CS 536

Runtime Environments

Roadmap

- Type checks
  - Went through a couple of type system design points
  - Inferred the types of expressions in YES
  - Showed how to propagate type errors
- Today
  - Begin looking at how to lower code down to assembly

Outline

- Talk about what a runtime environment is
- Discuss the “semantic gap”
  - The difference between level of abstraction in source code and executables
- How memory is laid out in an abstract machine

WYSINWYX

- What You See (in source code) Is Not What You eXecute
  - We think in terms of high-level abstractions
  - Many of these abstractions have no explicit representation in machine code

What Abstractions are we missing?

- Loops
- Variables
- Scope
- Functions

- Flat list of opcodes
- Byte-addressable memory

Runtime Environment

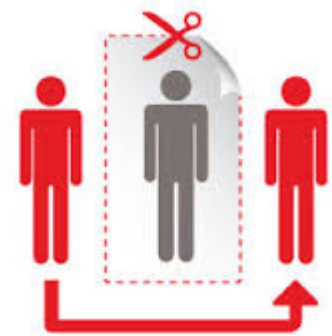
- Underlying software and hardware configuration assumed by the program
  - May include an OS (may not!)
  - May include a virtual machine

The Role of the Operating System

- Program piggybacks on the OS
  - Provides functions to access hardware
  - Provides illusion of uniqueness
  - Enforces some boundaries on what is allowed

Mediation is Slow

- It’s up to the compiler to use the runtime environment as best it can
  - Limited number of very fast registers with which to do computation
  - Comparatively large region of memory to hold data
  - Some basic instructions from which to build more complex behaviors



Conventions

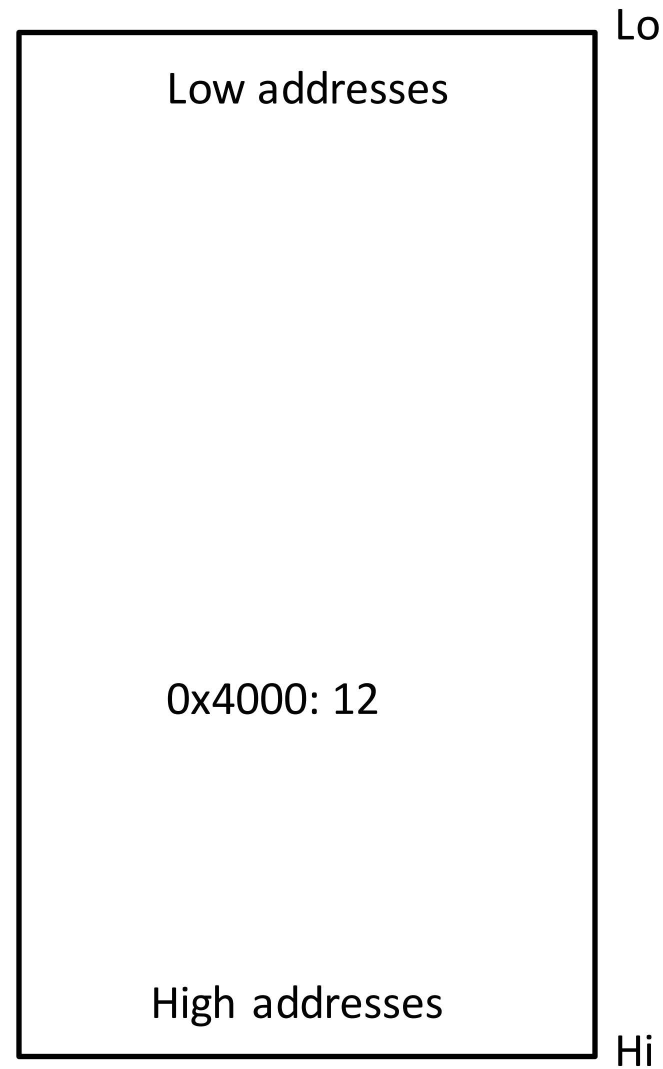
- Assembly code enforces very few rules
  - We'll have to structure the way we access memory ourselves
- These conventions help to guarantee that isolated code can work together
  - Allows modularity
  - Increase efficiency

Issues to consider

- Variables
  - How do we store them?
  - How do we access them?
- How do we represent functions in straight-line code?
  - How do we simulate function calls?
  - How do we simulate function entry?
  - How do we simulate function return?

