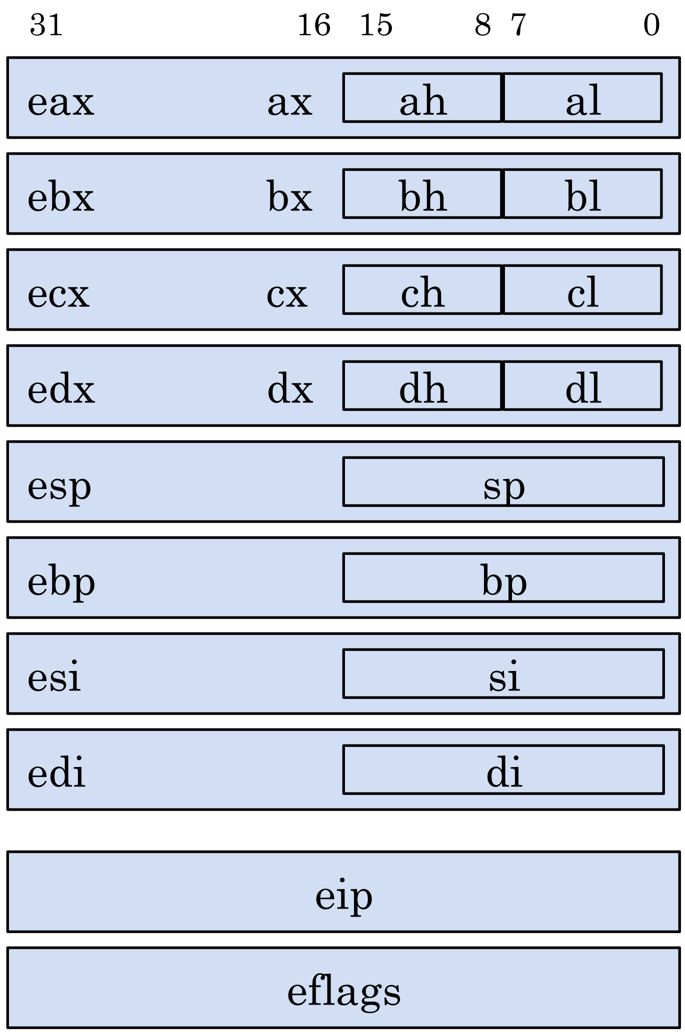
CS24: Introduction to Computing Systems

Spring 2015

Lecture 5

LAST TIME

- Began our tour of the IA32 instruction set architecture
- IA32 provides 8 general-purpose registers
  - eax, ebx, ecx, edx are used for general operations
  - esp is the stack pointer, ebp is the frame pointer (a.k.a. “base pointer”)
  - esi, edi used for string operations
- Two additional registers:
  - eip is the instruction pointer
  - eflags contains status flags



IA32 Instructions

- Instructions follow this pattern:
  - *opcode* *operand*, *operand*, …
- Examples:
  - **`add $5, %ax`**
  - **`mov %ecx, %edx`**
  - **`push %ebp`**
- **Important note!**
  - Above assembly-code syntax is called AT&T syntax
  - GNU assembler uses this syntax by default
  - Intel IA32 manuals, other assemblers use Intel syntax
- Some big differences between the two formats!
  - **`mov %ecx, %edx # AT&T: Copies ecx to edx`**
  - **`mov edx, ecx # Intel: Copies ecx to edx`**

IA32 Instructions (2)

- Some general categories of instructions:
  - Data movement instructions
  - Arithmetic and logical instructions
  - Flow-control instructions
  - (many others too, e.g. floating point, SIMD, etc.)

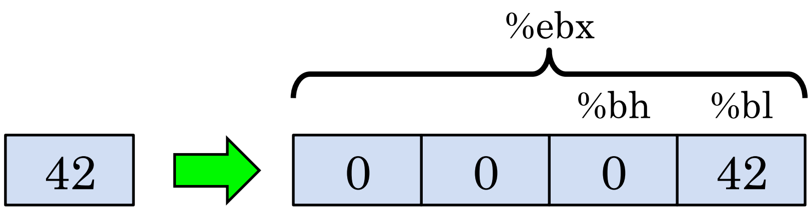
- Data movement:
  - **`mov`** Move data value from source to destination
  - **`movs`** Move value with sign-extension
  - **`movz`** Move value with zero-extension
  - **`push`** Push value onto the stack
  - **`pop`** Pop value off of the stack

IA32 Data Movement Instructions

- Data movement instructions can specify a suffix to indicate size of operand(s)
  - b = byte, w = word, l = doubleword, q = quadword
- Some instructions work with one data size:
  - **`movl  %ecx, %edx`**
    - Moves doubleword (4 byte) register **`ecx`** into **`edx`**
  - **`pushb %al`**
    - Pushes register **`al`** (1 byte) onto stack
- Move with sign/zero extension takes two sizes:
  - **`movsbl %al, %edx`**
    - Moves byte **`al`** into doubleword (4 bytes) register **`edx`**, extending sign-bit of value into remaining bytes
  - **`movzwq %cx, %rax`**
    - Moves word (2 bytes) **`cx`** into quadword (8 bytes) register **`rax`**, zeroing out higher-order bytes in destination

IA32 Operand Types

- Many different operand types and combinations supported by IA32 instruction set
- Immediate values – numeric constants:
  - Must specify **`$`** prefix to use a numeric constant
  - **`$5`**, **`$-37`**, **`$0xF005B411`**
- Registers:
  - Specify **`%`** prefix on register name
  - **`%ebp`**, **`%eax`**, **`%rcx`**
- Example:
  - **`movl $42, %ebx`**
    - Moves the value 42_{10} into ebx register



