Assemblers and Linkers

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Goals for this Lecture

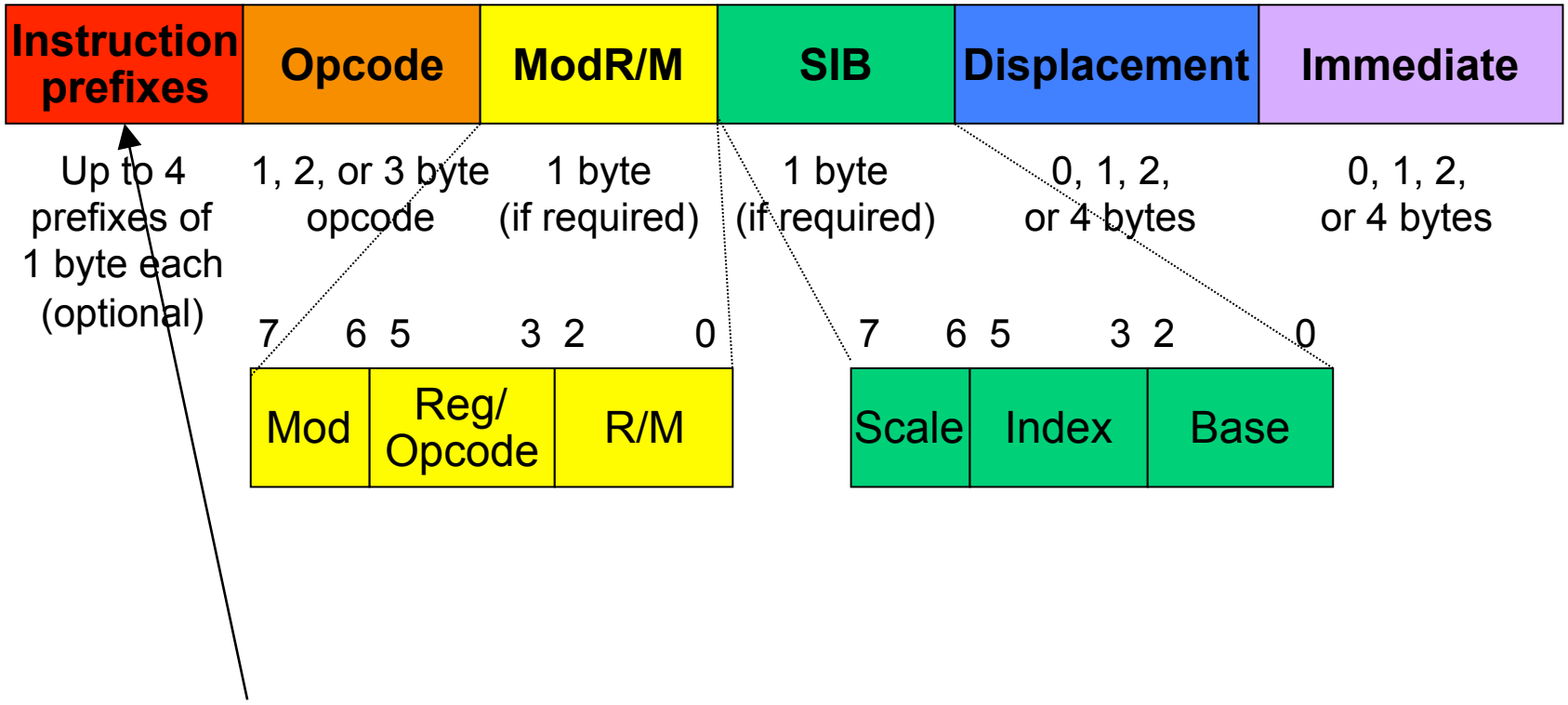
- Machine language
  - The last stop on the "language levels" tour
- IA-32 machine language
  - Useful for the next programming assignment
- Assembly and linking processes
  - To understand how to create an executable

Part 1: Machine Language

IA-32 Machine Language

- IA-32 machine language
  - Difficult to generalize about IA-32 instruction format
  - Generally, instructions use the following format
- We'll go over
  - The format of instructions
  - Two example instructions
- Just to give a sense of how it works…

