15-213

"The course that gives CMU its Zip!"

Machine-Level Programming I: Introduction Jan. 22, 2008

Topics

- Assembly Programmer's Execution Model
- Accessing Information
  - Registers
  - Memory
- Arithmetic operations

Synchronization

Lab 1

- Time roughly 50% done
- Many have started early and made good progress
  - Good
- Warning to others...
  - This isn't the same kind of thing you've done before
  - Please don't leave it to the last minute

Fish-machine log-ins

- Please let us know (staff mailing list) if you can't log in to any machine

Outline

Some computer languages

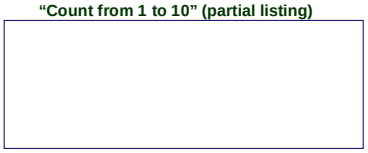
- Whitespace
- Intercal
- M

Some discussion of x86, x86-64

- Warning: Chapter 3 doesn't compress well
  - 100 pages of discussion about machine language
  - ... after 75 pages of data representation in Chapter 2
- Please plan to spend time reading the text!

A Whitespace Program

"Count from 1 to 10" (partial listing)



Features of Whitespace

- Only space, tab, and line-feed encode program statements
- All other characters (A-Z, a-z, 0-9, etc.) encode comments
- Simple stack-based language

Whitespace "Explained"

Statement	Meaning
[Space][Space][Space][Tab][LF]	Push 1 onto stack
[LF][Space][Space][Space][Tab][Space][Space][Space][Space][Tab][Tab][LF]	Set a label at this point
[Space][LF][Space]	Duplicate the top stack item
[Tab][LF][Space][Tab]	Output the current value
...	...

INTERCAL

Features of INTERCAL

- Designed late one night in 1972 by two Princeton students
- Deliberately obfuscated language

Variables

- 16-bit integers, .1 through .65535
- 32-bit integers, :1 through :65535

Operators

- Binary: "mingle", "select"
- Unary: AND, OR, XOR
  - How are those unary???
  - Simple: AND and's together adjacent bits in a word
- Simplest way to put 65536 in a 32-bit variable?
  - `DO :1 <- #0¢#256`

The language “M”

Features of M

- Also designed in the 1970's
- More widely used than Whitespace, INTERCAL

Variables

- 32-bit integer variables: A, B, C, D, DI, F, S, SI
- One array, M[]
  - Valid subscripts range from near zero to a large number
  - But most subscripts in that range will crash your program!

Statements

- Lots of arithmetic and logical operations
- Input and output use a special statement called OUCH!

A Program in M

C Code

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

M

```
sum:
   A = M[S+4]
   A += M[S+8]
   DONE
```


A Program in M

C Code

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

M

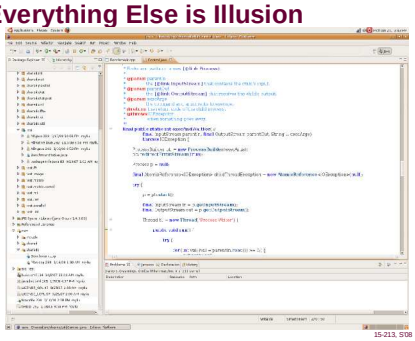
```
sum:
   A = M[S+4]
   A += M[S+8]
   DONE
```

Had enough of M?

- Too bad! We'll study it for much of the semester!
- Why???

M is “The Language of the Machines”

Everything Else is Illusion



IA32 Processors

Totally Dominate Computer Market

Evolutionary Design

- Starting in 1978 with 8086
- Added more features as time goes on
- Still support old features, although obsolete

Complex Instruction Set Computer (CISC)

- Many different instructions with many different formats
  - But, only small subset encountered with Linux programs
- Hard to match performance of Reduced Instruction Set Computers (RISC)
- But, Intel has done just that!

x86 Evolution: Programmer's View (Abbreviated)

Name	Date	Transistors
8086	1978	29K

- 16-bit processor. Basis for IBM PC & DOS
- Limited to 1MB address space. DOS only gives you 640K

386	1985	275K

- Extended to 32 bits. Added "flat addressing"
- Capable of running Unix
- Referred to as "IA32"
- 32-bit Linux/gcc uses no instructions introduced in later models

x86 Evolution: Programmer's View

Machine Evolution

486	1989	1.9M
Pentium	1993	3.1M
Pentium/MMX	1997	4.5M
PentiumPro	1995	6.5M
Pentium III	1999	8.2M
Pentium 4	2001	42M

Added Features

- Instructions to support multimedia operations
  - Parallel operations on 1, 2, and 4-byte data, both integer & FP
- Instructions to enable more efficient conditional operations

Linux/GCC Evolution

- None!

