程序的机器级表示（2）

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C and Assembly Language

Characteristics of the high level programming languages

- 抽象
  - 语句表达能力强（指令型/描述性）
  - 可靠
- 类型检查
- 像手写底层代码一样高效
- 能够编译，并在不同的机器上执行

Characteristics of the assembly programming languages

- 直接管理内存
- 低层次指令来进行计算
- 高度机器相关：
  - 特定CPU硬件->特定指令集（机器语言）->特定汇编语言
  - 例如x86汇编，MIPS汇编
  - Intel在PC和服务器领域占绝对统治地位
    - AMD也是x86架构
    - IBM等大型机已经式微（只在金融等领域应用）
    - ARM在嵌入式领域应用还是很广泛，不过汇编大同小异

Why should we understand the assembly code

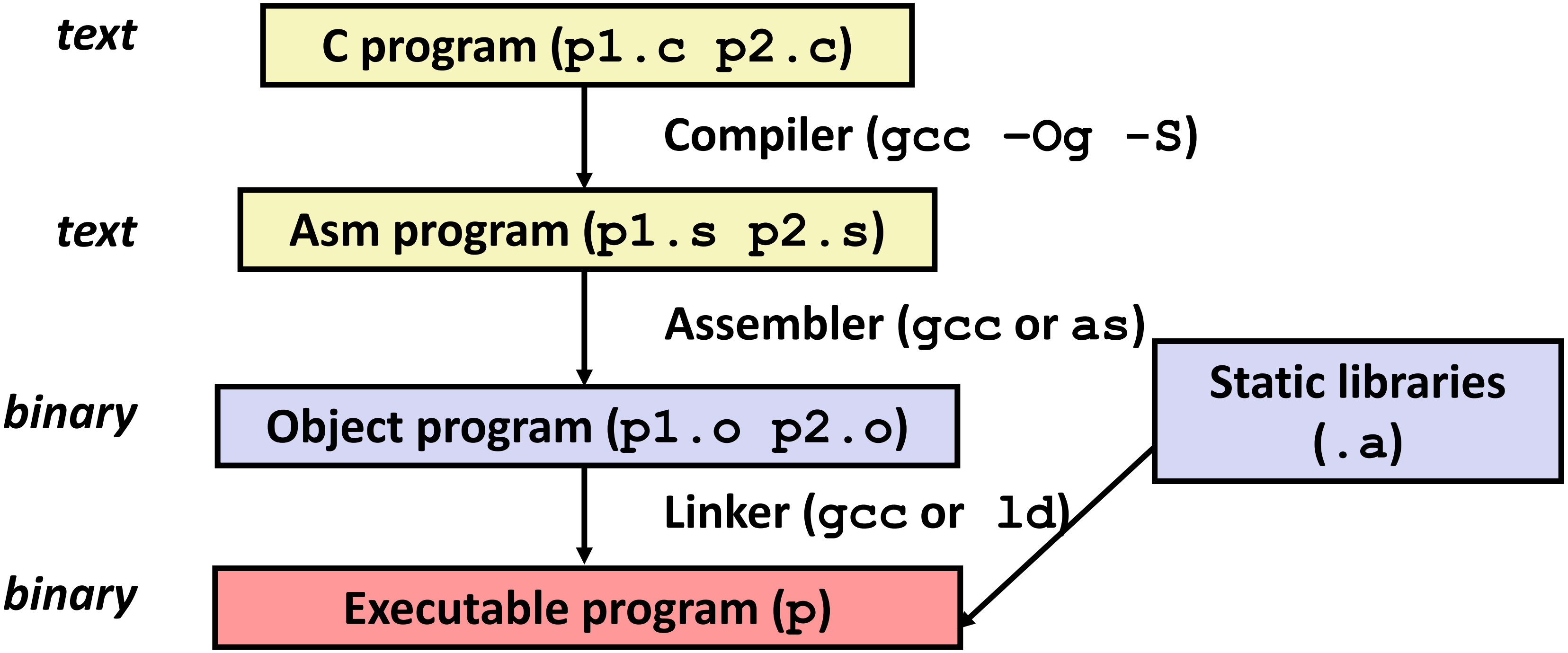
- 理解编译器的优化能力
  - 不能过于贬低：比绝大多数人工强
  - 也不能过于夸大：
    - 有些看似简单的地方，为了避免bug，不敢优化
    - 有些复杂问题还是很难优化（例如并行编译）
- 分析代码中低效的部分，以便提升程序性能
  - 汇编与性能直接对应

From writing assembly code to understand assembly code

- 直接写汇编程序
  - 熟悉汇编语言
  - 习惯汇编的思维方式（可以直接操控硬件）
  - 建立高级语言（C）和汇编之间的联系
- 逆向工程
  - 从C翻译到汇编
  - 理解在系统中程序到底做了什么
  - 帮助找出bug
  - 帮助找出程序的安全隐患
  - 帮助找出性能差的环节

Turning C into Object Code

- Code in files `p1.c p2.c`
- Compile with command: `gcc –Og p1.c p2.c -o p`
  - Use basic optimizations (–Og) [New to recent versions of GCC]
  - Put resulting binary in file `p`



Compiling Into Assembly

C Code

```
long plus(long x, long y);

void sumstore(long x, long y,
              long *dest)
{
    long t = plus(x, y);
    *dest = t;
}
```

Generated x86-64 Assembly

```
sumstore:
   pushq   %rbx
   movq    %rdx, %rbx
   call    plus
   movq    %rax, (%rbx)
   popq    %rbx
   ret
```

Obtain (on shark machine) with command

```
gcc –Og –S sum.c
```

Produces file `sum.s`

Warning: Will get very different results on other machines (Andrew Linux, Mac OS-X, …) due to different versions of gcc and different compiler settings.

