Cool Typechecking and Runtime Organization

Martin Kellogg

Agenda

- Finish discussion of SELF_TYPE
- Object Lifetimes
- Activation Records
- Stack Frames

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Recall: Why Do We Want SELF_TYPE?

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class Count {
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  inc() : Count {
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  name() : String { … };
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without SELF_TYPE, the type rules will cause a typechecking error here, because inc() returns a Count (not a Stock)

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  - therefore the return value will be the same type as “self”
  - which could be **Count** *or any subtype* of **Count**
  - In the case of `(new Stock).inc()`, the type is **Stock**
- We introduce the keyword **SELF_TYPE** to use for the return value of such functions
  - We will need to modify the type rules to handle SELF_TYPE

Recall: Typechecking SELF_TYPE (properly)

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  - subtyping: $T_1 \leq T_2$
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- To handle **SELF_TYPE** properly, we need to extend these operations to handle it
    - need to consider all four combinations of **SELF_TYPE** and "normal" types (cf. Punnett squares)
    - see last lecture's slides for the details on how we did this

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- Read as "An expression **e** occurring in the body of C has static type **T** given a variable type environment Γ and method signatures $\mathbf{M}$"

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- E.g.,:

$$\frac{\Gamma, \mathrm{M}, \mathrm{C} \vdash e_1 : T_1 \quad \Gamma(id) = T_0 \quad T_1 \leq T_0}{\Gamma, \mathrm{M}, \mathrm{C} \vdash id \texttt{ <- } e_1 : T_1} \text{ [Assign]}$$

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- The type T_0 of the dispatch expression *could* be SELF_TYPE

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- The static dispatch class cannot be SELF_TYPE

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- There are a number of other places in the rules where SELF_TYPE appears - read the CRM carefully

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```
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); ...
...
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  - SELF_TYPE as the return type in an invoked method might have ***nothing to do*** with the current class

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  - but at the cost of **additional complexity**
- SELF_TYPE itself isn't that important
  - although you have to get it right for PA2…
- But it is **illustrative** of a class of ideas that trade-off expressiveness for complexity
  - and gives you a taste of how this works in practice!

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  - Wednesday: formal description of how a program actually runs (***operational semantics***)
- Goal of all of this: make sure you have the **foundation** for PA3
  - (also, operational semantics + type rules are closely related)

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- Standard Way:
    - Code
    - Stack
    - Heap

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- How does “space” work?

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- 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.

Space: Virtual Memory (OS/Arch review?)

- 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 other information on MachineX, we would have to collude to use different physical addresses (= different parts of the address space).

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- ***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.

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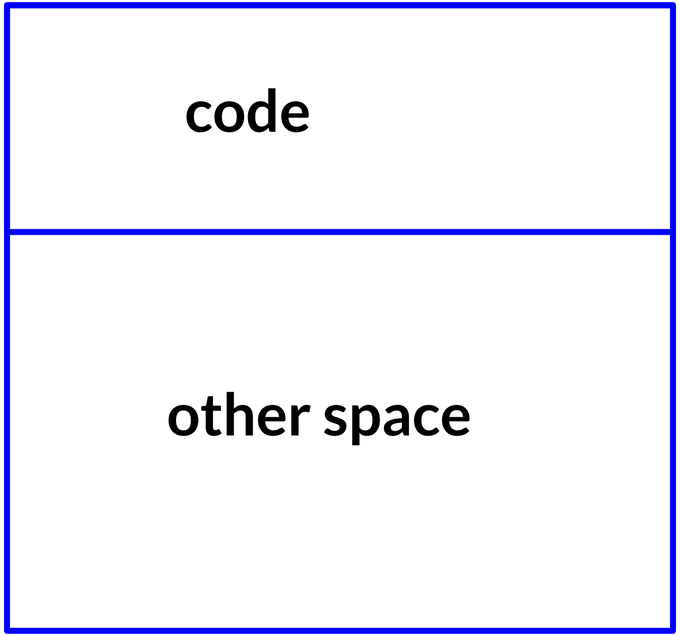
  - e.g., **P1 0x4444** virtual -> 0x1000 physical
  - and **P2 0x4444** virtual -> 0x8000 physical

Program Memory Layout

a program's virtual memory:



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Notes on How I’ve Presented This

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  - manage the program’s run-time data itself
- Of these two, the compiler’s task is **much harder**: the compiler must **predict** the program’s behavior to do it right!

