CS 432
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Runtime Environments

Runtime Environment

- Programs run in the context of a system
  - Instructions, registers, memory, I/O ports, etc.
- Compilers must emit code that uses this system
  - Must obey the rules of the hardware and OS
  - Must be interoperable with shared libraries compiled by a different compiler
- Memory conventions:
  - Stack (used for procedure calls)
  - Heap (used for dynamic memory allocation)

Procedures

- A procedure is a portion of code packaged for re-use
  - Key abstraction in software development
  - Provides modularity, encapsulation, and information hiding
- Common characteristics
  - Single entry point, (potentially) multiple exit points
  - Caller is suspended while procedure is executing
  - Control returns to caller when procedure completes
  - Caller and callee info stored on stack
- Procedure vs. function vs. method
  - We'll use "subprogram" as a synonym for "procedure"
  - Functions generally have return values
  - Methods have an associated object (the receiver)

Procedures

- New-ish terms
  - Header: signaling syntax for defining a procedure
  - Parameter profile: number, types, and order of parameters
  - Signature/protocol: parameter types and return type(s)
  - Prototype: declaration without a full definition
  - Referencing environment: variables visible inside a procedure
  - Name space / scope: set of visible names
  - Aliases: different names for the same location
  - Caller: procedure that calls another procedure
  - Callee: procedure called by another procedure
  - Call site: location of a procedure invocation
  - Return address: destination in caller after call completes

Parameters

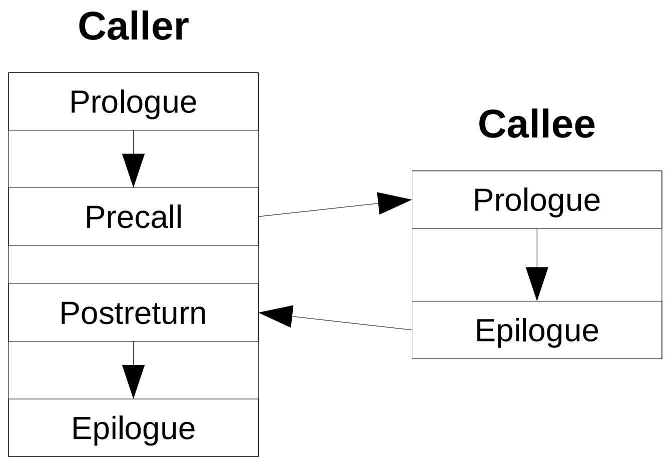
- Formal vs. actual parameters
  - Formal: parameter inside procedure definition
  - Actual: parameter at call site
- Semantic models: *in*, *out*, *in-out*
- Implementations (key differences are *when* values are copied and exactly *what* is being copied)
  - **Pass-by-value (*in, value*)**
  - Pass-by-result (*out, value*)
  - Pass-by-copy (*in-out, value*)
  - **Pass-by-reference (*in-out, reference*)**
  - Pass-by-name (*in-out, name*)

Parameters

- Pass-by-value
  - Pro: simple
  - Con: costs of allocation and copying
  - Often the default
- Pass-by-reference
  - Pro: efficient (only copy 32/64 bits)
  - Con: hard to reason about, extra layer of indirection, aliasing issues
  - Often used in object-oriented languages

Procedure Activation

- Caller and callee must agree on calling conventions
- Standard calling contract:
  - Caller: precall sequence
    - Evaluate and store parameters
    - Save return address
    - Transfer control to callee
  - Callee: prologue sequence
    - Save & initialize base pointer
    - Allocate space for local variables
  - Callee: epilogue sequence
    - De-allocate activation record
    - Transfer control back to caller
  - Caller: postreturn sequence
    - Clean up parameters



