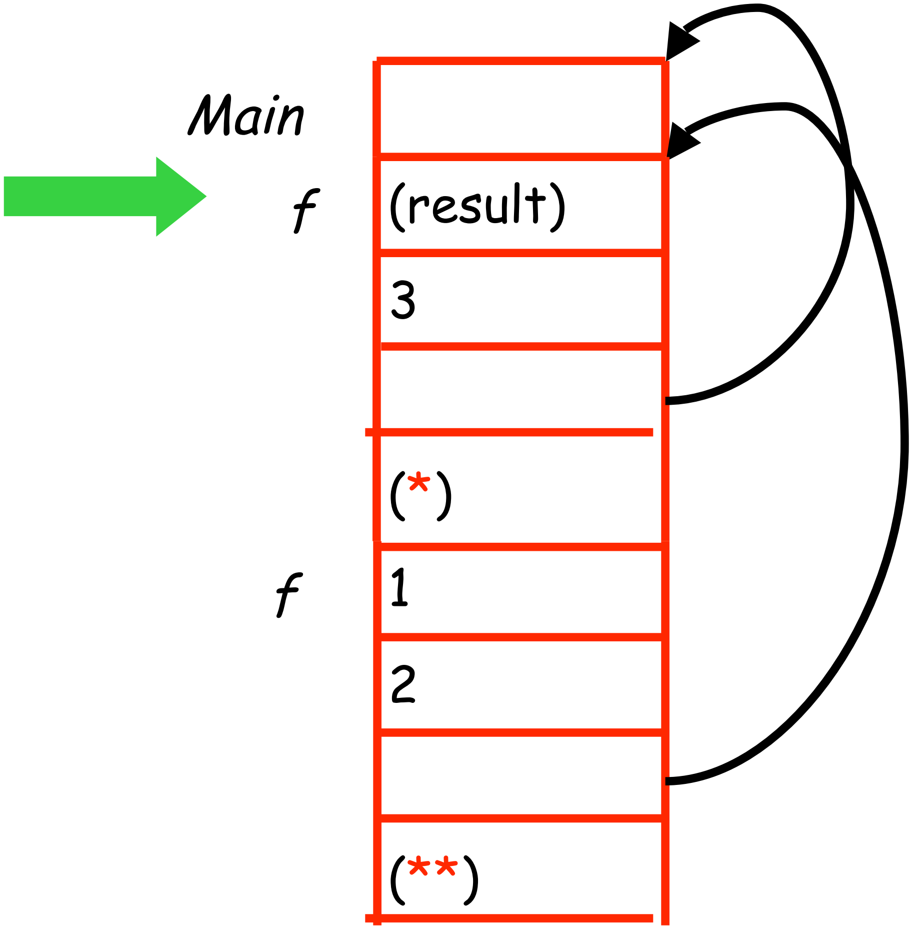
- Main has no argument or local variables and its result is never used; its AR is uninteresting
- (*) and (**) are return addresses of the invocations of f
  - The return address is where execution resumes after a procedure call finishes
- This is only one of many possible AR designs
  - Would also work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

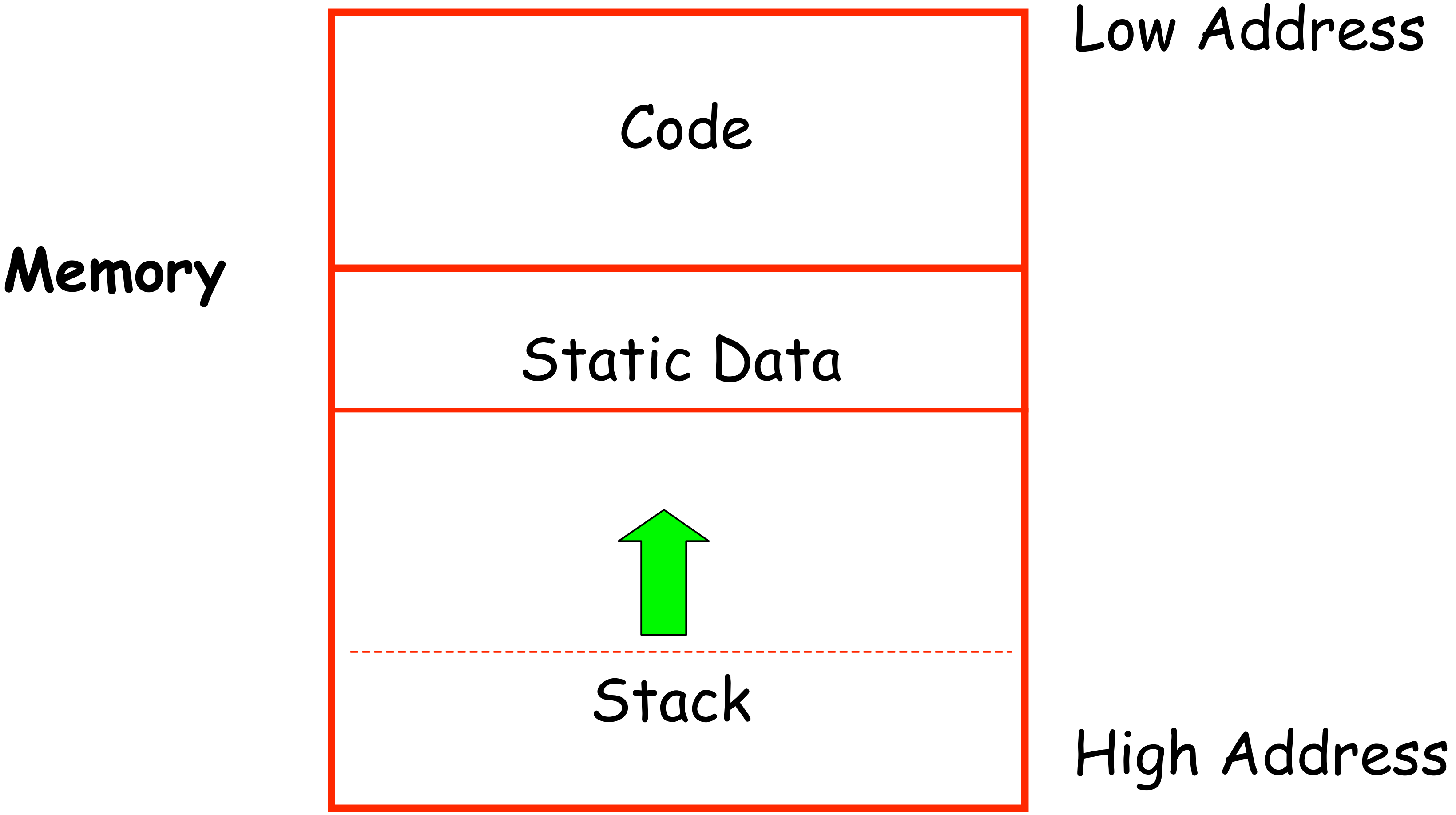
Discussion (Cont.)

