Run-time Environments

Status

- We have so far covered the front-end phases
  - Lexical analysis
  - Parsing
  - Semantic analysis
- Next come the back-end phases
  - Code generation
  - Optimization
  - Register allocation
  - Instruction scheduling
- We will examine 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

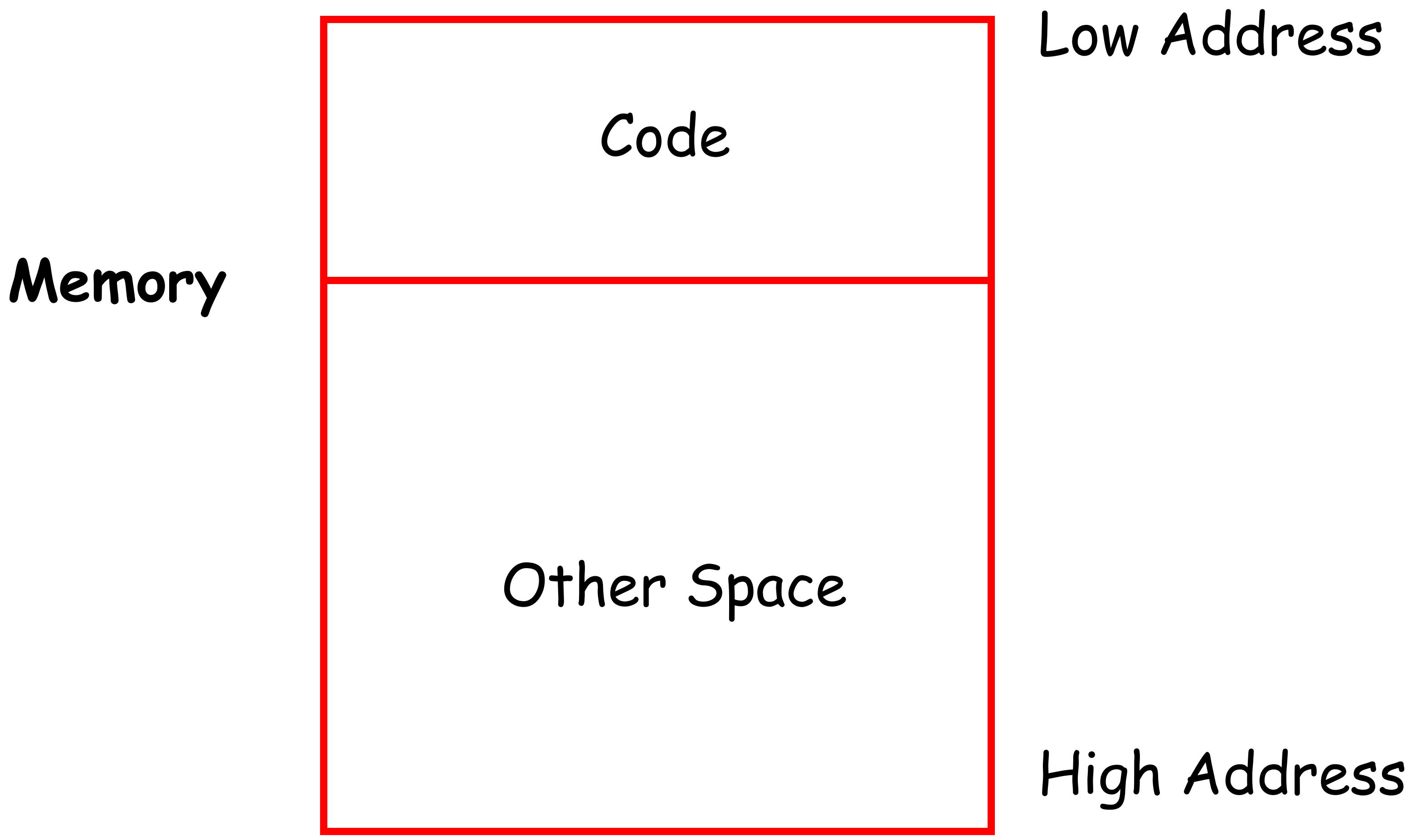
- Management of run-time resources
- Correspondence between static (compile-time) and dynamic (run-time) structures
- Storage organization