New Species: IA64

Name	Date	Transistors
Itanium	2001	10M

Extends to IA64, a 64-bit architecture

Radically new instruction set designed for high performance

Can run existing IA32 programs
- On-board "x86 engine"

Joint project with Hewlett-Packard

Itanium 2	2002	221M

Big performance boost

Itanium 2 Dual-Core	2006	1.7B

Itanium has not taken off in marketplace

Lack of backward compatibility

X86 Evolution: Clones

Advanced Micro Devices (AMD)

- Historically
  - AMD has followed just behind Intel
  - A little bit slower, a lot cheaper
- Recently
  - Recruited top circuit designers from Digital Equipment Corp. and other downward trending companies
  - Exploited fact that Intel distracted by IA64
  - Now are close competitors to Intel
- Developed x86-64, its own extension to 64 bits
  - Started eating into Intel's high-end server market

Intel's 64-Bit Dilemma

Intel Attempted Radical Shift from IA32 to IA64

- Totally different architecture
- Executes IA32 code only as legacy
- Performance disappointing

AMD Stepped in with Evolutionary Solution

- x86-64 (now called "AMD64")

Intel Felt Obligated to Focus on IA64

- Hard to admit mistake or that AMD is better

2004: Intel Announces EM64T extension to IA32

- Extended Memory 64-bit Technology
- Almost identical to x86-64!
- Our Saltwater fish machines

Our Coverage

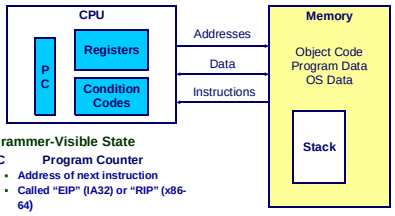
IA32
- The traditional x86

x86-64
- The emerging standard

Presentation
- Book has IA32
- Handout has x86-64
- Lecture will cover both

Labs
- Lab #2 x86-64
- Lab #3 IA32

Assembly Programmer's View



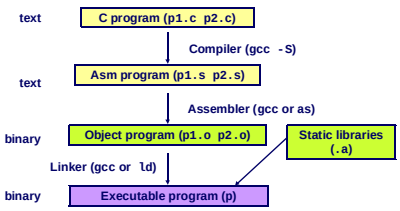
Programmer-Visible State

- **PC** Program Counter
  - Address of next instruction
  - Called "EIP" (IA32) or "RIP" (x86-64)
- Register File
  - Heavily used program data
- Condition Codes
  - Store status information about most recent arithmetic operation
  - Used for conditional branching

- Memory
  - Byte addressable array
  - Code, user data, (some) OS data
  - Includes stack used to support procedures

Turning C into Object Code

- Code in files `p1.c p2.c`
- Compile with command: `gcc -O p1.c p2.c -o p`
  - Use optimizations (`-O`)
  - Put resulting binary in file p



Compiling Into Assembly

C Code

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

Generated IA32 Assembly

```
_sum:
    pushl %ebp
    movl %esp,%ebp
    movl 12(%ebp),%eax
    addl 8(%ebp),%eax
    movl %ebp,%esp
    popl %ebp
    ret
```

Obtain with command

```
gcc -O -S code.c
```

Produces file `code.s`

Assembly Characteristics

Minimal Data Types

- "Integer" data of 1, 2, or 4 bytes
  - Data values
  - Addresses (untyped pointers)
- Floating point data of 4, 8, or 10 bytes
- No aggregate types such as arrays or structures
  - Just contiguously allocated bytes in memory

Primitive Operations

- Perform arithmetic function on register or memory data
- Transfer data between memory and register
  - Load data from memory into register
  - Store register data into memory
- Transfer control
  - Unconditional jumps to/from procedures
  - Conditional branches

Object Code

Code for `sum`

```
0x401040 <sum>:
    0x55
    0x89
    0xe5
    0x8b
    0x45
    0x0c
    0x03
    0x45
    0x08
    0x89
    0xec
    0x5d
    0xc3
```