- 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
  - Don't generally 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:

  ```
  Bar foo() { return new Bar }
  ```

  The Bar value must survive deallocation of foo's AR

- Language implementations with dynamically allocated data use a *heap* to store dynamic data
  - (confusingly, *not* the same as the heap used for priority queues!)

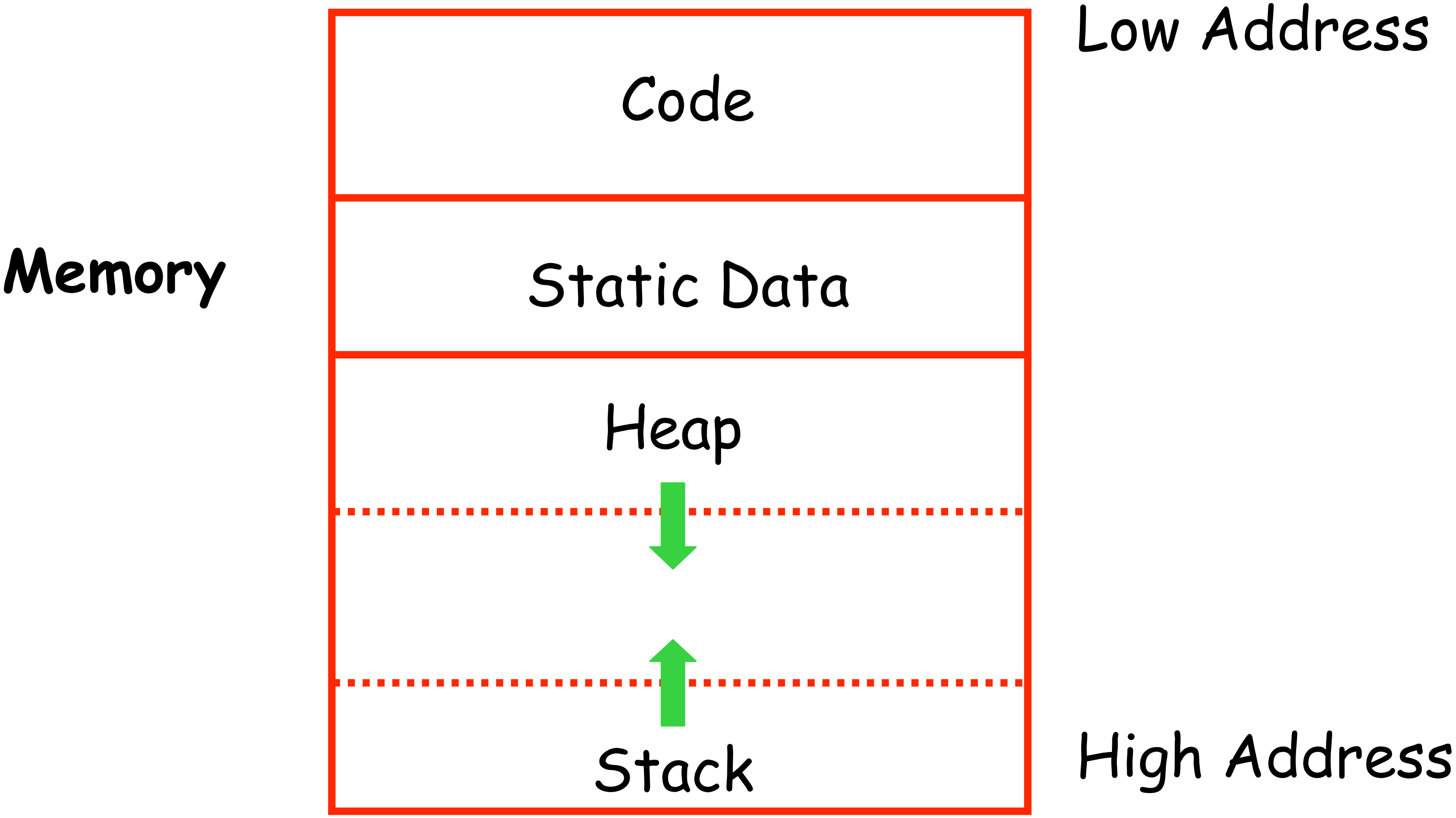
Notes

- 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*

