Cool Type Checking
Cool Run-Time Organization

One-Slide Summary

- We will use **SELF_TYPE$_C$** for "C or any subtype of C". It shows off the subtlety of our type system and allows us to check methods that return self objects.
- The **lifetime** of an activation of (i.e., a call to) procedure P is all the steps to execute P plus all the steps in procedures that P calls.
- Lifetime is a run-time (dynamic) notion; we can model it with trees or **stacks**.

Lecture Outline

- SELF_TYPE
- Object Lifetime
- Activation Records
- Stack Frames

SELF_TYPE Dynamic Dispatch

- If the return type of the method is SELF_TYPE then the type of the dispatch is the type of the dispatch expression:

$$O,M,C \vdash e_0 : T_0 \quad \text{A}$$

$$\ldots$$

$$O,M,C \vdash e_n : T_n \quad \text{B}$$

$$M(T_0, f) = (T_1',\ldots,T_n', \text{SELF\_TYPE}) \quad \text{C}$$

$$T_i \leq T_i' \qquad 1 \leq i \leq n \quad \text{D}$$

$$\overline{O,M,C \vdash e_0.f(e_1,\ldots,e_n) : T_0}$$

Where is SELF_TYPE Illegal in COOL?

m(x : T) : T' { … }

- Only T' can be SELF_TYPE! *Not T.*

What could go wrong if T were SELF_TYPE?

```
class A {  comp(x : SELF_TYPE) : Bool  {…};  };
class B inherits A {
    b() : int { … };
    comp(y : SELF_TYPE) : Bool { … y.b() …};  };
…
  let x : A ← new B in  … x.comp(new A); …
…
```

Summary of SELF_TYPE

- The extended $\leq$ and lub operations do a lot of the work. Implement them to handle SELF_TYPE
- SELF_TYPE can be used only in a few places. Be sure it isn't used anywhere else.
- A use of SELF_TYPE always refers to any subtype in the current class
  - The exception is the type checking of dispatch, where SELF_TYPE *as the return type* of an invoked method might have nothing to do with the current enclosing class

Why Cover SELF_TYPE ?

- SELF_TYPE is a research idea
  - It adds more expressiveness to the type system
- SELF_TYPE is itself not so important
  - except for the project
- Rather, SELF_TYPE is meant to illustrate that type checking can be quite subtle
- In practice, there should be a balance between the complexity of the type system and its expressiveness

Type Systems

- The rules in these lecture were Cool-specific
  - Other languages have very different rules
  - We'll survey a few more type systems later
- General themes
  - Type rules are defined on the **structure of expressions**
  - Types of variables are **modeled by an environment**
- Type systems tradeoff flexibility and safety

Course Goals

- At the end of this course, you will be acquainted with the fundamental concepts in the **design** and **implementation** of high-level programming **languages**. In particular, you will understand the **theory** and **practice** of **lexing**, **parsing**, **semantic** analysis, and **code** interpretation. You will also have gained practical experience programming in multiple **different** languages.

Status

- We have covered the front-end phases
  - Lexical analysis
  - Parsing
  - Semantic analysis
- Next are the back-end phases
  - Optimization (optional)
  - Code execution (or code generation)

- We'll do **code execution** first . . .

Run-time environments

- Before discussing code execution, we need to understand what we are trying to execute
- There are a number of standard techniques that are widely used for structuring executable code
- Standard Way:
  - Code
  - Stack
  - Heap

Run-Time Organization Outline

- Management of run-time resources
- Correspondence between static (compile-time) and dynamic (run-time) structures
  - "Compile-time" == "Interpret-time"
- 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")
- How does "space" work?

Space

Space is big. Really big. You just won't believe how vastly, hugely, mind-bogglingly big it is. I mean, you may think it's a long way down the road to the chemist's, but that's just peanuts to space. -- Douglas Adams

Space is as infinite as we can imagine, and expanding this perspective is what adjusts humankind's focus on conquering our true enemies, the formidable foes: ignorance and limitation. -- Vanna Bonta

