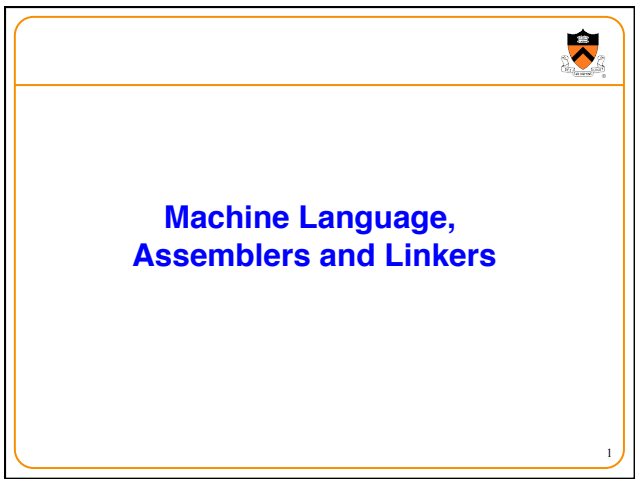


Machine Language, Assemblers and Linkers

1

Goals for this Lecture

- Help you to learn about:
  - IA-32 machine language
  - The assembly and linking processes

2

Why Learn Machine Language

- Last stop on the "language levels" tour
- A power programmer knows the relationship between assembly and machine languages
- A systems programmer knows how an assembler translates assembly to machine language

3

Part 1: Machine Language

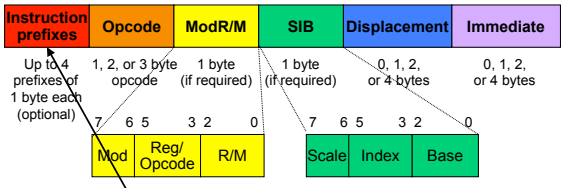
4

IA-32 Machine Language

- IA-32 machine language
  - Difficult to generalize about IA-32 instruction format
    - Many (most) instructions are exceptions to the rules
  - Generally, instructions use format in following slides
- We'll go over
  - The format of instructions
  - Two example instructions
- Just to convey a sense of how it works…

5

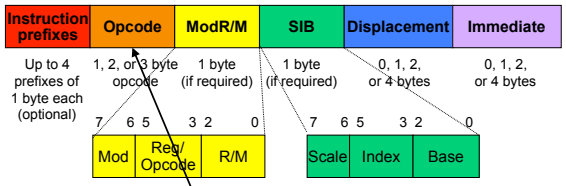
IA-32 Instruction Format



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

6

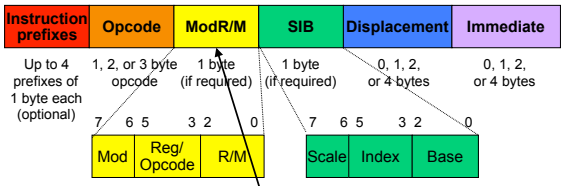
IA-32 Instruction Format (cont.)



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

7

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

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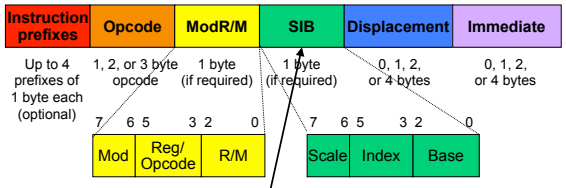
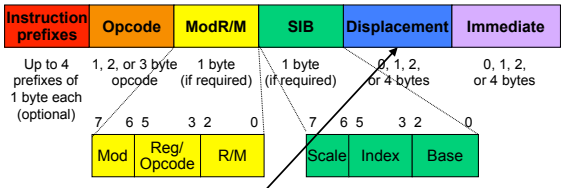
IA-32 Instruction Format (cont.)