- Total of 13 bytes
- Each instruction 1, 2, or 3 bytes
- Starts at address `0x401040`

Assembler

- Translates `.s` into `.o`
- Binary encoding of each instruction
- Nearly-complete image of executable code
- Missing linkages between code in different files

Linker

- Resolves references between files
- Combines with static run-time libraries
  - E.g., code for `malloc`, `printf`
- Some libraries are *dynamically linked*
  - Linking occurs when program begins execution

Machine Instruction Example

```
int t = x+y;
```

```
addl 8(%ebp),%eax
```

Similar to expression:

```
x += y
```

Or

```
int eax;
int *ebp;
eax += ebp[2]
```

```
0x401046:    03 45 08
```

C Code

- Add two signed integers

Assembly

- Add 2 4-byte integers
  - "Long" words in GCC parlance
  - Same instruction whether signed or unsigned
- Operands:
  - x: Register %eax
  - y: Memory M[%ebp+8]
  - t: Register %eax
    - » Return function value in %eax

Object Code

- 3-byte instruction
- Stored at address 0x401046

Disassembling Object Code

Disassembled

```
00401040 <_sum>:
   0:    55              push   %ebp
   1:    89 e5           mov    %esp,%ebp
   3:    8b 45 0c        mov    0xc(%ebp),%eax
   6:    03 45 08        add    0x8(%ebp),%eax
   9:    89 ec           mov    %ebp,%esp
   b:    5d              pop    %ebp
   c:    c3              ret
   d:    8d 76 00        lea    0x0(%esi),%esi
```

Disassembler

`objdump -d p`

- Useful tool for examining object code
- Analyzes bit pattern of series of instructions
- Produces approximate rendition of assembly code
- Can be run on either `a.out` (complete executable) or `.o` file

Alternate Disassembly

Object

```
0x401040:
    0x55
    0x89
    0xe5
    0x8b
    0x45
    0x0c
    0x03
    0x45
    0x08
    0x89
    0xec
    0x5d
    0xc3
```

Disassembled

```
0x401040 <sum>:      push   %ebp
0x401041 <sum+1>:    mov    %esp,%ebp
0x401043 <sum+3>:    mov    0xc(%ebp),%eax
0x401046 <sum+6>:    add    0x8(%ebp),%eax
0x401049 <sum+9>:    mov    %ebp,%esp
0x40104b <sum+11>:   pop    %ebp
0x40104c <sum+12>:   ret
0x40104d <sum+13>:   lea    0x0(%esi),%esi
```

Within gdb Debugger

`gdb p`

`disassemble sum`

- Disassemble procedure

`x/13b sum`

- Examine the 13 bytes starting at `sum`

What Can be Disassembled?

```
% objdump -d WINWORD.EXE

WINWORD.EXE:     file format pei-i386

No symbols in "WINWORD.EXE".
Disassembly of section .text:

30001000 <.text>:
30001000:  55              push   %ebp
30001001:  8b ec           mov    %esp,%ebp
30001003:  6a ff           push   $0xffffffff
30001005:  68 90 10 00 30  push   $0x30001090
3000100a:  68 91 dc 4c 30  push   $0x304cdc91
```

- Anything that can be interpreted as executable code
- Disassembler examines bytes and reconstructs assembly source

Moving Data: IA32

Moving Data

`movl` *Source*,*Dest*:

- Move 4-byte ("long") word
- Lots of these in typical code

Operand Types

- Immediate: Constant integer data
  - Like C constant, but prefixed with '$'
  - E.g., `$0x400`, `$-533`
  - Encoded with 1, 2, or 4 bytes
- Register: One of 8 integer registers
  - But `%esp` and `%ebp` reserved for special use
  - Others have special uses for particular instructions
- Memory: 4 consecutive bytes of memory
  - Various "address modes"

`movl` Operand Combinations

	Source	Dest	Src,Dest	C Analog
movl	*Imm*	*Reg*	`movl $0x4,%eax`	`temp = 0x4;`
		Mem	`movl $-147,(%eax)`	`*p = -147;`
	Reg	*Reg*	`movl %eax,%edx`	`temp2 = temp1;`
		Mem	`movl %eax,(%edx)`	`*p = temp;`
	Mem	*Reg*	`movl (%eax),%edx`	`temp = *p;`

Cannot do memory-memory transfer with a single instruction

So Many Addressing Modes?