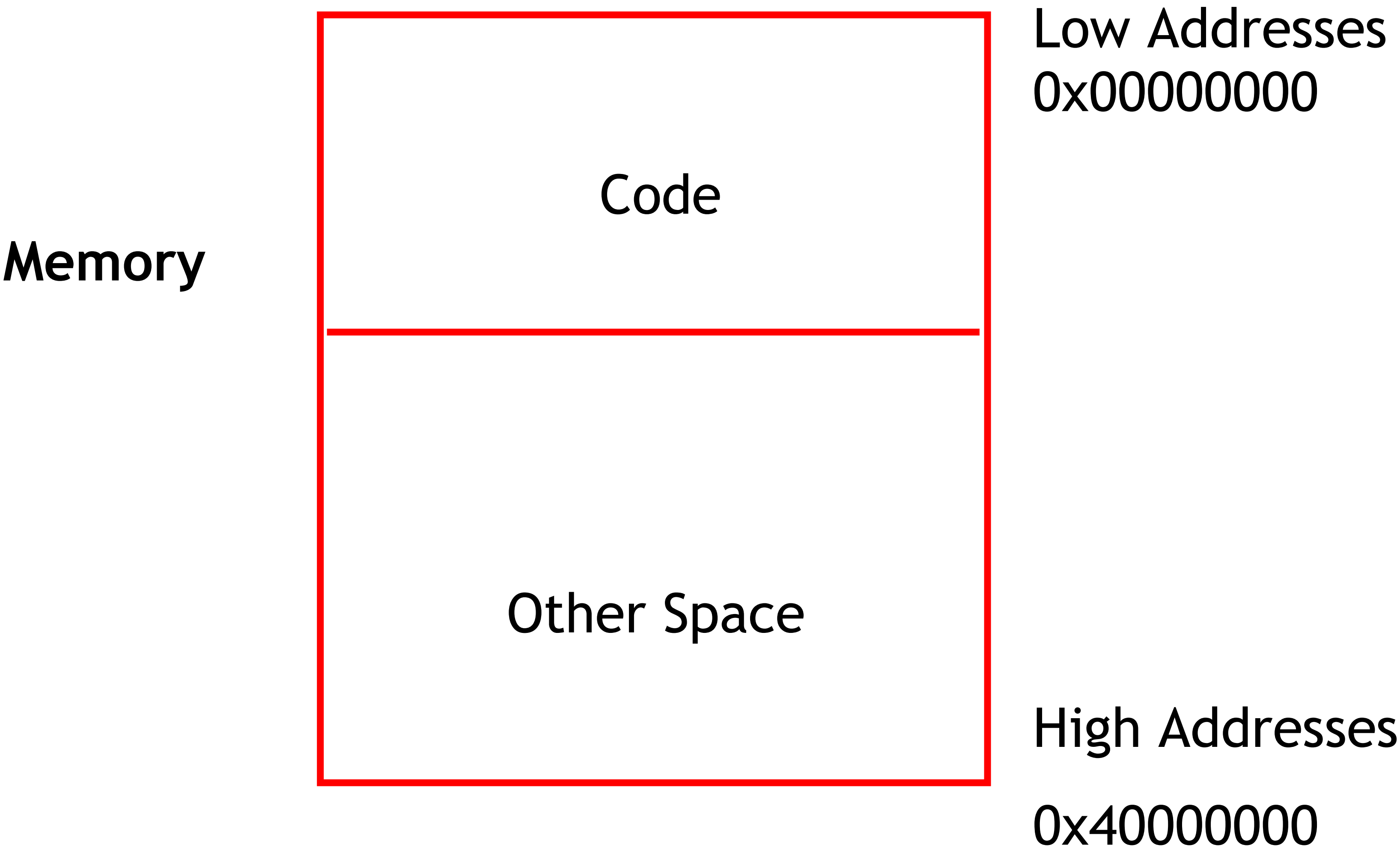
(Digression) Virtual Memory

- An **address space** is a partial mapping from addresses to values. Like a big array: the value at memory address 0x12340000 might be 87. *Partial* means some addresses may be invalid.
- There is an address space associated with the **physical memory** in your computer. If you have 1GB of RAM, addresses 0 to 0x40000000 are valid.
- If I want to store some information on MachineX and you want to store some information on MachineX, we would have to collude to use *different* physical addresses (= different parts of the address space).

(Digression) Virtual Memory 2

- **Virtual memory** is an abstraction in which each process gets its own *virtual address space*. The OS and hardware work together to provide this abstraction. All modern general computers use it.
- Each virtual address space is then mapped separately into a different part of physical memory. *(simplification)*
- So Process1 can store information at its virtual address 0x4444 and Process2 can *also* store information at its virtual address 0x4444 and there will be *no overlap* in physical memory.
  - e.g., P1 0x4444 virtual -> 0x1000 physical
  - and P2 0x4444 virtual -> 0x8000 physical

