CS412/413

Introduction to Compilers
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Lecture 19: X86 Code Generation
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Calling Sequences

- How to generate the code that builds the frames?
- Generate code which pushes values on stack:
  1. Before call instructions (caller responsibilities)
  2. At function entry (callee responsibilities)
- Generate code which pops values from stack:
  3. After call instructions (caller responsibilities)
  4. At return instructions (callee responsibilities)
- Calling sequences = sequences of instructions performed in each of the above 4 cases

Push Values on Stack

- Code before call instruction:
  - Push caller-saved registers
  - Push each actual parameter (in reverse order)
  - Push static link (if necessary)
  - Push return address (current program counter) and jump to caller code
- Prologue = code at function entry
  - Push dynamic link (i.e. current fp)
  - Old stack pointer becomes new frame pointer
  - Push local variables
  - Push callee-saved registers

Pop Values from Stack

- Epilogue = code at return instruction
  - Pop (restore) callee-saved registers
  - Restore old stack pointer (pop callee frame!)
  - Pop old frame pointer
  - Pop return address and jump to that address
- Code after call
  - Pop (restore) caller-saved registers
  - Pop parameters from the stack
  - Use return value

Example: X86

- Consider call `foo(3, 5)`, %ecx caller-saved, %ebx callee-saved, no static links, result passed back in %eax
- Code before call instruction:

```
push %ecx   // push caller saved registers
push $5     // push first parameter
push $3     // push second parameter
call _foo   // push return address, jump to callee
```

- Prologue:

```
push %ebp       // push old fp
mov %esp, %ebp  // compute new fp
sub $12, %esp   // push 3 integer local variables
push %ebx       // push callee saved registers
```


Example: X86

- Epilogue:

```
pop %ebx      // restore callee-saved registers
mov %ebp,%esp // pop callee frame, including locals
pop %ebp      // restore old fp
ret           // pop return address and jump
```

- Code after call instruction:

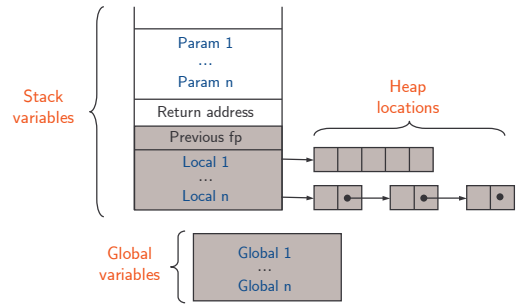
```
add $8,%esp   // pop parameters
pop %ecx      // restore caller-saved registers
```

Simple Code Generation

- Three-address code makes it easy to generate assembly
  - Complex expressions in the input program already lowered to sequences of simple IR instructions
  - Just need to translate each low IR instruction into a sequence of assembly instructions

    e.g. `a = p+q` ⇒
    ```
    mov 16(%ebp), %ecx
    add 8(%ebp), %ecx
    mov %ecx, -8(%ebp)
    ```
- Need to consider many language constructs:
  - Operations: arithmetic, logic, comparisons
  - Accesses to local variables, global variables
  - Array accesses, field accesses
  - Control flow: conditional and unconditional jumps
  - Method calls, dynamic dispatch
  - Dynamic allocation (new)
  - Run-time checks

Memory Layout



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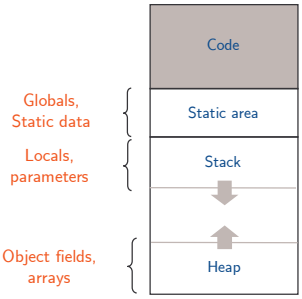
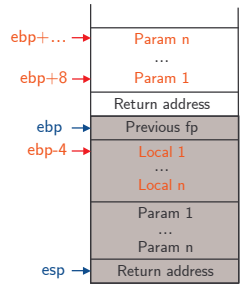


Accessing Stack Variables

- To access stack variables: use offsets from ebp
- Example:
  8(%ebp) = parameter 1
  12(%ebp) = parameter 2
  -4(%ebp) =local 1



Accessing Stack Variables

- Translate accesses to variables:
  - For parameters, compute offset from %ebp using:
    - Parameter number
    - Sizes of other parameters
  - For local variables, decide upon data layout and assign offsets from frame pointer to each local
  - Store offsets in the symbol table
- Example:
  - a: local, offset –4
  - p: parameter, offset +16, q: parameter, offset +8
  - Assignment a = p + q becomes equivalent to:
    ```
    -4(%ebp) = 16(%ebp) + 8(%ebp)
    ```
  - How do we write this in assembly?