Disassembling Object Code

Disassembled

```
0000000000400595 <sumstore>:
  400595:  53                push   %rbx
  400596:  48 89 d3          mov    %rdx,%rbx
  400599:  e8 f2 ff ff ff    callq  400590 <plus>
  40059e:  48 89 03          mov    %rax,(%rbx)
  4005a1:  5b                pop    %rbx
  4005a2:  c3                retq
```

- Disassembler

  `objdump -d sum`

  - 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

```
0x0400595:
    0x53
    0x48
    0x89
    0xd3
    0xe8
    0xf2
    0xff
    0xff
    0xff
    0x48
    0x89
    0x03
    0x5b
    0xc3
```

Disassembled

```
Dump of assembler code for function sumstore:
 0x0000000000400595 <+0>: push   %rbx
 0x0000000000400596 <+1>: mov    %rdx,%rbx
 0x0000000000400599 <+4>: callq  0x400590 <plus>
 0x000000000040059e <+9>: mov    %rax,(%rbx)
 0x00000000004005a1 <+12>:pop    %rbx
 0x00000000004005a2 <+13>:retq
```

- Within gdb Debugger

  ```
  gdb sum
  disassemble sumstore
  ```

  - Disassemble procedure

  ```
  x/14xb sumstore
  ```

  - Examine the 14 bytes starting at `sumstore`

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:
30001001:
30001003:
30001005:
3000100a:
```

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

Code Examples

```c
//C code
int accum = 0;
int sum(int x, int y)
{
   int t = x+y;
   accum += t;
   return t;
}
```

Code Examples

```
//C code
int accum = 0;
int sum(int x, int y)
{
  int t = x+y;
  accum += t;
  return t;
}
```

Obtain with command