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- We have two goals when generating code to execute:
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- Which of these **matters more**?
  - **Correctness**! First rule of compilers…
- Most complications in run-time organization, though, come from trying to be both fast *and* correct

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- Note the relation with **scope**: scope is static, lifetimes are dynamic

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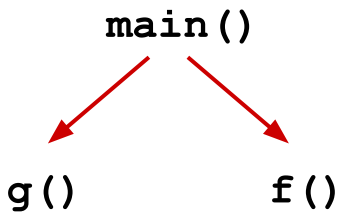

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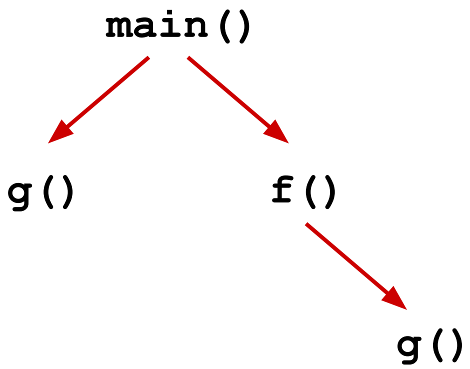

Activation Trees: Another Example

- What's the activation tree for this example?

```
class Main {
  g() : Int { 1 };
  f(x : Int) : Int {
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  main() : Int {{ f(3); }};
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```

(on the whiteboard)

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  - This is the ***call stack***

Activation Tree Example Revisited

- Let’s track activations with a stack on the example from before:

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Revised Memory Layout

a program's virtual memory:

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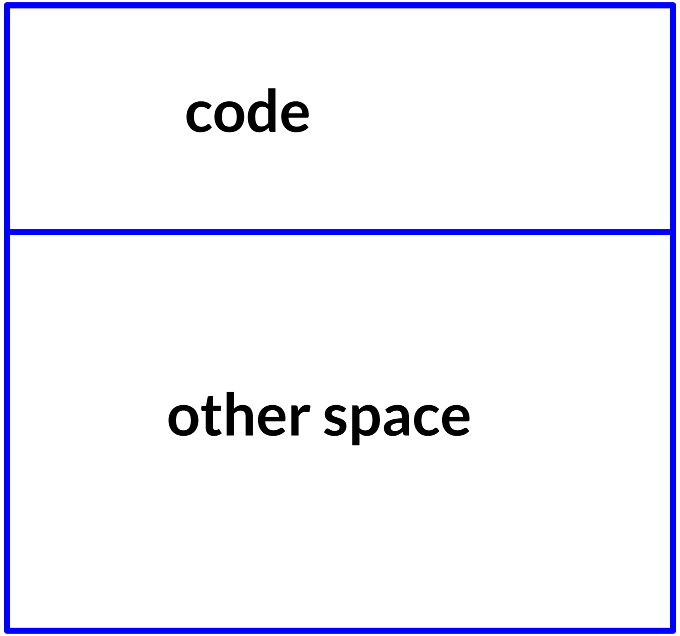

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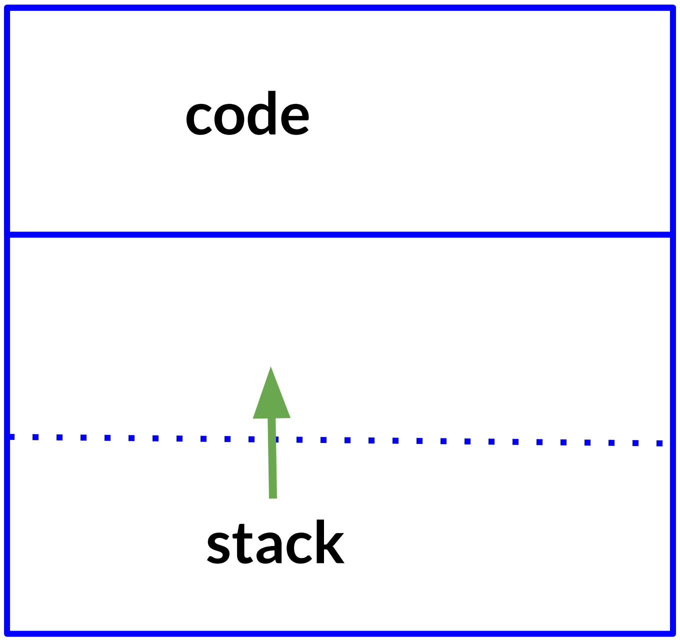

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Trivia Break: Computer Science

