Introduction to Compiler Design

Lesson 13:

Runtime Environment

Roadmap

- Type checking
  - Discussed a couple of points in the design space of type systems
  - Showed how to infer and check the types of expressions in C--
  - Showed how to propagate type errors
- This lesson
  - Begin looking at how to “lower” the code down to the assembly-code level

Outline

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

What Abstractions are We Missing?

- Loops
- Variables
- Scope
- Functions

- Flat list of opcodes
- Byte-addressable memory

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
- Complicates looking for bugs and security vulnerabilities in machine code

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 is 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 impose conventions on the way our program accesses memory

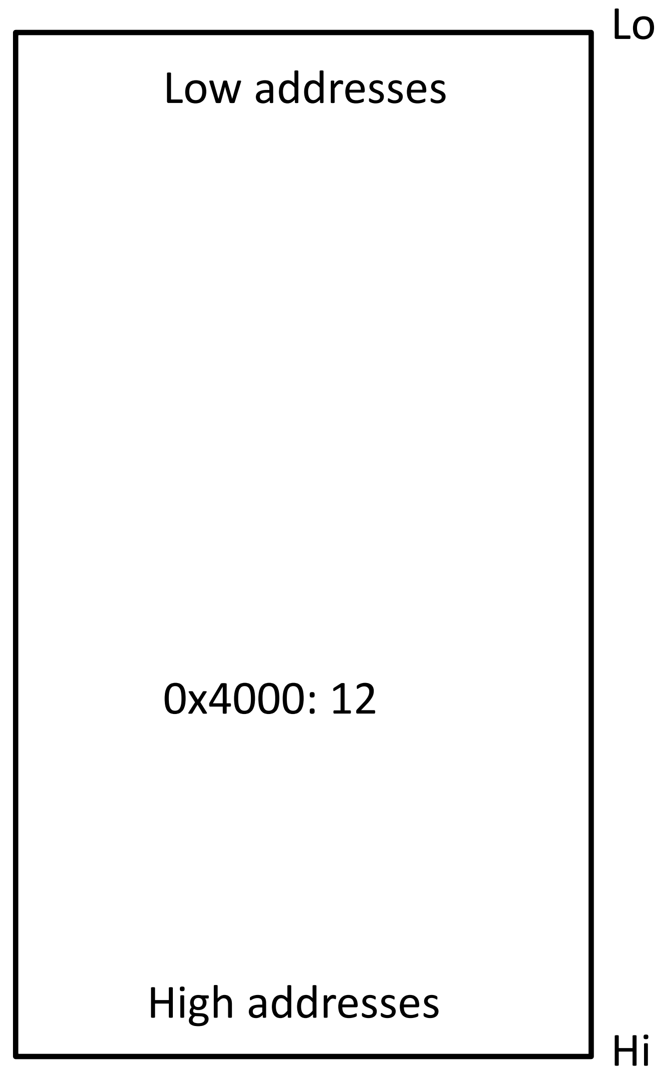
- These conventions help to guarantee that separately developed code works together
  - Allows modularity
  - Increases (programmer) efficiency

Issues to Consider

- Variables
  - How are they stored?
  - What happens when a variable's value is needed?
- How do functions work?
  - What should happen when client code calls a function?
  - What should happen when a function is entered?
  - What should happen when a function returns?