Program Memory Layout

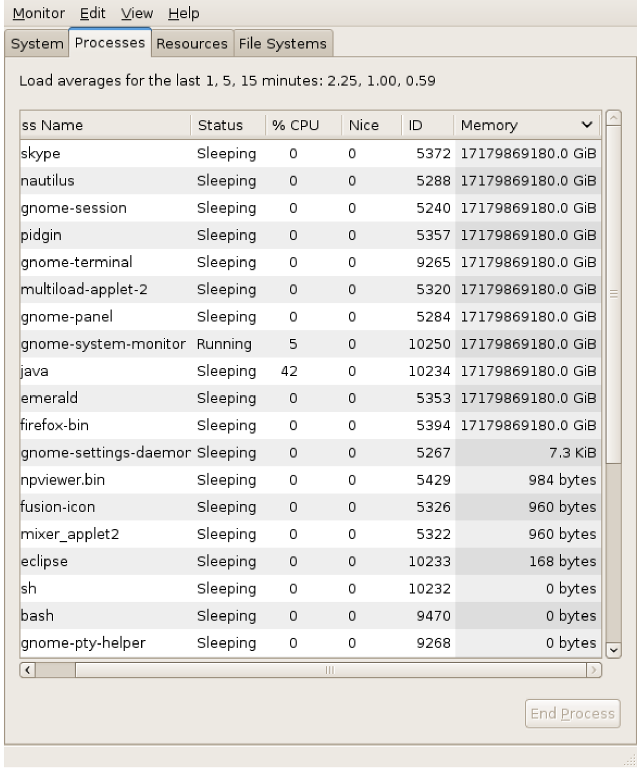


Notes

- Our 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
- In some textbooks lower addresses are at bottom (doesn't matter)

What is Other Space?

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



- A **compiler** is responsible for:
  - Generating code (that is run later)
  - Orchestrating use of the data area
- An **interpreter** is responsible for:
  - Executing the code directly (now)
  - Orchestrating use of the (run-time) data

Code Execution Goals

- Two goals:
  - Correctness
  - Speed
- Most complications at this stage come from trying to be fast as well as correct

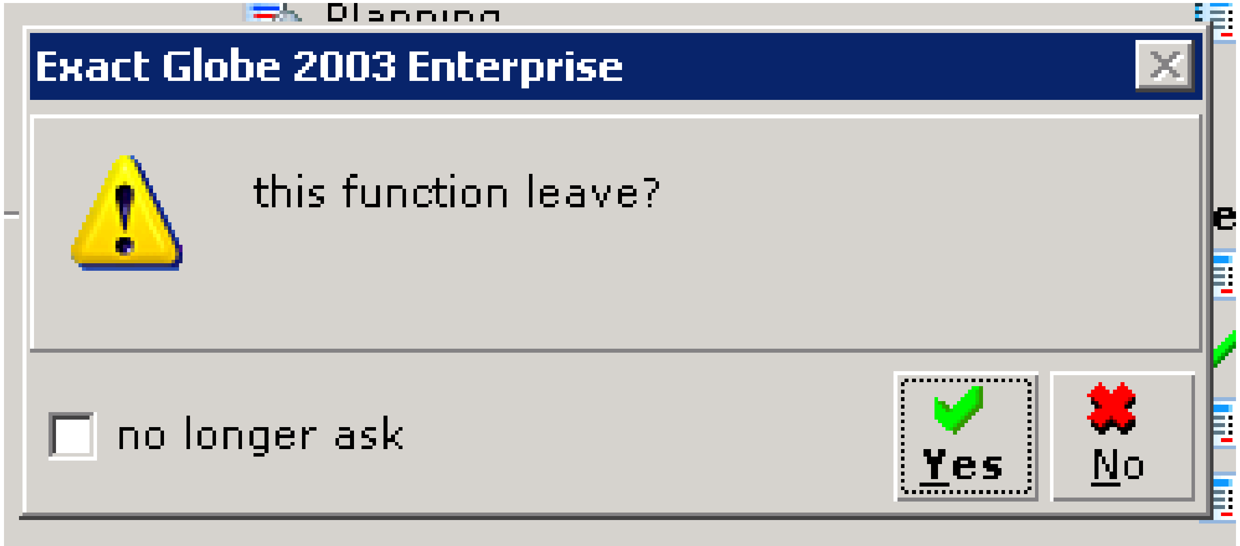
Assumptions about Execution

- (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?

