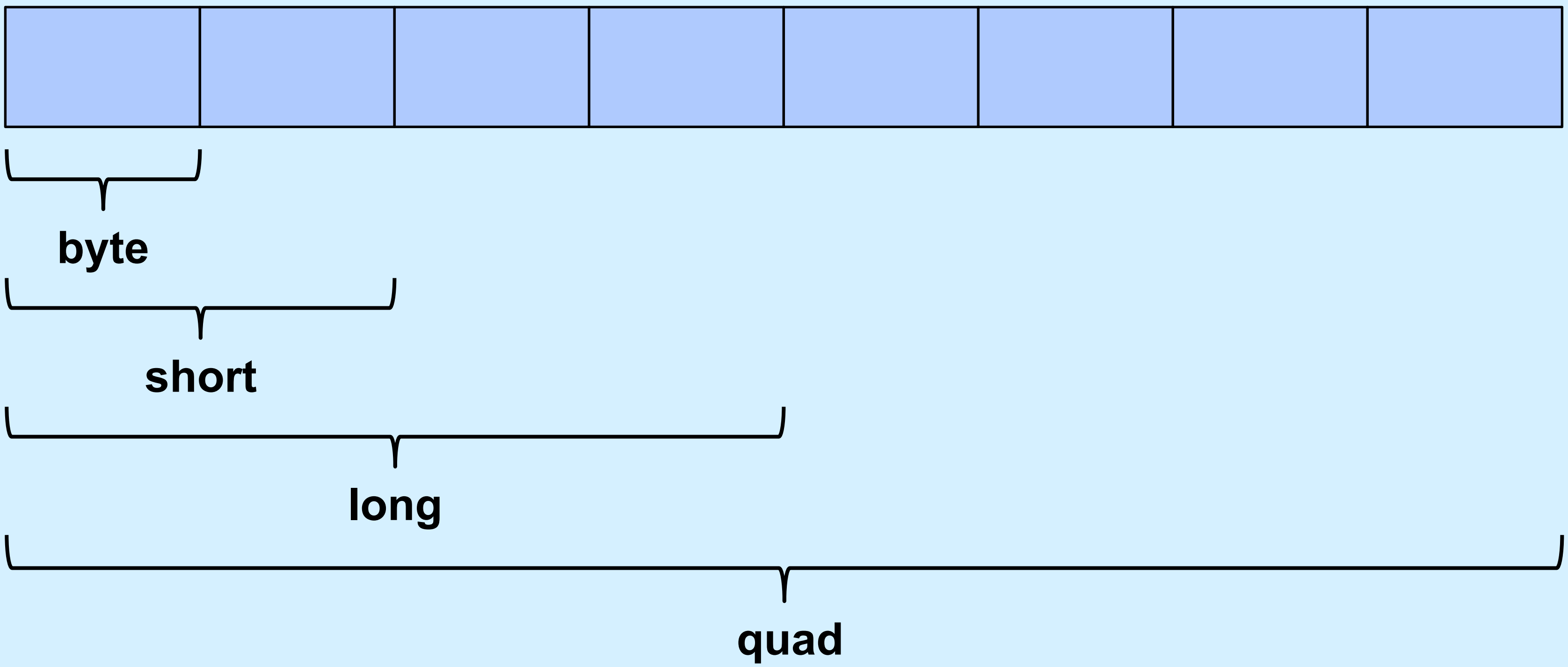
CS 33

Machine Programming (1)