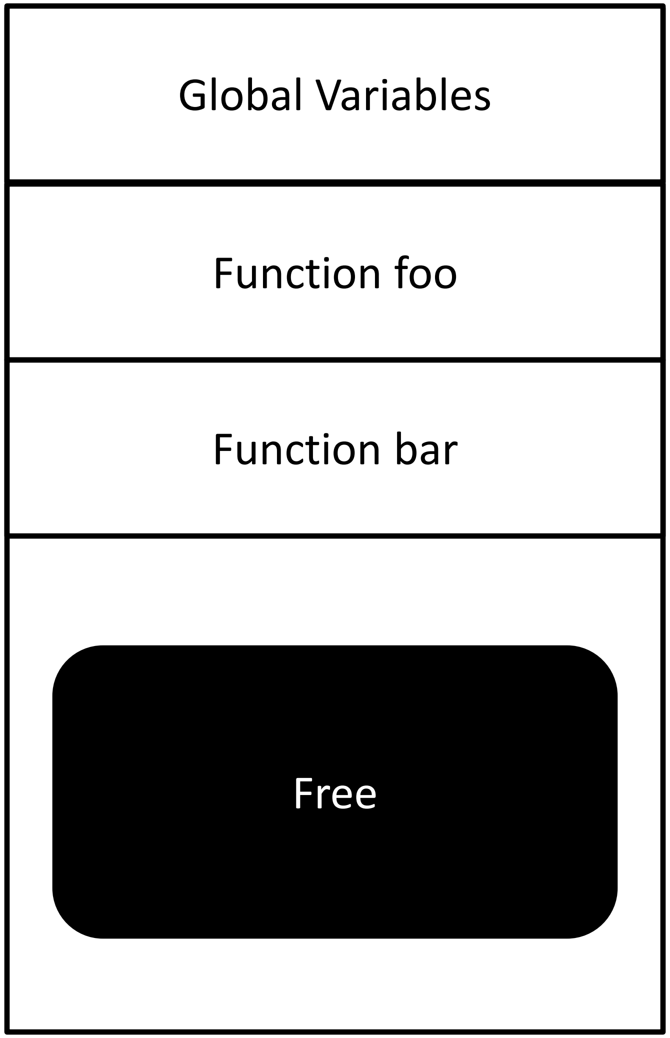
General Memory Layout

- Think of program memory as a single array
- Individual memory cells can be accessed via their address
  - Represent address using a hex value
  - Represent contents using a decimal value
- Very common to represent program memory as a "tower"
  - Low addresses at the "top"
  - High addresses at the "bottom"



Memory Layout : Static Allocation

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



Memory: The Stack

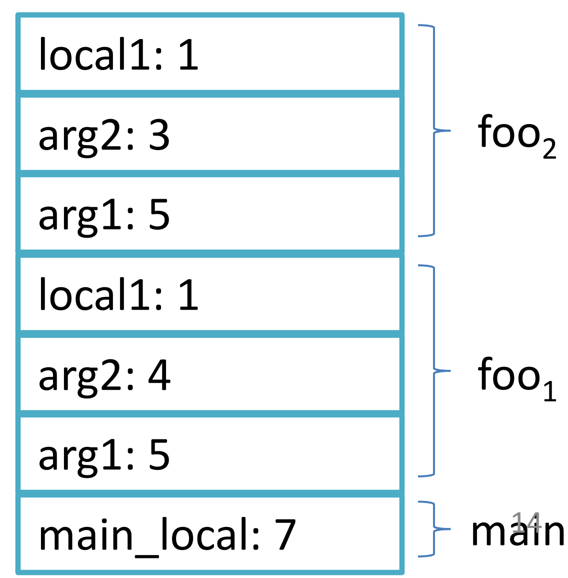
- Keep the procedure-frame idea, but allocate *per invocation*
  - Also known as “activation records”
  - We don’t know statically how many frames there might be
    - Fix a point in memory for the base; grow from there
    - By convention, grows from high addresses to low addresses

A Closer Look at Activation Records (ARs)