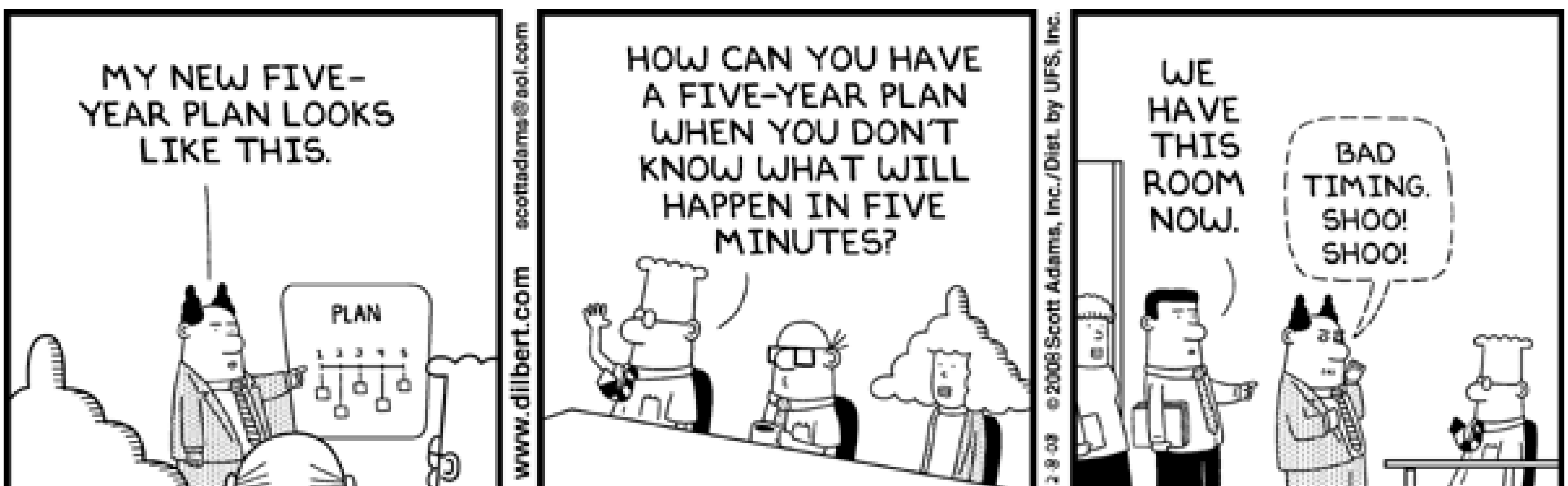
Activations

- 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 that P calls



Lifetimes of Variables

- The **lifetime** of a variable x is the portion of execution during which x is defined
- Note that
  - Scope is a static concept
  - Lifetime is a dynamic (run-time) concept



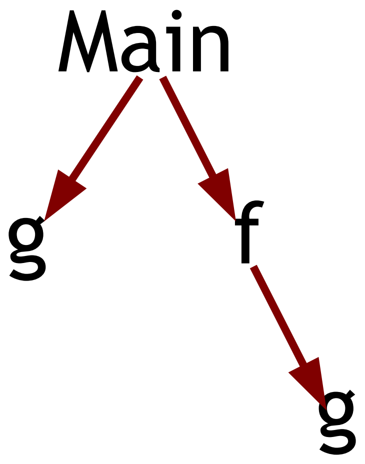
Activation Trees

- 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
  - This is the **call stack**

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() };
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```
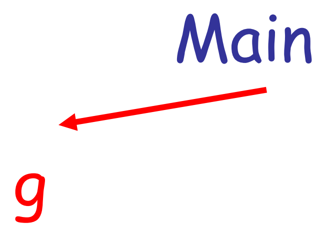