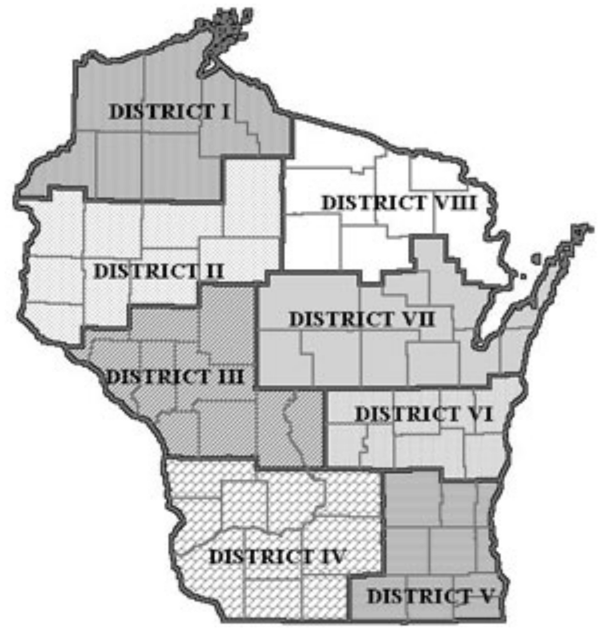
General Memory Layout

- We can think of program memory as a single array
- Addressable via memory cell
  - Represent using a hex value
- Very common to represent program memory as a "tower"
  - Low addresses at the "top"
  - High addresses at the "bottom"



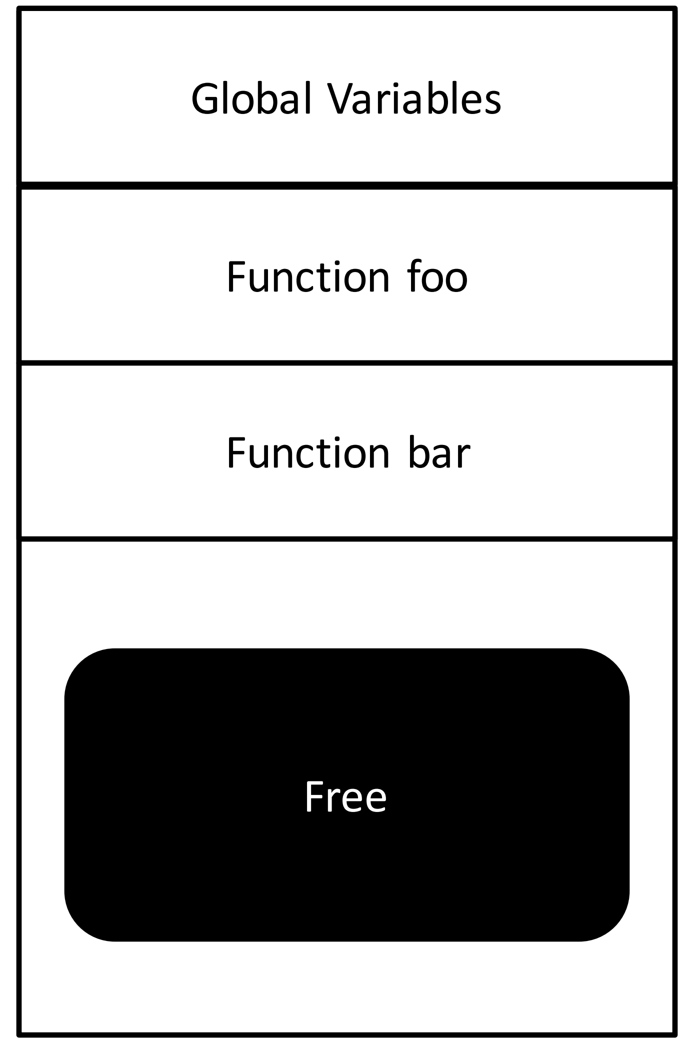
How do we divide up memory?

- Goals
  - Flexibility
  - Efficiency
  - Speed



Memory Layout : Static Allocation

- Region for global memory
- 1 “frame” for each subroutine of the program
  - Memory “slot” for each local, param
  - “slot” for caller
- Fast but impractical
  - Why?