Consider C code

```
struct s {
   double  d;        // Occupies bytes 0...7
   int i;            // Occupies bytes 8...B
   int j;            // Occupies bytes C...F
};

int get_i(struct s *sarray, int which)
{
   return sarray[which].i;
}
```

Where is "sarray[which].i"?

- `i` starts byte 8 of a struct...
- ...which is located at (which*16) from the base of `sarray`
- ...which somebody knows the "base address" of...
- So our value is at M[8 + (base + (which*16))]
  - Parts: constant 8, variable `which`, variable/constant base

Simple Addressing Modes

Normal (R) Mem[Reg[R]]

- Register R specifies memory address

```
movl (%ecx),%eax
```

Displacement D(R) Mem[Reg[R]+D]

- Register R specifies start of memory region
- constant displacement D specifies offset

```
movl 8(%ebp),%edx
```


Simple Addressing Modes

Normal (R) Mem[Reg[R]]

- Register R specifies memory address

```
movl (%ecx),%eax
```

Displacement D(R) Mem[Reg[R]+D]

- Register R specifies start of memory region
- constant displacement D specifies offset

```
movl 8(%ebp),%edx
```


Using Simple Addressing Modes

```
void swap(int *xp, int *yp)
{
  int t0 = *xp;
  int t1 = *yp;
  *xp = t1;
  *yp = t0;
}
```

```
swap:
    pushl %ebp              } Set
    movl  %esp,%ebp         } Up
    pushl %ebx

    movl 12(%ebp),%ecx      } Body
    movl 8(%ebp),%edx
    movl (%ecx),%eax
    movl (%edx),%ebx
    movl %eax,(%edx)
    movl %ebx,(%ecx)

    movl -4(%ebp),%ebx      } Finish
    movl %ebp,%esp
    popl %ebp
    ret
```


Using Simple Addressing Modes

```
void swap(int *xp, int *yp)
{
  int t0 = *xp;
  int t1 = *yp;
  *xp = t1;
  *yp = t0;
}
```

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swap:
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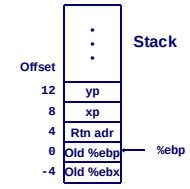
    movl 8(%ebp),%edx
    movl (%ecx),%eax
    movl (%edx),%ebx
    movl %eax,(%edx)
    movl %ebx,(%ecx)

    movl -4(%ebp),%ebx      } Finish
    movl %ebp,%esp
    popl %ebp
    ret
```


Understanding Swap

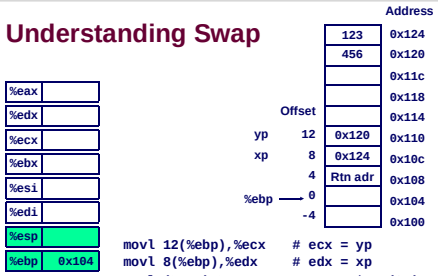
```
void swap(int *xp, int *yp)
{
  int t0 = *xp;
  int t1 = *yp;
  *xp = t1;
  *yp = t0;
}
```



Register	Variable
%ecx	yp
%edx	xp
%eax	t1
%ebx	t0

```
movl 12(%ebp),%ecx  # ecx = yp
movl 8(%ebp),%edx   # edx = xp
movl (%ecx),%eax    # eax = *yp (t1)
movl (%edx),%ebx    # ebx = *xp (t0)
movl %eax,(%edx)    # *xp = eax
movl %ebx,(%ecx)    # *yp = ebx
```


Understanding Swap