Run-time Resources

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

- When a program is invoked:
  - The OS allocates space for the program
  - The program code is loaded into part of this space
  - The OS jumps to the entry point of the program (i.e., to the beginning of the "**`main`**" function)

Memory Layout

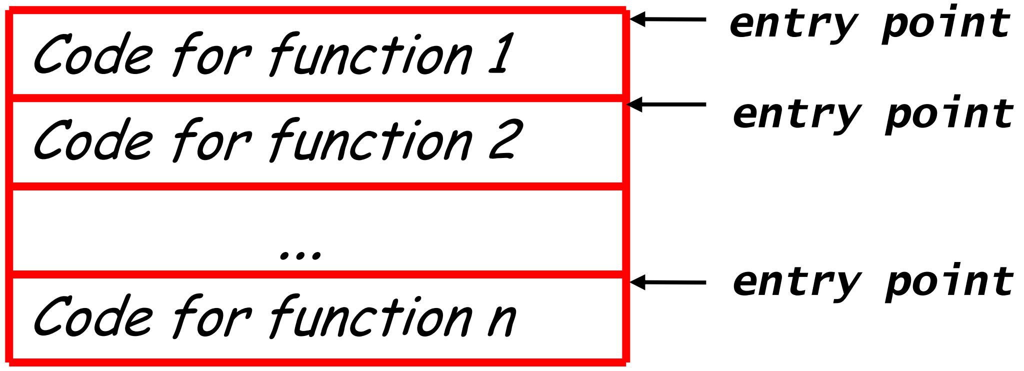


Notes

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

Organization of Code Space

- Usually, code is generated one function at a time. The code area thus is of the form:



- Careful layout of code within a function can improve i-cache utilization and give better performance
- Careful attention in the order in which functions are processed can also improve i-cache utilization

What is Other Space?

- Holds all data needed for the program's execution
- Other Space = Data Space

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

Code Generation Goals

- Two goals:
  - Correctness
  - Efficiency

- Most complications in code generation come from trying to be efficient as well as correct

Assumptions about Flow of Control

(1) Execution is sequential; at each step, control is at some specific program point and moves from one point to another in a well-defined order

(2) When a procedure is called, control eventually returns to the point immediately after the place where the call was made

Do these assumptions always hold?

Language Issues that affect the Compiler

- Can procedures be recursive?
- What happens to the values of the locals on return from a procedure?
- Can a procedure refer to non-local variables?
- How are parameters to a procedure passed?
- Can procedures be passed as parameters?
- Can procedures be returned as results?
- Can storage be allocated dynamically under program control?
- Must storage be deallocated explicitly?

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 that 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 (usually) a static concept

Activation Trees

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

Example 1

```
g(): int { return 42; }
f(): int { return g(); }
main() { g(); f(); }
```

$$\begin{tikzcd}
 & \text{main} \arrow[dl] \arrow[dr] & \\
g & & f \arrow[d] \\
 & & g
\end{tikzcd}$$

Example 2

```
g(): int { return 42; }
f(x:int): int {
   if x = 0 then return g();
   else return f(x - 1);
}
main() { 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 *(control) stack* can track currently active procedures

- push info about an activation at the procedure entry
- pop the info when the activation ends; i.e., at the return from the call

Example

```
g(): int { return 42; }
f(): int { return g(); }
main() { g(); f(); }
```

main

Stack

main

Example