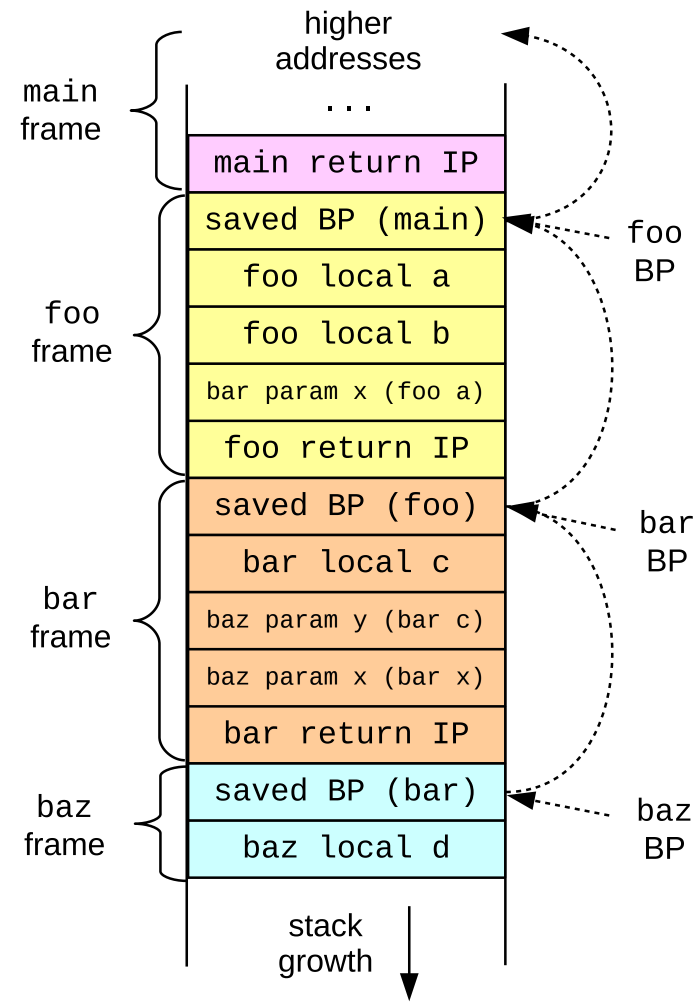
General Stack Layout

- Stack pointer (SP)
  - Top of stack (lowest address)
- Base pointer (BP)
  - Start of current frame (i.e., saved BP)
  - r_{arp} in EAC (CS 432)
  - EP in Sebesta (CS 430)
- Stack frame / activation record per call
  - Parameters
    - Positive offset from BP
  - **Saved return address (required)**
  - Saved BP (dynamic link)
  - Local variables
    - Negative offset from BP
    - Allocated by decrementing SP

```
void foo()
{
    int a,b;
    bar(a)
    return;
}
```

```
void bar(x)
{
    int c;
    baz(x,c);
    return;
}
```

```
void baz(x,y)
{
    int d;
    return;
}
```



Calling Conventions

	Integral parameters	Base pointer	Caller-saved registers	Return value
cdecl (x86)	On stack (RTL)	Always saved	EAX, ECX, EDX	EAX
x86-64 (x64)	RDI, RSI, RDX, RCX, R8, R9, then on stack (RTL)	Saved only if necessary	RAX, RCX, RDX, R8-R11	RAX
ILOC	On stack (RTL)	Always saved	All virtual registers	RET

x86 Calling Conventions

Prologue:

```
push %ebp                 ; save old base pointer
mov  %esp, %ebp           ; save top of stack as base pointer
sub  X, %esp              ; reserve X bytes for local vars
```

Within function:

```
+OFFSET(%ebp)             ; function parameter
-OFFSET(%ebp)             ; local variable
```

Epilogue:

```
<optional: save return value in %eax>
mov  %ebp, %esp           ; restore old stack pointer
pop  %ebp                 ; restore old base pointer
ret                       ; pop stack and jump to popped address
```

Function calling:

```
<push parameters>         ; precall
call <fname>              ; save return address and jump
<dealloc parameters>      ; postreturn
```

Much of prologue & epilogue is optional in x86-64

ILOC Calling Conventions

Prologue:

```
push BP                 ; save old base pointer
i2i  SP => BP           ; save top of stack as base pointer
addI SP, -X => SP       ; reserve X bytes for local vars
```

(required even if there are no local vars – X may need to be adjusted during register allocation for spilled registers)

Within function:

```
[BP+OFFSET]             ; function parameter
[BP-OFFSET]             ; local variable
```

Epilogue:

```
<optional: save return value in RET>
i2i  BP => SP           ; restore old stack pointer
pop  BP                 ; restore old base pointer
return                  ; pop stack and jump to popped address
```

Function calling:

```
<push parameters>       ; precall
call <fname>            ; save return address and jump
<dealloc parameters>    ; postreturn
```