IA32 Memory-Reference Operands

- IA32 has very rich support for memory references
  - Denote memory access as M[Address]
- Absolute memory access
  - Immediate value with no **`$`** prefix
  - **`movl 0xE700, %edx`**
    - Retrieves memory value M[0xE700] into **`edx`**
- Indirect memory access
  - Register name, enclosed with parens: **`(Reg)`**
  - **`movw %cx, (%ebx)`**
    - Stores word (2 bytes) in **`%cx`** into memory location M[**`%ebx`**]
- Base + displacement memory access
  - **`Imm(Reg)`** accesses M[Imm + Reg]
  - **`movl -8(%ebp), %eax`**
    - Retrieves dword M[-8 + **`%ebp`**] into **`%eax`**
    - (Presumably, **`%ebp`** – 8 > 0)

IA32 Memory-Reference Operands (2)

- Indexed memory access
  - **`(RegB, RegI)`** accesses M[RegB + RegI]
    - RegB is the base (i.e. starting) address of a memory array
    - RegI is an index into the memory array
  - **`Imm(RegB, RegI)`** accesses M[Imm + RegB + RegI]
  - Assumes that array elements are bytes
- Examples:
  - **`%eax`** = 150, **`%ebx`** = 400
  - **`movl (%eax, %ebx), %edx`**
    - Retrieves value at M[150 + 400] = M[550] into **`edx`**
  - **`movl %ecx, -200(%ebx, %eax)`**
    - Stores **`ecx`** into location M[-200 + 400 + 150] = M[350]

IA32 Memory-Reference Operands (3)

- Scaled indexed memory access
  - With scale factor s = 1, 2, 4, 8:
  - **`(, Reg, s)`** M[Reg × s]
  - **`Imm(, Reg, s)`** M[Imm + Reg × s]
  - **`(RegB, RegI, s)`** M[RegB + RegI × s]
  - **`Imm(RegB, RegI, s)`** M[Imm + RegB + RegI × s]
  - For arrays with elements that are 1/2/4/8 bytes
- Examples:
  - **`%eax`** = 150, **`%ebx`** = 400
  - **`movl (, %eax, 4), %edx`**
    - Retrieves value at M[150×4] = M[600] into **`edx`**
  - **`movl %ecx, 350(%ebx, %eax, 2)`**
    - Stores **`ecx`** into M[350 + 400 + 150×2] = M[1050]

IA32 Memory-Reference Summary

- Summary chart, from IA32 manual:

Base	+	Index	×	Scale	+	Displacement
eax **ebx** **ecx** **edx** **esp** **ebp** **esi** **edi**	+	**eax** **ebx** **ecx** **edx** *(<u>not</u>* ***esp!****)* **ebp** **esi** **edi**	×	1 2 4 8	+	None 8-bit 16-bit 32-bit

  - Base, Index, Displacement are all optional
  - Scale is only allowed when Index is specified
  - Note that **esp** can only be used as a base value, but never as an index value

IA32 OPERAND COMBINATIONS

- Important constraints on combinations of operand types
- Source argument can be:
  - Immediate, Register, Memory (direct or indirect)
- Destination argument can be:
  - Register, Memory (direct or indirect)
- Both arguments cannot be memory references
  - To move data from one memory location to another, must move Mem1 → Register, then Register → Mem2

- These constraints apply to data movement instructions, and most other instructions too

IA32 Arithmetic/Logical Operations

- Unary arithmetic/logical operations:
  - `inc Dst` — Dst = Dst + 1
  - `dec Dst` — Dst = Dst – 1
  - `neg Dst` — Dst = –Dst
  - `not Dst` — Dst = ~Dst
- Binary arithmetic/logical operations:
  - `add Src, Dst` — Dst = Dst + Src
  - `sub Src, Dst` — Dst = Dst – Src
  - `xor Src, Dst` — Dst = Dst ^ Src
  - `or Src, Dst` — Dst = Dst | Src
  - `and Src, Dst` — Dst = Dst & Src
- Specify byte-width of operands via suffixes, as usual
  - `decb %cl`
    - Decrements the 1-byte value in **cl** register
  - `addl 4(%ebp), %eax`
    - Adds M[4 + **ebp**] to contents of **eax**

IA32 Shift Operations

- Shift operations:
  - **`shl   k, Dst`** Dst = Dst << k
  - **`shr   k, Dst`** Dst = Dst >> k (logical)
  - **`sal   k, Dst`** Dst = Dst << k
  - **`sar   k, Dst`** Dst = Dst >> k (arithmetic)
  - **`shl`**, **`sal`** are identical
  - **`k`** is a constant, or **`%cl`** register
  - Can only shift values by up to 32 bits
    - …even when Dst is a 64-bit register!

- Also rotate operations
  - See docs for **`rol`**, **`ror`**, **`rcl`**, **`rcr`**
  - Similar form, constraints as shift operations

IA32 Multiply, Divide Operations

- Multiplication and division are more challenging
  - 32-bit value × 32-bit value = 64-bit value
  - 64-bit value ÷ 32-bit value = 32-bit quotient,
    32-bit remainder
- Two-argument multiplication:
  - **`imul Src, Dst`**
  - Use width modifier, as usual: **`imull (%ebx), %ecx`**
  - For Src, Dst of bit-width w, produces result also of width w
  - Dst = (Src × Dst) **mod** 2^w
- Also three-argument multiplication:
  - **`imul Src1, Src2, Dst`**
  - Dst = (Src1 × Src2) **mod** 2^w

IA32 Multiply, Divide Operations (2)

- One-argument multiplication:
  - **`imull Src`** – 32-bit signed multiplication
    - **`edx:eax`** = Src × **`eax`**
    - **`edx`** is top 4 bytes of result, **`eax`** is bottom 4 bytes of result
  - **`mull Src`** – 32-bit unsigned multiplication
- One-argument division:
  - **`idivl Src`** – 32-bit signed division
    - **`eax`** = **`edx:eax`** ÷ Src
    - **`edx`** = **`edx:eax`** **mod** Src
  - **`divl Src`** – 32-bit unsigned division
- Can use **`cltd`** to set up **`edx:eax`** for division
  - **`cltd`** – "convert long-word to double-word"
    - Sign-extends **`eax`** into **`edx`**, creating **`edx:eax`**
    - **Note:** in Intel manual, this instruction is called **`cdq`**