```
g(): int { return 42; }
f(): int { return g(); }
main() { g(); f(); }
```

$$\begin{tikzcd} & \text{main} \arrow[dl] \\ g & \end{tikzcd}$$

Stack

main

g

Example

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Stack

main

f

Example

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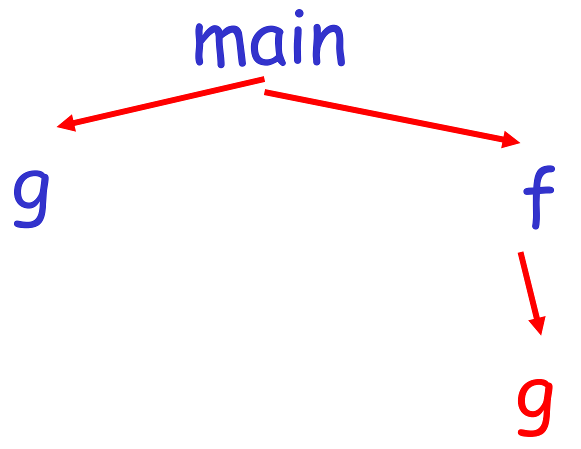


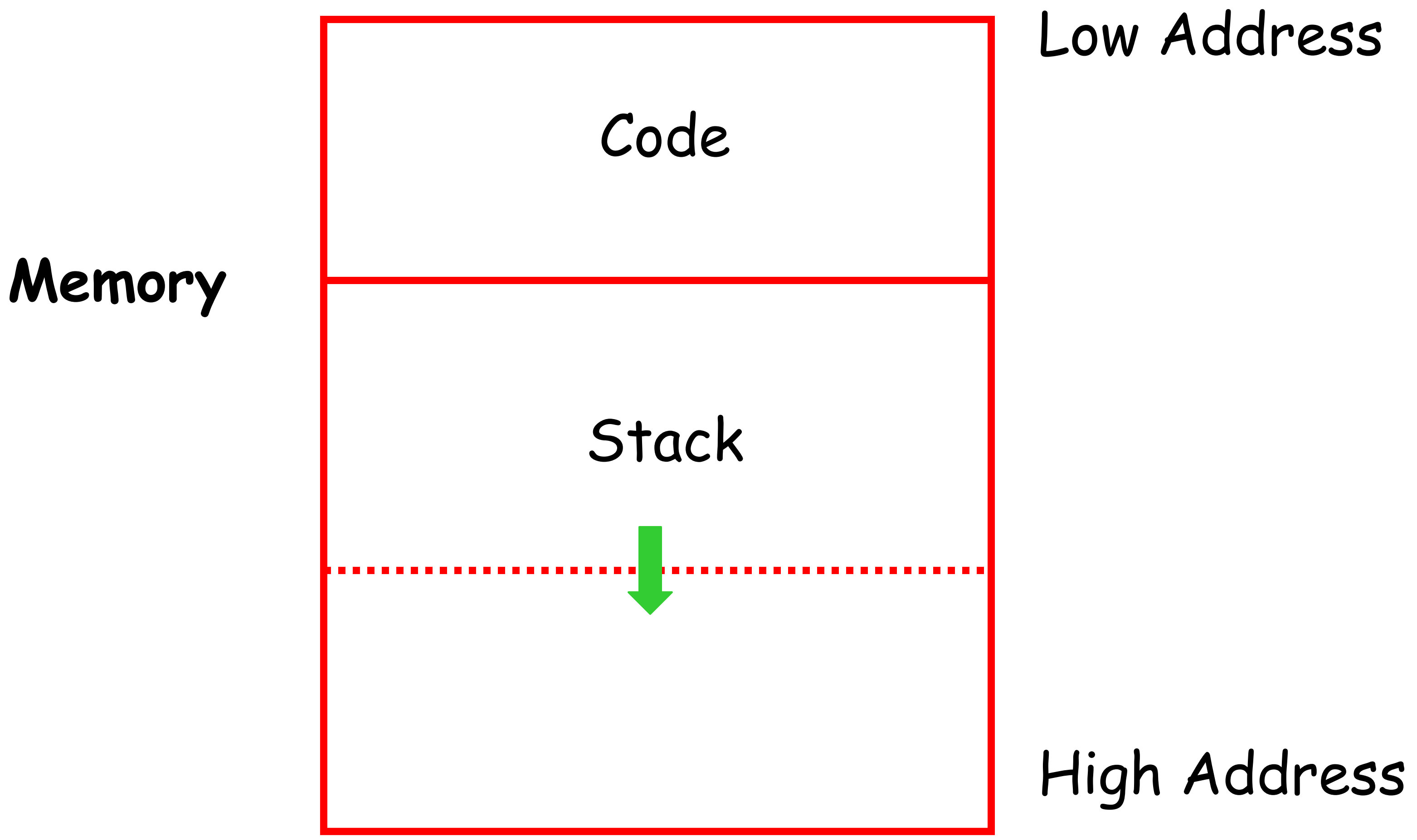
Stack

main

f

g

Revised Memory Layout



Activation Records

- The information needed to manage a single procedure activation is called an *activation record* (AR) or a *stack frame*