Data Types on Intel x86

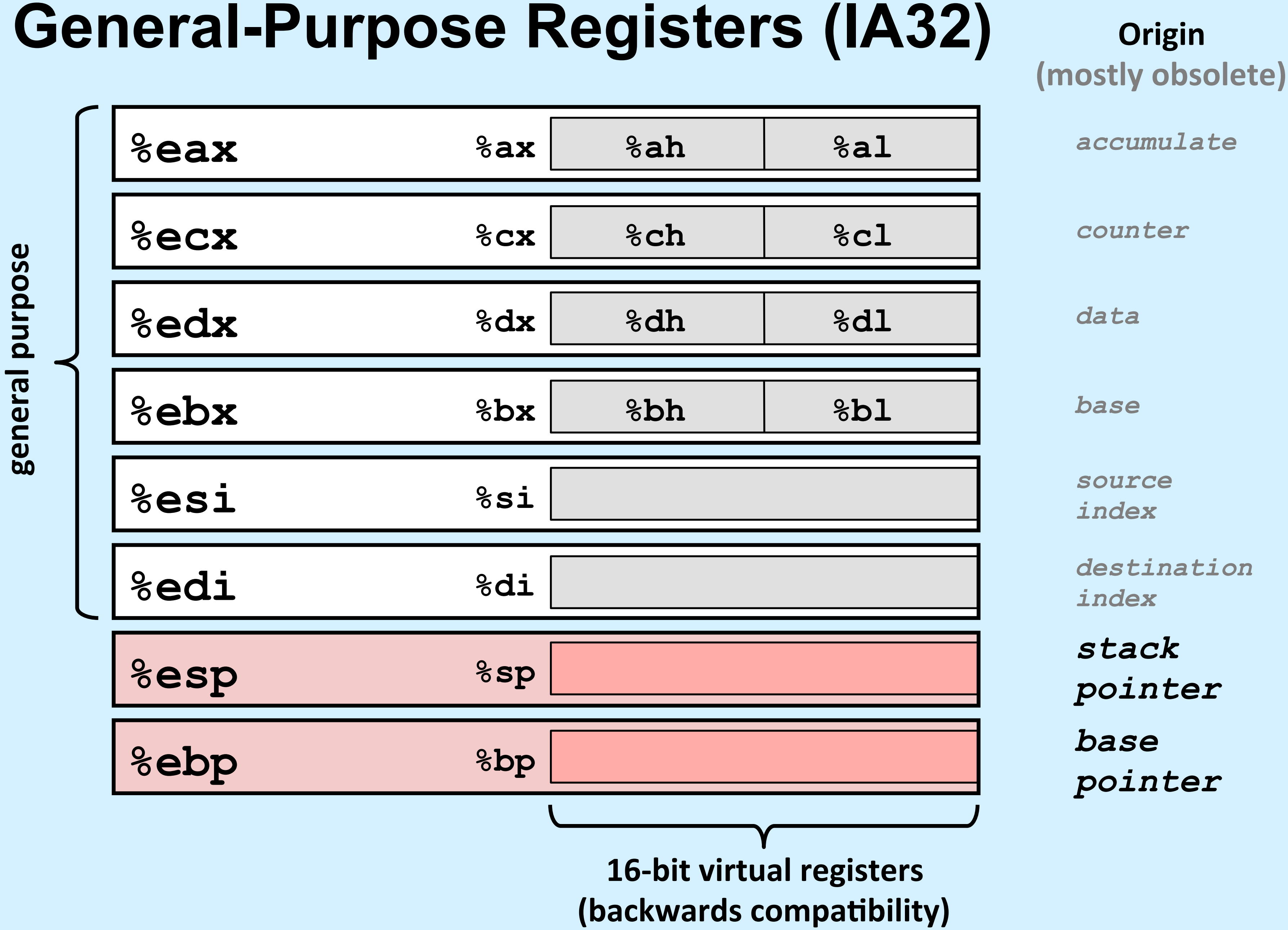
- “Integer” data of 1, 2, or 4 bytes (plus 8 bytes on x86-64)
  - data values
    - » whether signed or unsigned depends on interpretation
  - addresses (untyped pointers)
- Floating-point data of 4, 8, or 10 bytes
- No aggregate types such as arrays or structures
  - just contiguously allocated bytes in memory

Operand Size

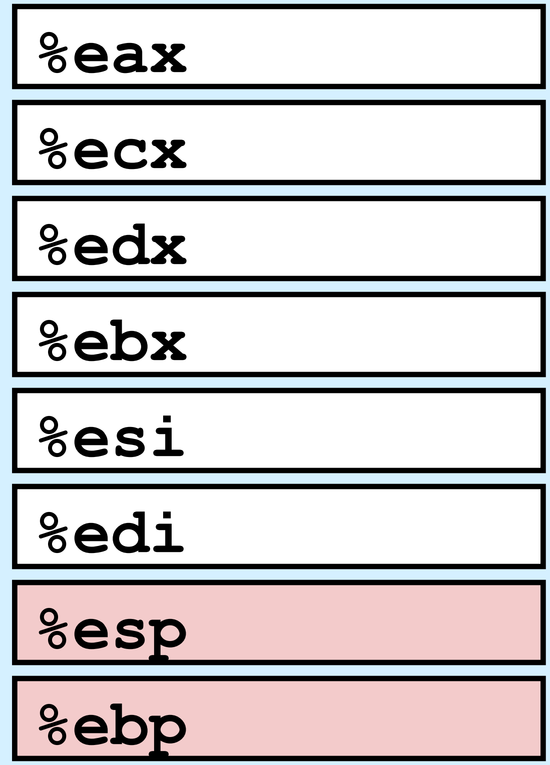


- Rather than `mov` ...
  - `movb`
  - `movs`
  - `movl`
  - `movq` (x86-64 only)