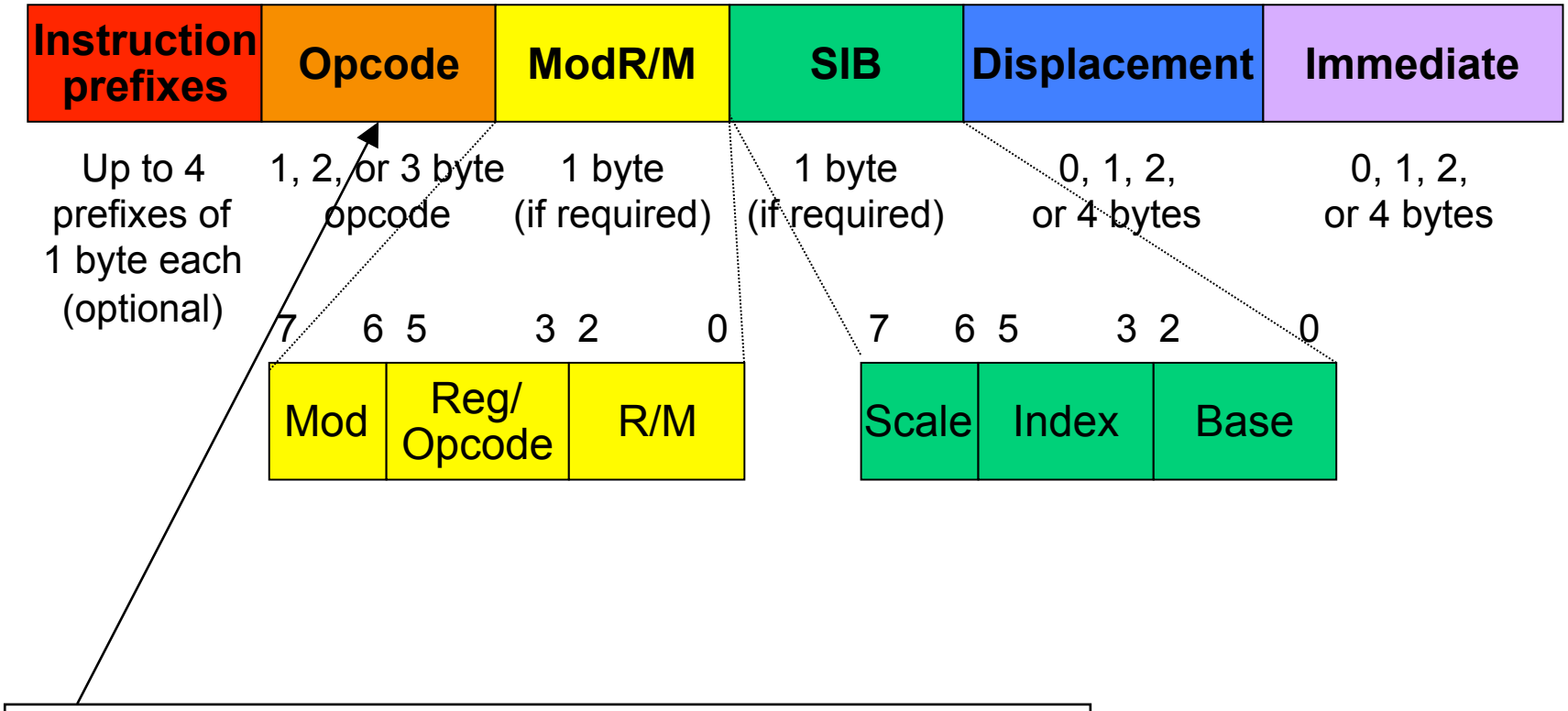
IA-32 Instruction Format



Instruction prefix

- Sometimes a repeat count
- Rarely used; don't be concerned

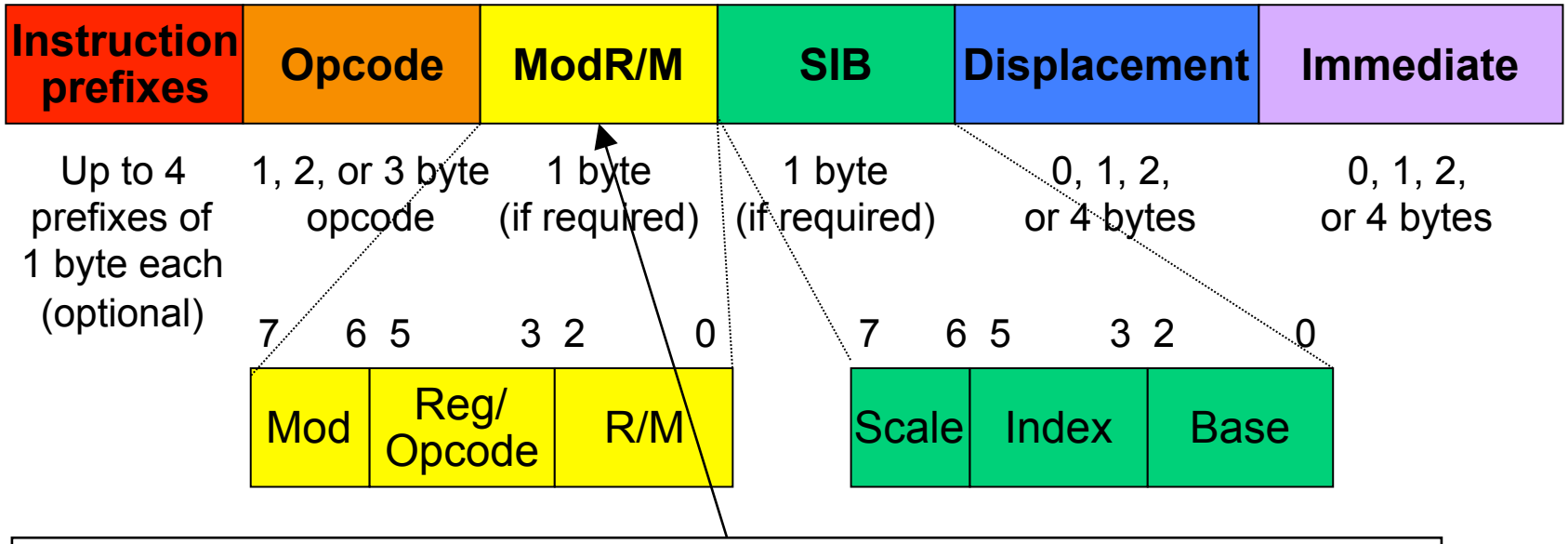
IA-32 Instruction Format (cont.)



Opcode

- Specifies which operation should be performed
- Add, move, call, etc.

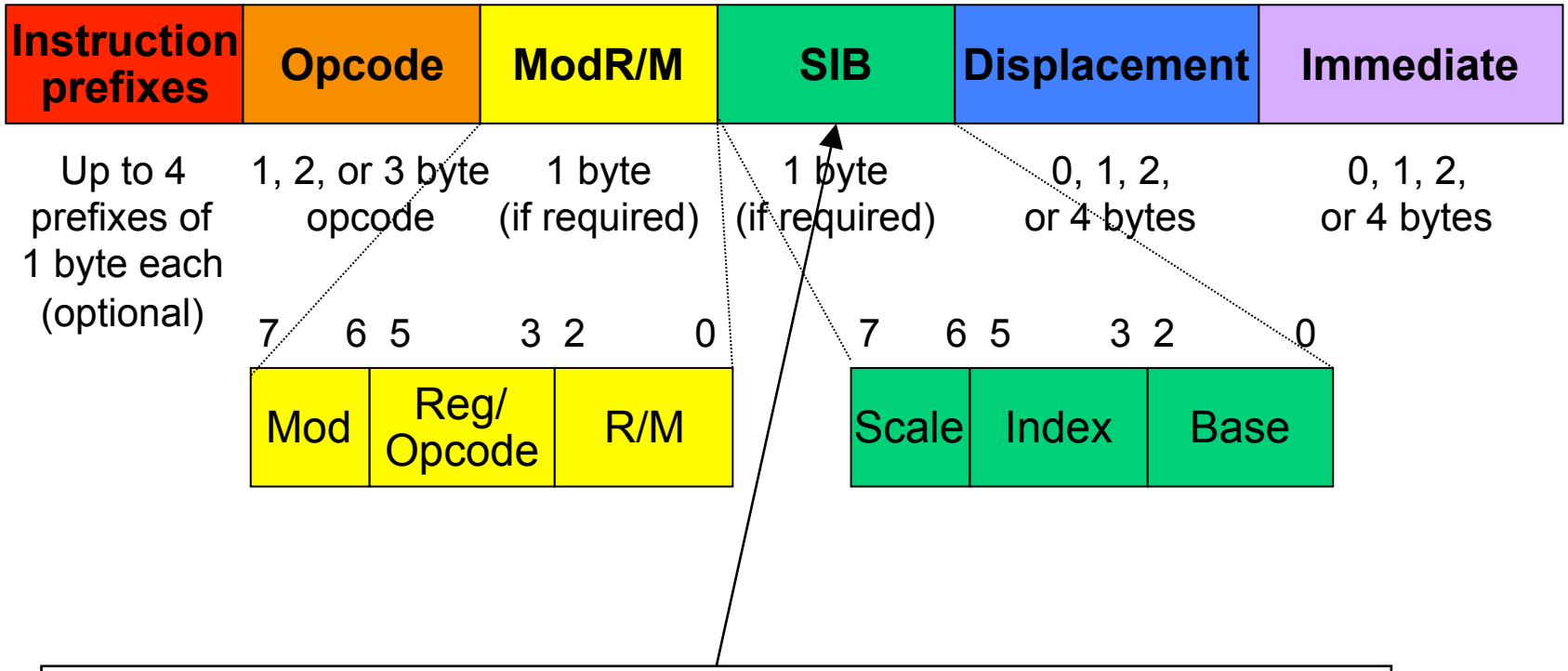
IA-32 Instruction Format (cont.)