```
gcc -O2 -S code.c
```

Assembly file `code.s`

instruction

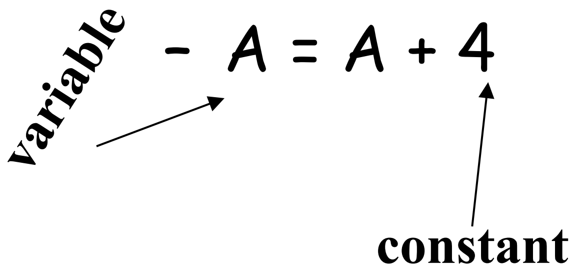
```
_sum:
      pushl %ebp
      movl %esp,%ebp
      movl 12(%ebp),%eax
      addl 8(%ebp),%eax
      addl %eax, accum
      movl %ebp,%esp
      popl %ebp
      ret
```

From C Codes to Assembly codes

- Instruction
  - Performs a very elementary operation only
- Add two signed integers
  - C code:
    - int t = x+y;
  - Assembly code:
    - addl 8(%ebp),%eax
    - Add 2 4-byte integers
    - Similar to expression x +=y

Operands

- In high level languages
  - Either constants
  - Or variable
- Example
  - A = A + 4



variable

constant

Assembly Code

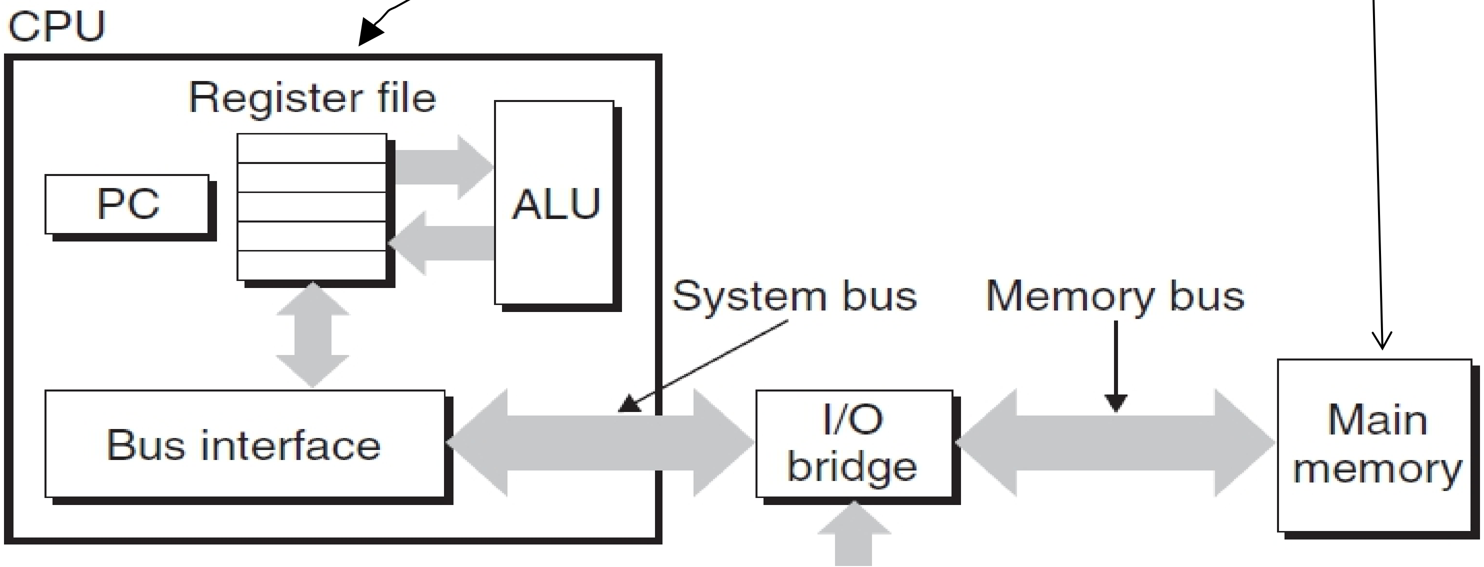
- Operands:

– x:	Register	%eax
– y:	Memory	M[%ebp+8]
– 4:	Immediate	$4

IA-32

Register

Memory



The fastest storage units in computer systems, 32-bit long

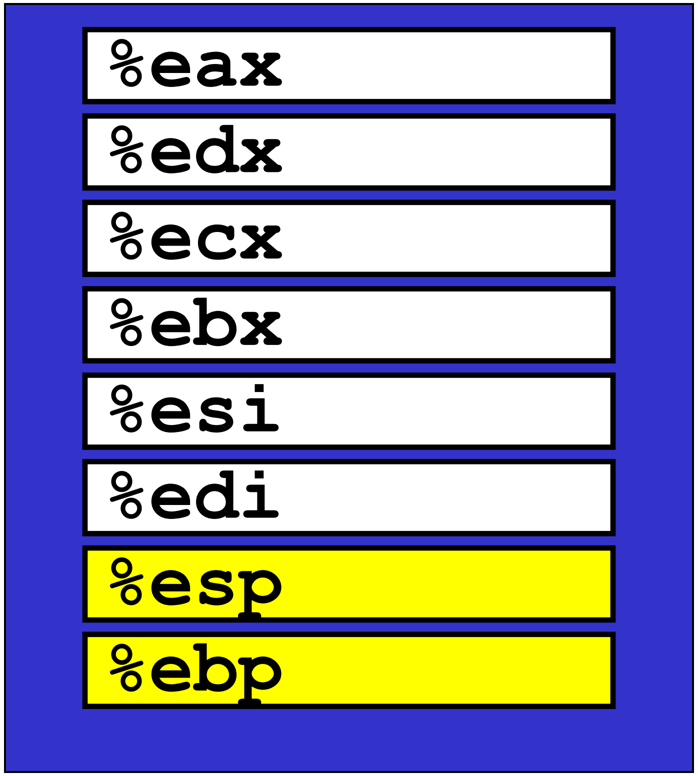
READ/WRITE operations

- Two important concepts
  - Name and value
- WRITE(*name, value*)   value ← READ(*name*)