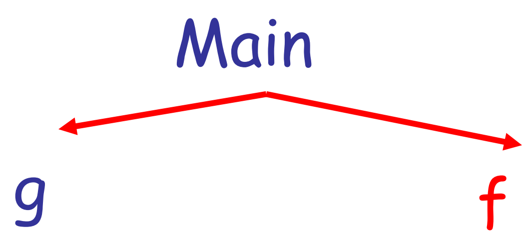
Stack

Main

g

Example

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



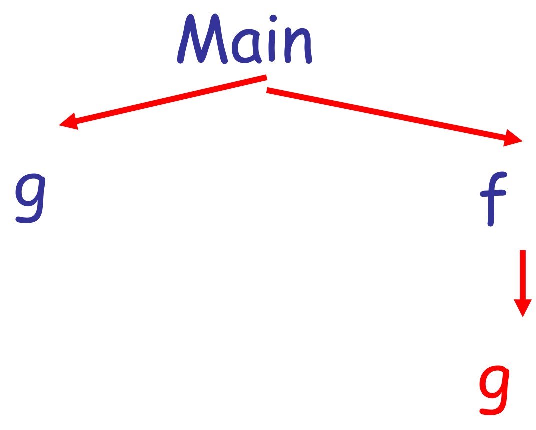
Stack

Main

f

Example

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



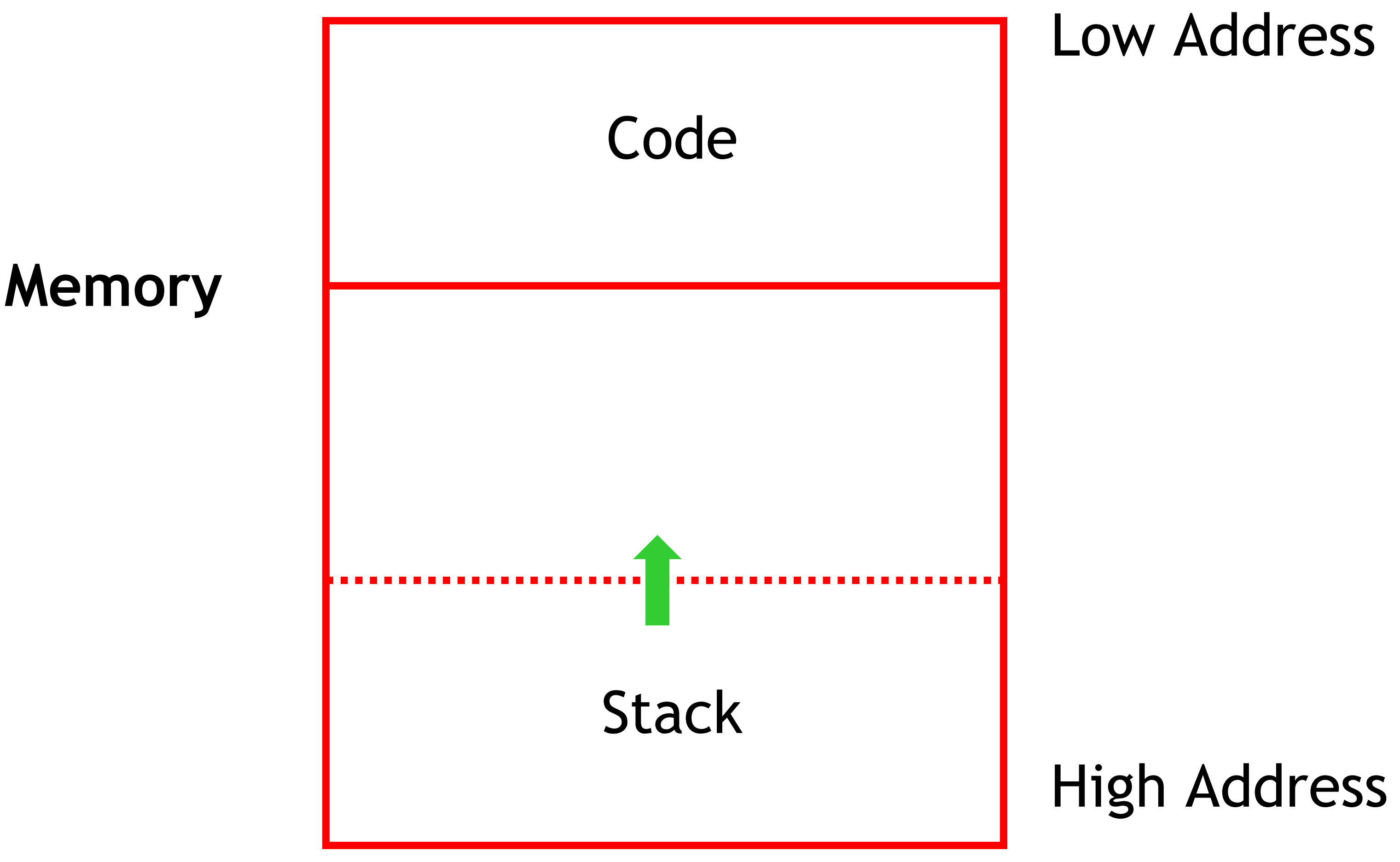
Stack

Main

f

g

Revised Memory Layout



Q: TV (110 / 842)

- Name the series and either of the characters involved in the first interracial kiss on US television. The kiss took place in the 1968 episode "Plato's Stepchildren".

Trivia: Harry Potter

(kwh5ye memorial)

- In *HP and the Philosopher's Stone*, where is the Philosopher's Stone magically stored before it passes to Harry?
- In *A Very P Musical*, complete Harry's first draft lyrics: "I'm the Mickey to your Minnie / You're the Tigger to my Winnie / ..."
- In *HP and the Methods of Rationality*, what is the form of Harry's Patronus?

Trivia: Yu-Gi-Oh

(ho2es memorial)

- In Yu-Gi-Oh, Yugi Moto is aided by the spirit of an ancient *what* as he plays Shadow Games and seeks Millenium Items? In the story, who invented the Duel Monsters card game?
- YTAS Bonus: Pithily explain Seto Kaiba's perspective on how wealth frees one from traditional strictures.

Real-World Languages

- This Asian language features a relatively small vocabulary of sounds, a focus on the relative status of the speaker and listener in the conversation, three written scripts, and S-O-V ordering. Ex: 日本に行きたい。

Real-World Languages

- This Southern Athabaskan language is the most commonly-spoken Native American language north of Mexico. It has four basic vowels, two tones, inflected verbs, and was used as encryption to relay tactical secret messages in World War II.