ModR/M

- Specifies types of operands (immediate, register, memory)
- Specifies sizes of operands (byte, word, long)
- Sometimes denotes a register:
  000 = EAX/AL; 011 = EBX/BL; 001 = ECX/CL; 010 = EDX/DL;
  110 = ESI/DH; 111 = EDI/BH; 101 = EBP/CH; 110 = ESP/AH
- Sometimes contains an extension of the opcode

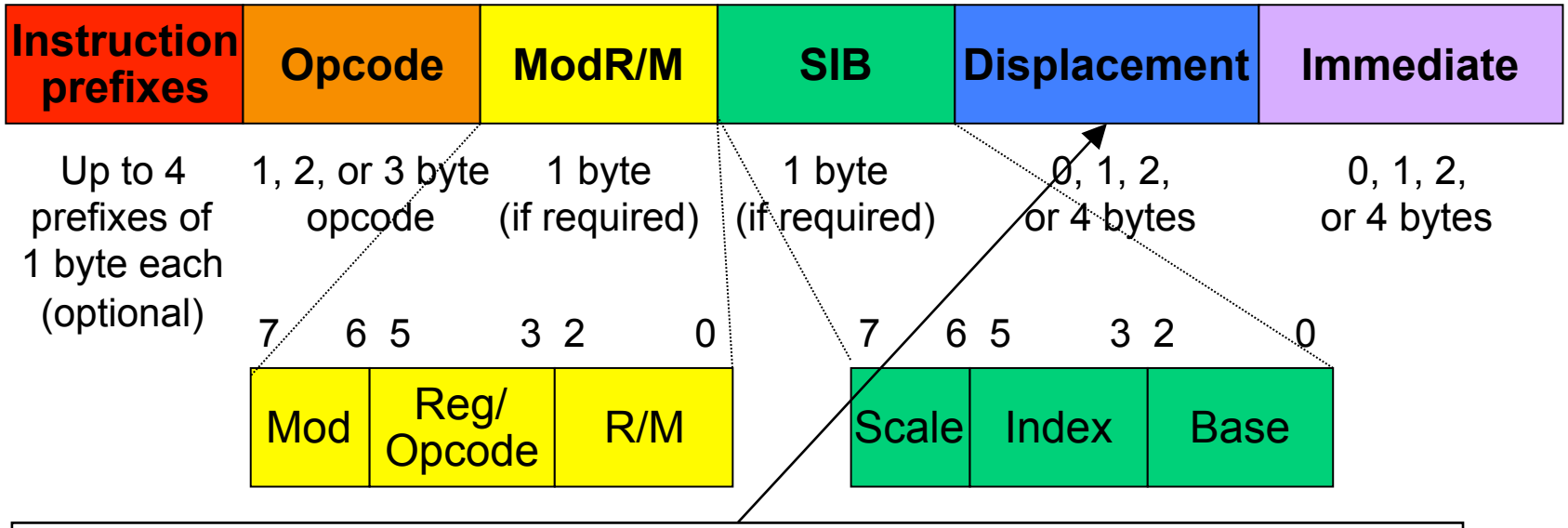
IA-32 Instruction Format (cont.)



SIB

- Used when one of the operands is a memory operand that uses a **s**cale, an **i**ndex register, and/or a **b**ase register

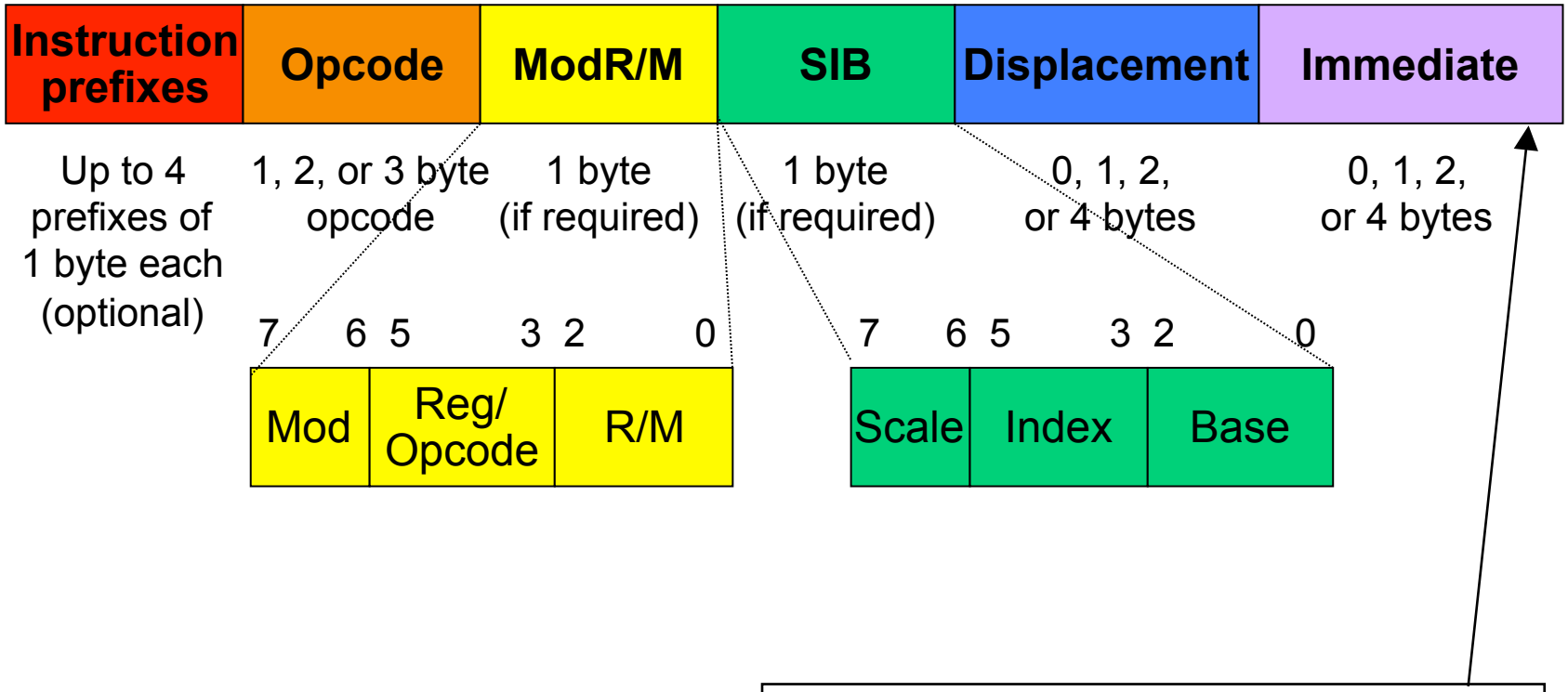
IA-32 Instruction Format (cont.)



Displacement

- Used in jump and call instructions
- Indicates the displacement between the destination instruction and the jump/call instruction
- More precisely, indicates:
  [addr of destination instr] – [addr of instr following the jump/call]
- Uses little-endian byte order

IA-32 Instruction Format (cont.)