- WRITE operation specifies
  - a value to be remembered
  - a name by which one can recall that value in the future
- READ operation specifies
  - the name of some previous remembered value
  - the memory device returns that value

Registers vs. Virtual Memory

- How to name registers
  - Using specific names,
  - For example, in IA-32
    - %eax, %ecx, %edx, %ebx, %esi, %edi, %esp, %ebp
- How to name virtual memory
  - Using address as we have studied
- What's the difference
  - Accessing values in Registers is fast
  - Number of the registers is small
  - Most modern instructions can access registers only（RISC）

Where are the variables? — registers & Memory



%eax

%edx

%ecx

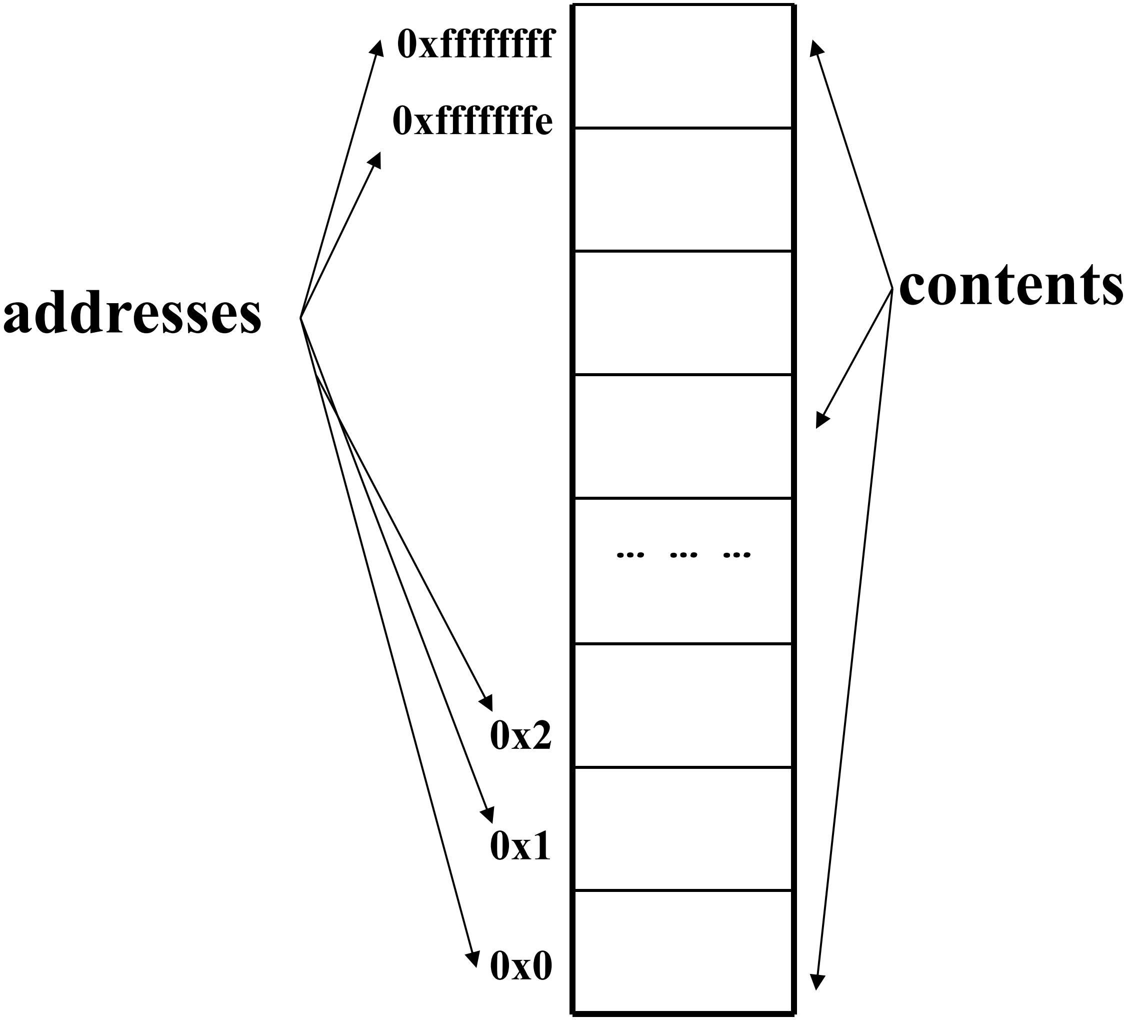
%ebx

%esi

%edi

%esp

%ebp



addresses

0xffffffff

0xfffffffe

… … …

0x2

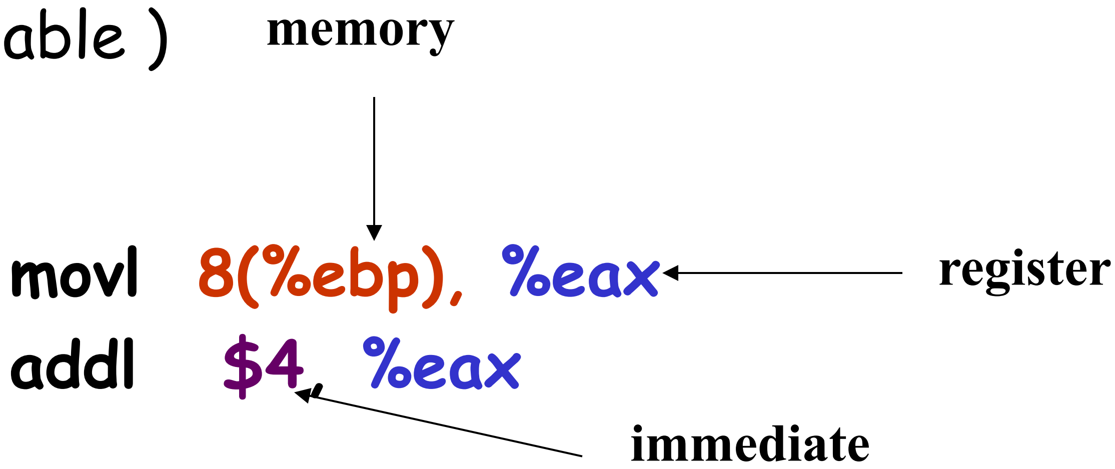
0x1

0x0

contents

Operands

- Counterparts in assembly languages
  - Immediate (constant)
  - Register (variable)
  - Memory (variable)
- Example



memory