Memory: The Stack

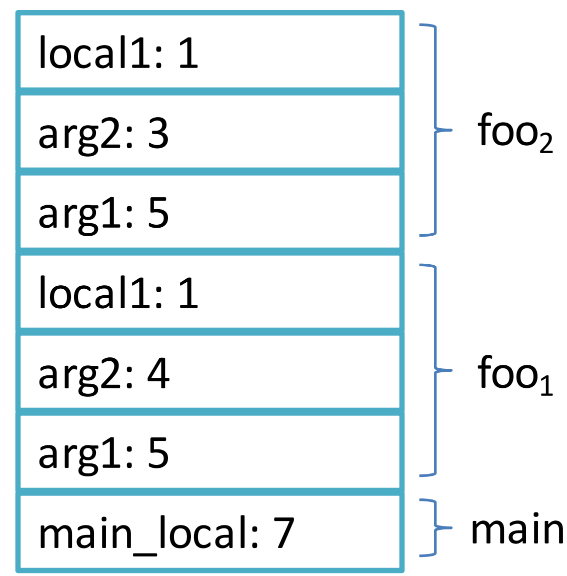
- Keep the function frame idea, but allocate per invocation
  - AKA activation records
  - We don't statically know how many frames we might have
    - Fix a point in memory grow from there
    - By convention, grows downwards

A Closer look at Activation Records (ARs)

- Push a new frame on function entry
- Pop the frame on function exit
- To keep size down, we can put static data in the global area
  - In particular, strings
- Allows conceptually infinite recursion depth
  - In practice, we'll eventually hit the global data

```
foo(int arg1, int arg2){
    int local1 = arg1 - arg2;
    if (local1 > 0) { foo( arg1, 3); }
}
main(){
    int main_local = 7;
    foo(5, 4);
}
```

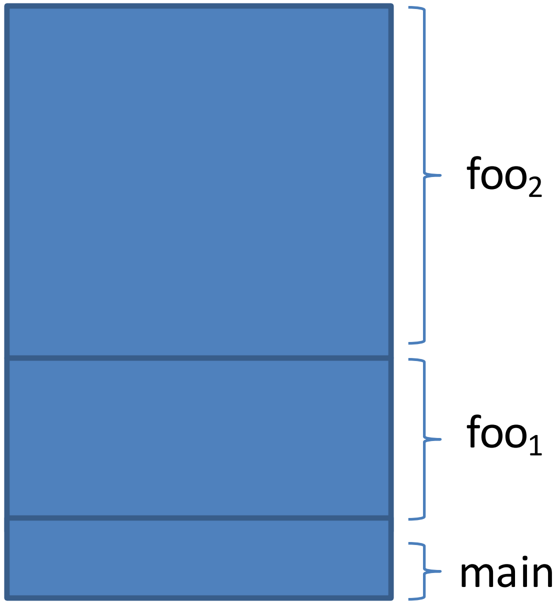
Disclaimer:
High-level idea only



Activation Records: Dynamic Locals

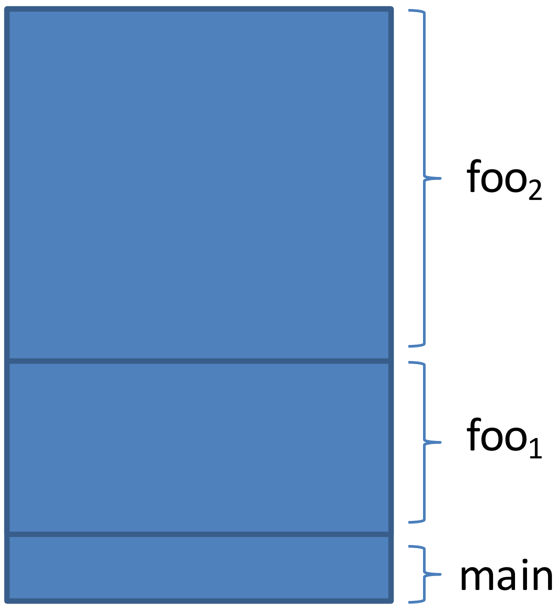
- The stack can handle local variables whose size is unknown
  - Grow the frame as needed during its execution
- This means stack size is unknown at compile time!
  - Store the previous frame's boundaries in the current frame

```
foo(int arg){
    int locArr[arg];
    …
    foo(arg * 2);
}
main(int argc, char * argv[]){
    int main_local = 7;
    foo(argc);
}
```



Activation Record: Summary

- Things in the frame
  - Local variable values
  - Space for the caller's frame
    - Data context
      - Enough info to remember the boundaries of the frame we called from (the caller)
    - Control context
      - Enough info to know what line of code we were at when we made the call