Activation Records

- On many machines the stack starts at high-addresses and grows towards lower addresses
- 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:
  - Actual parameters to G (supplied by F)
  - G's return value (needed 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 F (caller of G)
  - (possibly also called the **frame pointer**)
- Machine status prior to calling G
  - Local variables
  - (Compiler: register & program counter contents)
- Other temporary values

Example 2, Revisited

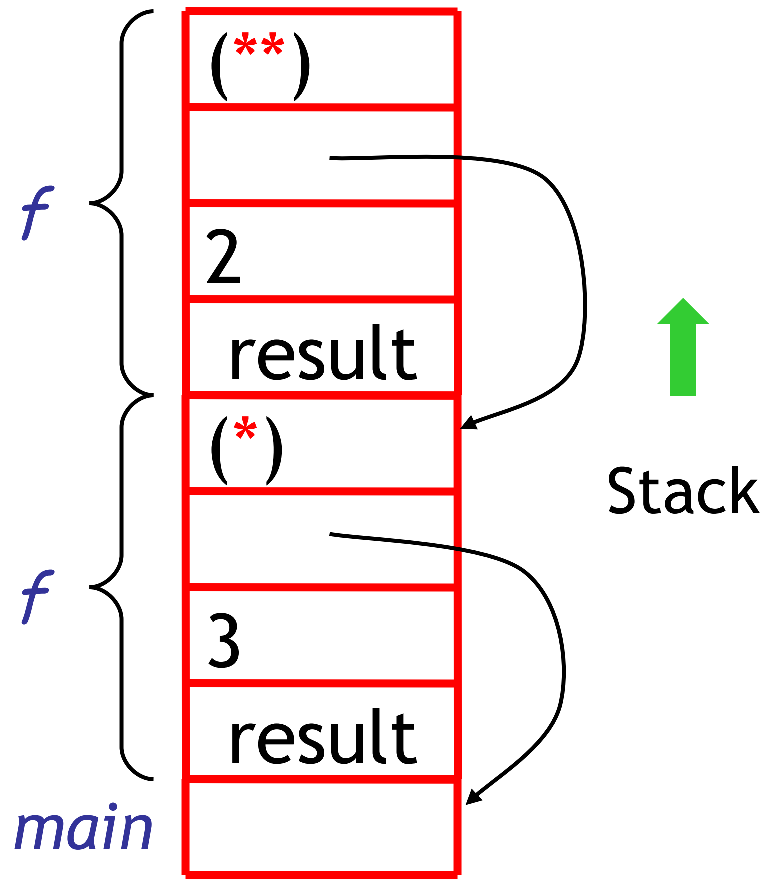
```
Class Main {
  g() : Int { 1 };
  f(x:Int):Int {
      if x=0 then g() else f(x - 1) (**) fi
  };
  main(): Int {{f(3); (*) }};}
```

AR for f:

return address
control link
argument
space for result

Stack After Two Calls to f

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



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, when executed at run-time, correctly accesses locations in those activation records.

Thus, the AR layout and the compiler must be designed together!