```
movl   8(%ebp), %eax
addl    $4, %eax
```

register

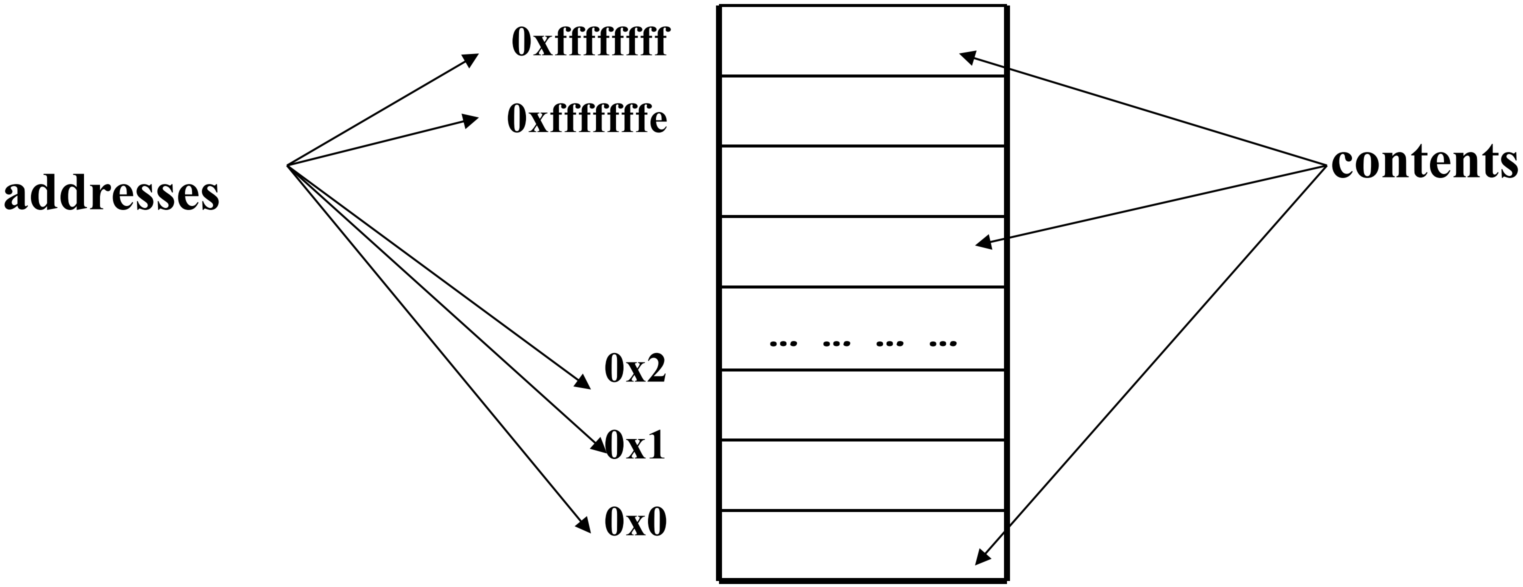
immediate

Express Operands in Assembly (Addressing Mode**)**

- Immediate
  - represents a constant
  - The format is $imm ($4, $0xffffffff)
- Registers
  - Register mode E_a
    - %eax
    - The value stored in the register %eax
      - Noted as R[E_a] (R[%eax])

Virtual spaces

- A linear array of bytes
  - each with its own unique address (array index) starting at zero



Memory References

- The name of the array is annotated as M
- If *addr* is a memory address
- M[*addr*] is the content of the memory starting at *addr*
- *addr* is used as an array index
- How many bytes are there in M[*addr*]?
  - It depends on the context

Indexed Addressing Mode

- An expression for
  - a memory address (or an array index)
- Most general form
  - Imm(E_b, E_i, *s*)
  - Constant “displacement” Imm: 1, 2 or 4 bytes
  - Base register E_b: Any of 8 integer registers
  - Index register E_i : Any, except for `%esp`
  - `S`: Scale: 1, 2, 4, or 8

Memory Addressing Mode（寻址方式）

- The address represented by the above form
  - imm + R[E_b] + R[E_i] * s
- It gives the value
  - M[imm + R[E_b] + R[E_i] * s]

Addressing Mode（寻址方式）

Type	Form	Operand value	Name
Immediate	\$Imm	Imm	Immediate
Register	E_a	R[E_a]	Register
Indexed	Imm	M[Imm]	Absolute
Indexed	(E_a)	M[R[E_a]]	Indirect