- If a 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
- (optional) Pointer to the previous activation record
  - The *control link;* points to the AR of caller of *G*
- (optional) *Access link* for access to non-local names
  - Points to the AR of the function that statically contains *G*
- Machine status prior to calling *G*
  - Return address, values of registers & program counter
  - Local variables
- Other temporary values used during evaluation

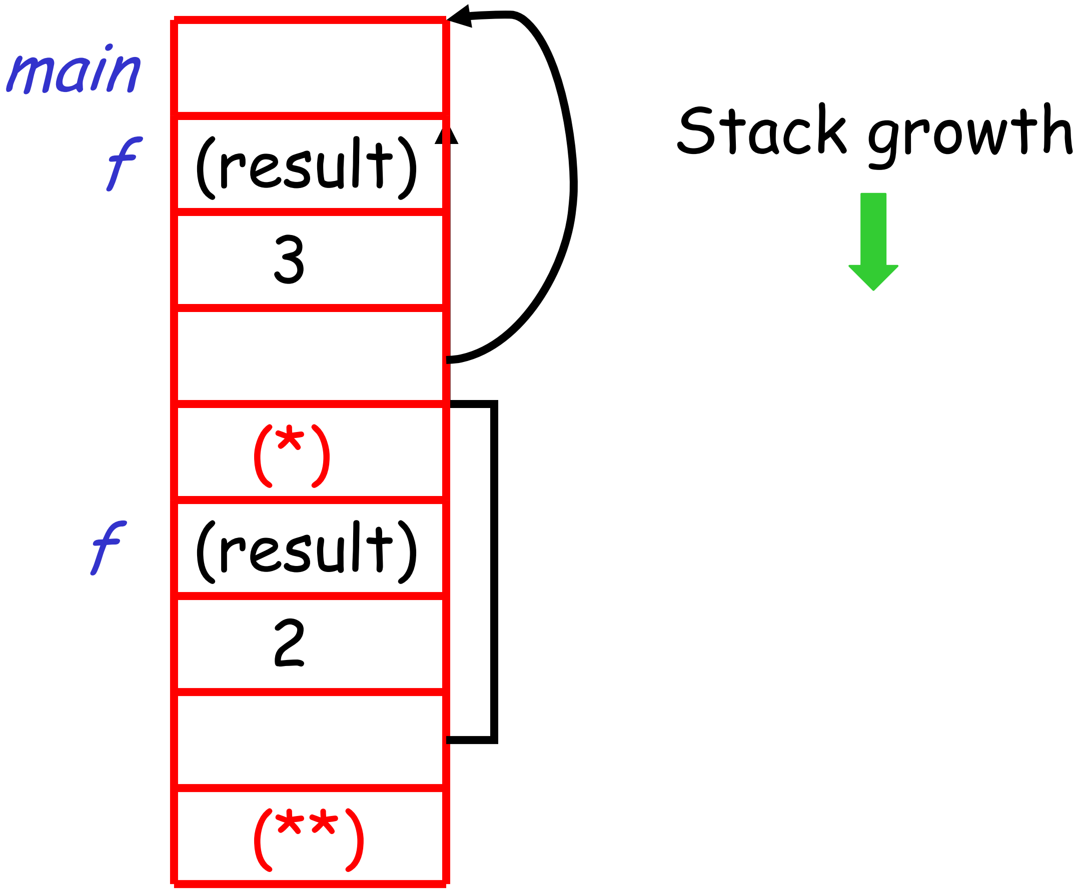
Example 2, Revisited