IA32 Multiply, Divide Operations (3)

- Can perform multiplication and division on varying input widths, too
- Examples:
  - **`imulw Src`** – 16-bit signed multiplication
    - **`dx:ax`** = Src × **`ax`**
  - **`idivb Src`** – 8-bit signed division
    - **`al`** = **`ax`** ÷ Src
    - **`ah`** = **`ax` mod** Src
- Also variants of **`cltd`** to set up for division on different input widths
  - **`cbtw`** – sign-extends al into ax
  - **`cwtl`** – sign-extends ax into eax
  - **`cwtd`** – sign-extends ax into dx:ax

IA32 Multiply/Divide Examples

- Values:
  - x at location **`8(%ebp)`**, y at location **`12(%ebp)`**
  - Both signed values, doublewords (4 bytes)
- Compute signed product of x and y

```
movl 8(%ebp), %eax     # eax = x
imull 12(%ebp)         # edx:eax = x * y
pushl %edx             # Save 64-bit result
pushl %eax             #     onto stack.
```

- Compute signed quotient and remainder of x ÷ y

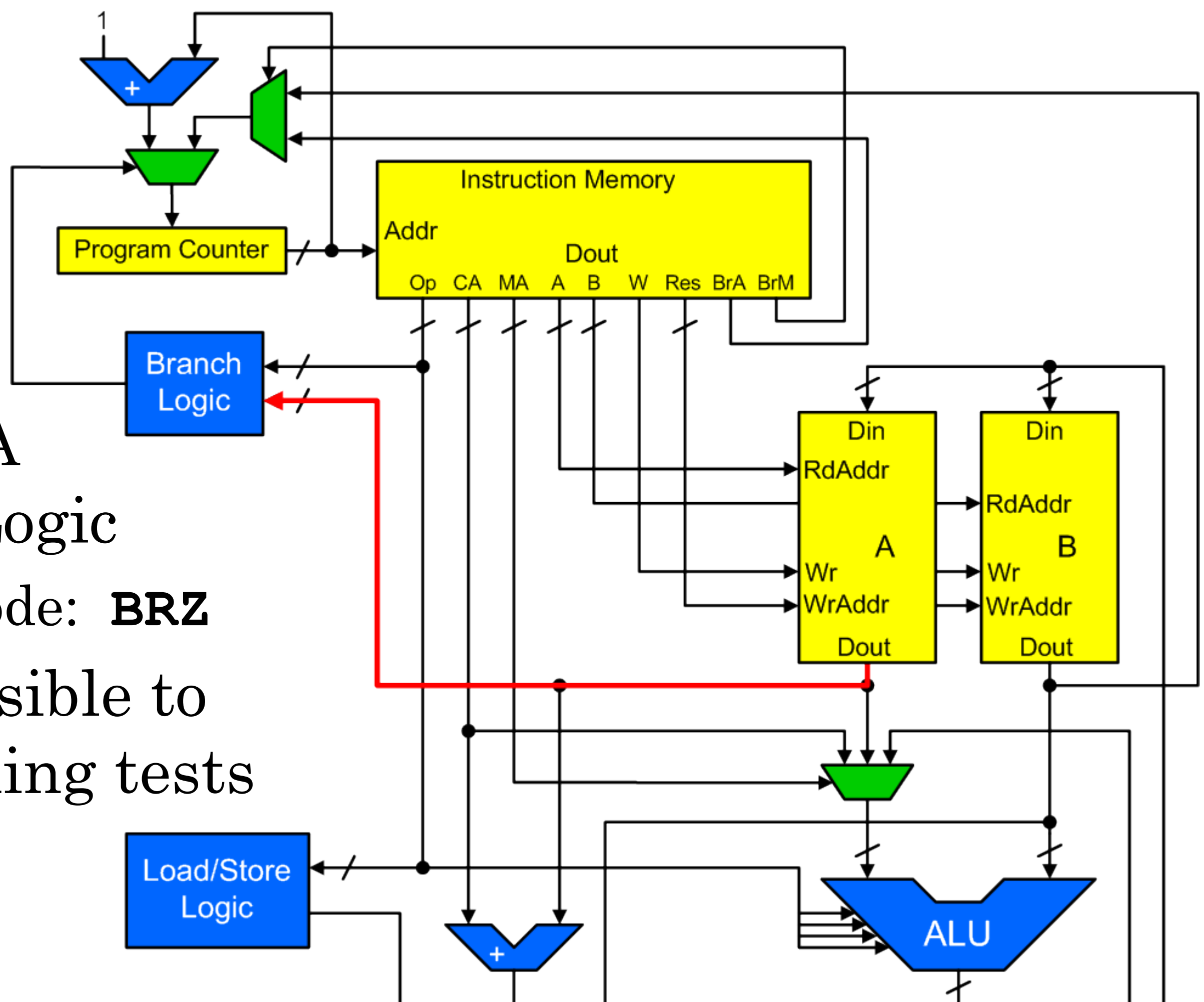
```
movl 8(%ebp), %eax     # eax = x
cltd                   # edx:eax = x
idivl 12(%ebp)         # Compute x / y
pushl %eax             #     eax = quotient
pushl %edx             #     edx = remainder
```

IA32 Flow-Control Instructions

- Many different instructions for branching in IA32
- Simplest version: unconditional jump
  - **`jmp Label`** Direct jump to address
  - **`jmp *Operand`** Indirect jump to address
    - **`jmp *%eax`** – jumps to address stored in **`eax`**
    - **`jmp *(%eax)`** – jumps to address stored at M[**`eax`**]
  - Can use indirect addressing with unconditional jumps! Very useful in many situations:
    - Implementing switch statements: jump tables
    - Object oriented programming: virtual function ptr tables
    - Other flow-control mechanisms in high-level languages
- Other jumps are <u>conditional</u> jumps
  - Jump occurs based on flags in eflags status register