Indexed	Imm(E_b)	M[Imm+ R[E_b]]	Base+displacement
Indexed	(E_b, E_i)	M[R[E_b]+ R[E_i]]	Indexed
Indexed	Imm(E_b, E_i)	M[Imm+ R[E_b]+ R[E_i]]	Scaled indexed
Indexed	(, E_i, s)	M[R[E_i]*s]	Scaled indexed
Indexed	(E_b, E_i, s)	M[R[E_b]+ R[E_i]*s]	Scaled indexed
Indexed	Imm(E_b, E_i, s)	M[Imm+ R[E_b]+ R[E_i]*s]	Scaled indexed

Address	Value
0x100	0xFF
0x104	0xAB
0x108	0x13
0x10C	0x11

Register	Value
%eax	0x100
%ecx	0x1
%edx	0x3

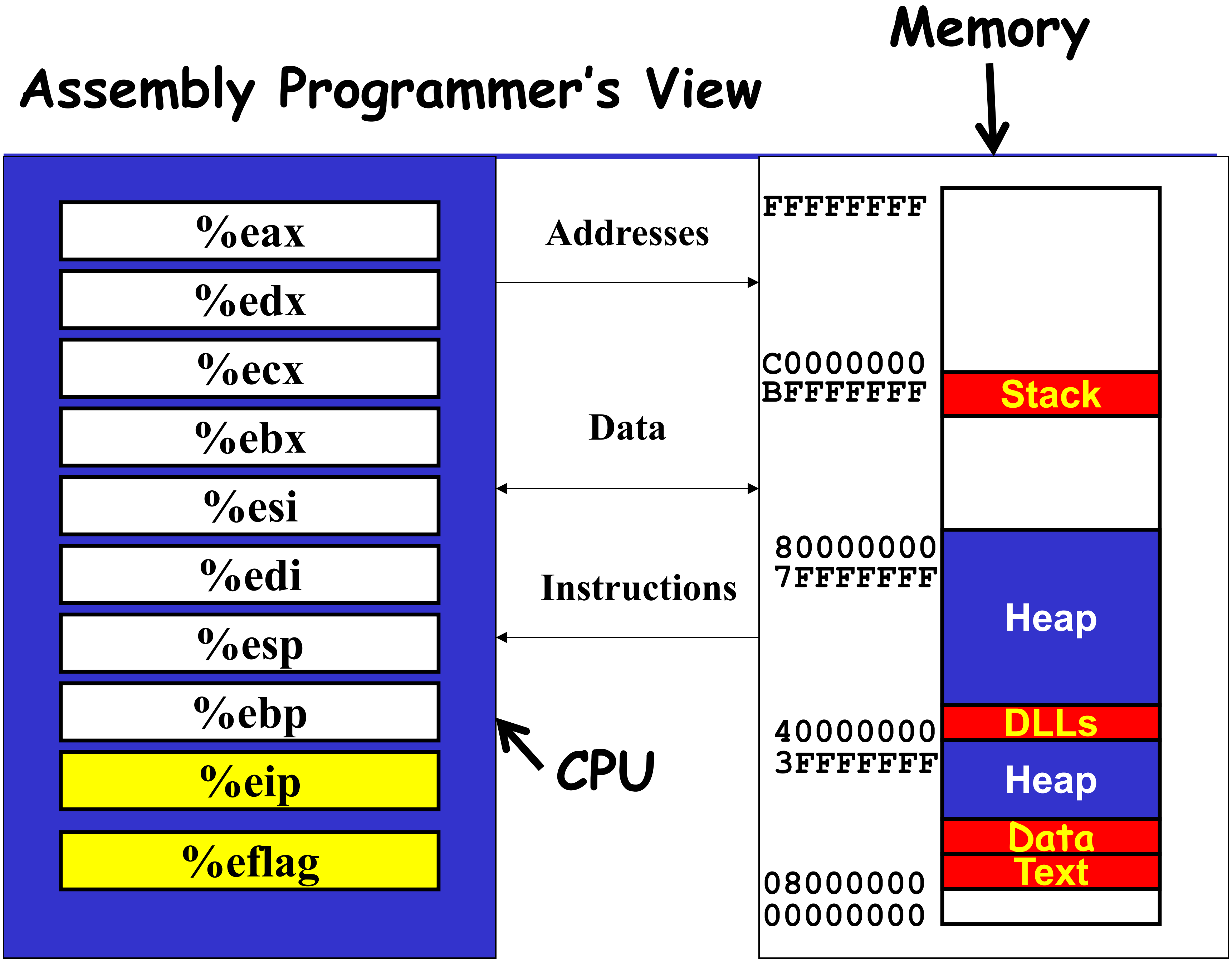
Operand	Value
%eax	0x100
(%eax)	0xFF
$0x108	0x108
0x108	0x13
260(%ecx,%edx)	(0x108) 0x13
(%eax,%edx,4)	(0x10C) 0x11

Understanding Machine Execution

Outline

- Machine states
- Machine execution
- Virtual Memory Layout

Assembly Programmer's View



Programmer-Visible States

- Program Counter(%eip)
  - Address of the next instruction
- Register File
  - Heavily used program data
  - Integer and floating-point

Programmer-Visible States

- Conditional code register (%eflags)
  - Hold status information about the most recently executed instruction
  - Implement conditional changes in the control flow
- Virtual Memory

Operations in Assembly Instructions

- Instruction
  - Performs only o
- Program
  - is a sequence o
- Sequential exec
  - Normally one b
  - Conditionally br
- Typically opera
- Transfers data r

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

Understanding Machine Execution