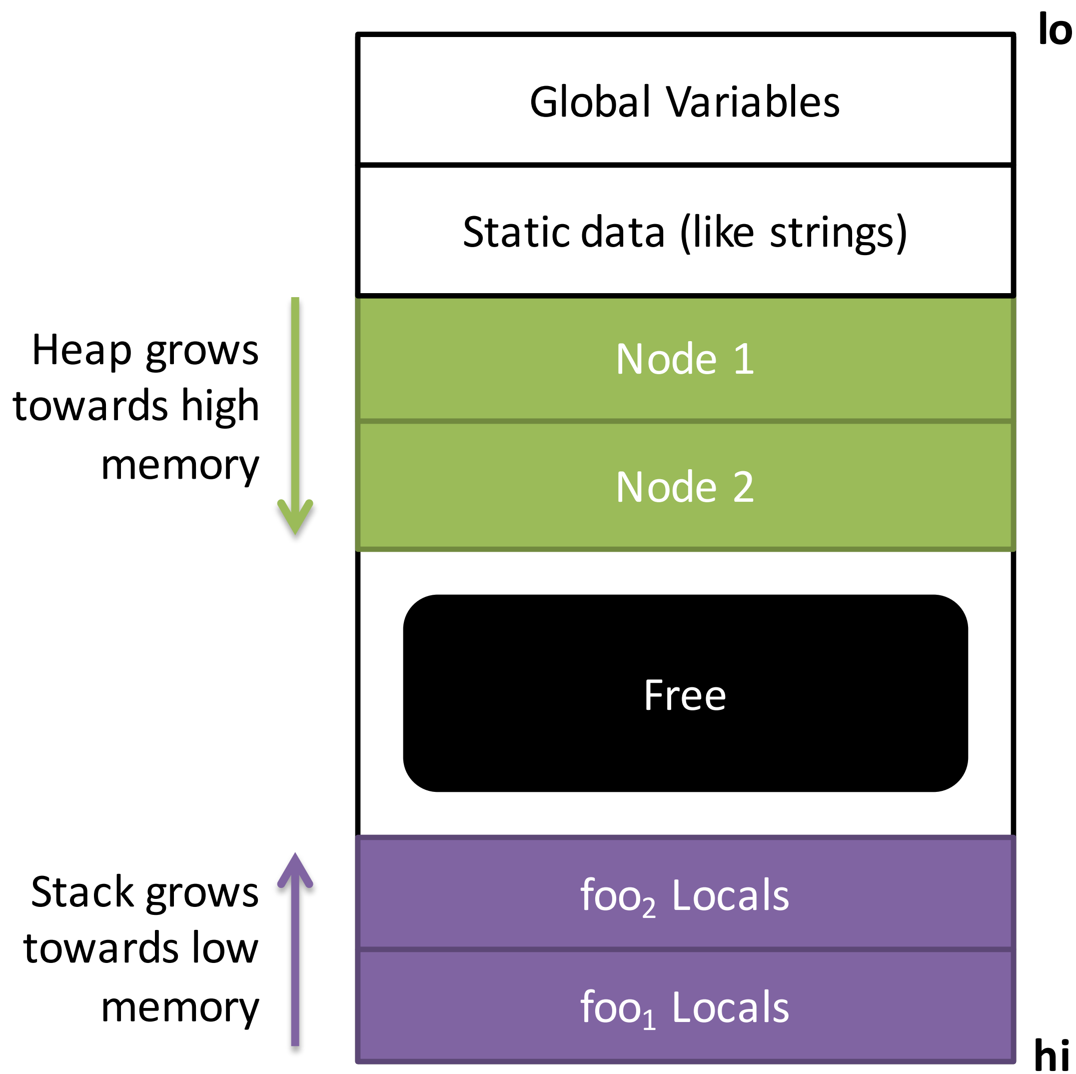
Non-Local Dynamic Memory

- Surely we don't want *all* data allocated in a function call to disappear on return
- Don't know how much space we'll need
  - Can allocate many such objects
  - Can be sized dynamically

```
public makeList(){
    Node n = new Node();
    Node t = new Node();
    n.next = t;
    return n;
}
```

The Heap

- Region of memory independent of the stack
- Allocate at program's command
- How do we get rid of it?
  - Ask programmer to specify when it's unused
  - Can track automatically when it's unused



Function Calls

- Where convention meets implementation
  - Function calls are so common that their semantics are partially encoded into architecture
  - Registers often have “nicknames” that hint at their purpose in representing ARs
  - Some instructions implement “shortcuts” for building up and breaking down ARs

When are we “in” a function?