```
movl 12(%ebp),%ecx  # ecx = yp
movl 8(%ebp),%edx   # edx = xp
movl (%ecx),%eax    # eax = *yp (t1)
movl (%edx),%ebx    # ebx = *xp (t0)
movl %eax,(%edx)    # *xp = eax
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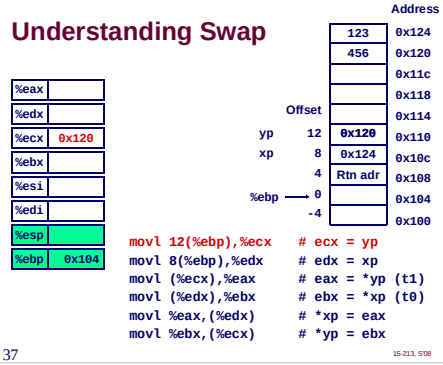
```

Understanding Swap

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movl 8(%ebp),%edx     # edx = xp
movl (%ecx),%eax      # eax = *yp (t1)
movl (%edx),%ebx      # ebx = *xp (t0)
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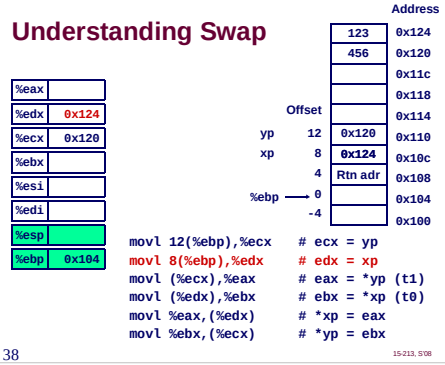
Understanding Swap

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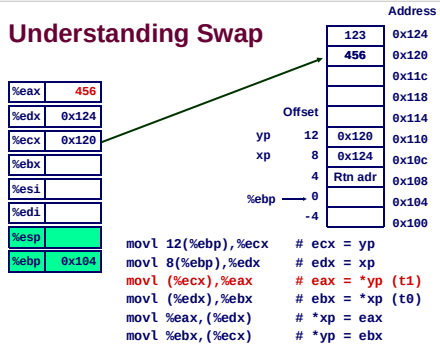


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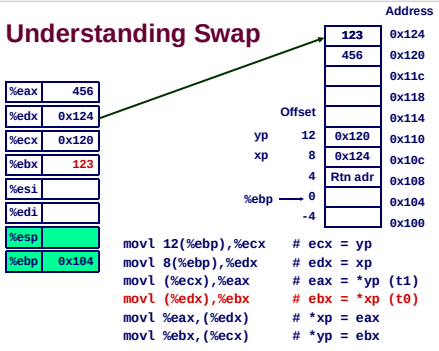


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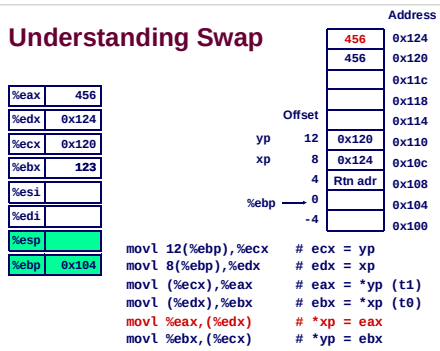


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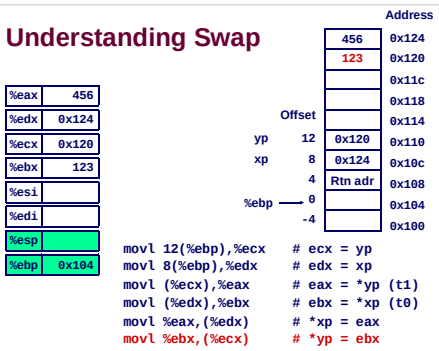


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movl (%edx),%ebx      # ebx = *xp (t0)
movl %eax,(%edx)      # *xp = eax
movl %ebx,(%ecx)      # *yp = ebx
```

Indexed Addressing Modes

Most General Form

D(Rb,Ri,S) Mem[Reg[Rb]+S*Reg[Ri]+ D]

- D: Constant "displacement" 1, 2, or 4 bytes
- Rb: Base register: Any of 8 integer registers
- Ri: Index register: Any, except for %esp
  - Unlikely you'd use %ebp, either
- S: Scale: 1, 2, 4, or 8

Special Cases

(Rb,Ri) Mem[Reg[Rb]+Reg[Ri]]

D(Rb,Ri) Mem[Reg[Rb]+Reg[Ri]+D]

(Rb,Ri,S) Mem[Reg[Rb]+S*Reg[Ri]]

Address Computation Examples

%edx	0xf000
%ecx	0x100

Expression	Computation	Address
0x8(%edx)	0xf000 + 0x8	0xf008
(%edx,%ecx)	0xf000 + 0x100	0xf100
(%edx,%ecx,4)	0xf000 + 4*0x100	0xf400
0x80(,%edx,2)	2*0xf000 + 0x80	0x1e080

Address Computation Instruction

`leal` ***Src*,*Dest***

- ***Src*** is address mode expression
- Set ***Dest*** to address denoted by expression

Uses

- Computing addresses without a memory reference
  - E.g., translation of `p = &x[i];`
- Computing arithmetic expressions of the form x + k*y
  - k = 1, 2, 4, or 8.