Described in detail in section 8 of Decaf reference

Example

```
def void foo()
{
}

def int main()
{
    foo();
    return 0;
}
```

```
foo:
  push BP                  ; prologue
  i2i SP => BP             ;
  addI SP, 0 => SP         ;
l0:
  i2i BP => SP             ; epilogue
  pop BP                   ;
  return                   ;

main:
  push BP                  ; prologue
  i2i SP => BP             ;
  addI SP, 0 => SP         ;
  call foo
  addI SP, 0 => SP
  loadI 0 => r0
  i2i r0 => RET
  jump l1
l1:
  i2i BP => SP             ; epilogue
  pop BP                   ;
  return                   ;
```

Example

```
def int add(int x, int y)
{
    int sum;
    sum = x + y;
    return sum;
}

def int main()
{
    return add(3, 7);
}
```

```
add:
  push BP                    ; prologue
  i2i SP => BP               ;
  addI SP, -8 => SP          ;
  loadAI [BP+16] => r0       ; load param x
  loadAI [BP+24] => r1       ; load param y
  add r0, r1 => r2
  storeAI r2 => [BP-8]       ; store local sum
  loadAI [BP-8] => r3        ; load local sum
  i2i r3 => RET
  jump l0
l0:
  i2i BP => SP               ; epilogue
  pop BP                     ;
  return                     ;

main:
  push BP                    ; prologue
  i2i SP => BP               ;
  addI SP, 0 => SP           ;
  loadI 3 => r4
  loadI 7 => r5
  push r5                    ; precall
  push r4                    ;
  call add
  addI SP, 16 => SP          ; postreturn
  i2i RET => r6
  i2i r6 => RET
  jump l1
l1:
  i2i BP => SP               ; epilogue
  pop BP                     ;
  return                     ;
```

PL Design Issues

- There are many procedure-related design questions; decisions are made by language designers w/ impacts on compiler writers
- How are name spaces defined?
  - Lexical (static) vs. dynamic scope
  - Parent scope determined by code vs. call order
- How are formal/actual parameters associated?
  - Positionally, by name, or both?
- Are parameter default values allowed?
  - For all parameters or just the last one(s)?
- Are method parameters type-checked?
  - Statically or dynamically?

PL Design Issues

- Can procedures be passed as parameters?
  - How is this implemented? (e.g., with *closures*)
- Can procedures be *nested*?
  - *Lexical* or *dynamic* scoping?
- Can procedures be *polymorphic*?
  - Ad-hoc/manual, subtype, or parametric/generic?
- Can method calls be resolved at runtime?
  - *Static* vs. *dynamic* dispatch (and *single* vs. *multiple* dispatch)
- Are function side effects allowed?
- Can a function return multiple values?

Object-Oriented Languages

- Classes vs. objects
- Inheritance relationships (subclass/superclass)
  - Single vs. multiple inheritance
- Closed vs. open class structure
- Visibility: public vs. private vs. protected
- Static vs. dynamic dispatch (and single vs. multiple)
- Object-records and virtual method tables

Miscellaneous Topics

- Macros
  - Call-by-name, “executed” at compile time
  - Often provide call-by-name semantics
- Closures
  - A procedure and its referencing environment
  - Requires a more general structure than the stack
- Just-in-time (JIT) compilation
  - Defer compilation of each function until it is called
  - New chapter in EAC3e!

Heap Management

- Desired properties
  - Space efficiency
  - Exploitation of locality (time and space)
  - Low overhead
- Allocation (malloc/new)
  - First-fit vs. best-fit vs. next-fit
  - Coalescing free space (defragmentation)
- Manual deallocation (free/delete)
  - Dangling pointers
  - Memory leaks

Automatic De-allocation

- Criteria: overhead, pause time, space usage, locality impact
- Basic problem: finding reachable structures
  - Root set: static and stack pointers
  - Recursively follow pointers through heap structures
- Reference counting (incremental)
  - Memory/time overhead to track the number of active references to each structure
  - Catch the transition to unreachable (count becomes zero)
  - Has trouble with cyclic data structures
- Mark-sweep (batch-oriented)
  - Occasionally pause and detect unreachable structures
  - High time overhead and potentially undesirable "pause the world" semantics
  - Partial collection: collect only a subset of memory on each run
  - Generational collection: collect newer objects more often