- Push a new frame on function entry
- Pop the frame on function exit
- To reduce the size, put static data in the global area
  - In particular, string constants
- Conceptually, allows infinite recursion
  - In practice, the stack can grow so large that it hits 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);
}
```

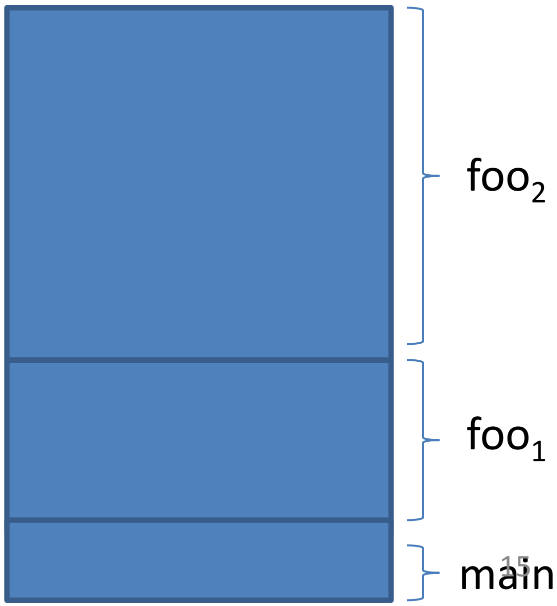
Disclaimer: High-level idea only



Activation Records: Dynamic Locals

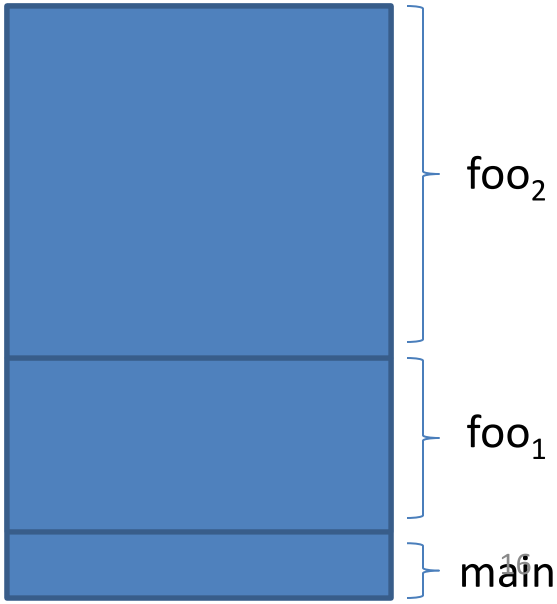
- The stack can handle local variables whose size is unknown
  - Grow the frame as needed during its execution
- Consequently, the stack size is not known at compile time!