Some Arithmetic Operations

Format	Computation	
Two-operand Instructions		
`addl` *Src,Dest*	*Dest = Dest + Src*	
`subl` *Src,Dest*	*Dest = Dest - Src*	
`imull` *Src,Dest*	*Dest = Dest * Src*	
`sall` *Src,Dest*	*Dest = Dest << Src*	Also called `shll`
`sarl` *Src,Dest*	*Dest = Dest >> Src*	Arithmetic
`shrl` *Src,Dest*	*Dest = Dest >> Src*	Logical
`xorl` *Src,Dest*	*Dest = Dest ^ Src*	
`andl` *Src,Dest*	*Dest = Dest & Src*	
`orl` *Src,Dest*	*Dest = Dest | Src*	

Some Arithmetic Operations

Format	Computation
One-operand Instructions	
`incl` *Dest*	*Dest = Dest + 1*
`decl` *Dest*	*Dest = Dest - 1*
`negl` *Dest*	*Dest = - Dest*
`notl` *Dest*	*Dest = ~ Dest*

Using `leal` for Arithmetic Expressions

```
int arith
  (int x, int y, int z)
{
  int t1 = x+y;
  int t2 = z+t1;
  int t3 = x+4;
  int t4 = y * 48;
  int t5 = t3 + t4;
  int rval = t2 * t5;
  return rval;
}
```

```
arith:
    pushl %ebp
    movl %esp,%ebp

    movl 8(%ebp),%eax
    movl 12(%ebp),%edx
    leal (%edx,%eax),%ecx
    leal (%edx,%edx,2),%edx
    sall $4,%edx
    addl 16(%ebp),%ecx
    leal 4(%edx,%eax),%eax
    imull %ecx,%eax

    movl %ebp,%esp
    popl %ebp
    ret
```

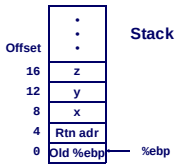
Set Up

Body

Finish

Understanding arith

```
int arith
  (int x, int y, int z)
{
  int t1 = x+y;
  int t2 = z+t1;
  int t3 = x+4;
  int t4 = y * 48;
  int t5 = t3 + t4;
  int rval = t2 * t5;
  return rval;
}
```




```
movl 8(%ebp),%eax          # eax = x
movl 12(%ebp),%edx         # edx = y
leal (%edx,%eax),%ecx      # ecx = x+y  (t1)
leal (%edx,%edx,2),%edx    # edx = 3*y
sall $4,%edx               # edx = 48*y (t4)
addl 16(%ebp),%ecx         # ecx = z+t1 (t2)
leal 4(%edx,%eax),%eax     # eax = 4+t4+x (t5)
imull %ecx,%eax            # eax = t5*t2 (rval)
```


Understanding arith

```
int arith
  (int x, int y, int z)
{
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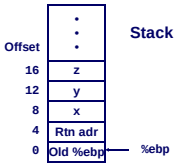
  int t3 = x+4;
  int t4 = y * 48;
  int t5 = t3 + t4;
  int rval = t2 * t5;
  return rval;
}
```




```
movl 8(%ebp),%eax          # eax = x
movl 12(%ebp),%edx         # edx = y
leal (%edx,%eax),%ecx      # ecx = x+y  (t1)
leal (%edx,%edx,2),%edx    # edx = 3*y
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addl 16(%ebp),%ecx         # ecx = z+t1 (t2)
leal 4(%edx,%eax),%eax     # eax = 4+t4+x (t5)
imull %ecx,%eax            # eax = t5*t2 (rval)
```


Understanding arith

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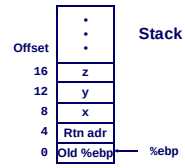
  int t3 = x+4;
  int t4 = y * 48;
  int t5 = t3 + t4;
  int rval = t2 * t5;
  return rval;
}
```