```
g(): int { return 42; }
f(x:int): int {
   if x = 0 then return g();
   else return f(x - 1);(**)
}
main() { 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 returns no result; its AR is uninteresting
- (*) and (**) are return addresses (continuation points) 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.

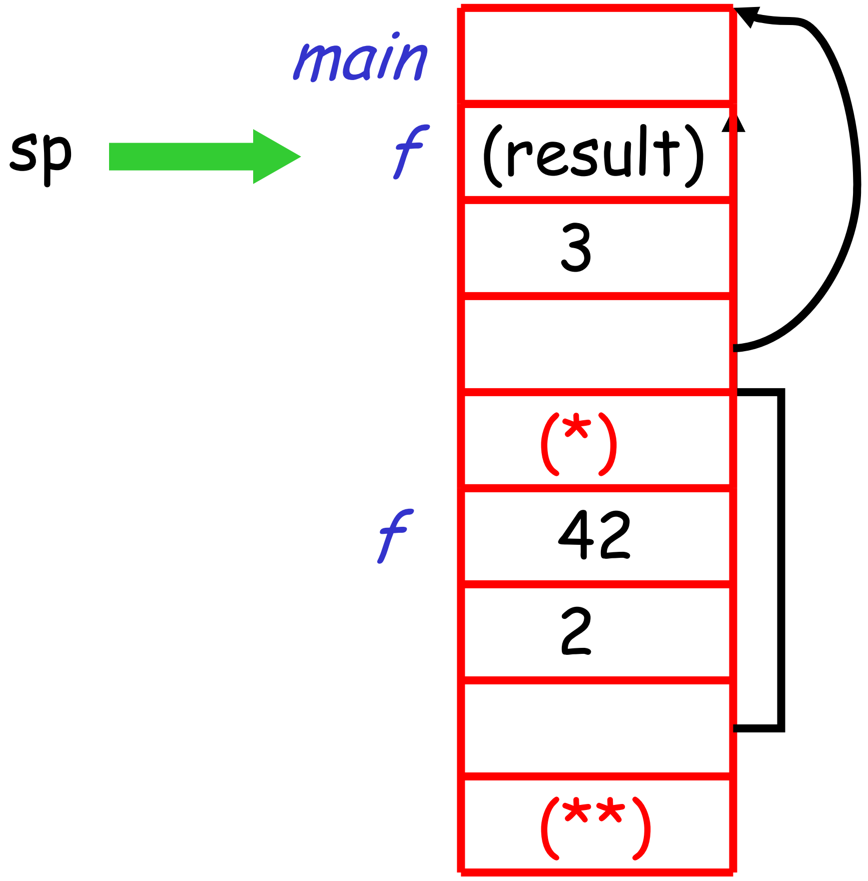
The Main Point

- The compiler must determine, at compile-time, the layout of activation records and generate code that correctly accesses locations in the activation record (as displacements from **sp**)

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

Example 2, continued

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 magical about this run-time 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 function result and (some of) the arguments

Storage Allocation Strategies for Activation Records (1)

Static Allocation (Fortran 77)

- Storage for all data objects is laid out at compile time
- Can be used only if size of data objects and constraints on their position in memory can be resolved at compile time $\Rightarrow$ no dynamic structures
- Recursive procedures are restricted, since all activations of a procedure must share the same locations for local names

Storage Allocation Strategies for Activation Records (2)

Stack Allocation (Pascal, C)

- Storage organized as a stack
- Activation record pushed when activation begins and popped when it ends
- Cannot be used if the values of local names must be retained when the evaluation ends or if the called invocation outlives the caller