Immediate

- Specifies an immediate operand
- Uses little-endian byte order

Example: Push on to Stack

- Assembly language:

```
pushl %edx
```

- Machine code:
  - IA32 has a separate opcode for push for each register operand
    - 50: pushl %eax
    - 51: pushl %ecx
    - 52: pushl %edx → 0101 0010
    - …
  - Results in a *one-byte* instruction
- Observe: sometimes one assembly language instruction can map to a *group* of different opcodes

Example: Load Effective Address

- Assembly language:

```
leal (%eax,%eax,4), %eax
```

- Machine code:
  - Byte 1: 8D (opcode for "load effective address")
  - Byte 2: 04 (dest %eax, with scale-index-base)
  - Byte 3: 80 (scale=4, index=%eax, base=%eax)

1000 1101

0000 0100

1000 0000

Load the address %eax + 4 * %eax into register %eax

CISC and RISC

- IA-32 machine language instructions are **complex**
- IA-32 is a
  - **Complex Instruction Set Computer (CISC)**
- Alternative:
  - **Reduced Instruction Set Computer (RISC)**

Characteristics of CISC and RISC

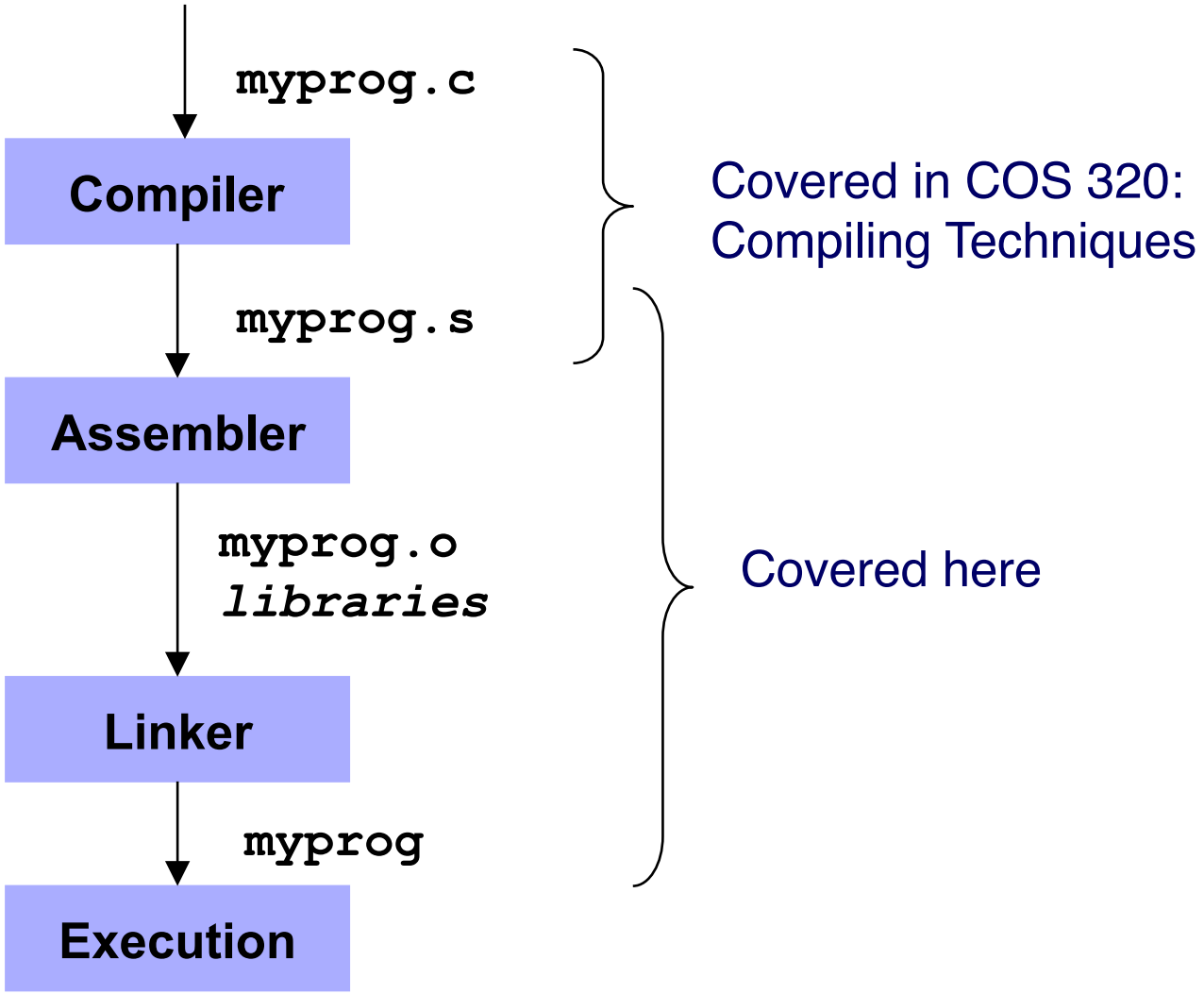
- CISC
  - **Many** instructions
  - **Many** addressing modes (direct, indirect, indexed, base-pointer)
  - Hardware interpretation is **complex**
  - **Few** instructions required to accomplish a given job (expressive)
  - Example: IA-32
- RISC
  - **Few** instructions
  - **Few** addressing modes (typically only direct and indirect)
  - Hardware interpretation is **simple**
  - **Many** instructions required for a given job (not expressive)
  - Examples: MIPS, SPARC

Brief History of CISC and RISC

- Stage 1: Programmers write assembly language
  - Important that assembly/machine language be expressive
  - CISC dominates (especially Intel)
- Stage 2: Programmers write high-level language
  - Not important that assembly/machine language be expressive; the compiler generates it
  - Important that compilers work well => assembly/machine language should be simple
  - RISC takes a foothold (but CISC, especially Intel, persists)
- Stage 3: Compilers get smarter
  - Less important that assembly/machine language be simple
  - Much motivation for RISC disappears
  - CISC (especially Intel) dominates the computing world

Part 2: The Assembly Process

The Build/Execute Process



Two Aspects of the Assembler/Linker

- Translating each instruction
  - Mapping an assembly-language instruction
  - … into the corresponding machine-language instruction
- Dealing with references across instructions
  - Jumps to other locations in same chunk of code
  - Accesses a global variable by the name of its memory location
  - Calling to and returning from functions defined in other code

```
main:
        pushl   %ebp
        movl    %esp, %ebp
        call    getchar
        cmpl    $'A', %eax
        jne     skip
        pushl   $msg
        call    printf
        addl    $4, %esp
skip:
        movl    $0, %eax
        movl    %ebp, %esp
        popl    %ebp
        ret
```

References Across Instructions

- Many instructions can be assembled independently
  - pushl %edx
  - leal (%eax, %eax, 4), %eax
  - movl $0, %eax
  - addl %ebx, %ecx
- But, some make references to other data or code
  - jne skip
  - pushl $msg
  - call printf
- Need to fill in those references
  - To generate a final executable binary

The Forward Reference Problem

- Problem

```
        …
        jmp mylabel
        …
mylabel:
        …
```

Any assembler must deal with the forward reference problem

- Assembler must generate machine language code for “jmp mylabel”
- But assembler hasn’t yet *seen* the definition of mylabel
  - I.e., the jmp instruction contains a forward reference to mylabel