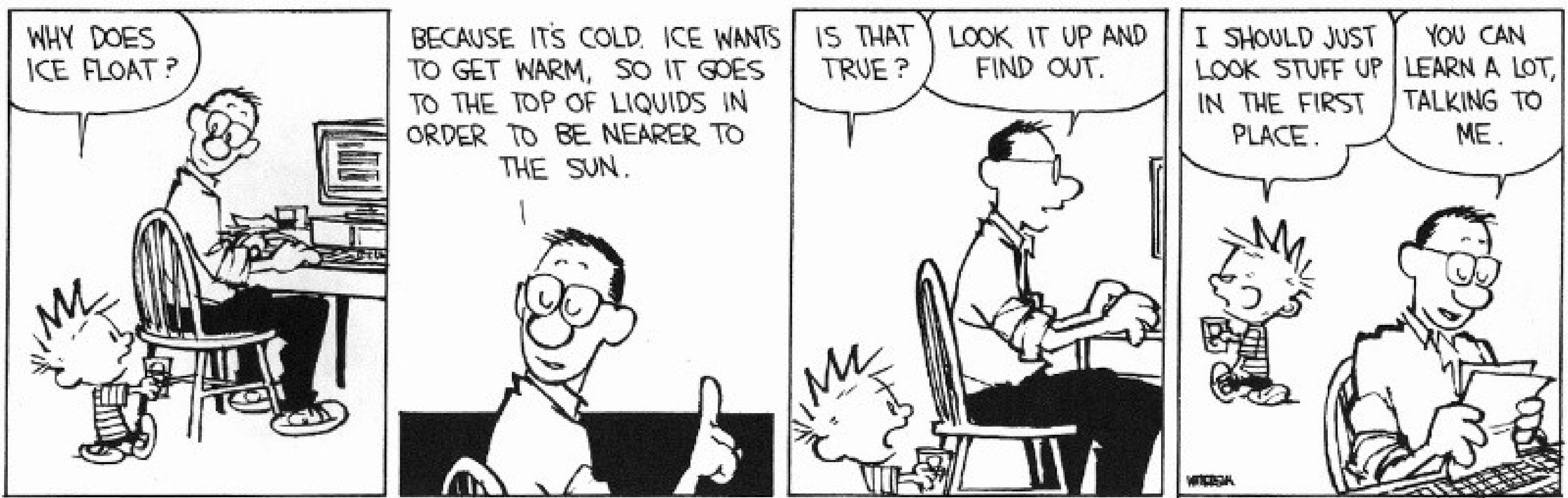
Discussion

- 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
  – The caller must write the return address there

- 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
    - Ask me about what embedded devices do.

Discussion (Cont.)

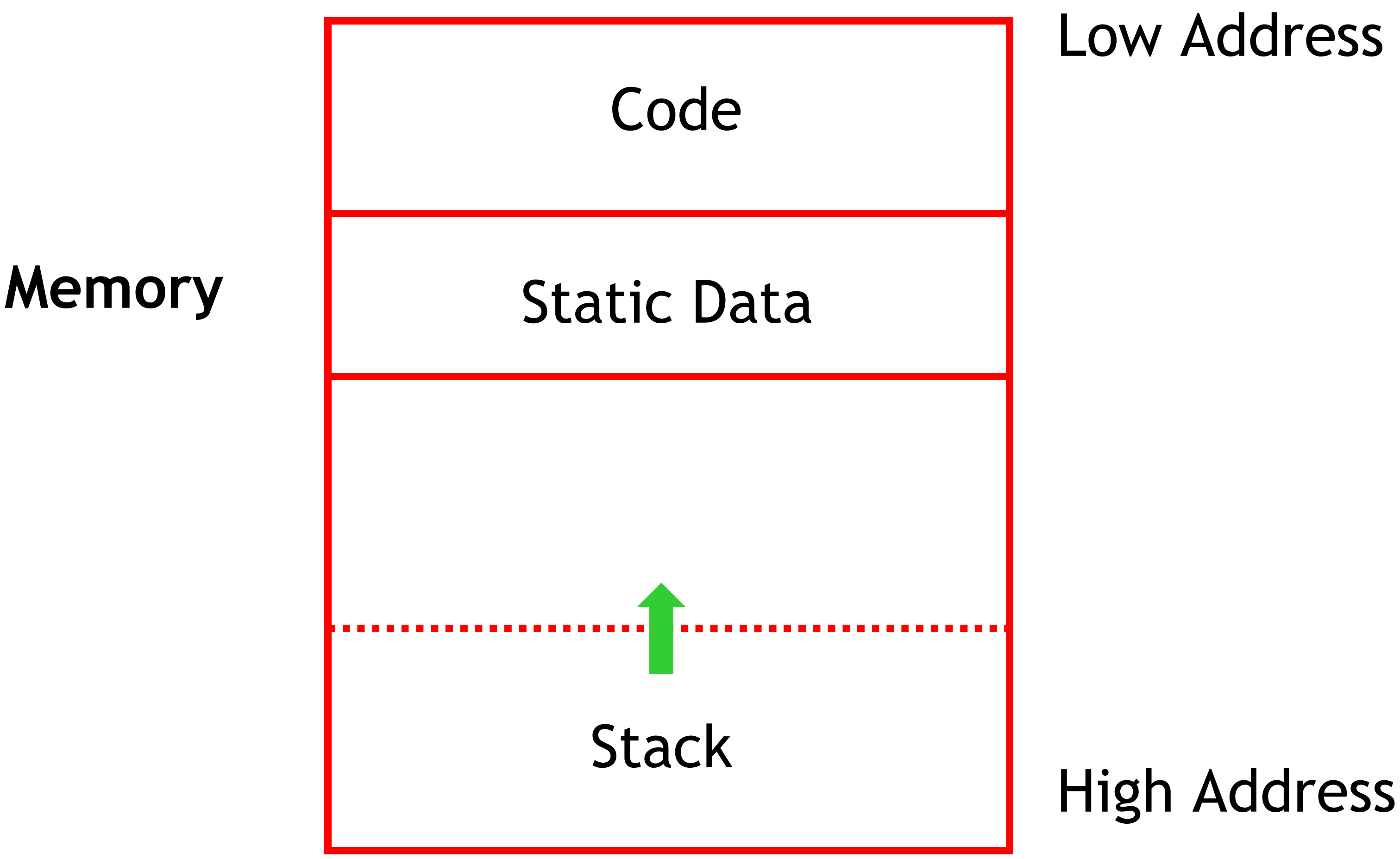
- Real compilers hold as much of the frame as possible in registers
  - Especially the method result and arguments
- Why?