This prolific Hungarian-American was a professor at Princeton, and lived in New Jersey from 1933 until his death. He made major contributions to multiple fields, including mathematics, physics, economics, and computer science. While he is the inventor of the merge sort algorithm, he is best known in computing for the architecture named after him (despite the fact that he did not directly invent it - J. Presper Eckert and John Mauchly did, while working on the ENIAC), which is the basis for the architecture of most modern digital computers.

Trivia Break: Holidays

This holiday, typically occurring sometime in February or March, marks the final day of new year celebrations in a widely-used lunar calendar. It is always celebrated during the full moon. As early as two millennia ago, it had become a festival of great significance. The day is traditionally marked by the consumption of tangyuan, a traditional dessert made of glutinous rice shaped into balls; and by the releasing of paper lanterns, which are typically red to symbolize good luck.

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- Other temporary values

Revisiting An Example

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class Main {
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  f(x : Int) : Int {
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AR for **f**:

return address
control link
argument
space for result

Revisiting An Example: Stack after 2 Calls to f()

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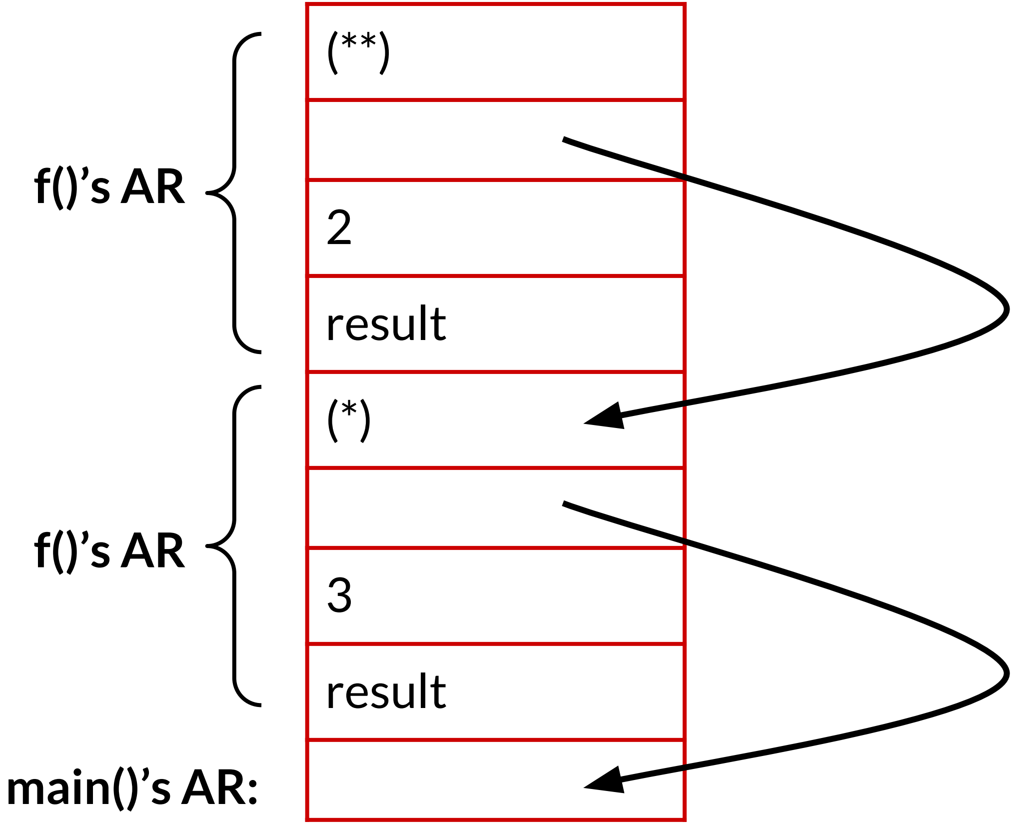

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- **(*)** and **(**)** are return addresses of the invocations of f
  - The ***return address*** is where execution resumes after a procedure call finishes
- This is only one of many possible AR designs