General-Purpose Registers (IA32)



Moving Data: IA32



- **Moving data**

  `movl` ***source*, *dest***

- **Operand types**
  - ***Immediate:*** **constant integer data**
    - » example: `$0x400`, `$-533`
    - » like C constant, but prefixed with `'$'`
    - » encoded with 1, 2, or 4 bytes
  - ***Register:*** **one of 8 integer registers**
    - » example: `%eax, %edx`
    - » but `%esp` and `%ebp` reserved for special use
    - » others have special uses for particular instructions
  - ***Memory:*** **4 consecutive bytes of memory at address given by register(s)**
    - » simplest example: `(%eax)`
    - » various other “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 (normally) do memory-memory transfer with a single instruction

Simple Memory 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
    movl  %esp,%ebp
    pushl %ebx

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

    popl  %ebx
    popl  %ebp
    ret
```

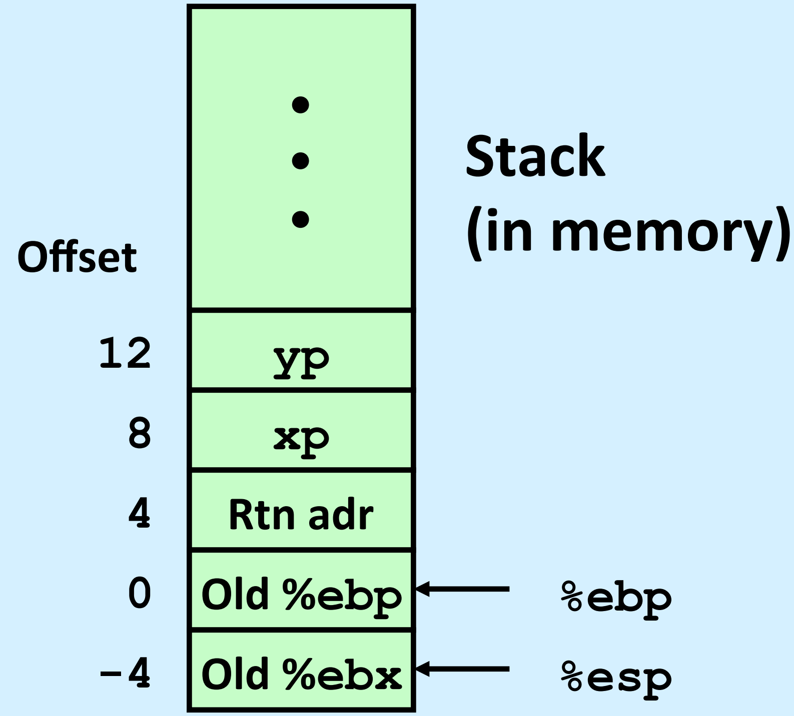
Set Up (pushl %ebp; movl %esp,%ebp; pushl %ebx)

Body (movl 8(%ebp), %edx … movl %ebx, (%ecx))

Finish (popl %ebx; popl %ebp; ret)

Understanding Swap

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



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

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