Globals

- All references to a global variable point to the same object
  - Can't store a global in an activation record
    - Is this true?
- 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

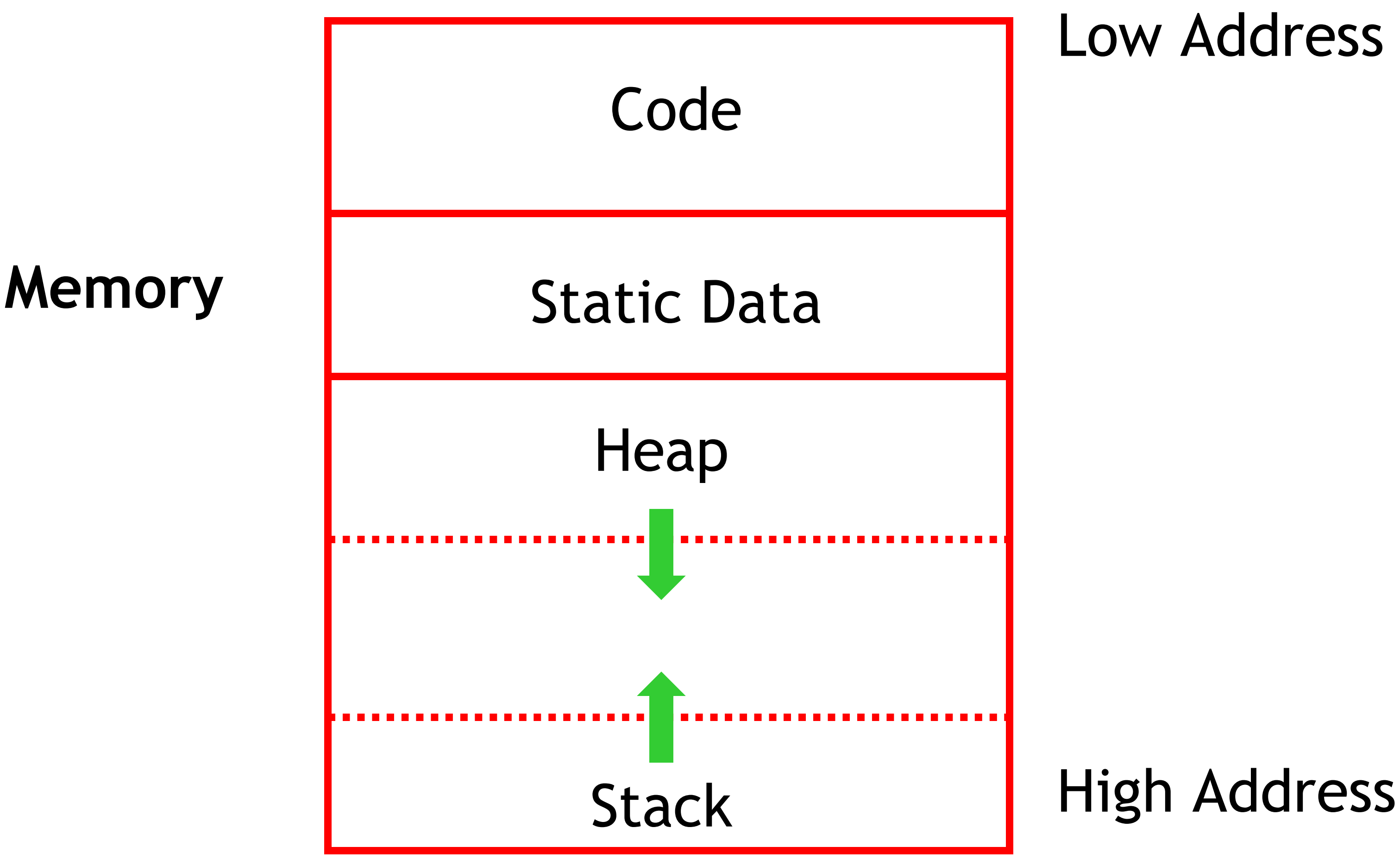
Notes

- 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
- Compilers 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



Your Own Heap

- CA4 must emit assembly code for things like:

```
let x = new Counter(5) in
let y = x in {
   x.increment(1);
   print( y.getCount() ); // what does this print?
}
```

- You'll need to use and manage explicit heap (as described today and also next week). A heap maps addresses (integers) to values.

Homework

- RS4 recommended today
- PA4 due Tue March 22