```
55 89 e5 8b 45 0c
03 45 08 01 05 00
00 00 00 89 ec 5d
c3
```

Obtain with command

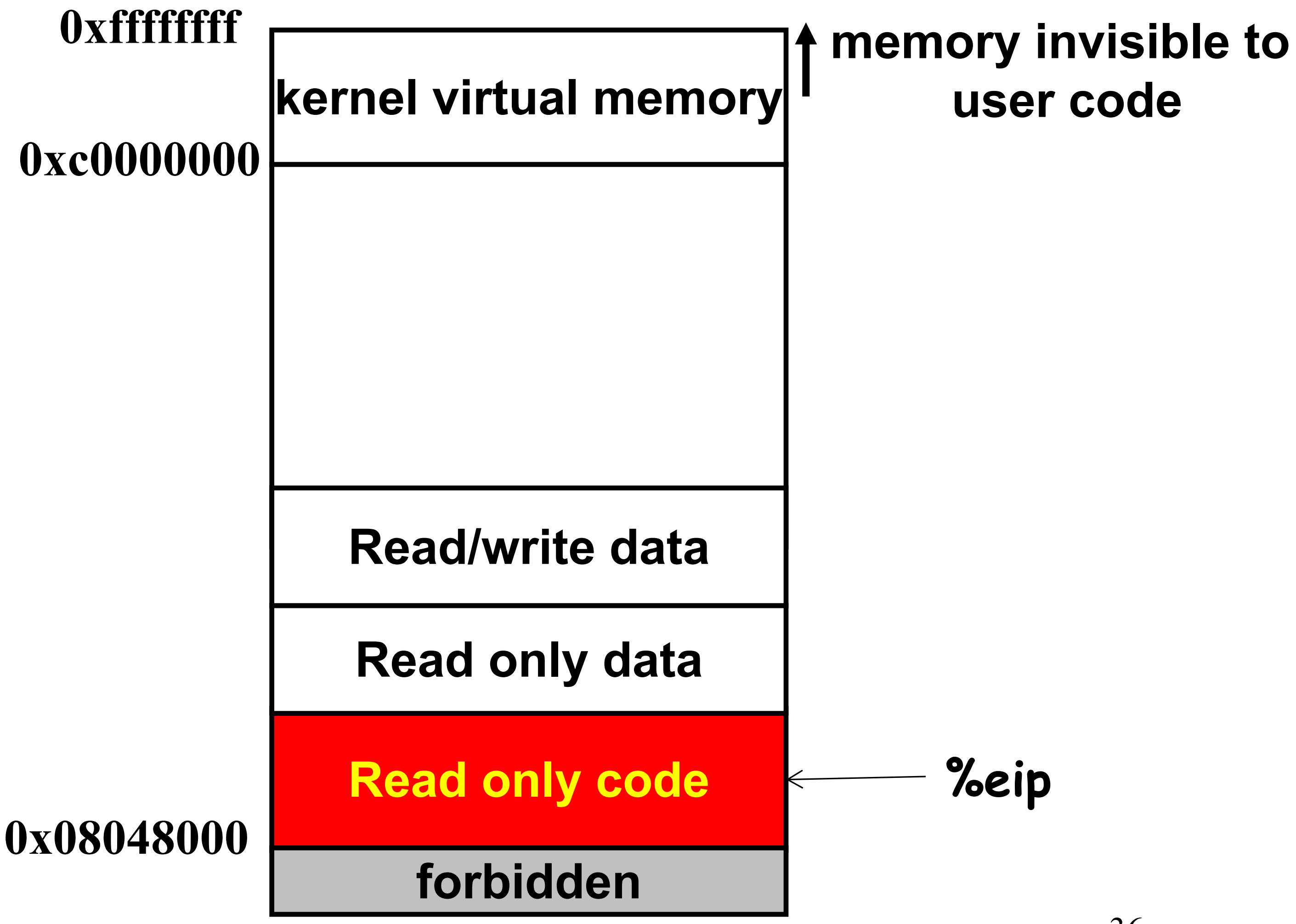
```
gcc –O2 -c code.c
```

Relocatable object file `code.o`

- increase %eip
  - %eip is also called program counter (PC)

Code Layout

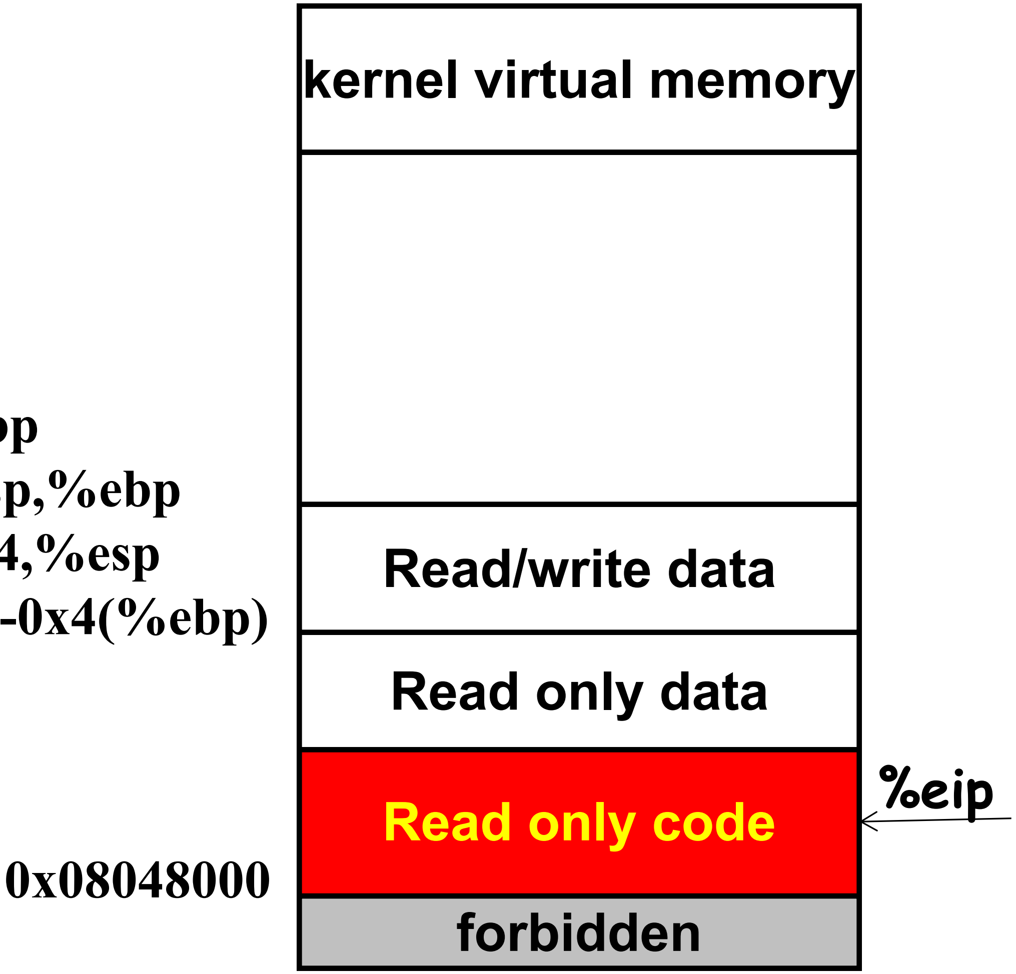
Linux/x86 process memory image



Sequential execution