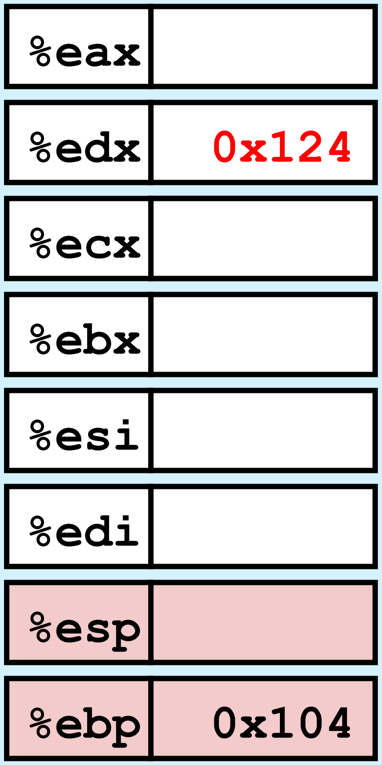
Understanding Swap

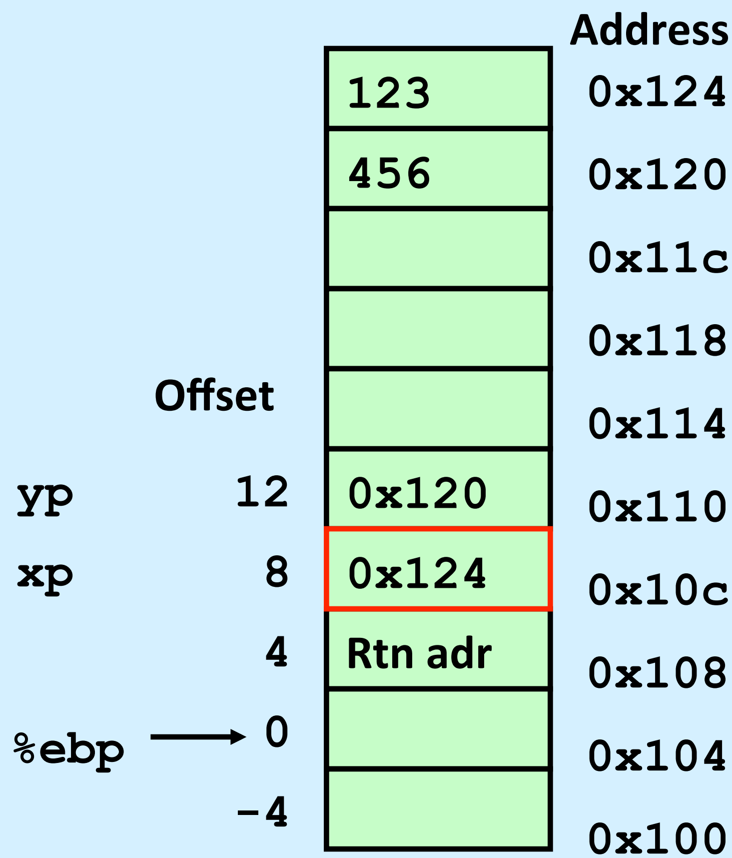
%eax	
%edx	
%ecx	
%ebx	
%esi	
%edi	
%esp	
%ebp	0x104

	Offset		Address
		123	0x124
		456	0x120
			0x11c
			0x118
			0x114
yp	12	0x120	0x110
xp	8	0x124	0x10c
	4	Rtn adr	0x108
%ebp →	0		0x104
	-4		0x100

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

Understanding Swap






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

Understanding Swap

%eax	
%edx	0x124
%ecx	0x120
%ebx	
%esi	
%edi	
%esp	
%ebp	0x104

	Offset		Address
		123	0x124
		456	0x120
			0x11c
			0x118
			0x114
yp	12	0x120	0x110
xp	8	0x124	0x10c
	4	Rtn adr	0x108
%ebp →	0		0x104
	-4		0x100

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

Understanding Swap

Register	Value
%eax	
%edx	0x124
%ecx	0x120
%ebx	123
%esi	
%edi	
%esp	
%ebp	0x104

	Offset		Address
		123	0x124
		456	0x120
			0x11c
			0x118
			0x114
yp	12	0x120	0x110
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%ebp →	0		0x104
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```
movl  8(%ebp), %edx    # edx = xp
movl  12(%ebp), %ecx   # ecx = yp
movl  (%edx), %ebx     # ebx = *xp (t0)
movl  (%ecx), %eax     # eax = *yp (t1)
movl  %eax, (%edx)     # *xp = t1
movl  %ebx, (%ecx)     # *yp = t0
```