Arithmetic

- How to translate: p+q ?
  - Assume p and q are locals or parameters
  - Determine offsets for p and q
  - Perform the arithmetic operation
- Problem: the ADD instruction in x86 cannot take both operands from memory; notation for possible operands:
  - mem32: memory 32 bit (similar for mem8, mem16)
  - reg32: register 32 bit (similar for reg8, reg16)
  - r/m32: register or memory 32 bit (similar for r/m8, r/m16)
  - imm32: immediate 32 bit (similar for imm8, imm16)
  - At most one operand can be mem !
- Translation requires using an extra register
  - Place p into a register (e.g. %ecx): `mov 16(%ebp), %ecx`
  - Perform addition of q and %ecx: `add 8(%ebp), %ecx`

Data Movement

- Translate a = p+q:
  - Load memory location (p) into register (%ecx) using a move instr.
  - Perform the addition
  - Store result from register into memory location (a):

```
mov 16(%ebp), %ecx      (load)
add 8(%ebp), %ecx       (arithmetic)
mov %ecx, -8(%ebp)      (store)
```

- Move instructions cannot take both operands from memory
  Therefore, copy instructions must be translated using a an extra register:

```
a = p   ⇒mov 16(%ebp), %ecx
         mov %ecx, -8(%ebp)
```

- However, loading constants doesn't require extra registers:

```
a = 12  ⇒mov $12, -8(%ebp)
```


Accessing Global Variables

- Global (static) variables are not allocated on the run-time stack
- Have fixed addresses throughout the execution of the program
  - Compile-time known addresses (relative to the base address where program is loaded)
  - Hence, can directly refer to these addresses using symbolic names in the generated assembly code
- Example: string constants

```
str:  .string  "Hello world!"
```

  - The string will be allocated in the static area of the program
  - Here, "str" is a label represting the address of the string
  - Can use $str as a constant in other instructions:

```
push $str
```


Accessing Heap Data

- Heap data allocated with new (Java) or malloc (C/C++)
  - Such allocation routines return address of allocated data
  - References to data stored into local variables
  - Access heap data through these references
- Array accesses in Java
  - access a[i] requires:
    - To compute address of element: a + i * size
    - And access memory at that address
  - Can use indexed memory accesses to compute addresses
  - Example: assume size of array elements is 4 bytes, and local variables a, i (offsets –4, -8)

```
a[i] = 1 ➡  mov –4(%ebp), %ebx          (load a)
            mov –8(%ebp), %ecx          (load i)
            mov $1, (%ebx,%ecx,4)       (store into the heap)
```


Control-Flow

- Label instructions
  - Simply translated as labels in the assembly code
  - E.g., `label2:  mov $2, %ebx`
- Unconditional jumps:
  - Use jump instruction, with a label argument
  - E.g., `jmp label2`
- Conditional jumps:
  - Translate conditional jumps using test/cmp instructions:
  - E.g., `tjump b L`

```
cmp %ecx, $0
jnz L
```

  where %ecx hold the value of b, and we assume booleans are represented as 0=false, 1=true

Run-time Checks

- Run-time checks:
  - Check if array/object references are non-null
  - Check if array index is within bounds
- Example: array bounds checks:
  - if v holds the address of an array, insert array bounds checking code for v before each load (...=v[i]) or store (v[i] = ...)
  - Assume array length is stored just before array elements:

```
cmp $0, -12(%ebp)          (compare i to 0)
jl ArrayBoundsError        (test lower bound)
mov –8(%ebp), %ecx         (load v into %ecx)
mov –4(%ecx), %ecx         (load array length into %ecx)
cmp –12(%ebp), %ecx        (compare i to array length)
jle ArrayBoundsError       (test upper bound)
...
```


X86 Assembly Syntax

- Two different notations for assembly syntax:
  - AT&T syntax and Intel syntax
  - In the examples: AT&T syntax
- Summary of differences:

	AT&T	Intel
Order of operands	op a, b : b is destination	op a, b : a is destination
Memory addressing	disp(base,offset,scale)	[base + offset*scale + disp]
Size of memory operands	instruction suffixes (b,w,l) (e.g., movb, movw, movl)	operand prefixes (byte ptr, word ptr, dword ptr)
Registers	%eax, %ebx, etc.	eax, ebx, etc.
Constants	$4, $foo, etc	4, foo, etc