The Forward Reference Solution

- Solution
  - Assembler performs **2 passes** over assembly language program
- Different assemblers perform different tasks in each pass
- One straightforward design…

Assembler Passes

- Pass1
  - Assembler traverses assembly program to create…
  - Symbol table
    - Key: label
    - Value: information about label
      - Label name, which section, what offset within that section, …
- Pass 2
  - Assembler traverses assembly program again to create…
  - RODATA section
  - DATA section
  - BSS section
  - TEXT section
  - Relocation record section
    - Each relocation record indicates an area the linker must patch

An Example Program

- A simple (nonsensical) program:

```
#include <stdio.h>
int main(void) {
   if (getchar() == 'A')
      printf("Hi\n");
   return 0;
}
```

- Let's consider how the assembler handles that program…

```
        .section ".rodata"
msg:
        .asciz  "Hi\n"
        .section ".text"
        .globl  main
main:
        pushl   %ebp
        movl    %esp, %ebp
        call    getchar
        cmpl    $'A', %eax
        jne     skip
        pushl   $msg
        call    printf
        addl    $4, %esp
skip:
        movl    $0, %eax
        movl    %ebp, %esp
        popl    %ebp
        ret
```

Assembler Data Structures (1)

- Symbol Table

Label	Section	Offset	Local?	Seq#

- Relocation Records

Section	Offset	Rel Type	Seq#

- RODATA Section (location counter: 0)

Offset	Contents	Explanation

- No DATA or BSS section in this program
- Initially all sections are empty

- TEXT Section (location counter: 0)

Offset	Contents	Explanation

Assembler Pass 1

```
        .section ".rodata"
msg:
        .asciz  "Hi\n"
        .section ".text"
        .globl  main
main:
        pushl   %ebp
        movl    %esp, %ebp
        call    getchar
        cmpl    $'A', %eax
        jne     skip
        pushl   $msg
        call    printf
        addl    $4, %esp
skip:
        movl    $0, %eax
        movl    %ebp, %esp
        popl    %ebp
        ret
```

Assembler notes that the current section is RODATA

Assembler adds binding to Symbol Table…

Assembler Data Structures (2)

- Symbol Table

Label	Section	Offset	Local?	Seq#
msg	RODATA	0	local	0

- msg marks a spot in the RODATA section at offset 0
- msg is a local label
- Assign msg sequence number 0

- Relocation Records
  - (Same)
- RODATA Section (location counter: 0)
  - (Same)
- TEXT Section (location counter: 0)
  - (Same)

Assembler Pass 1 (cont.)


```
        .section ".rodata"
msg:
        .asciz  "Hi\n"
        .section ".text"
        .globl  main
main:
        pushl   %ebp
        movl    %esp, %ebp
        call    getchar
        cmpl    $'A', %eax
        jne     skip
        pushl   $msg
        call    printf
        addl    $4, %esp
skip:
        movl    $0, %eax
        movl    %ebp, %esp
        popl    %ebp
        ret
```

Assembler increments RODATA section ***location counter*** by byte count of the string (4)…

Assembler Data Structures (3)

- Symbol Table

Label	Section	Offset	Local?	Seq#
msg	RODATA	0	local	0

- Relocation Records
  - (Same)
- RODATA Section (location counter: 4)
  - (Same)
- TEXT Section (location counter: 0)
  - (Same)

- RODATA location counter now is 4
- If another label were defined in at this point, it would mark a spot in RODATA at offset 4

Assembler Pass 1 (cont.)

```
        .section ".rodata"
msg:
        .asciz  "Hi\n"
        .section ".text"
        .globl  main
main:
        pushl   %ebp
        movl    %esp, %ebp
        call    getchar
        cmpl    $'A', %eax
        jne     skip
        pushl   $msg
        call    printf
        addl    $4, %esp
skip:
        movl    $0, %eax
        movl    %ebp, %esp
        popl    %ebp
        ret
```

Assembler notes that current section is TEXT

Assembler does nothing

Assembler adds binding to Symbol Table…

Assembler Data Structures (4)

- Symbol Table

Label	Section	Offset	Local?	Seq#
msg	RODATA	0	local	0
main	TEXT	0	local	1

- main marks a spot in the TEXT section at offset 0
- main is a local label (assembler will discover otherwise in Pass 2)
- Assign main sequence number 1

- Relocation Records
  - (Same)
- RODATA Section (location counter: 4)
  - (Same)
- TEXT Section (location counter: 0)
  - (Same)

Assembler Pass 1 (cont.)


```
        .section ".rodata"
msg:
        .asciz  "Hi\n"
        .section ".text"
        .globl  main
main:
        pushl   %ebp
        movl    %esp, %ebp
        call    getchar
        cmpl    $'A', %eax
        jne     skip
        pushl   $msg
        call    printf
        addl    $4, %esp
skip:
        movl    $0, %eax
        movl    %ebp, %esp
        popl    %ebp
        ret
```

Assembler increments TEXT section location counter by the length of each instruction…

Assembler Data Structures (5)

- Symbol Table

Label	Section	Offset	Local?	Seq#
msg	RODATA	0	local	0
main	TEXT	0	local	1

- Relocation Records
  - (Same)
- RODATA Section (location counter: 4)
  - (Same)
- TEXT Section (location counter: 26)
  - (Same)

- TEXT location counter now is 26
- If another label were defined at this point, it would mark a spot in TEXT at offset 26

Assembler Pass 1 (cont.)

```
        .section ".rodata"
msg:
        .asciz  "Hi\n"
        .section ".text"
        .globl  main
main:
        pushl   %ebp
        movl    %esp, %ebp
        call    getchar
        cmpl    $'A', %eax
        jne     skip
        pushl   $msg
        call    printf
        addl    $4, %esp
skip:
        movl    $0, %eax
        movl    %ebp, %esp
        popl    %ebp
        ret
```

Assembler adds binding to Symbol Table…

Assembler Data Structures (6)

- Symbol Table

Label	Section	Offset	Local?	Seq#
msg	RODATA	0	local	0
main	TEXT	0	local	1
skip	TEXT	26	local	2

- skip marks a spot in the TEXT section at offset 26
- skip is a local label
- Assign skip sequence number 2

- Relocation Records
  - (Same)
- RODATA Section (location counter: 4)
  - (Same)
- TEXT Section (location counter: 26)
  - (Same)

Assembler Pass 1 (cont.)

```
        .section ".rodata"
msg:
        .asciz  "Hi\n"
        .section ".text"
        .globl  main
main:
        pushl   %ebp
        movl    %esp, %ebp
        call    getchar
        cmpl    $'A', %eax
        jne     skip
        pushl   $msg
        call    printf
        addl    $4, %esp
skip:
        movl    $0, %eax
        movl    %ebp, %esp
        popl    %ebp
        ret
```

Assembler increments TEXT section location counter by the length of each instruction…

Assembler Data Structures (7)

- Symbol Table

Label	Section	Offset	Local?	Seq#
msg	RODATA	0	local	0
main	TEXT	0	local	1
skip	TEXT	26	local	2

- Relocation Records
  - (Same)
- RODATA Section (location counter: 4)
  - (Same)
- TEXT Section (location counter: 35)
  - (Same)