Understanding Swap

Register	Value
%eax	456
%edx	0x124
%ecx	0x120
%ebx	123
%esi	
%edi	
%esp	
%ebp	0x104

	Offset		Address
		123	0x124
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```
movl   8(%ebp), %edx     # edx = xp
movl   12(%ebp), %ecx    # ecx = yp
movl   (%edx), %ebx      # ebx = *xp (t0)
movl   (%ecx), %eax      # eax = *yp (t1)
movl   %eax, (%edx)      # *xp = t1
movl   %ebx, (%ecx)      # *yp = t0
```

Understanding Swap

Register	Value
%eax	456
%edx	0x124
%ecx	0x120
%ebx	123
%esi	
%edi	
%esp	
%ebp	0x104

	Offset		Address
		456	0x124
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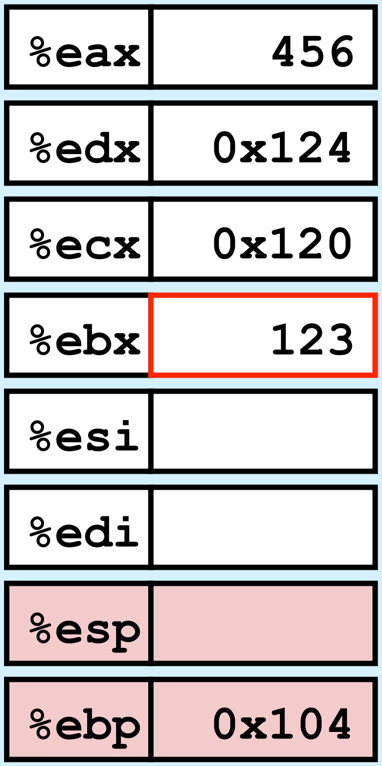
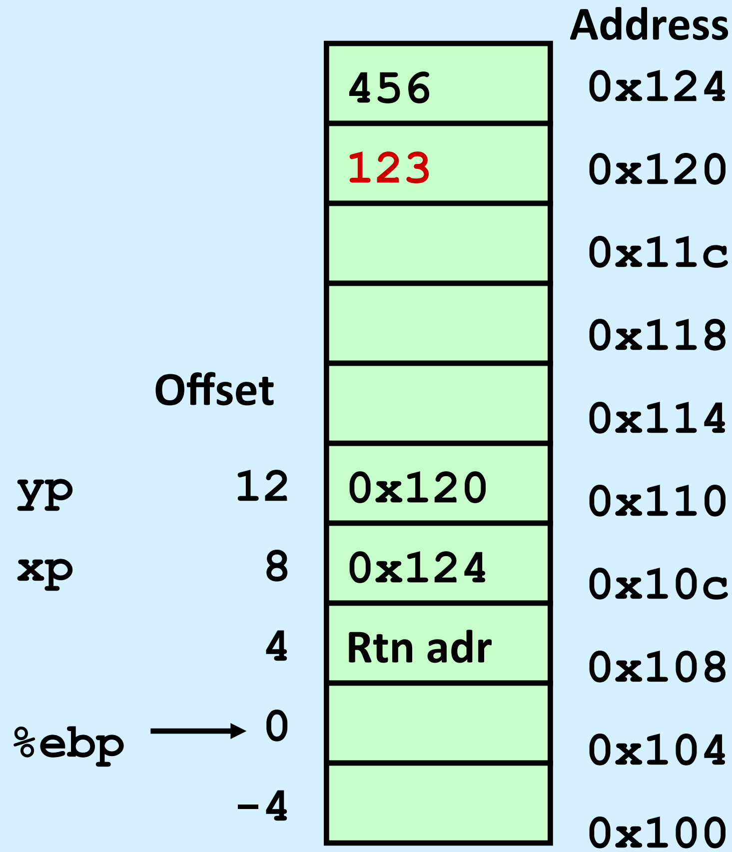
	-4		0x100

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

Understanding Swap

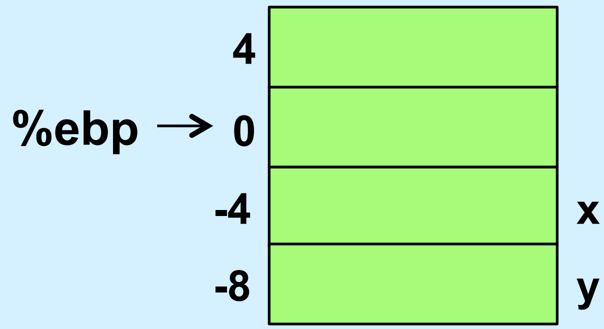





```
movl   8(%ebp), %edx     # edx = xp
movl   12(%ebp), %ecx    # ecx = yp
movl   (%edx), %ebx      # ebx = *xp (t0)
movl   (%ecx), %eax      # eax = *yp (t1)
movl   %eax, (%edx)      # *xp = t1
movl   %ebx, (%ecx)      # *yp = t0
```

Quiz 1

```
movl -4(%ebp), %eax
movl (%eax), %eax
movl (%eax), %eax
movl %eax, -8(%ebp)
```



Which C statements best describe the assembler code?

```
// a
int x;
int y;
y = x;
```

```
// b
int *x;
int y;
y = *x;
```

```
// c
int **x;
int y;
y = **x;
```

```
// d
int ***x;
int y;
y = ***x;
```

Complete Memory-Addressing Modes

- **Most general form**

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

  – **D: constant "displacement"**
  – **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]]
D	Mem[D]

Address-Computation Examples

`%edx`	`0xf000`
`%ecx`	`0x0100`

Expression	Address Computation	Address
`0x8(%edx)`	**`0xf000 + 0x8`**	**`0xf008`**
`(%edx,%ecx)`	**`0xf000 + 0x0100`**	**`0xf100`**
`(%edx,%ecx,4)`	**`0xf000 + 4*0x0100`**	**`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
- Example

```
int mul12(int x)
{
  return x*12;
}
```

Converted to ASM by compiler:

```
movl 8(%ebp), %eax          # get arg
leal (%eax,%eax,2), %eax    # t <- x+x*2
sall $2, %eax               # return t<<2
```

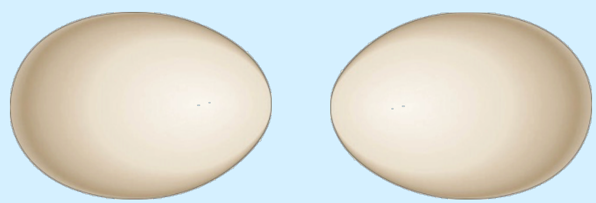
Quiz 2

What value ends up in %ecx?