Branch Logic, Conditional Jumps

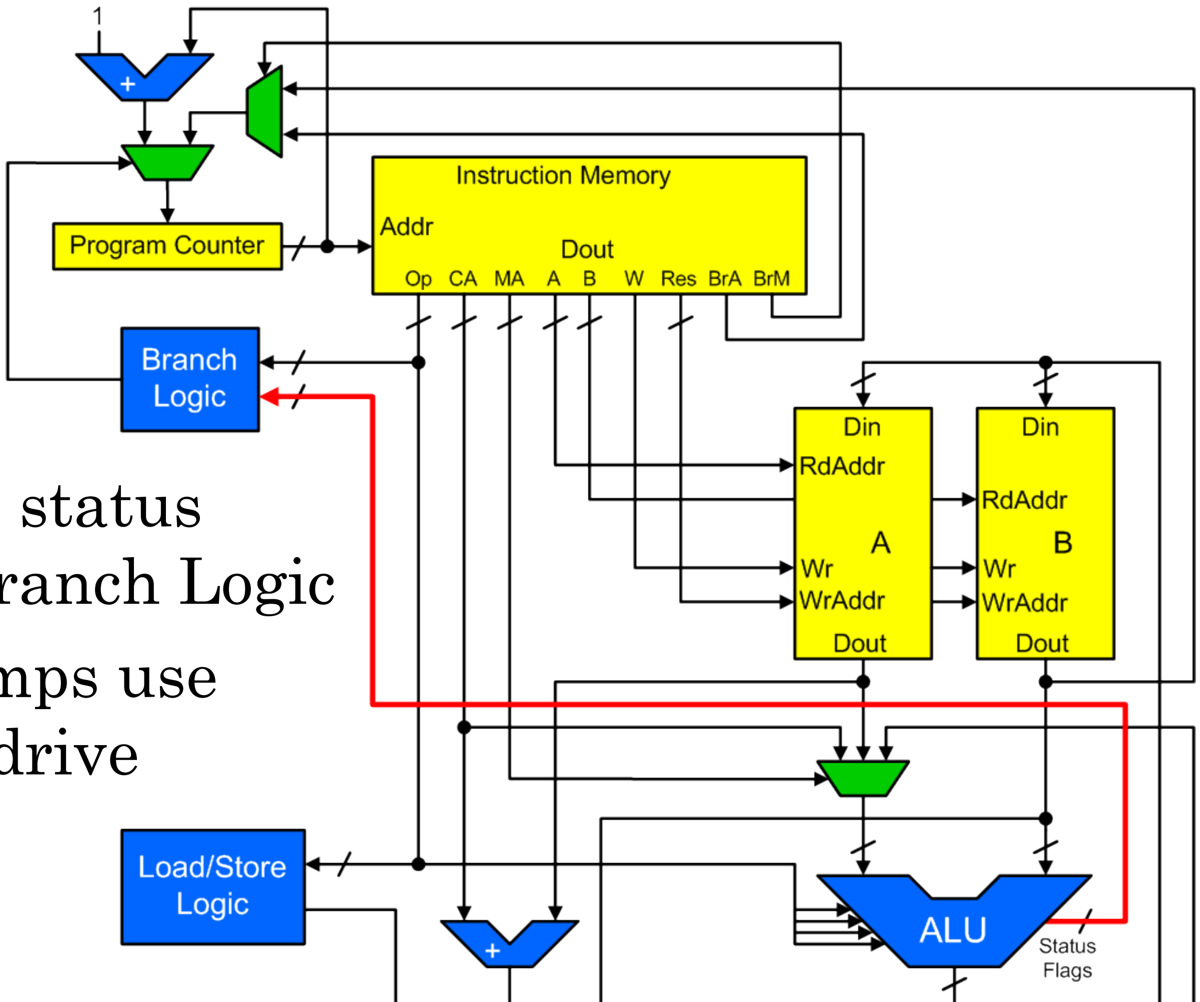
- Previous branching logic:



- Fed output of A to Branching Logic
  - Have one opcode: **BRZ**
- Not very extensible to general branching tests

Branch Logic, Conditional Jumps (2)

- More powerful branching logic:



- ALU generates status flags; feed to Branch Logic
- Conditional jumps use status flags to drive branching

IA32 Conditional Operations

- Status bits in **`eflags`** register:
  - CF = carry flag (1 indicates unsigned overflow)
  - SF = sign flag (1 = result is negative)
  - OF = overflow flag (1 indicates signed overflow)
  - ZF = zero flag (1 = result is zero)
- Conditional jump instructions use these flags to control program flow
- <u>All</u> arithmetic and logical operations set these flags
  - Good to know how these instructions affect above flags!
- Can also update these flags with **`cmp`**, **`test`**
  - **`cmp Src2, Src1`**
    - Updates flags as for Src1 – Src2 (i.e. **`sub Src2, Src1`**)
  - **`test Src2, Src1`**
    - Updates flags as for Src1 & Src2 (i.e. **`and Src2, Src1`**)
  - Src1, Src2 are <u>unchanged</u> by comparison/test operation
  - Can specify size prefixes, as usual: **`cmpl %ecx, $0`**

IA32 Conditional Jumps

- Conditional jumps can only use a label
  - Can't specify an indirect conditional jump
- Some operations:
  - **`je Label`** "Jump if equal" (ZF = 1)
  - **`jne Label`** "Jump if not equal" (ZF = 0)
    - **`sub Src2, Src1`** produces zero result if Src1 == Src2
    - **`cmp Src2, Src1`** sets zero-flag in this case
  - **`js Label`** "Jump if sign" (SF = 1)
  - **`jns Label`** "Jump if not sign" (SF = 0)
    - Jump if answer is negative (SF = 1) or nonnegative (SF = 0)
  - **`jc/jnc Label`** "Jump if [not] carry"
    - Unsigned overflow tests
  - **`jo/jno Label`** "Jump if [not] overflow"
    - Signed overflow tests