- TEXT location counter now is 35
- If another label were defined at this point, it would mark a spot in TEXT at offset 35

From Assembler Pass 1 to Pass 2

- End of Pass 1
  - Assembler has (partially) created Symbol Table
  - So assembler now knows which location each label marks
- Beginning of Pass 2
  - Assembler resets all section location counters…

Assembler Data Structures (8)

- Symbol Table

Label	Section	Offset	Local?	Seq#
msg	RODATA	0	local	0
main	TEXT	0	local	1
skip	TEXT	26	local	2

- Relocation Records
  - (Same)
- RODATA Section (location counter: 0)
  - (Same)
- TEXT Section (location counter: 0)
  - (Same)

- Location counters reset to 0

Assembler Pass 2

```
        .section ".rodata"
msg:
        .asciz  "Hi\n"
        .section ".text"
        .globl  main
main:
        pushl   %ebp
        movl    %esp, %ebp
        call    getchar
        cmpl    $'A', %eax
        jne     skip
        pushl   $msg
        call    printf
        addl    $4, %esp
skip:
        movl    $0, %eax
        movl    %ebp, %esp
        popl    %ebp
        ret
```

Assembler notes that the current section is RODATA

Assembler does nothing

Assembler places bytes in RODATA section, and increments location counter…

Assembler Data Structures (9)

- Symbol Table
  - (Same)
- Relocation Records
  - (Same)
- RODATA Section (location counter: 4)

Offset	Contents (hex)	Explanation
0	48	ASCII code for 'H'
1	69	ASCII code for 'i'
2	0A	ASCII code for '\n'
3	00	ASCII code for null char

- TEXT Section (location counter: 0)
  - (Same)

- Location counter incremented to 4

- RODATA section contains the bytes comprising the string

Assembler Pass 2 (cont.)

```
        .section ".rodata"
msg:
        .asciz  "Hi\n"
        .section ".text"
        .globl  main
main:
        pushl   %ebp
        movl    %esp, %ebp
        call    getchar
        cmpl    $'A', %eax
        jne     skip
        pushl   $msg
        call    printf
        addl    $4, %esp
skip:
        movl    $0, %eax
        movl    %ebp, %esp
        popl    %ebp
        ret
```

Assembler notes that the current section is TEXT

Assembler updates Symbol Table…

Assembler Data Structures (10)

- Symbol Table

Label	Section	Offset	Local?	Seq#
msg	RODATA	0	local	0
main	TEXT	0	global	1
skip	TEXT	26	local	2

- main is a global label

- Relocation Records
  - (Same)
- RODATA Section (location counter: 4)
  - (Same)
- TEXT Section (location counter: 0)
  - (Same)

Assembler Pass 2 (cont.)

```
        .section ".rodata"
msg:
        .asciz  "Hi\n"
        .section ".text"
        .globl  main
main:
        pushl   %ebp
        movl    %esp, %ebp
        call    getchar
        cmpl    $'A', %eax
        jne     skip
        pushl   $msg
        call    printf
        addl    $4, %esp
skip:
        movl    $0, %eax
        movl    %ebp, %esp
        popl    %ebp
        ret
```

Assembler does nothing

Assembler generates machine language code in current (TEXT) section…

Assembler Data Structures (11)

- Symbol Table
  - (Same)
- Relocation Records
  - (Same)
- RODATA Section (location counter: 4)
  - (Same)
- TEXT Section (location counter: 1)

Offset	Contents	Explanation
0	55	pushl %ebp 01010101 This is a "pushl %ebp" instruction

Assembler Pass 2 (cont.)

```
        .section ".rodata"
msg:
        .asciz  "Hi\n"
        .section ".text"
        .globl  main
main:
        pushl   %ebp
        movl    %esp, %ebp
        call    getchar
        cmpl    $'A', %eax
        jne     skip
        pushl   $msg
        call    printf
        addl    $4, %esp
skip:
        movl    $0, %eax
        movl    %ebp, %esp
        popl    %ebp
        ret
```

Assembler generates machine language code in current (TEXT) section…

Assembler Data Structures (12)

- Symbol Table
  - (Same)
- Relocation Records
  - (Same)
- RODATA Section (location counter: 4)
  - (Same)
- TEXT Section (location counter: 3)

Offset	Contents	Explanation
…	…	…
1-2	89 E5	movl %esp,%ebp 10001001 11 100 101 This is a "movl" instruction whose source operand is a register The M field designates a register The source register is ESP The destination register is EBP

Assembler Pass 2 (cont.)

```
        .section ".rodata"
msg:
        .asciz  "Hi\n"
        .section ".text"
        .globl  main
main:
        pushl   %ebp
        movl    %esp, %ebp
        call    getchar
        cmpl    $'A', %eax
        jne     skip
        pushl   $msg
        call    printf
        addl    $4, %esp
skip:
        movl    $0, %eax
        movl    %ebp, %esp
        popl    %ebp
        ret
```

Assembler generates machine language code in current (TEXT) section…

Assembler Data Structures (12)

- Symbol Table
  - (Same)
- Relocation Records
  - (Same)
- RODATA Section (location counter: 4)
  - (Same)
- TEXT Section (location counter: 8)

- Assembler looks in Symbol Table to find offset of getchar
- getchar is not in Symbol Table
- Assembler cannot compute displacement that belongs at offset 4
- So…

Offset	Contents	Explanation
…	…	…
3-7	E8 ????????	call getchar 11101000 ???????????????????????????????? This is a "call" instruction with a 4-byte immmediate operand This the displacement

Assembler Data Structures (13)

- Symbol Table

Label	Section	Offset	Local?	Seq#
msg	RODATA	0	local	0
main	TEXT	0	global	1
skip	TEXT	26	local	2
getchar	?	?	global	3

- Relocation Records
  - (Same)
- RODATA Section (location counter: 4)
  - (Same)
- TEXT Section (location counter: 8)
  - (Same)

- Assembler adds getchar to Symbol Table
- Then…

Assembler Data Structures (14)

- Symbol Table
  - (Same)
- Relocation Records

Section	Offset	Rel Type	Seq#
TEXT	4	displacement	3

- Assembler generates a relocation record, thus asking linker to patch code

Dear Linker,
Please patch the TEXT section at offset 4. Do a "displacement" type of patch. The patch is with respect to the label whose seq number is 3 (i.e. getchar).
Sincerely,
Assembler

- RODATA Section (location counter: 4)
  - (Same)
- TEXT Section (location counter: 8)
  - (Same)

Assembler Pass 2 (cont.)


```
        .section ".rodata"
msg:
        .asciz  "Hi\n"
        .section ".text"
        .globl  main
main:
        pushl   %ebp
        movl    %esp, %ebp
        call    getchar
        cmpl    $'A', %eax
        jne     skip
        pushl   $msg
        call    printf
        addl    $4, %esp
skip:
        movl    $0, %eax
        movl    %ebp, %esp
        popl    %ebp
        ret
```

Assembler generates machine language code in current (TEXT) section…

Assembler Data Structures (15)

- Symbol Table
  - (Same)
- Relocation Records
  - (Same)
- RODATA Section (location counter: 4)
  - (Same)
- TEXT Section (location counter: 11)