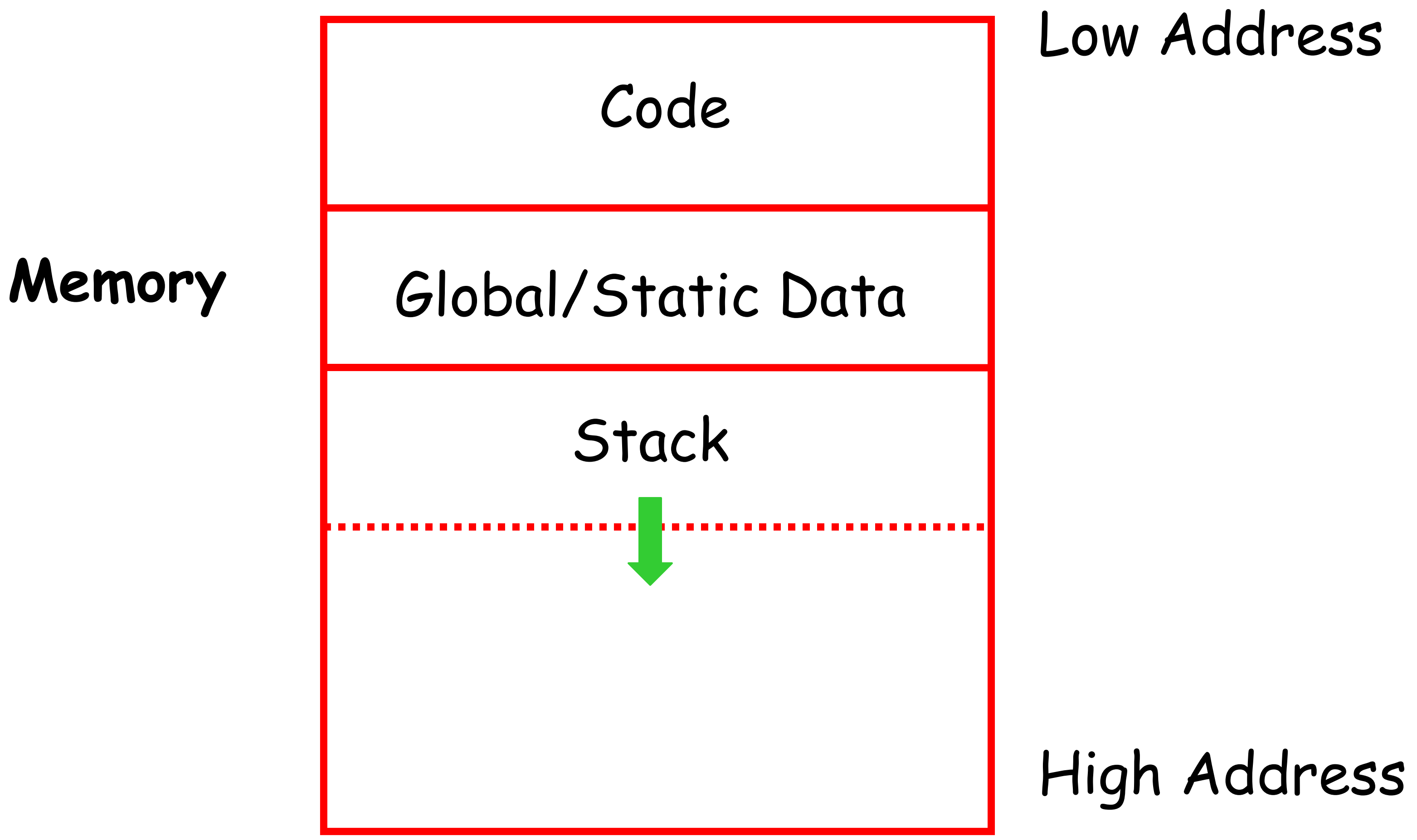
Heap Allocation (Lisp, ML)

- Activation records may be allocated and deallocated in any order
- Some form of garbage collection is needed to reclaim free space

Global Variables

- 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
  - e.g., static variables in C