```
movl $1000,%eax
movl $1,%ebx
movl 2(%eax,%ebx,4),%ecx
```

a) **0x02030405**
b) **0x05040302**
c) **0x06070809**
d) **0x09080706**

	1009:	0x09
	1008:	0x08
	1007:	0x07
	1006:	0x06
	1005:	0x05
	1004:	0x04
	1003:	0x03
	1002:	0x02
	1001:	0x01
%eax →	1000:	0x00

Hint: 

x86-64 General-Purpose Registers

	%rax	%eax	%r8	%r8d	a5
	%rbx	%ebx	%r9	%r9d	a6
a4	%rcx	%ecx	%r10	%r10d	
a3	%rdx	%edx	%r11	%r11d	
a2	%rsi	%esi	%r12	%r12d	
a1	%rdi	%edi	%r13	%r13d	
	%rsp	%esp	%r14	%r14d	
	%rbp	%ebp	%r15	%r15d	

– Extend existing registers to 64 bits. Add 8 new ones.

– No special purpose for `%ebp`/`%rbp`

32-bit Instructions on x86-64

- addl 4(%rdx), %eax
  - memory address must be 64 bits
  - operands (in this case) are 32-bit
    - » result goes into %eax
      - lower half of %rax
      - upper half is filled with zeroes

32-bit code for swap

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

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

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

   popl   %ebx         } Finish
   popl   %ebp
   ret
```

64-bit code for swap

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

```
swap:
                                  } Set Up

    movl   (%rdi), %edx          }
    movl   (%rsi), %eax          } Body
    movl   %eax, (%rdi)          }
    movl   %edx, (%rsi)          }

    ret                           } Finish
```

- **Arguments passed in registers (why useful?)**
  - 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

64-bit code for long int swap

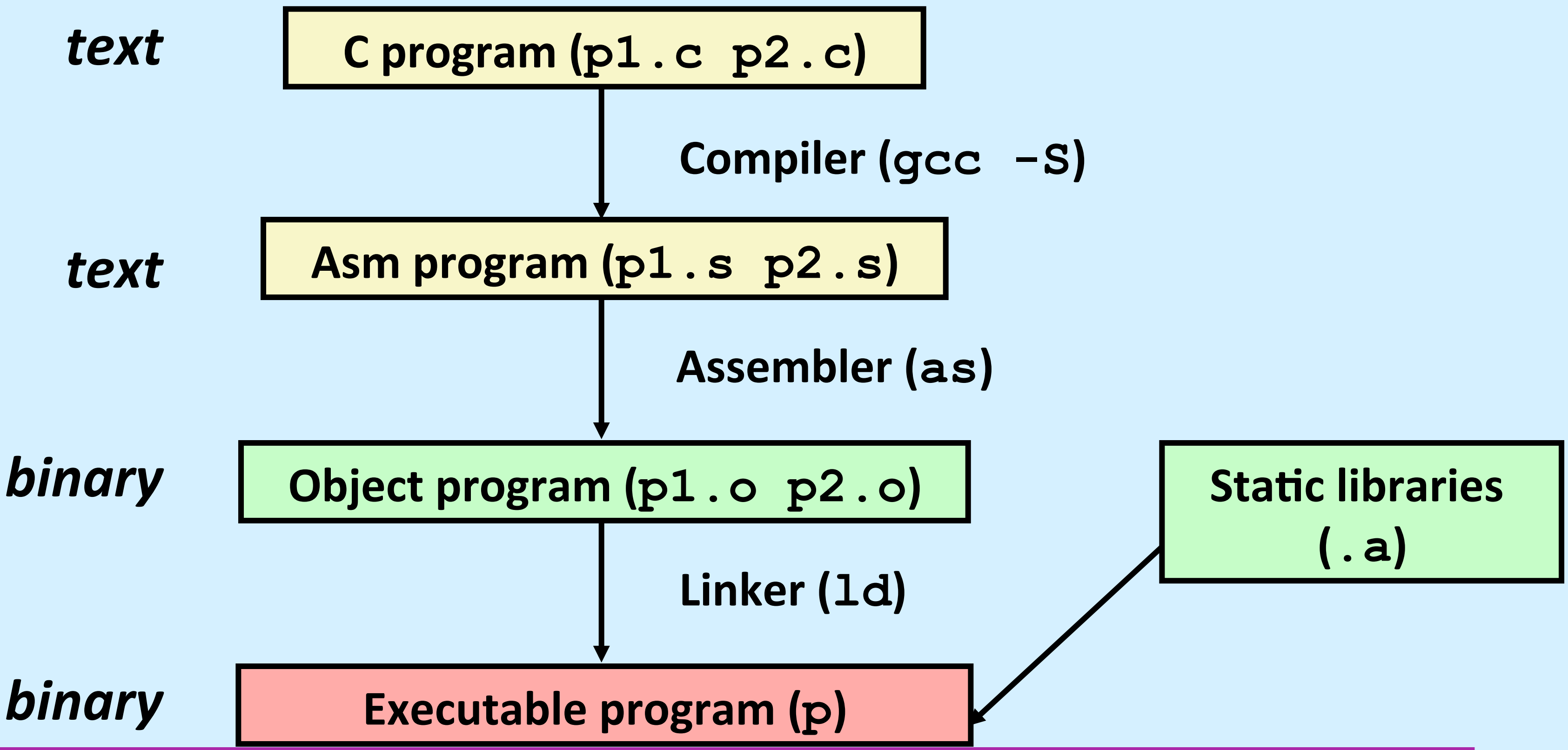
```
void swap(long *xp, long *yp)
{
  long t0 = *xp;
  long t1 = *yp;
  *xp = t1;
  *yp = t0;
}
```

```
swap_l:
                                    Set Up

    movq    (%rdi), %rdx
    movq    (%rsi), %rax            Body
    movq    %rax, (%rdi)
    movq    %rdx, (%rsi)

    ret                             Finish
```