  - Store the previous frame's boundaries in the current frame
  - In essence, there is a linked list of activation records

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



Activation Record: Summary

- Items in the AR
  - Local variables
  - Info about the call made by the caller
    - Data context
      - Enough info to determine the boundaries of the frame in use when the current procedure was called
    - Control context
      - Enough info to know what code invoked the current procedure



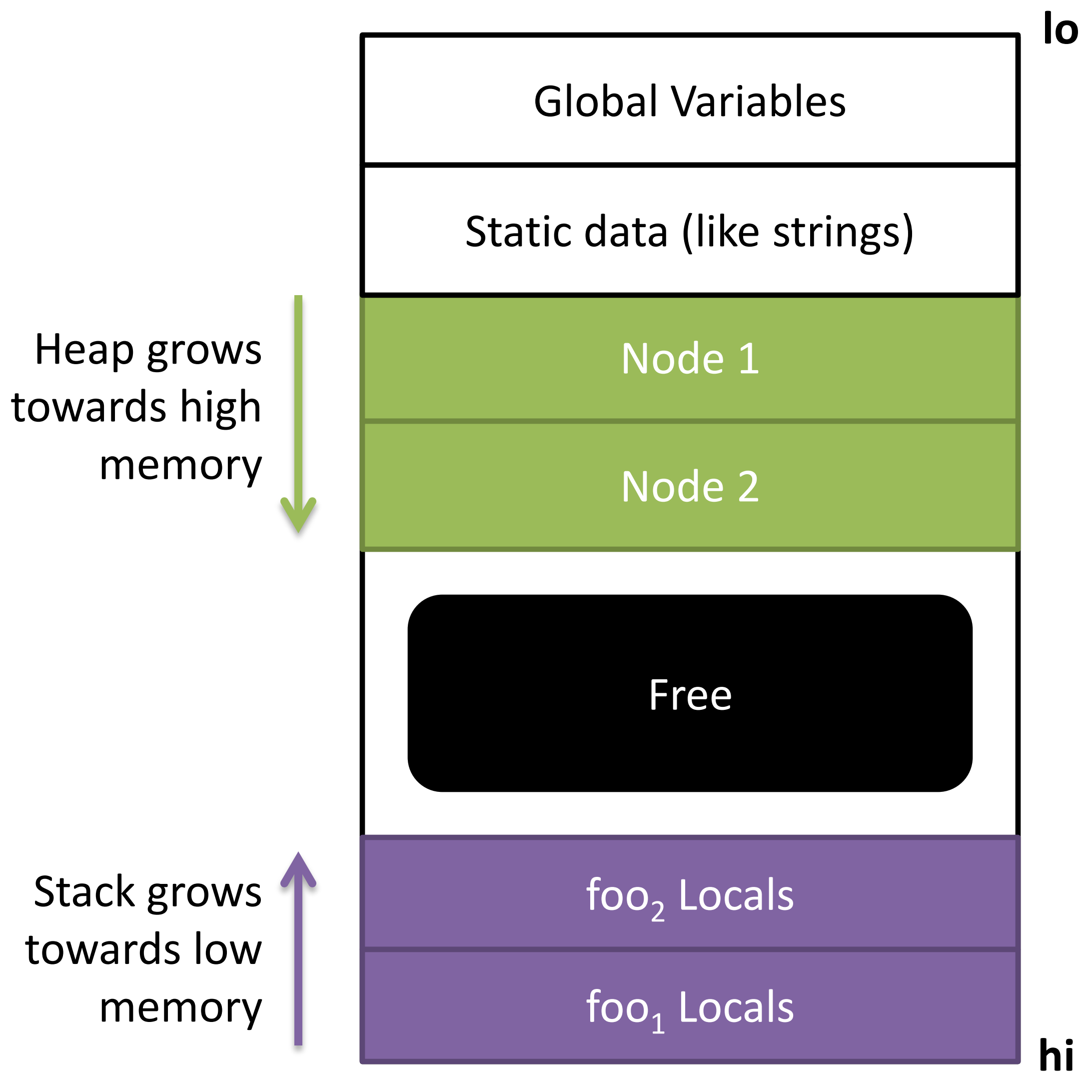
Non-Local Dynamic Memory

- 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