Memory Layout with Static Data



Heap Storage

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

```
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

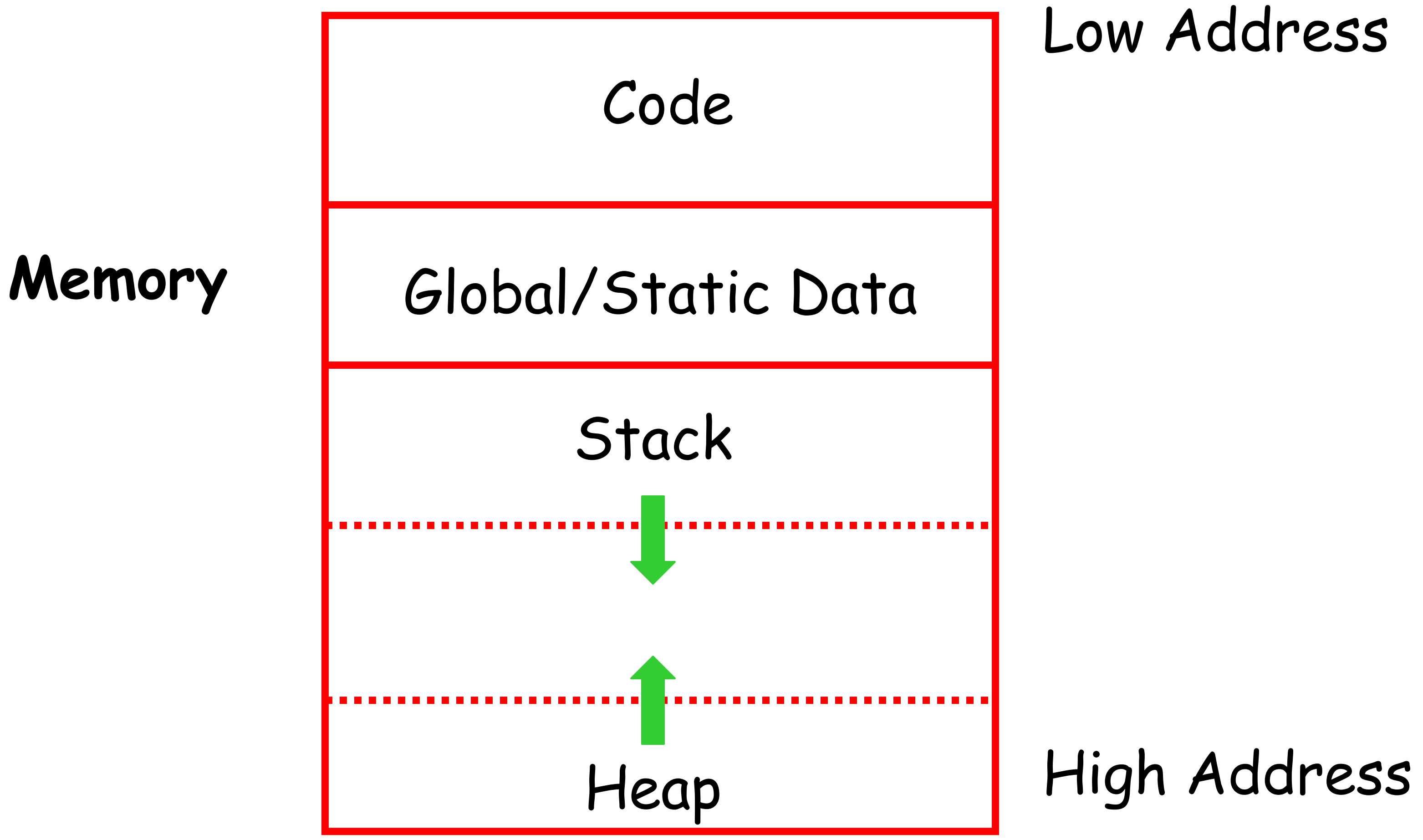
Review of Runtime Organization

- 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 has fixed size, contains locals
- The heap contains all other data
  - In C, heap is managed explicitly by **`malloc()`** and **`free()`**
  - In Java, heap is managed by **`new()`** and garbage collection
  - In ML, both allocation and deallocation in the heap is managed implicitly

Notes

- Both the heap and the stack grow
- Must take care so 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



Data Layout

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

- Chief among these concerns is *alignment* of data

Alignment

- Most modern machines are 32 or 64 bit
  - 8 bits in a byte
  - 4 or 8 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: An ASCII string:

`"Hello"`

Takes 5 characters (without the terminating \0)

- To word-align next datum on a 32-bit machine, add 3 “padding” characters to the string
- The padding is not part of the string, it’s just unused memory