IA32 Signed Conditional-Jumps

- **`jg Label`** "Jump if greater" (signed >)
  - **`jnle`** is synonym – "Jump if not less or equal"
  - All comparison opcodes have synonyms like this
- Also:
  - **`jge`** Jump if greater or equal
  - **`jl`** Jump if less
  - **`jle`** Jump if less or equal
- These look at sign flag, overflow flag, zero flag
  - Remember: OF = signed overflow, CF = unsigned overflow
  - ZF indicates if Src1 == Src2 (Src2 – Src1 == 0)
  - SF + OF indicate whether Src2 – Src1 > 0 or < 0 (when nonzero)
    - Logic is slightly involved; see CS:APP §3.6.2 for details

IA32 Unsigned Conditional-Jumps

- Unsigned comparisons are similar:
  - **`ja Label`** “Jump if above” (unsigned >)
    - **`jnbe`** is synonym – “Jump if not below or equal”
  - Also:
    - **`jae`** Jump if above or equal
    - **`jb`** Jump if below
    - **`jbe`** Jump if below or equal
  - These look at carry flag and zero flag
    - CF indicates whether unsigned overflow occurred from Src2 – Src1
    - If Src2 – Src1 generates unsigned overflow, (CF = 1) then Src2 < Src1
    - Again, ZF indicates if Src1 == Src2

IA32 Conditional-Set Instructions

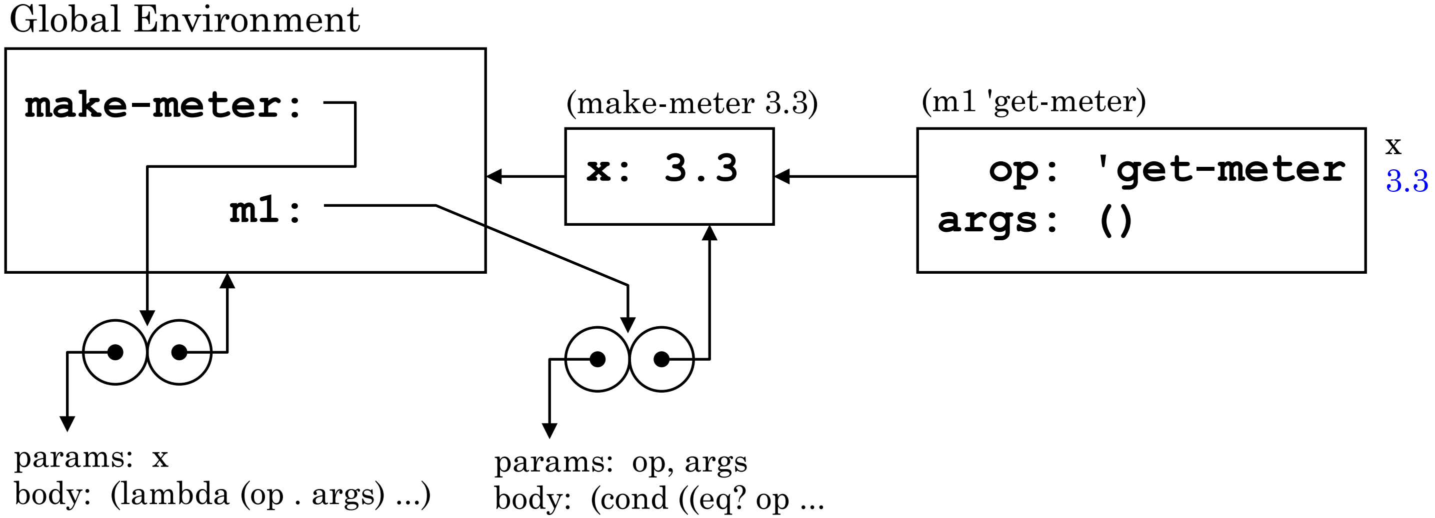
- Also a variety of conditional-set instructions
- Examples:
  - **`sete Dst`** "Set if equal"
    - Stores ZF into 8-bit target Dst
    - Result is 0 or 1
    - Synonym: **`setz`** "Set if zero"
  - Others:
    - **`sets/setns Dst`** "Set if sign" / "Set if not sign"
    - **`setg Dst`** "Set if greater" (signed >)
    - **`setl Dst`** "Set if less" (signed <)
    - **`seta Dst`** "Set if above" (unsigned >)
    - **`setb Dst`** "Set if below" (unsigned <)
    - etc. (same as for conditional-jump instructions)
- All instructions modify a single 8-bit destination

But Wait, There's More!

- Really only scratched the surface of IA32
  - Covered a lot of what you will see in CS24…
  - …but there's a *lot* more where that came from!
- The book reading for Week 2 covers several more instructions, and goes into greater detail
  - Chapter 3 – 3.7
- If you see an instruction you don't recognize, look it up in the IA32 manuals (provided on Moodle)
  - If it still doesn't make sense, ask Donnie or a TA ☺

More Advanced Language Features

- Last time, introduced higher-level abstractions
  - Subroutines, the stack, stack frames, frame pointers
- Many different languages, calling conventions, computational models to choose from!
  - e.g. Scheme environment model allows functions to be created and passed around dynamically
  - When an environment or function is no longer used, it is garbage collected automatically



C Functions

- Start with a simple abstraction: C functions
  - Relatively simple computational model
  - No trapped frames, no lambdas, no garbage collection
- Pretty easy to implement with IA32 assembly

- To implement subroutines (tasks from last time):
  - Need a way to pass arguments and return values between caller and subroutine
  - Need a way to transfer control from caller to subroutine, then return back to caller
  - Need to isolate subroutine's state from caller's state

EXAMPLE C PROGRAM

- A simple accumulator:
- Uses a global variable to store current value
- Functions to update accumulator, or reset it
- Main function to exercise the accumulator