Offset	Contents	Explanation
…	…	…
8-10	83 F8 41	cmpl %'A',%eax 10000011 11 111 000 01000001 This is some "1" instruction that has a 1 byte immediate operand The M field designates a register This is a "cmp" instruction The destination register is EAX The immediate operand is 'A'

Assembler Pass 2 (cont.)


```
        .section ".rodata"
msg:
        .asciz  "Hi\n"
        .section ".text"
        .globl  main
main:
        pushl   %ebp
        movl    %esp, %ebp
        call    getchar
        cmpl    $'A', %eax
        jne     skip
        pushl   $msg
        call    printf
        addl    $4, %esp
skip:
        movl    $0, %eax
        movl    %ebp, %esp
        popl    %ebp
        ret
```

Assembler generates machine language code in current (TEXT) section…

Assembler Data Structures (16)

- Symbol Table
  - (Same)
- Relocation Records
  - (Same)
- RODATA Section (location counter: 4)
  - (Same)
- TEXT Section (location counter: 13)

- Assembler looks in Symbol Table to find offset of skip (26)
- Assembler subtracts offset of next instruction (13)
- Resulting displacement is 13

Offset	Contents	Explanation
…	…	…
11-12	75 0D	jne skip 01110101 00001101 This is a jne instruction that has a 1 byte immediate operand The displacement between the destination instr. and the next instr. is 13

Assembler Pass 2 (cont.)


```
        .section ".rodata"
msg:
        .asciz  "Hi\n"
        .section ".text"
        .globl  main
main:
        pushl   %ebp
        movl    %esp, %ebp
        call    getchar
        cmpl    $'A', %eax
        jne     skip
        pushl   $msg
        call    printf
        addl    $4, %esp
skip:
        movl    $0, %eax
        movl    %ebp, %esp
        popl    %ebp
        ret
```

Assembler generates machine language code in current (TEXT) section…

Assembler Data Structures (16)

- Symbol Table
  - (Same)
- Relocation Records
  - (Same)
- RODATA Section (location counter: 4)
  - (Same)
- TEXT Section (location counter: 18)

- Assembler knows offset of msg (0) within RODATA section
- But assembler does not know location of RODATA section
- So assembler does not know location of msg
- So…

Offset	Contents	Explanation
…	…	…
13-17	68 ????????	pushl $msg 001101000 ???????????????????????????????? This is a pushl instruction with a 4 byte immediate operand This is the data to be pushed

Assembler Data Structures (17)

- Symbol Table
  - (Same)
- Relocation Records

Section	Offset	Rel Type	Seq#
…	…	…	…
TEXT	14	absolute	0

- Assembler generates a relocation record, thus asking linker to patch code

- RODATA Section (location counter: 4)
  - (Same)
- TEXT Section (location counter: 18)
  - (Same)

Dear Linker,
Please patch the TEXT section at offset 14. Do an "absolute" type of patch. The patch is with respect to the label whose seq number is 0 (i.e. msg).
Sincerely,
Assembler

Assembler Pass 2 (cont.)


```
        .section ".rodata"
msg:
        .asciz  "Hi\n"
        .section ".text"
        .globl  main
main:
        pushl   %ebp
        movl    %esp, %ebp
        call    getchar
        cmpl    $'A', %eax
        jne     skip
        pushl   $msg
        call    printf
        addl    $4, %esp
skip:
        movl    $0, %eax
        movl    %ebp, %esp
        popl    %ebp
        ret
```

Assembler generates machine language code in current (TEXT) section…

Assembler Data Structures (18)

- Symbol Table
  - (Same)
- Relocation Records
  - (Same)
- RODATA Section (location counter: 4)
  - (Same)
- TEXT Section (location counter: 23)

- Assembler looks in Symbol Table to find offset of printf
- printf is not in Symbol Table
- Assembler cannot compute displacement that belongs at offset 19
- So…

Offset	Contents	Explanation
…	…	…
18-22	E8 ????????	call printf 11101000 ???????????????????????????? This is a "call" instruction with a 4-byte immmediate operand This the displacement

Assembler Data Structures (19)

- Symbol Table

Label	Section	Offset	Local?	Seq#
msg	RODATA	0	local	0
main	TEXT	0	global	1
skip	TEXT	26	local	2
getchar	?	?	global	3
printf	?	?	global	4

- Relocation Records
  - (Same)
- RODATA Section (location counter: 4)
  - (Same)
- TEXT Section (location counter: 23)
  - (Same)

- Assembler adds printf to Symbol Table
- Then…

Assembler Data Structures (20)

- Symbol Table
  - (Same)
- Relocation Records

Section	Offset	Rel Type	Seq#
…	…	…	…
TEXT	19	displacement	4

- Assembler generates a relocation record, thus asking linker to patch code

Dear Linker,
Please patch the TEXT section at offset 19. Do a "displacement" type of patch. The patch is with respect to the label whose seq number is 4 (i.e. printf).
Sincerely,
Assembler

- RODATA Section (location counter: 4)
  - (Same)
- TEXT Section (location counter: 8)
  - (Same)

Assembler Pass 2 (cont.)

```
        .section ".rodata"
msg:
        .asciz  "Hi\n"
        .section ".text"
        .globl  main
main:
        pushl   %ebp
        movl    %esp, %ebp
        call    getchar
        cmpl    $'A', %eax
        jne     skip
        pushl   $msg
        call    printf
        addl    $4, %esp
skip:
        movl    $0, %eax
        movl    %ebp, %esp
        popl    %ebp
        ret
```

Assembler ignores

Assembler generates machine language code in current (TEXT) section…

Assembler Data Structures (21)

- Symbol Table, Relocation Records, RODATA Section
  - (Same)
- TEXT Section (location counter: 31)

Offset	Contents	Explanation
…	…	…
23-25	83 C4 04	addl $4,%esp 10000011 11 000 100 00000100 This is some "1" instruction that has a 1 byte immediate operand The M field designates a register This is an "add" instruction The destination register is ESP The immediate operand is 4
26-30	B8 00000000	movl $0,%eax 10111000 00000000000000000000000000000000 This is an instruction of the form "movl 4-byte-immediate, %eax" The immediate operand is 0

Assembler Data Structures (22)

- Symbol Table, Relocation Records, RODATA Section
  - (Same)
- TEXT Section (location counter: 35)

Offset	Contents	Explanation
…	…	…
31-32	89 EC	movl %ebp,%esp 10001001 11 101 100 This is a "movl" instruction whose source operand is a register The M field designates a register The source register is EBP The destination register is ESP
33	5D	popl %ebp 01011101 This is a "popl %ebp" instruction
34	C3	ret 11000011 This is a "ret" instruction

From Assembler to Linker

- Assembler writes its data structures to .o file
- Linker:
  - Reads .o file
  - Works in two phases: resolution and relocation

Linker Resolution

- Resolution
  - Linker resolves references
- For this program, linker:
  - Notes that Symbol Table contains undefined labels
    - getchar and printf
  - Fetches, from libc.a, machine language code defining getchar and printf
  - Adds that code to TEXT section
    - (May add code to other sections too)
  - Updates Symbol Table to note offsets of getchar and printf
  - Adds column to Symbol Table to note addresses of all labels

Linker Relocation

- Relocation
  - Linker patches ("relocates") code
  - Linker traverses relocation records, patching code as specified
- For this program

Section	Offset	Rel Type	Seq#
TEXT	4	displacement	3
TEXT	14	absolute	0
TEXT	19	displacement	4

- Linker looks up offset of getchar
- Linker computes:
  [offset of getchar] – 8
- Linker places difference in TEXT section at offset 4

Linker Relocation (cont.)

