Runtime Environments
Roadmap

• Type checks
  – Went through a couple of type system design points
  – Inferred the types of expressions in CATS
  – 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?

- Global Variables
- Function foo
- Function bar
- Free
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

```cpp
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

```c
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

```java
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

Stack grows towards low memory

Heap grows towards high memory

Global Variables

<table>
<thead>
<tr>
<th>Static data (like strings)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Node 1</td>
</tr>
<tr>
<td>Node 2</td>
</tr>
</tbody>
</table>

Free

foo₂ Locals

foo₁ Locals
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?

- **$\text{ip}$** 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 }
```

$\text{ip}$: #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

```c
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 its own AR
- Set up actual params
  - Set aside a slot for the return value
  - Push parameters onto the stack
- Copy return address out of $\text{ip}$
  - It’s about to get obliterated
- 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

```c
#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(){
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```
#1     int summation(int max){
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#4             sum += k;
#5         }
#6         return sum;
#7     }
#8     void main(){
#9         int x = summation(4);
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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 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
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?