- **$ip** the *instruction pointer* tracks the line of code we are executing. It tracks “where we are at” in the program
- If the instruction pointer points to code that was generated for some function, we’ll say we’re in that function

```
#1  int summation(int max){
#2    int sum = 1;
#3    for (int k = 1 ; k <= max
; k++){
#4      sum += k;
#5    }
#6    return sum;
#7  }
#8  void main(){
#9    int x = summation(4);
#10   cout << x;
#11 }
```

$ip: *#2*

Caller / Callee relationship

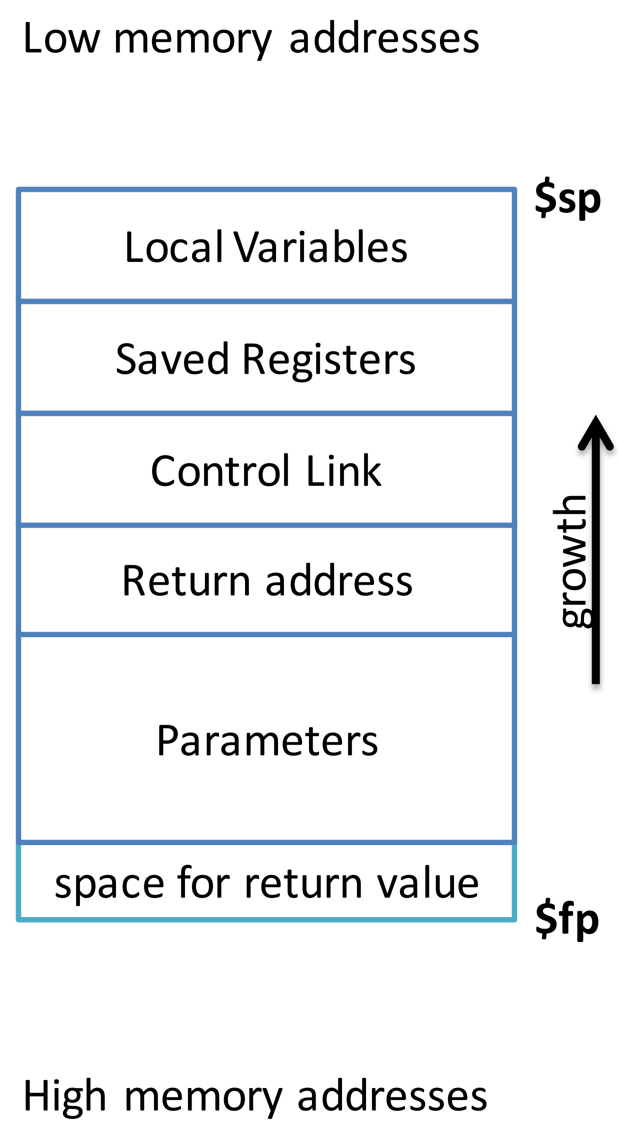
- Caller
  - The function doing the invocation
- Callee
  - The function being invoked
- Note that this is a per-call relationship
  - main is the caller at line 5
  - v is the callee at line 5