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

Turning C into Object Code

- Code in files `p1.c p2.c`
- Compile with command: `gcc -O1 p1.c p2.c -o p`
  - » use basic optimizations (`-O1`)
  - » put resulting binary in file `p`



Example

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


Object Code

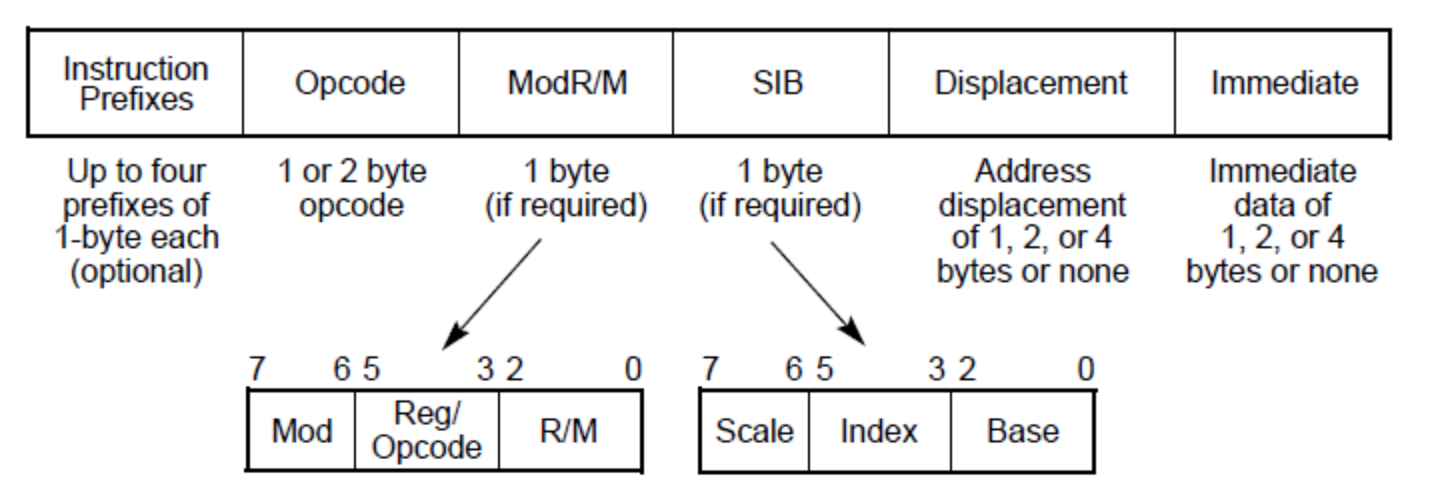
Code for `sum`

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

- Total of 11 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 `printf`
  - some libraries are *dynamically linked*
    - » linking occurs when program begins execution