  - The sizes can vary dynamically

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

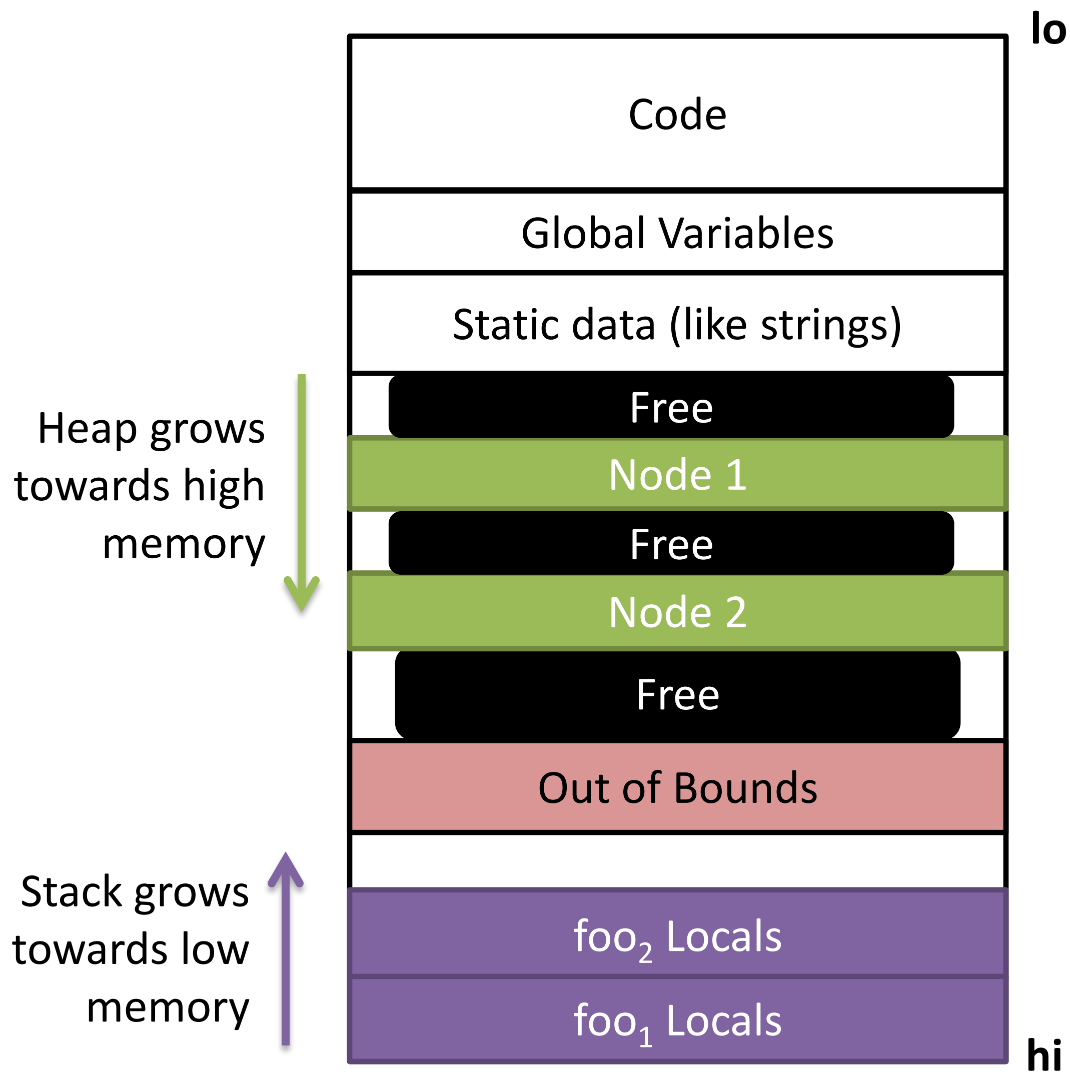
The Heap

- Region of memory independent of the stack
- Allocated according to calls in the program
- How do we give it back?
  - Programmer specifies when it will no longer be used (C)
  - Runtime environment can determine automatically when it could no longer be used (Java)



The Whole Picture

- The code resides in memory at addresses less than the region for the global variables



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 (fp, sp)