$ip

```
1.  void v(){
2.  }
3.
4.  int main(){
5.      v();
6.  }
```

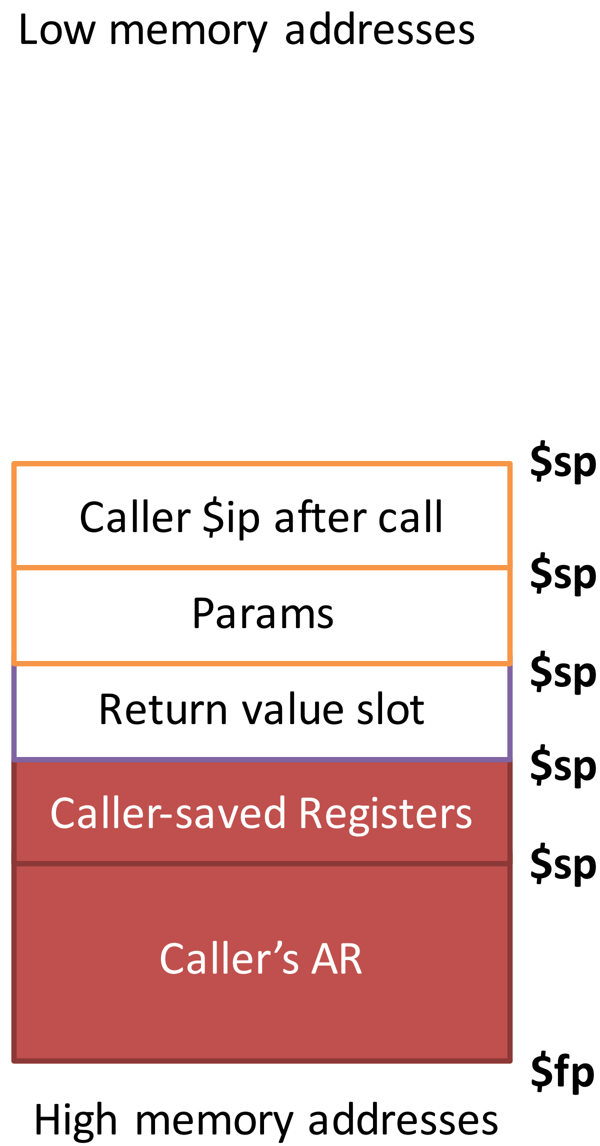
How ARs are *Actually* Implemented

- Two registers track the stack
  - Frame pointer (**$fp**) tracks the base of the stack
  - Stack pointer (**$sp**) tracks the top of the stack



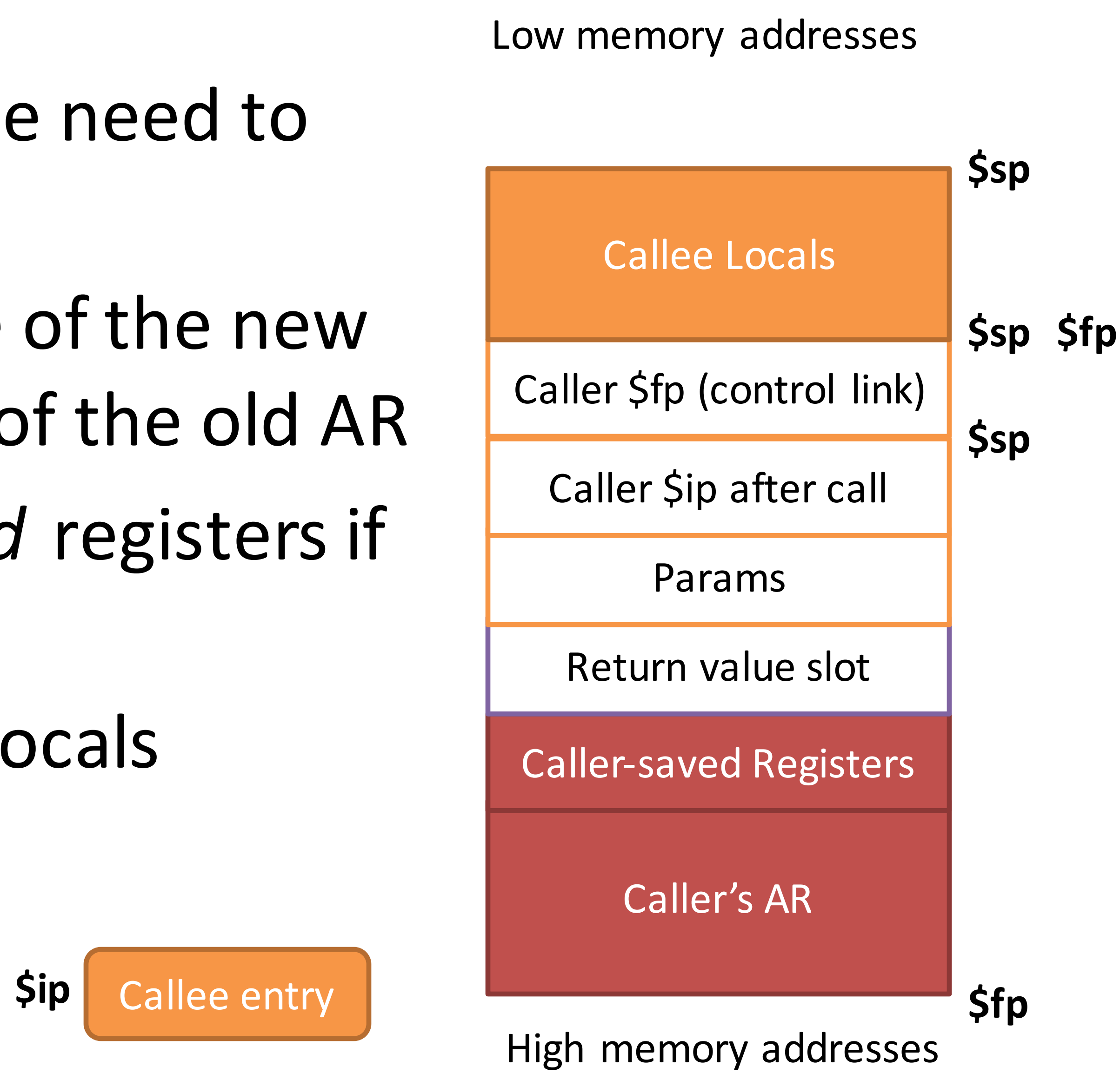
Function Entry: Caller Responsibilities

- Store the *caller-saved* registers in it's own AR
- Set up actual params
  - Set aside a slot for the return value
  - Push parameters onto the stack
- Copy return address out of **$ip**
  - It's about to get obliterated 删除
- Jump to the Callee's first instruction