Instruction Format



Disassembling Object Code

Disassembled

```
080483c4 <sum>:
 80483c4:  55         push   %ebp
 80483c5:  89 e5      mov    %esp,%ebp
 80483c7:  8b 45 0c   mov    0xc(%ebp),%eax
 80483ca:  03 45 08   add    0x8(%ebp),%eax
 80483cd:  5d         pop    %ebp
 80483ce:  c3         ret
```

- **Disassembler**

  `objdump -d <file>`

  – useful tool for examining object code

  – analyzes bit pattern of series of instructions

  – produces approximate rendition of assembly code

  – can be run on either executable or object (`.o`) file

Alternate Disassembly

Object

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

Disassembled

```
Dump of assembler code for function sum:
0x080483c4 <sum+0>:     push   %ebp
0x080483c5 <sum+1>:     mov    %esp,%ebp
0x080483c7 <sum+3>:     mov    0xc(%ebp),%eax
0x080483ca <sum+6>:     add    0x8(%ebp),%eax
0x080483cd <sum+9>:     pop    %ebp
0x080483ce <sum+10>:    ret
```

- **Within gdb debugger**

  `gdb <file>`

  `disassemble sum`

  – **disassemble procedure**

  `x/11xb sum`

  – **examine the 11 bytes starting at `sum`**

How Many Instructions are There?

- We cover ~29
- Implemented by Intel:
  - 80 in original 8086 architecture
  - 7 added with 80186
  - 17 added with 80286
  - 33 added with 386
  - 6 added with 486
  - 6 added with Pentium
  - 1 added with Pentium MMX
  - 4 added with Pentium Pro
  - 8 added with SSE
  - 8 added with SSE2
  - 2 added with SSE3
  - 14 added with x86-64
  - 10 added with VT-x
  - 2 added with SSE4a
- Total: 198
- Doesn't count:
  - floating-point instructions
  - SIMD instructions
  - AMD-added instructions
  - undocumented instructions

Some Arithmetic Operations

- Two-operand instructions:

Format		Computation	
`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	

  – watch out for argument order!
  – no distinction between signed and unsigned int (why?)

Some Arithmetic Operations

- **One-operand Instructions**

`incl`	Dest	= Dest + 1
`decl`	Dest	= Dest - 1
`negl`	Dest	= - Dest
`notl`	Dest	= ~Dest

- **See book for more instructions**

Arithmetic Expression Example

```
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:
    leal   (%rdi,%rsi), %eax
    addl   %edx, %eax
    leal   (%rsi,%rsi,2), %edx
    sall   $4, %edx
    leal   4(%rdi,%rdx), %ecx
    imull  %ecx, %eax
    ret
```

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;
}
```

%rdx	z
%rsi	y
%rdi	x

```
leal   (%rdi,%rsi), %eax
addl   %edx, %eax
leal   (%rsi,%rsi,2), %edx
sall   $4, %edx
leal   4(%rdi,%rdx), %ecx
imull  %ecx, %eax
ret
```

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;
}
```

%rdx	z
%rsi	y
%rdi	x

```
leal   (%rdi,%rsi), %eax     # eax = x+y     (t1)
addl   %edx, %eax            # eax = t1+z    (t2)
leal   (%rsi,%rsi,2), %edx   # edx = 3*y     (t4)
sall   $4, %edx              # edx = t4*16   (t4)
leal   4(%rdi,%rdx), %ecx    # ecx = x+4+t4  (t5)
imull  %ecx, %eax            # eax *= t5     (rval)
ret
```

Observations about `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;
}
```

- Instructions in different order from C code
- Some expressions might require multiple instructions
- Some instructions might cover multiple expressions

```
leal   (%rdi,%rsi), %eax     # eax = x+y      (t1)
addl   %edx, %eax            # eax = t1+z     (t2)
leal   (%rsi,%rsi,2), %edx   # edx = 3*y      (t4)
sall   $4, %edx              # edx = t4*16    (t4)
leal   4(%rdi,%rdx), %ecx    # ecx = x+4+t4   (t5)
imull  %ecx, %eax            # eax *= t5      (rval)
ret
```

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;
}
```

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

```
xorl %esi, %edi        # edi = x^y        (t1)
sarl $17, %edi         # edi = t1>>17     (t2)
movl %edi, %eax        # eax = edi
andl $8185, %eax       # eax = t2 & mask (rval)
```

Quiz 3

- **What is the final value in %esi?**

```
xorl %esi, %esi
incl %esi
sall %esi, %esi
addl %esi, %esi
```

a) 2
b) 4
c) 8
d) indeterminate