- Three kinds of variables
  - Global variables
  - Function arguments
  - Local variables

```
int value;

int accum(int n) {
  value += n;
  return value;
}

int reset() {
  int old = value;
  value = 0;
  return old;
}

int main() {
  int i, n;

  reset();
  for (i = 0; i < 10; i++) {
      n = rand() % 1000;
      printf("n = %d\taccum = %d\n",
             n, accum(n));
  }
  return 0;
}
```

Example C Program (2)

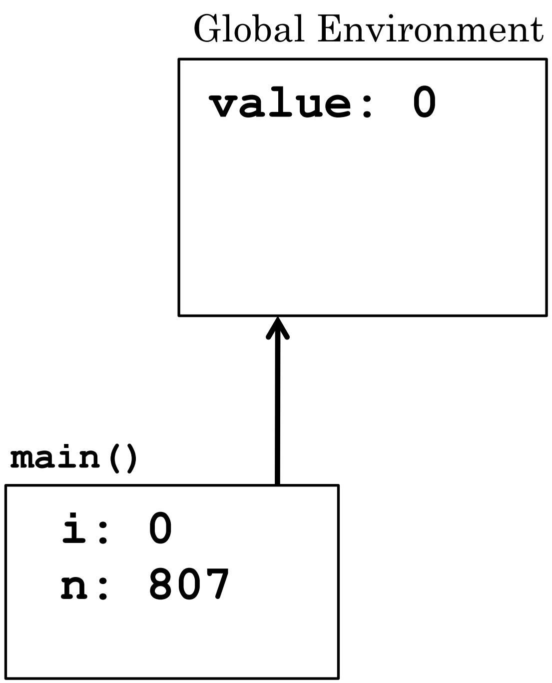
- Three kinds of variables
  - Global variables
  - Function arguments
  - Local variables

- C computational model:
  - *(approximately…)*
  - A global environment at the top level
  - When a function is called, a new environment is created to hold args, local variables
  - All functions in the file can access the contents of the global environment

```
int value;

int accum(int n) {
  value += n;
  return value;
}

int reset() {
  int old = value;
  value = 0;
  return old;
}

int main() {
  int i, n;

  reset();
  for (i = 0; i < 10; i++) {
      n = rand() % 1000;
      printf("n = %d\taccum = %d\n",
             n, accum(n));
  }
  return 0;
}
```

Example C Program (3)

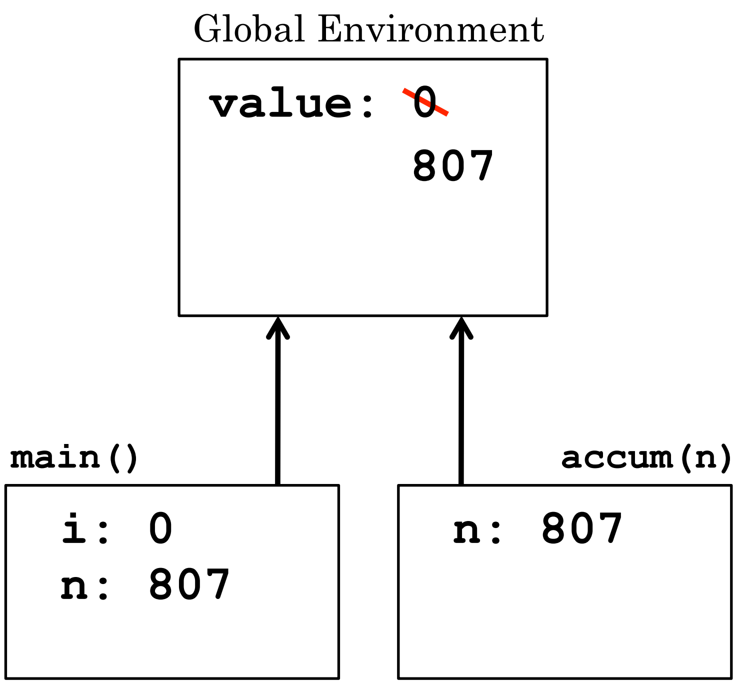
- After **`reset()`** call:
  - Also, **`rand()`** has returned 807




```
int value;

int accum(int n) {
  value += n;
  return value;
}

int reset() {
  int old = value;
  value = 0;
  return old;
}

int main() {
  int i, n;

  reset();
  for (i = 0; i < 10; i++) {
      n = rand() % 1000;
      printf("n = %d\taccum = %d\n",
             n, accum(n));
  }
  return 0;
}
```

EXAMPLE C PROGRAM (4)

- **`accum(807)`** call:
  - Function invocation has its own local environment specifying n = 807




```c
int value;

int accum(int n) {
  value += n;
  return value;
}

int reset() {
  int old = value;
  value = 0;
  return old;
}

int main() {
  int i, n;

  reset();
  for (i = 0; i < 10; i++) {
      n = rand() % 1000;
      printf("n = %d\taccum = %d\n",
             n, accum(n));
  }
  return 0;
}
```

Representing C Model

- Global variables
  - Store at specific location
  - Reference via absolute address
- Function arguments
  - Store on stack
  - Pushed by caller before invoking subroutine
  - IA32: frame pointer *plus* some offset
- Local variables
  - Also store on stack
  - Subroutine manages space for these variables
  - IA32: frame pointer *minus* some offset

```c
int value;

int accum(int n) {
  value += n;
  return value;
}

int reset() {
  int old = value;
  value = 0;
  return old;
}

int main() {
  int i, n;

  reset();
  for (i = 0; i < 10; i++) {
      n = rand() % 1000;
      printf("n = %d\taccum = %d\n",
             n, accum(n));
  }
  return 0;
}
```