- For this program

Section	Offset	Rel Type	Seq#
TEXT	4	displacement	3
TEXT	14	absolute	0
TEXT	19	displacement	4

- Linker looks up addr of msg
- Linker places addr in TEXT section at offset 14

Linker Relocation (cont.)

- For this program

Section	Offset	Rel Type	Seq#
TEXT	4	displacement	3
TEXT	14	absolute	0
TEXT	19	displacement	4

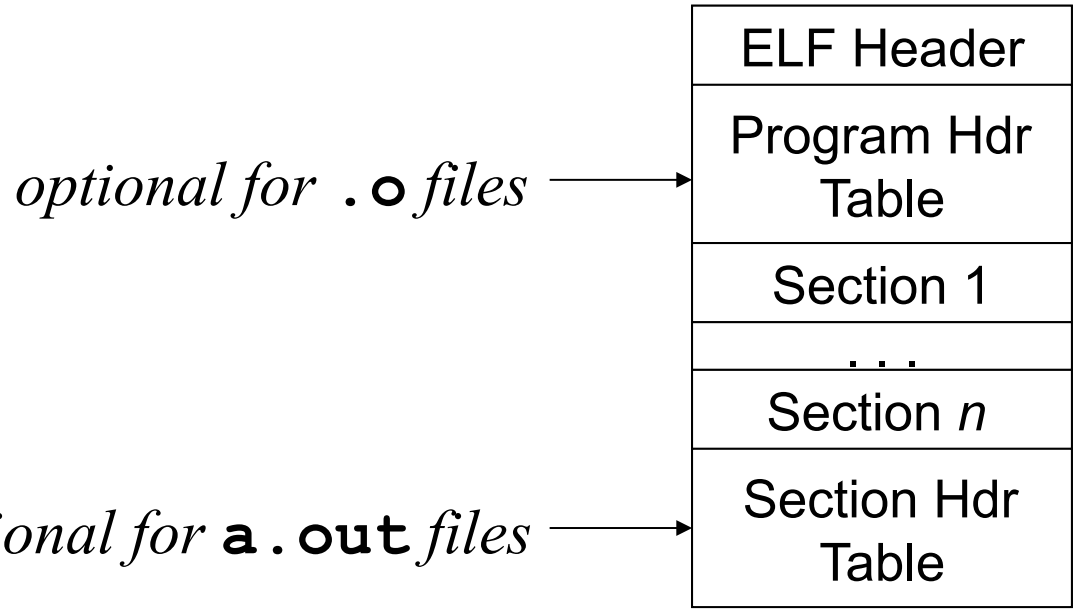
- Linker looks up offset of printf
- Linker computes:
  [offset of printf] – 23
- Linker places difference in TEXT section at offset 19

Linker Finishes

- Linker writes resulting TEXT, RODATA, DATA, BSS sections to executable binary file

ELF: Executable and Linking Format

- Unix format of object and executable files
  - Output by the assembler
  - Input and output of linker



Conclusions

- Assembler: reads assembly language file
  - Pass 1: Generates Symbol Table
    - Contains info about labels
  - Pass 2: Uses Symbol Table to generate code
    - TEXT, RODATA, DATA, BSS sections
    - Relocation Records
  - Writes object file (ELF)
- Linker: reads object files
  - Resolution: Resolves references to make Symbol Table complete
  - Relocation: Uses Symbol Table and Relocation Records to patch code
  - Writes executable binary file (ELF)

Appendix: Generating Machine Lang

- Hint for Buffer Overrun assignment…
- Given an assembly language instruction, how can you find the machine language equivalent?
- Option 1: Consult IA-32 reference manuals
  - See course Web pages for links to the manuals

Appendix: Generating Machine Lang

- Option 2:
  - Compose an assembly language program that contains the given assembly language instruction
  - Then use gdb…

Appendix: Generating Machine Lang

- Using gdb

```
$ gcc217 detecta.s -o detecta
$ gdb detecta
(gdb) x/12i main
0x80483b4 <main>:       push   %ebp
0x80483b5 <main+1>:     mov    %esp,%ebp
0x80483b7 <main+3>:     call   0x8048298 <getchar@plt>
0x80483bc <main+8>:     cmp    $0x41,%eax
0x80483bf <main+11>:    jne    0x80483ce <skip>
0x80483c1 <main+13>:    push   $0x80484b0
0x80483c6 <main+18>:    call   0x80482c8 <printf@plt>
0x80483cb <main+23>:    add    $0x4,%esp
0x80483ce <skip>:       mov    $0x0,%eax
0x80483d3 <skip+5>:     mov    %ebp,%esp
0x80483d5 <skip+7>:     pop    %ebp
0x80483d6 <skip+8>:     ret
(gdb) x/35b main
0x0 <main>:      0x55   0x89   0xe5   0xe8   0xfc   0xff   0xff   0xff
0x8 <main+8>:    0x83   0xf8   0x41   0x75   0x0d   0x68   0x00   0x00
0x10 <main+16>:  0x00   0x00   0xe8   0xfc   0xff   0xff   0xff   0x83
0x18 <main+24>:  0xc4   0x04   0xb8   0x00   0x00   0x00   0x00   0x89
0x20 <skip+6>:   0xec   0x5d   0xc3
(gdb) quit
```

Build program; run gdb from shell

Issue x/i command to examine memory as instructions

Issue x/b command to examine memory as raw bytes

Match instructions to bytes

Appendix: Generating Machine Lang

- Option 3:
  - Compose an assembly language program that contains the given assembly language instruction
  - Then use objdump – a special purpose tool…

Appendix: Generating Machine Lang

- Using objdump

Build program; run objdump

Machine language

Assembly language

```
$ gcc217 detecta.s -o detecta
$ objdump -d detecta
detecta:     file format elf32-i386
…
Disassembly of section .text:
…
080483b4 <main>:
 80483b4:       55                      push   %ebp
 80483b5:       89 e5                   mov    %esp,%ebp
 80483b7:       e8 dc fe ff ff          call   8048298 <getchar@plt>
 80483bc:       83 f8 41                cmp    $0x41,%eax
 80483bf:       75 0d                   jne    80483ce <skip>
 80483c1:       68 b0 84 04 08          push   $0x80484b0
 80483c6:       e8 fd fe ff ff          call   80482c8 <printf@plt>
 80483cb:       83 c4 04                add    $0x4,%esp

080483ce <skip>:
 80483ce:       b8 00 00 00 00          mov    $0x0,%eax
 80483d3:       89 ec                   mov    %ebp,%esp
 80483d5:       5d                      pop    %ebp
 80483d6:       c3                      ret
…
```