- Some instructions implement “shortcuts” for building up and breaking down ARs

When are We “In” a Function?

- **$ip** the *instruction pointer* tracks the line (address) of the code that is executing. It tracks “where we are at” in the program
- If **$ip** 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

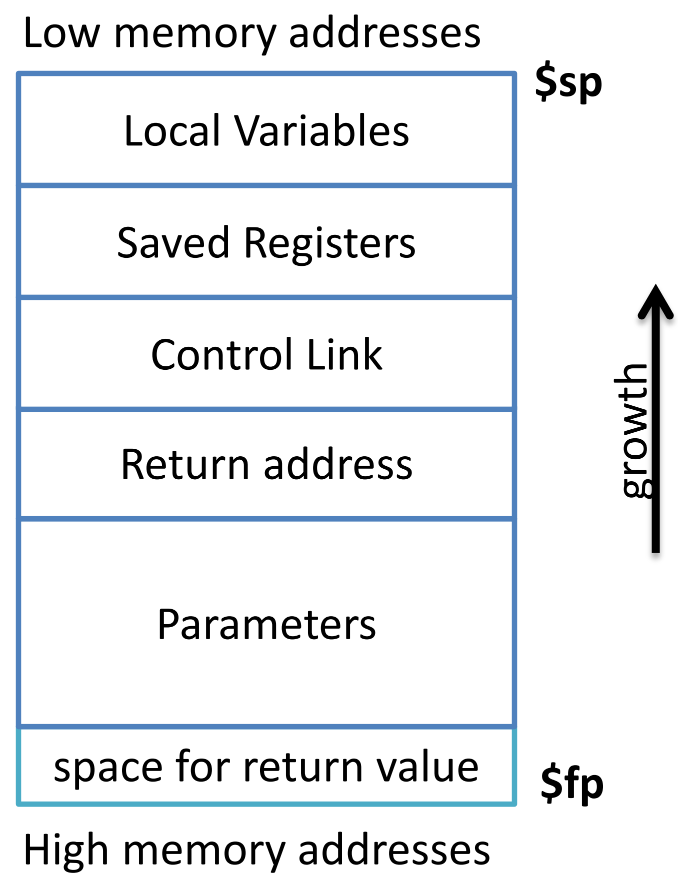
- Caller
  - The function doing the invocation
- Callee
  - The function being invoked
- Note that this is a per-call relationship
  - main is the caller at line 5
  - v is the callee at line 5

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

$ip

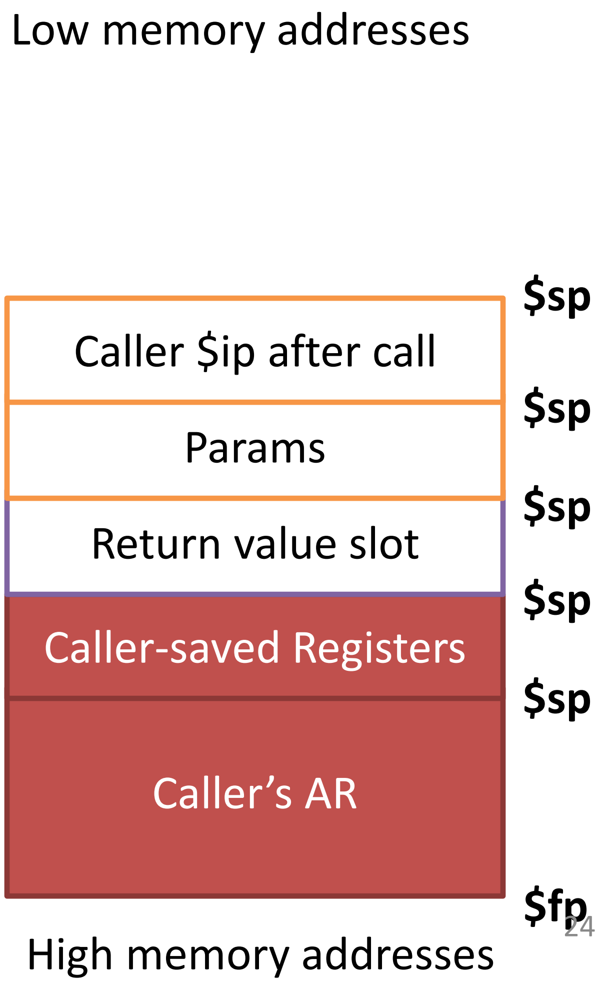