IA32 Subroutine Calls

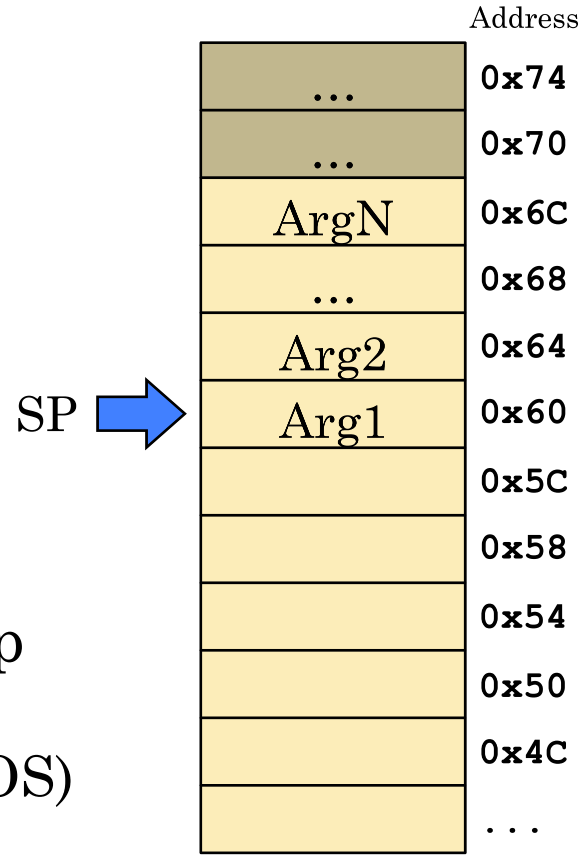
- IA32 provides specific features for subroutines
- Registers:
  - **`esp`** = stack pointer
    - Stack grows "downward" in memory
    - **`push`** decrements **`esp`**, then stores value to **`(%esp)`**
    - **`pop`** retrieves value at **`(%esp)`**, then increments **`esp`**
  - **`ebp`** = base pointer
    - IA32 name for frame pointer
- Instructions:
  - **`call Addr`**
    - Pushes **`eip`** onto stack (**`eip`** references *next* instruction)
    - Sets **`eip`** = Addr
  - **`ret`**
    - Pops top of stack into **`eip`**

IA32 Subroutine Calls and gcc

- Many different ways to organize stack frames!
- A calling convention is a particular way of passing information to/from a subroutine
- The *cdecl* convention is frequently used on x86 for C subroutines
- Both the procedure caller and the callee have to coordinate the operation!
  - Shared resources: the stack, the register file
- Calling convention specifies:
  - Who sets up which parts of the call
  - What needs to be saved, and by whom
  - How to return values back to the caller
  - Who cleans up which parts of the call

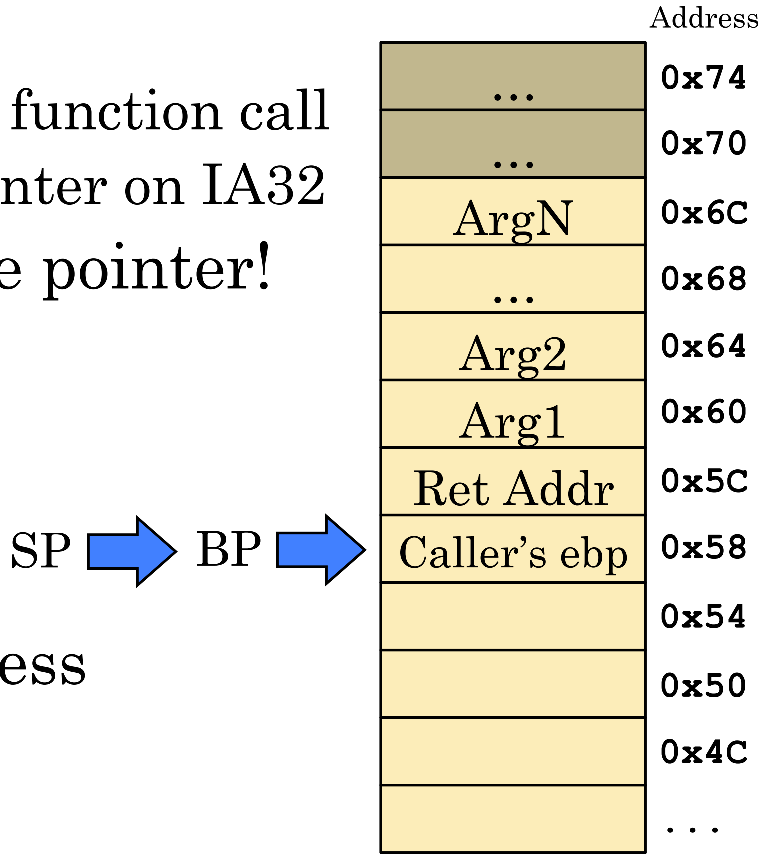
CDECL: Passing Arguments

- Caller is responsible for setting up arguments
- Arguments pushed onto stack in reverse order
  - Last argument is pushed first
  - 2nd argument pushed next-to-last
  - 1st argument is pushed last
- Two benefits:
  - Earlier arguments have a lower offset added to the frame pointer
  - If procedure is passed more args than it expects, it doesn't break the procedure's code
- Primitive values generally take up a doubleword (4 bytes) on stack
  - e.g. ints, floats, pointers (on 32-bit OS)



CDECL: INVOKING THE PROCEDURE

- Caller uses **`call`** to invoke the procedure
  - Pushes **`eip`** of *next* instruction onto the stack
- First task of callee:
  - Set up frame pointer for this function call
  - **`ebp`** is used for the frame pointer on IA32
- Must preserve caller's frame pointer!
- Typical code:
  - **`pushl %ebp`**
  - **`movl %esp, %ebp`**
- Now:
  - **`4(%ebp)`** = Return address
  - **`8(%ebp)`** = Arg1 value
  - **`12(%ebp)`** = Arg2 value