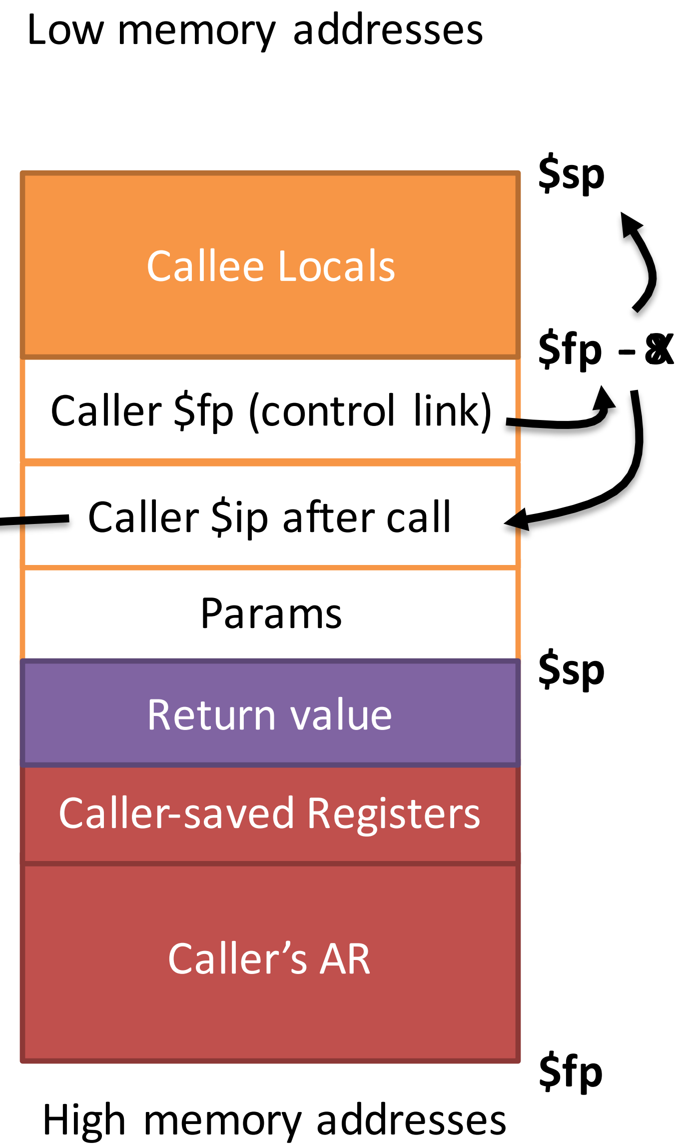
Function Entry: Callee Responsibilities

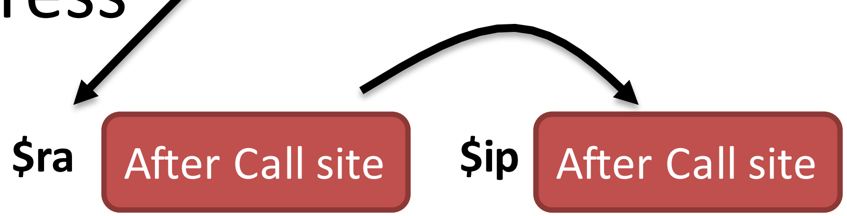
- Save **$fp** since we need to restore it later
- Update the base of the new AR to be to end of the old AR
- Save *callee-saved* registers if necessary
- Make space for locals