  - Would also work for C, Pascal, FORTRAN, etc.

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

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

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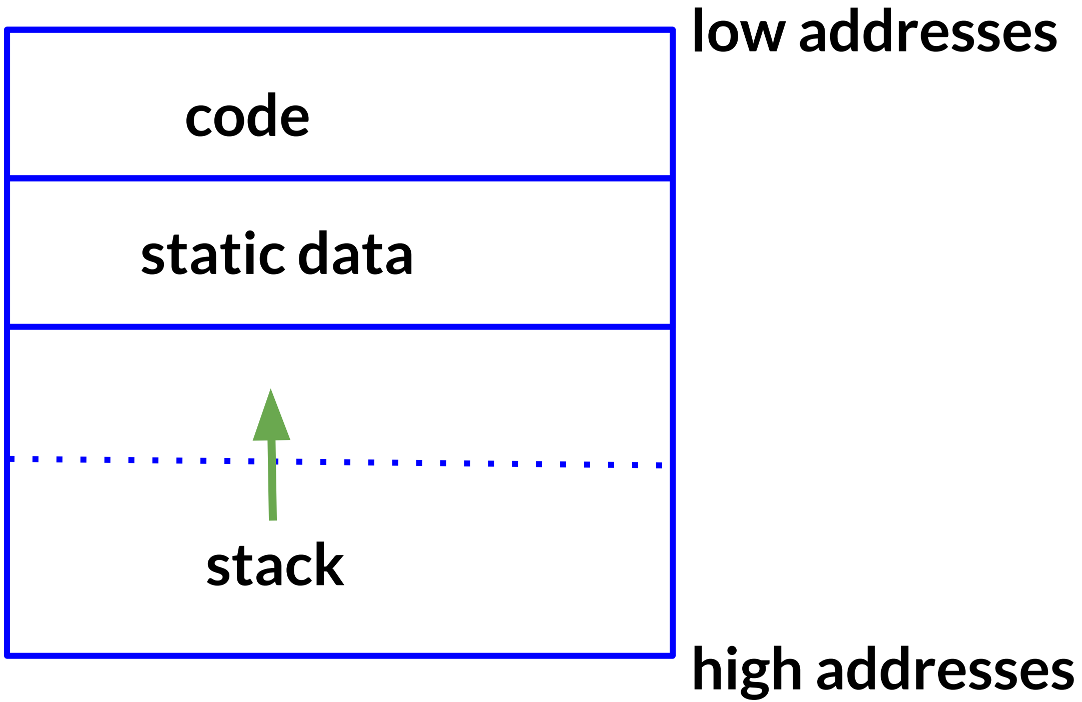
    - Variables with fixed address are “***statically allocated***”
- Depending on the language, there may be other statically allocated values

Memory Layout with Static Data

a program's virtual memory:



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    - this `Bar` value must survive deallocation of `foo`’s AR

Heap Storage

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- Languages with dynamically-allocated data (such as Cool!) use a ***heap*** to store such dynamic data

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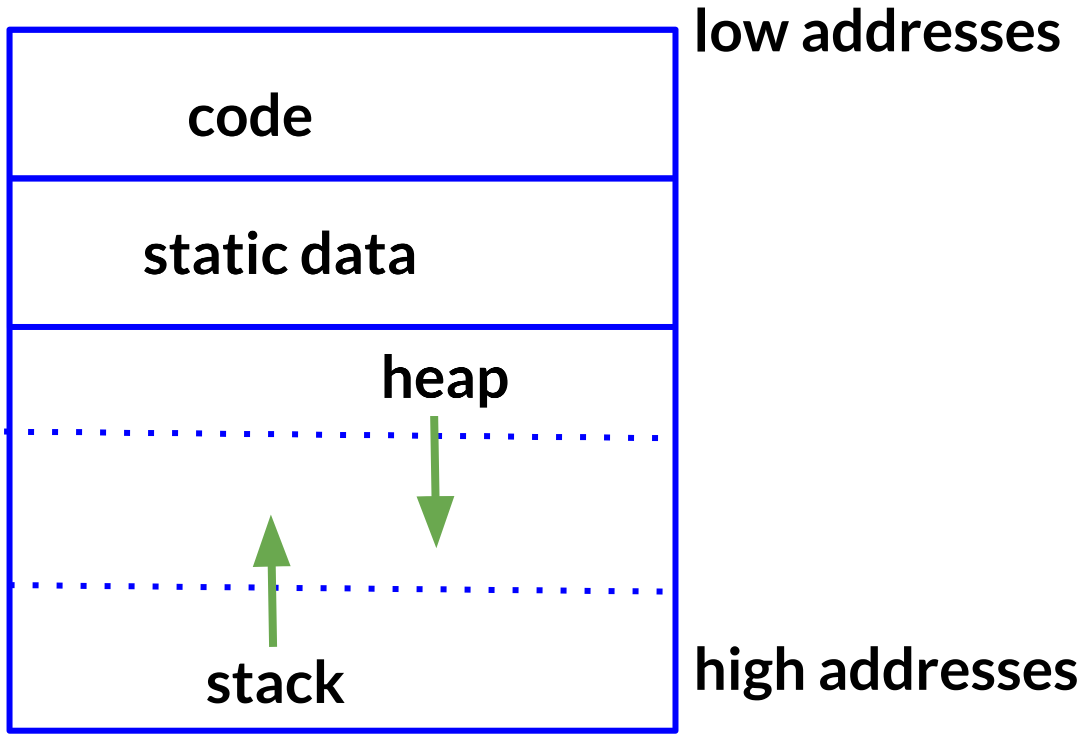
- Solution: start heap and stack at **opposite ends of memory**, let them grow towards each other

Memory Layout with Heap

a program's virtual memory:



Your Own Heap

- In PA3, you'll need to emit assembly code for things like:

```
let x = new Counter(5) in
let y = x in {
  x.increment(1);
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- You'll need to use and manage an **explicit heap** (introduced today and covered in more detail in later lectures). A heap maps addresses (i.e., integers) to values.

Course Announcements

- **PA2c2** due next Monday
  - requires typechecking + semantic analysis of everything but expressions
  - if you haven't started yet, I'm worried for you
  - don't forget that you can work in pairs!
    - I strongly recommend this option
    - it's not too late to pair up, even if both of you have started independently