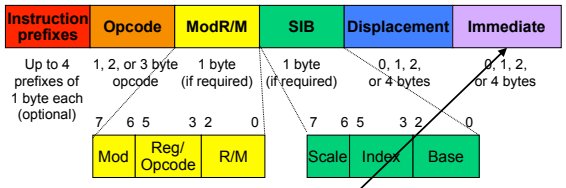
SIB
- Used when one of the operands is a memory operand that uses a **s**cale, an **i**ndex register, and/or a **b**ase register

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
- 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

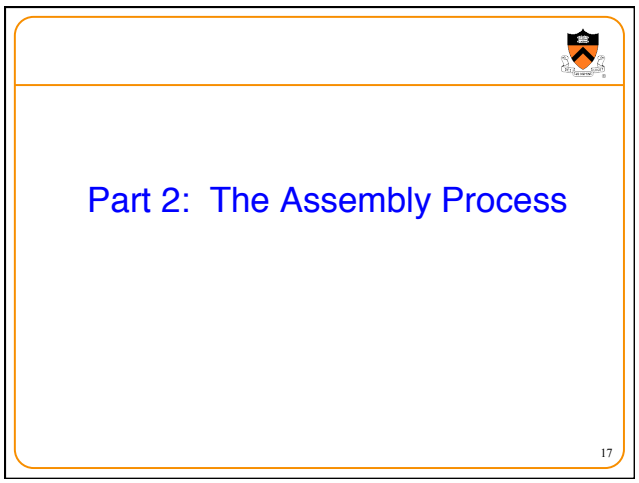
- IA-32 machine language instructions are **complex**
- IA-32 is a
  - **Complex Instruction Set Computer (CISC)**
- Alternative:
  - **Reduced Instruction Set Computer (RISC)**

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 to accomplish 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 (esp. 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, esp. Intel, persists)
- Stage 3: Compilers get smarter
  - Less important that assembly/machine language be simple
  - Hardware is plentiful, enabling complex implementations
  - Much motivation for RISC disappears
  - CISC (esp. Intel) dominates the computing world



Part 2: The Assembly Process

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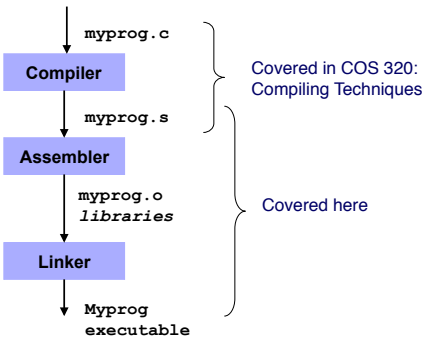
The Build/Execute Process