```
movl 8(%ebp),%eax          # eax = x
movl 12(%ebp),%edx         # edx = y
leal (%edx,%eax),%ecx      # ecx = x+y  (t1)
leal (%edx,%edx,2),%edx    # edx = 3*y
sall $4,%edx               # edx = 48*y (t4)
addl 16(%ebp),%ecx         # ecx = z+t1 (t2)
leal 4(%edx,%eax),%eax     # eax = 4+t4+x (t5)
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Understanding arith

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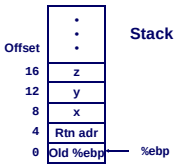
  int t4 = y * 48;
  int t5 = t3 + t4;
  int rval = t2 * t5;
  return rval;
}
```




```
movl 8(%ebp),%eax          # eax = x
movl 12(%ebp),%edx         # edx = y
leal (%edx,%eax),%ecx      # ecx = x+y  (t1)
leal (%edx,%edx,2),%edx    # edx = 3*y
sall $4,%edx               # edx = 48*y (t4)
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Understanding arith

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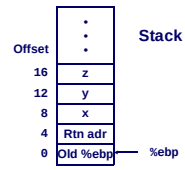
  int t4 = y * 48;
  int t5 = t3 + t4;
  int rval = t2 * t5;
  return rval;
}
```




```
movl 8(%ebp),%eax          # eax = x
movl 12(%ebp),%edx         # edx = y
leal (%edx,%eax),%ecx      # ecx = x+y  (t1)
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```


Understanding arith

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int arith
  (int x, int y, int z)
{
  int t1 = x+y;
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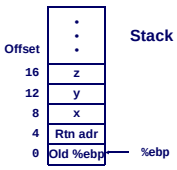
  int t3 = x+4;
  int t4 = y * 48;
  int t5 = t3 + t4;
  int rval = t2 * t5;
  return rval;
}
```




```
movl 8(%ebp),%eax          # eax = x
movl 12(%ebp),%edx         # edx = y
leal (%edx,%eax),%ecx      # ecx = x+y  (t1)
leal (%edx,%edx,2),%edx    # edx = 3*y
sall $4,%edx               # edx = 48*y (t4)
addl 16(%ebp),%ecx         # ecx = z+t1 (t2)
leal 4(%edx,%eax),%eax     # eax = 4+t4+x (t5)
imull %ecx,%eax            # eax = t5*t2 (rval)
```

Another Example

```
int logical(int x, int y)
{
  int t1 = x^y;
  int t2 = t1 >> 17;
  int mask = (1<<13) - 7;
  int rval = t2 & mask;
  return rval;
}
```

```
logical:
    pushl %ebp              } Set
    movl %esp,%ebp          } Up

    movl 8(%ebp),%eax       }
    xorl 12(%ebp),%eax      }
    sarl $17,%eax           }
    andl $8185,%eax         } Body

    movl %ebp,%esp          }
    popl %ebp               } Finish
    ret                     }
```

```
movl 8(%ebp),%eax     eax = x
xorl 12(%ebp),%eax    eax = x^y
sarl $17,%eax         eax = t1>>17
andl $8185,%eax       eax = t2 & 8185
```


Another Example

```
int logical(int x, int y)
{
  int t1 = x^y;
  int t2 = t1 >> 17;
  int mask = (1<<13) - 7;
  int rval = t2 & mask;
  return rval;
}
```

```
logical:
    pushl %ebp              } Set
    movl %esp,%ebp          } Up

    movl 8(%ebp),%eax       }
    xorl 12(%ebp),%eax      }
    sarl $17,%eax           }
    andl $8185,%eax         } Body

    movl %ebp,%esp          }
    popl %ebp               } Finish
    ret                     }
```

```
movl 8(%ebp),%eax     eax = x
xorl 12(%ebp),%eax    eax = x^y     (t1)
sarl $17,%eax         eax = t1>>17  (t2)
andl $8185,%eax       eax = t2 & 8185
```


Another Example

```
int logical(int x, int y)
{
  int t1 = x^y;
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```
logical:
    pushl %ebp              } Set
    movl %esp,%ebp          } Up

    movl 8(%ebp),%eax       }
    xorl 12(%ebp),%eax      }
    sarl $17,%eax           }
    andl $8185,%eax         } Body

    movl %ebp,%esp          }
    popl %ebp               } Finish
    ret                     }
```

```
movl 8(%ebp),%eax     eax = x
xorl 12(%ebp),%eax    eax = x^y     (t1)
sarl $17,%eax         eax = t1>>17  (t2)
andl $8185,%eax       eax = t2 & 8185
```


Another Example