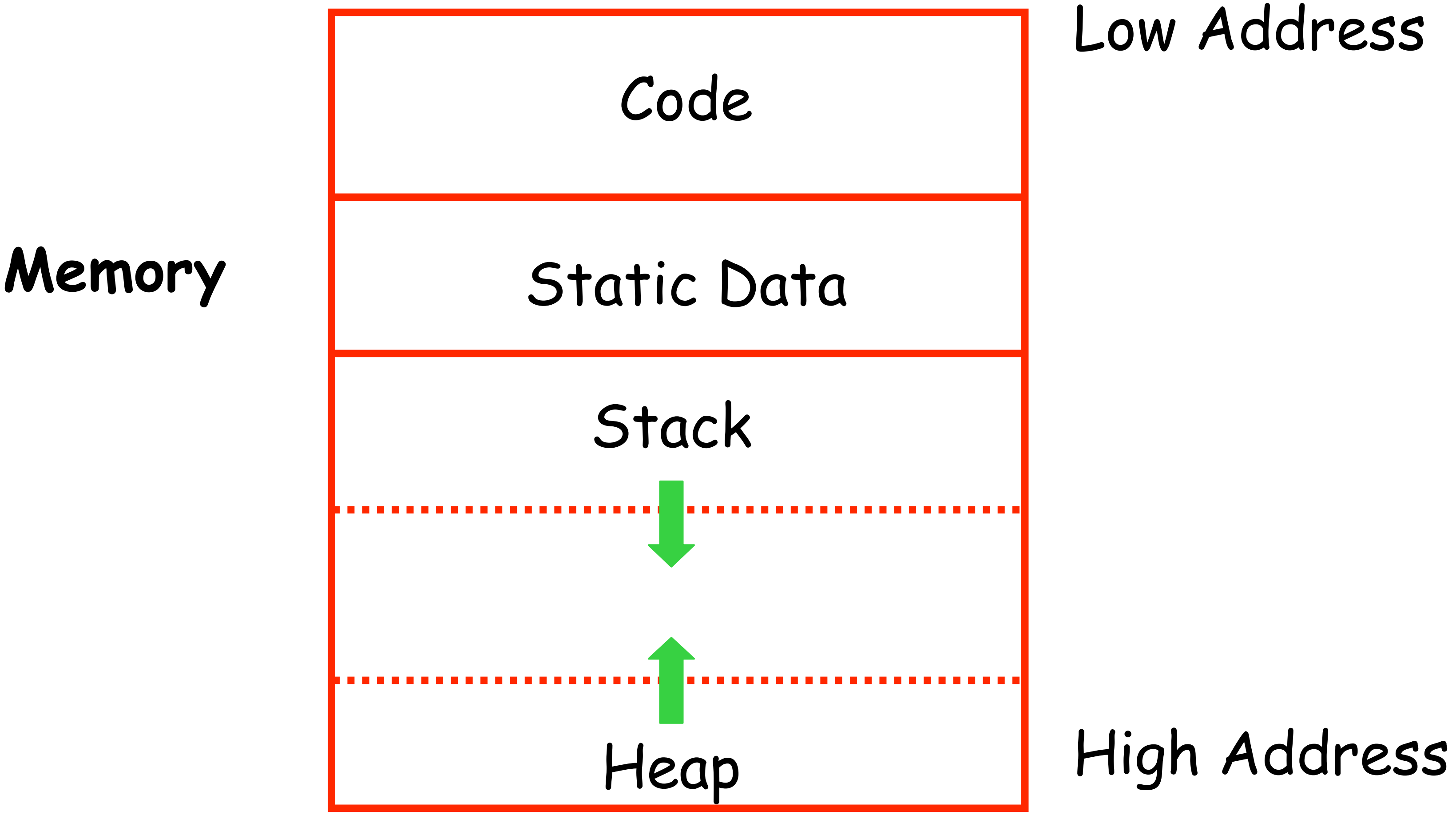
Notes (Cont.)

- 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 the grow towards each other

Memory Layout with Heap



Memory Layout with Heap (Alternative)



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

- Many installed machines are (still) 32 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
- New machines use 64-bit or 32/64-bit hardware and APIs.

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