How ARs are *Actually* Implemented

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



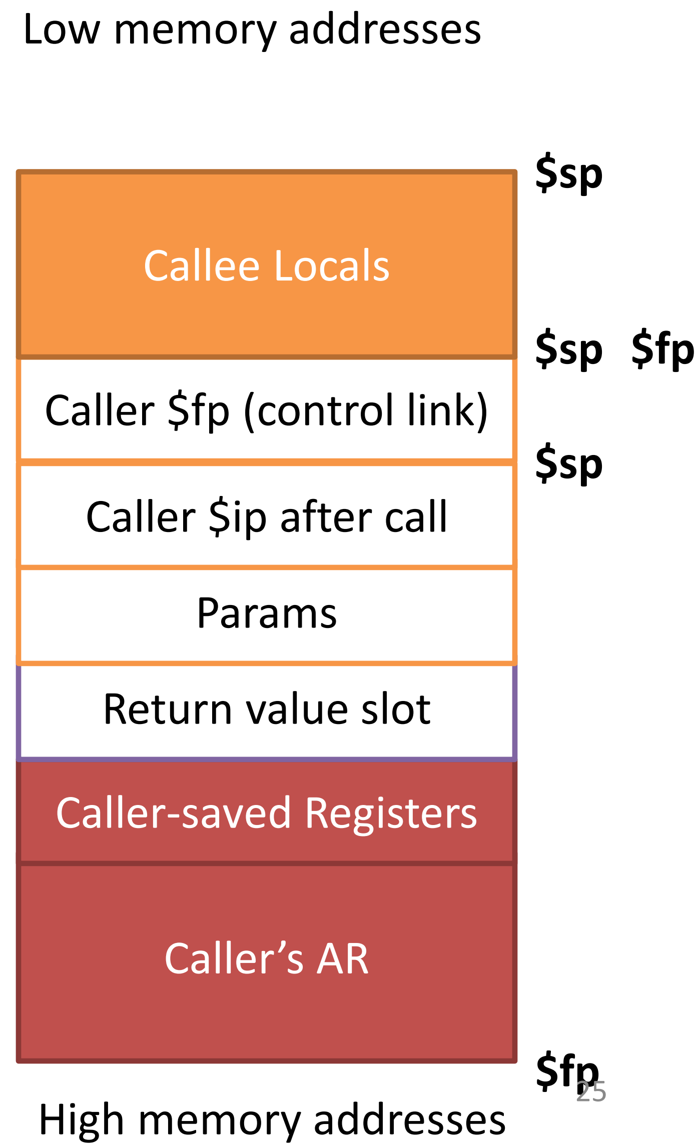
Function Entry: Caller Responsibilities

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



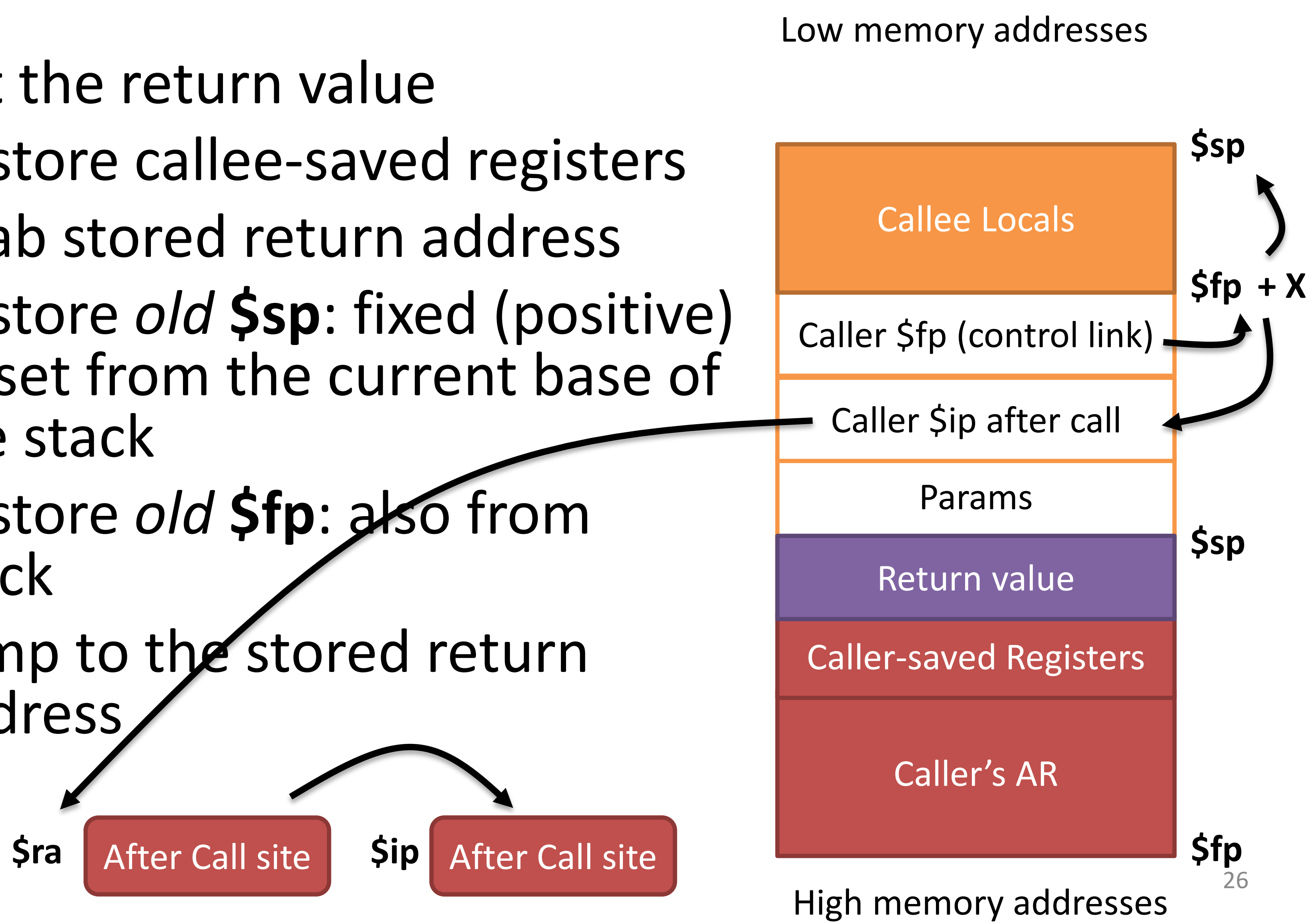
Function Entry: Callee Responsibilities

- Save **$fp** (because we need to restore it when the callee returns)
- 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



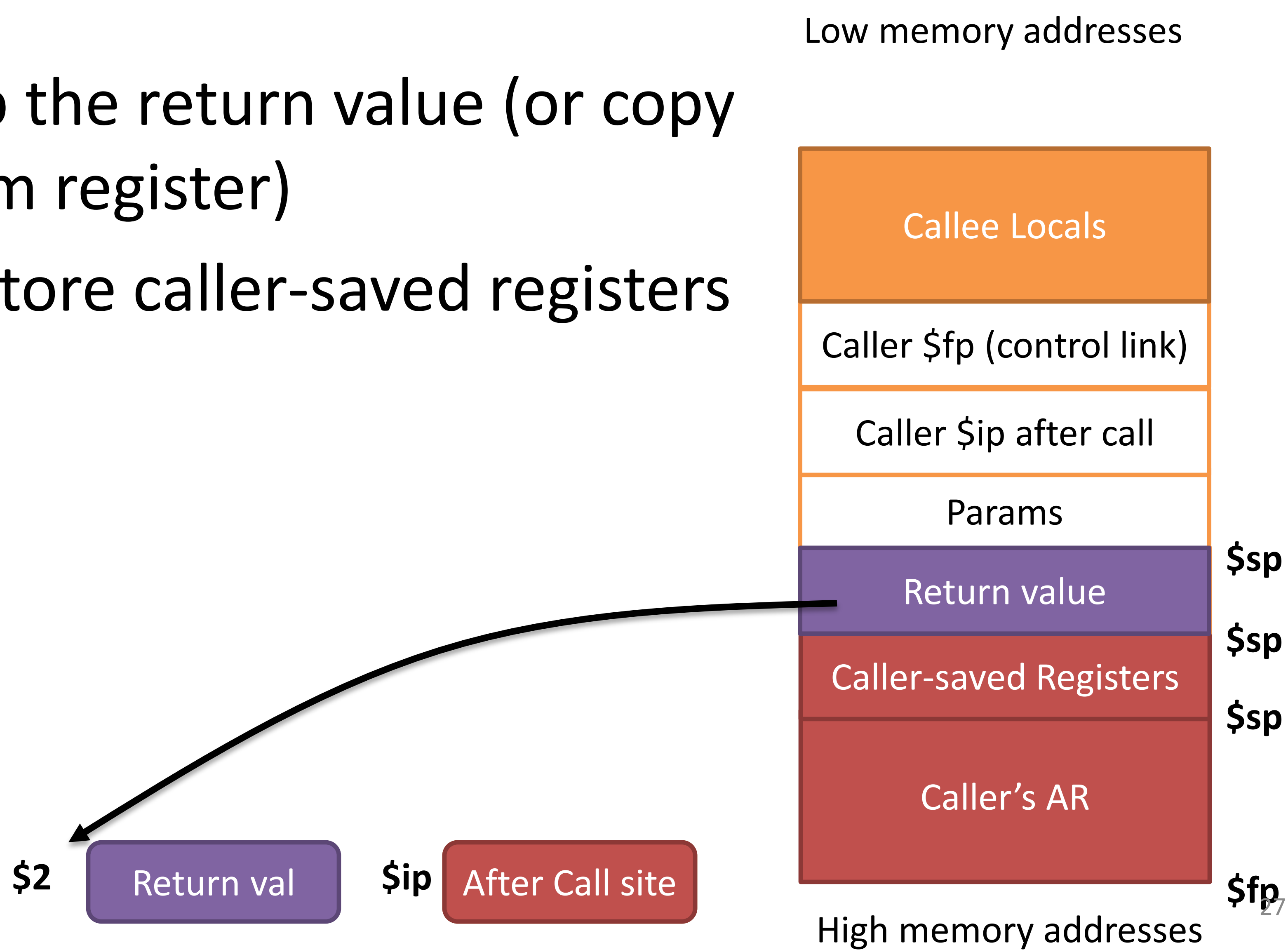
Function Exit: Callee Responsibilities

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



Function Exit: Caller Responsibilities

- Pop the return value (or copy from register)