CDECL: Saving Registers

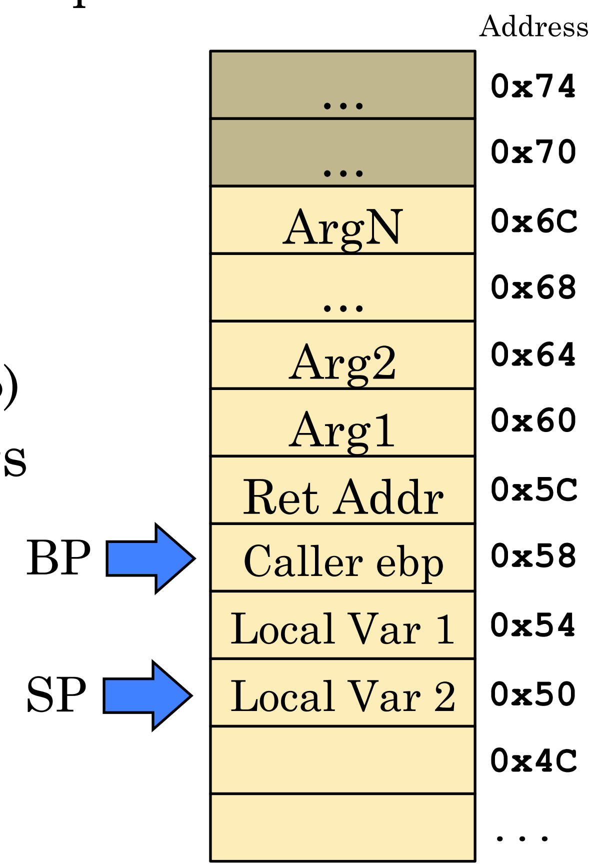
- "Callee must save **`ebp`** before it modifies it"
- A general issue:
  - The register file is a shared resource
  - Calling convention must specify how registers are managed
- Callee-save registers:
  - When callee returns, values *must* be same as when subroutine was invoked
  - **`ebp`**, **`ebx`**, **`esi`**, **`edi`** are callee-save registers
- Caller-save registers:
  - Callee may change these registers without saving them!
  - The *caller* must save these registers before the call, if the old values need to be preserved
  - **`eax`**, **`ecx`**, **`edx`** are caller-save registers

CDECL: RETURNING RESULTS

- For now, only consider simple results
  - e.g. **`int`** or pointer
- In these cases, callee returns the result in **`eax`**
  - Set **`eax`** to result, restore **`ebp`**, then return to caller
- Who removes the arguments from the stack??
- In cdecl, the *caller* cleans up stack
  - Linux / GNU calling convention
  - e.g. can add a constant to **`esp`** to remove arguments
- In stdcall (Win32), the *callee* cleans up stack
  - Microsoft Visual C++ calling convention
  - IA32 includes version of **`ret`** that takes an argument
  - **`ret n`**
    - Sets **`eip`** to **`(%esp)`**, then pops **`n`** bytes off stack

LOCAL VARIABLES

- Procedures sometimes need space for local variables
  - Compiler figures out how much space, from the source code
  - Sometimes allocates more than is strictly required
- Local variables reside just below the frame pointer
  - Accessed via **`-off(%ebp)`**
- Common pattern:
  - Allocate ***n*** bytes on stack for local vars
  - **`subl $n, %esp`** (or **`addl $-n, %esp`**)
- Example: allocate 8 bytes for local vars
  - **`subl $8, %esp`**
- **Note:** these memory locations are *not* initialized!
  - Contains whatever values were in that memory before the call…

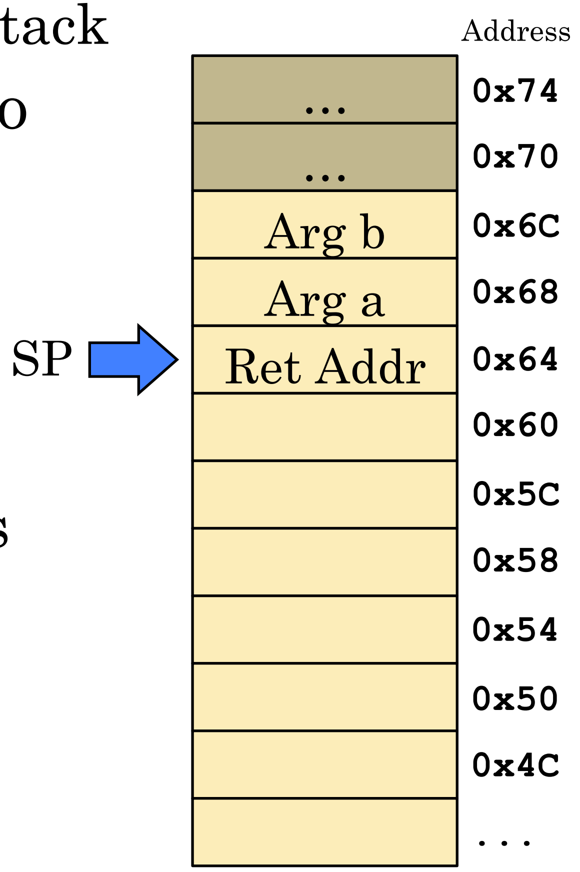


CDECL AND FRAME POINTER

- Note: subroutines don't *always* use **%ebp**
  - **%ebp** is primarily used when a function manages its own local state on the stack
- Example: a function that adds two values, and returns the result

```
int add(int a, int b) {
    return a + b;
}
```

  - Doesn't have any local variables!
- In this case, subroutine can access args **a** and **b** directly, via **%esp**:
  - **a** can be accessed via **4(%esp)**
  - **b** can be accessed via **8(%esp)**
  - Return address is at **(%esp)**



Next Time

- Look at how our simple C accumulator program is implemented in IA32 assembly language
  - Memory layout strategy for global variables, local variables, and arguments
  - **gcc** and the cdecl calling convention

- Begin to look at other C language features
  - C flow-control statements, and how they are translated into IA32 assembly