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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 (file) 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
```

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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

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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
  - One to record labels and addresses, e.g.
  - Another to patch them in
- 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

References Outside the File

- e.g. Call printf
  - printf is defined in another library; assembler doesn't know at what address that code will be placed in memory
- Defer to linker
  - Pass 1 defers symbol resolution to pass 2, pass 2 defers some to linker
- So, Pass 2 becomes…
  - Assembler traverses assembly program again to create…
  - RODATA section
  - DATA section
  - BSS section
  - TEXT section
  - Relocation record section
    - Each relocation record indicates something that 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 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)

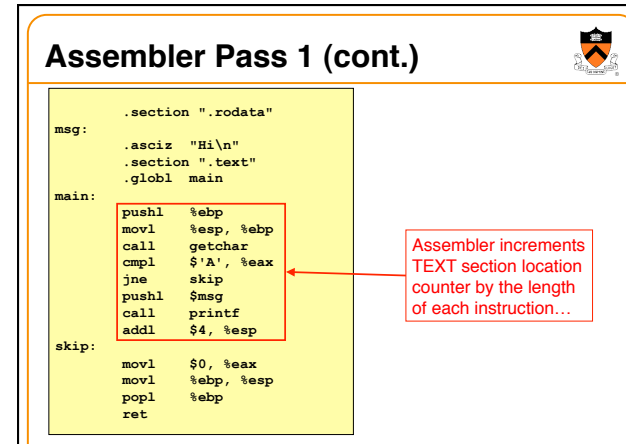
- Symbol Table

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)

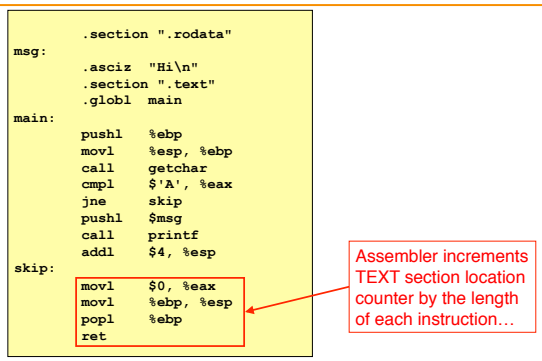
- Symbol Table

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 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…

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Assembler Data Structures (9)

- Symbol Table
  - (Same)
- Relocation Records
  - (Same)
- RODATA Section (location counter: 4)
  - Location counter incremented to 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)
  - RODATA section contains the bytes comprising the string

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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…

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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)

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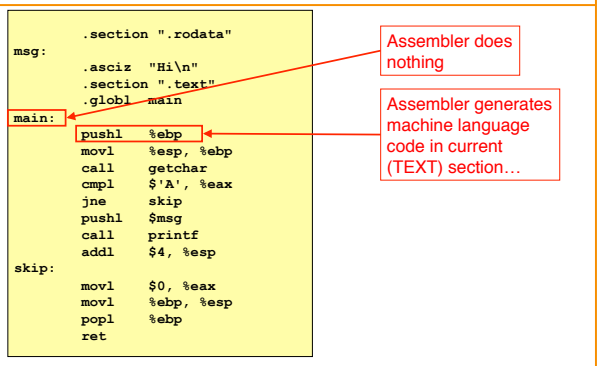
Assembler Pass 2 (cont.)



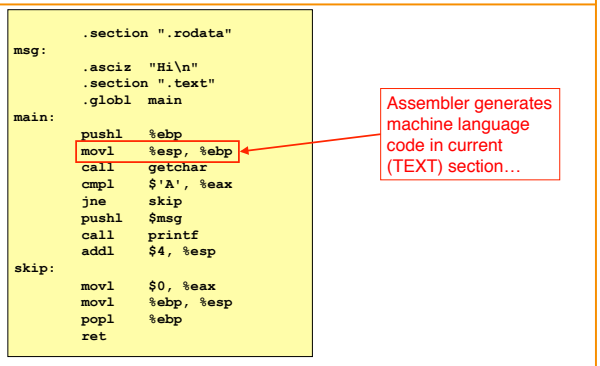
```
        .section ".rodata"
msg:
        .asciz  "Hi\n"
        .section ".text"
        .globl  main
main:
        pushl   %ebp
        movl    %esp, %ebp
        call    getchar
        cmpl    $'A', %eax
        jne     skip
        pushl   $msg
        call    printf
        addl    $4, %esp
skip: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


Assembler 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 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 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)

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

- 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…

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

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

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

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

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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

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From Assembler to Linker

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

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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

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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

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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

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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

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Linker Finishes

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

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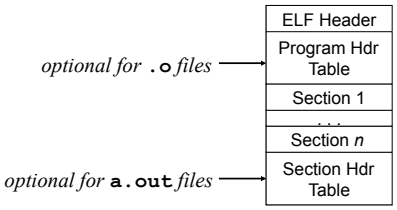
ELF: Executable and Linking Format

- 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

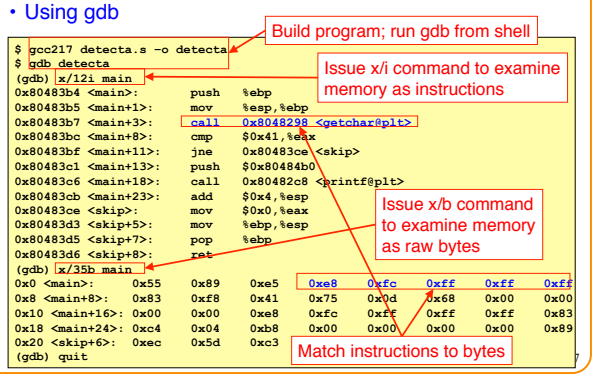
- Hint for Buffer Overrun assignment…
- Given an assembly language instruction, how can you find the machine language equivalent?
- Option 1: Consult IA-32 reference manuals
  - See course Web pages for links to the manuals

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



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…

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Appendix: Generating Machine Lang

- Using objdump