- Restore caller-saved registers



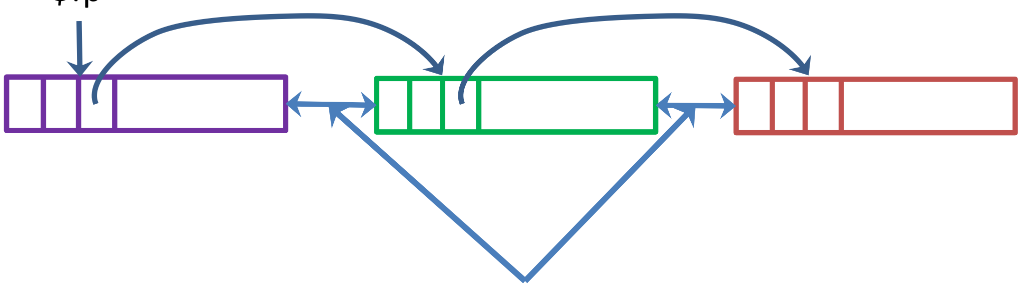
The Stack = A Linked List of ARs

Linked List

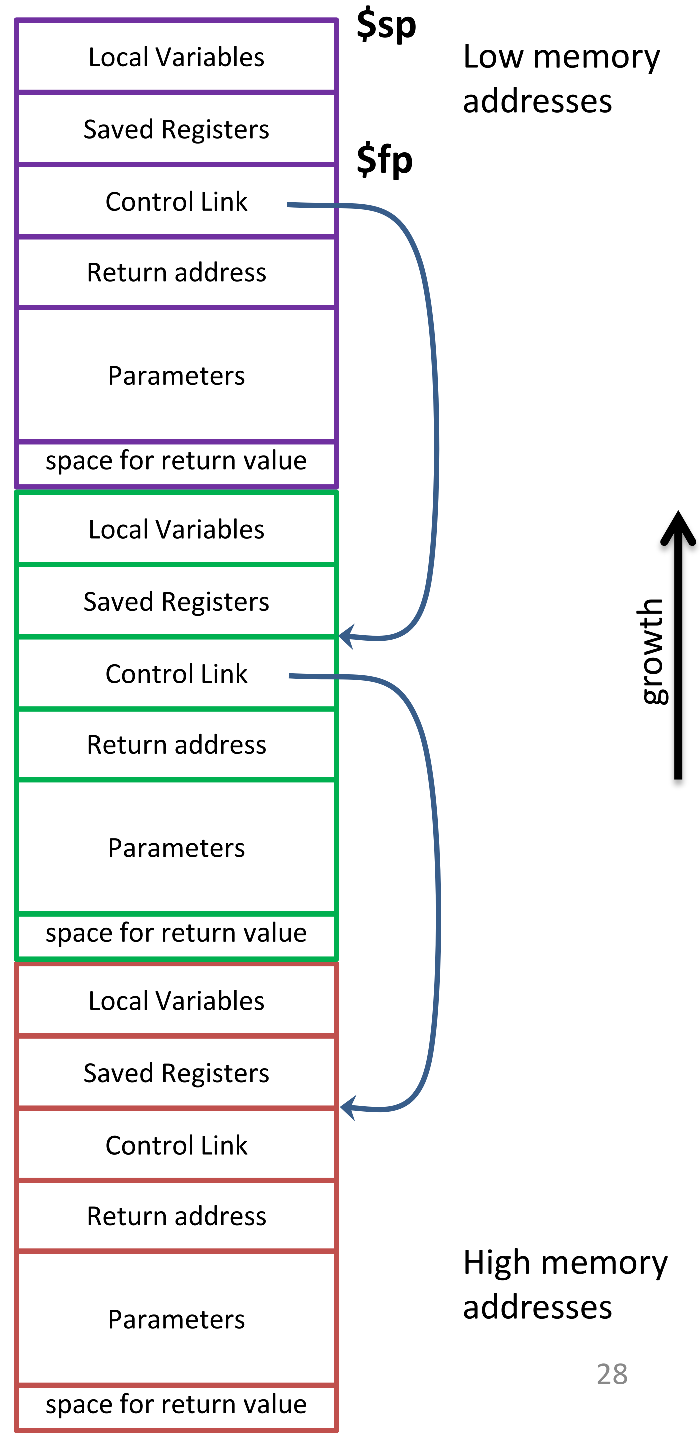
head

Linked List of ARs

$fp



with no space
in-between
list elements



Hardware Support for Functions

- Calls
  - JAL (Jump and Link): MIPS instruction that puts **$ip** in **$ra**, and then sets **$ip** to a given address
  - Call: x86 instruction that pushes **$ip** directly onto the stack, then sets **$ip** to a given address
- Return
  - JR (Jump Return): MIPS instruction that sets **$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