Function Exit: Callee Responsibilities

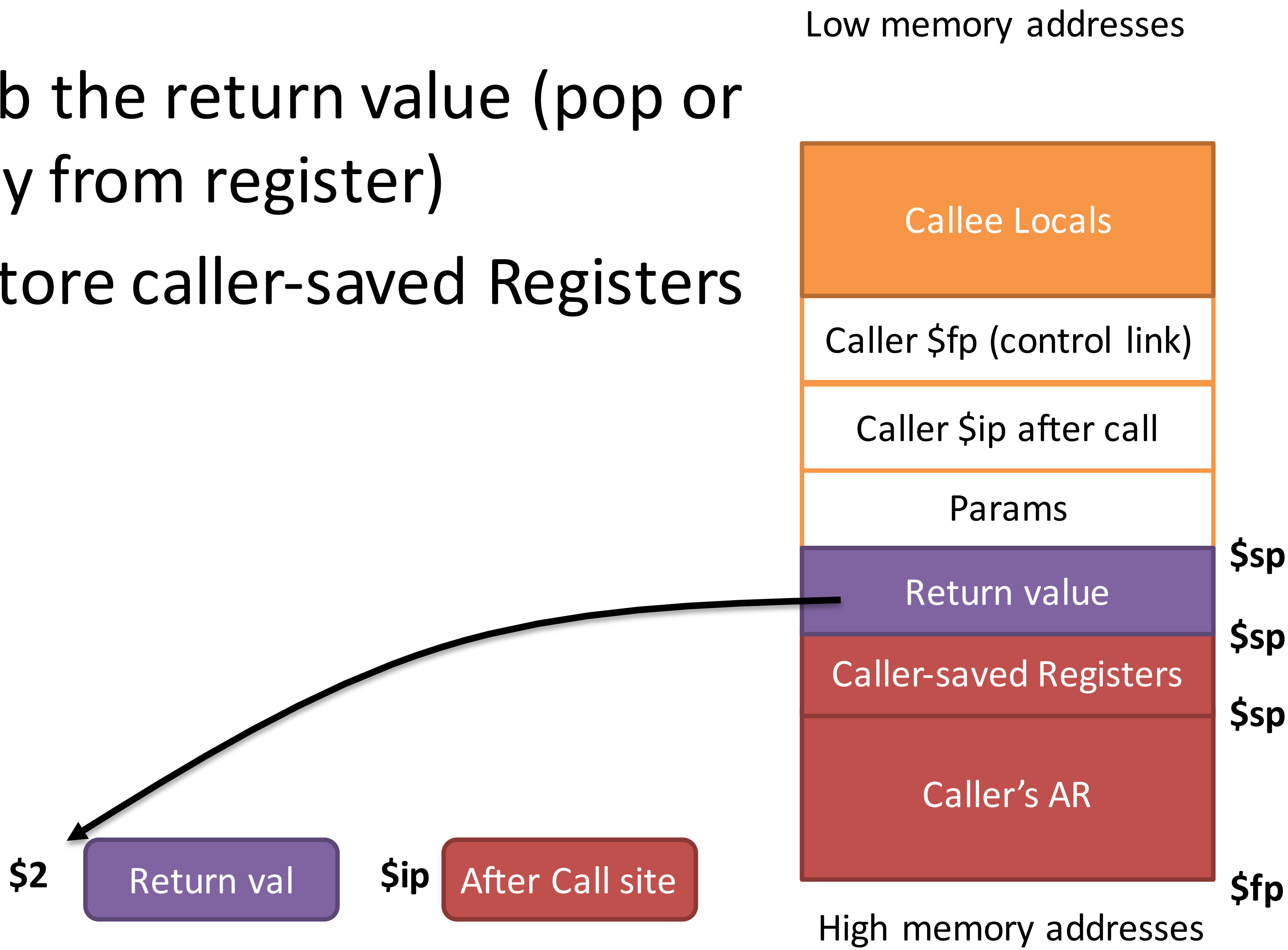
- Set the return value
- Restore callee-saved registers
- Grab stored return address
- Restore *old* **$sp**: fixed (negative) offset from the current base of the stack
- Restore *old* **$fp**: also from stack
- Jump to the stored return address





Function Exit: Caller Responsibilities

- Grab the return value (pop or copy from register)
- Restore caller-saved Registers



Example

```
int summation(int max){
   int sum = 1;
   for (int k = 1 ; k <= max ; k++){
      sum += k;
   }
   return sum;
}
void main(){
   int x = summation(4);
   cout << x;
}
```

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}
void main(){
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```

Hardware Support for Functions

- Calls
  - JAL (Jump and Link): MIPS instruction that puts **$ip** in **$ra** then, sets **$ip** to a given address
  - Call: x86 instruction that pushes **$ip** directly onto the stack, then sets **$ip** to given address
- Return
  - JR (Jump Return): MIPS instruction thast sets **$ip** to **$ra**
  - ret: x86 instruction that pops directly off the stack into **$ip**
- SPARC "Sliding Windows"
  - Crazy system where caller registers are automatically saved, new set of callee saved registers automatically exposed

Next Time

- MIPS
  - We will fix a concrete runtime environment, not just a pseudocode machine
- Variable access
  - We've shown how to store variables
  - How do we actually access them?
    - What about scope?