```
int logical(int x, int y)
{
  int t1 = x^y;
  int t2 = t1 >> 17;
  int mask = (1<<13) - 7;
  int rval = t2 & mask;
  return rval;
}
```

```
logical:
    pushl %ebp              } Set
    movl %esp,%ebp          } Up

    movl 8(%ebp),%eax       }
    xorl 12(%ebp),%eax      }
    sarl $17,%eax           }
    andl $8185,%eax         } Body

    movl %ebp,%esp          }
    popl %ebp               } Finish
    ret                     }
```

$2^{13} = 8192, 2^{13} - 7 = 8185$

```
movl 8(%ebp),%eax     eax = x
xorl 12(%ebp),%eax    eax = x^y     (t1)
sarl $17,%eax         eax = t1>>17  (t2)
andl $8185,%eax       eax = t2 & 8185  (rval)
```

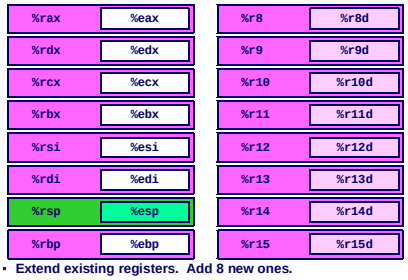

Data Representations: IA32 + x86-64

Sizes of C Objects (in Bytes)

C Data Type	Typical 32-bit	Intel IA32	x86-64
unsigned	4	4	4
int	4	4	4
long int	4	4	8
char	1	1	1
short	2	2	2
float	4	4	4
double	8	8	8
long double	8	10/12	16
char *	4	4	8

» Or any other pointer

x86-64 General Purpose Registers



- Extend existing registers. Add 8 new ones.
- Make %ebp/%rbp general purpose

Swap in 32-bit Mode

```
void swap(int *xp, int *yp)
{
  int t0 = *xp;
  int t1 = *yp;
  *xp = t1;
  *yp = t0;
}
```

```
swap:
    pushl %ebp              } Set
    movl  %esp,%ebp         } Up
    pushl %ebx

    movl 12(%ebp),%ecx      } Body
    movl 8(%ebp),%edx
    movl (%ecx),%eax
    movl (%edx),%ebx
    movl %eax,(%edx)
    movl %ebx,(%ecx)

    movl -4(%ebp),%ebx      } Finish
    movl %ebp,%esp
    popl %ebp
    ret
```


Swap in 64-bit Mode

```
void swap(int *xp, int *yp)
{
  int t0 = *xp;
  int t1 = *yp;
  *xp = t1;
  *yp = t0;
}
```

```
swap:
    movl   (%rdi), %edx
    movl   (%rsi), %eax
    movl   %eax, (%rdi)
    movl   %edx, (%rsi)
    ret
```

- Operands passed in registers
  - First (xp) in `%rdi`, second (yp) in `%rsi`
  - 64-bit pointers
- No stack operations required
- 32-bit data
  - Data held in registers `%eax` and `%edx`
  - `movl` operation

Swap Long Ints in 64-bit Mode

```
void swap_l
  (long int *xp, long int *yp)
{
  long int t0 = *xp;
  long int t1 = *yp;
  *xp = t1;
  *yp = t0;
}
```

```
swap_l:
    movq   (%rdi), %rdx
    movq   (%rsi), %rax
    movq   %rax, (%rdi)
    movq   %rdx, (%rsi)
    ret
```

- 64-bit data
  - Data held in registers `%rax` and `%rdx`
  - `movq` operation
    - "q" stands for quad-word

Summary

Machine Level Programming

- Assembly code is textual form of binary object code
- Low-level representation of program
  - Explicit manipulation of registers
  - Simple and explicit instructions
  - Minimal concept of data types
  - Many C control constructs must be implemented with multiple instructions

Formats

- IA32: Historical x86 format
- x86-64: Big evolutionary step

Credits

Languages

- http://compsoc.dur.ac.uk/whitespace/
- http://catb.org/~esr/intercal/

Screen shots

- http://mgccl.com/2007/03/30/simple-version-matrix-like-animated-dropping-character-effect-in-php
- Eclipse shot courtesy of Roy Liu, http://hubris.ucsd.edu