```
f()
{
   int i = 3 ;
}
```

```
08048390 <_f>:
  90:  55                   push   %ebp
  91:  89 e5                mov    %esp,%ebp
  93:  83 ec 14             sub    $0x14,%esp
  96:  c7 45 fc             movl  $03, -0x4(%ebp)
  9d:  c9  03 00 00 00      leave
  9e:  c3                   ret
```



kernel virtual memory

Read/write data

Read only data

Read only code

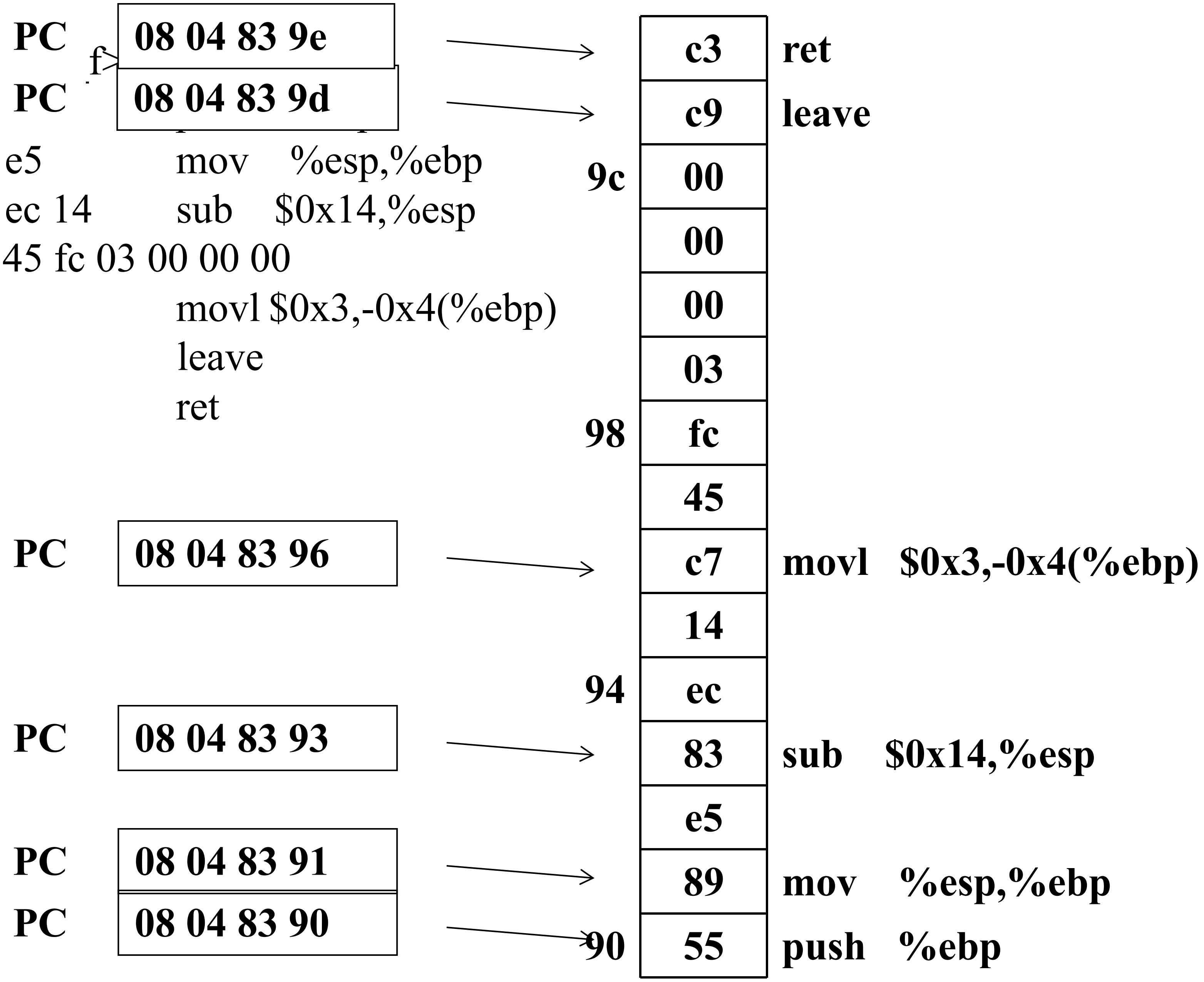
forbidden

0x08048000

%eip

Sequential execution

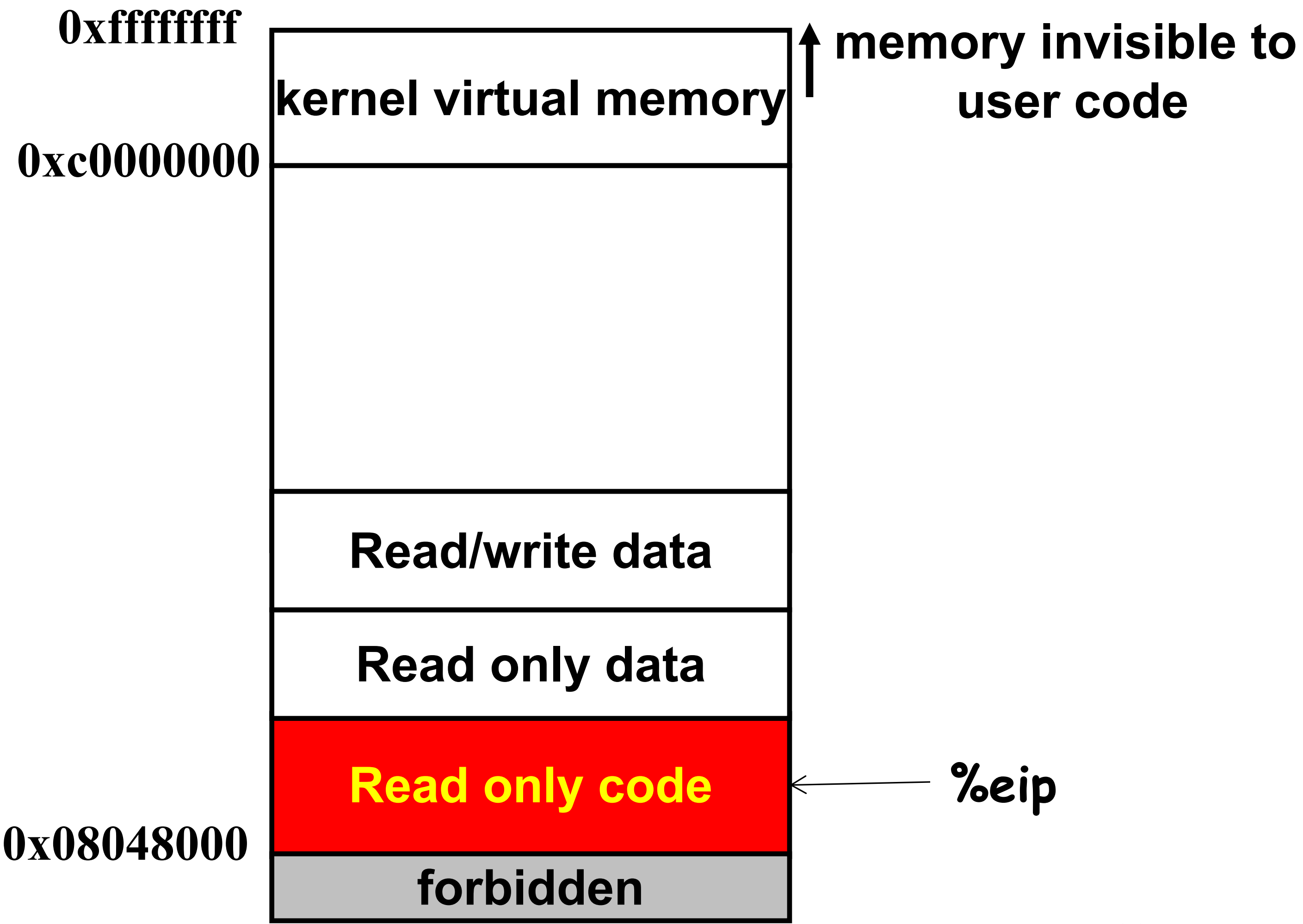
```
000000      f>
  0:  55
  1:  89 e5          mov    %esp,%ebp
  3:  83 ec 14       sub    $0x14,%esp
  6:  c7 45 fc 03 00 00 00
                     movl $0x3,-0x4(%ebp)
  d:  c9             leave
  e:  c3             ret
```



	c3	ret
	c9	leave
9c	00	
	00	
	00	
	03	
98	fc	
	45	
	c7	movl $0x3,-0x4(%ebp)
	14	
94	ec	
	83	sub $0x14,%esp
	e5	
	89	mov %esp,%ebp
90	55	push %ebp

Code Layout

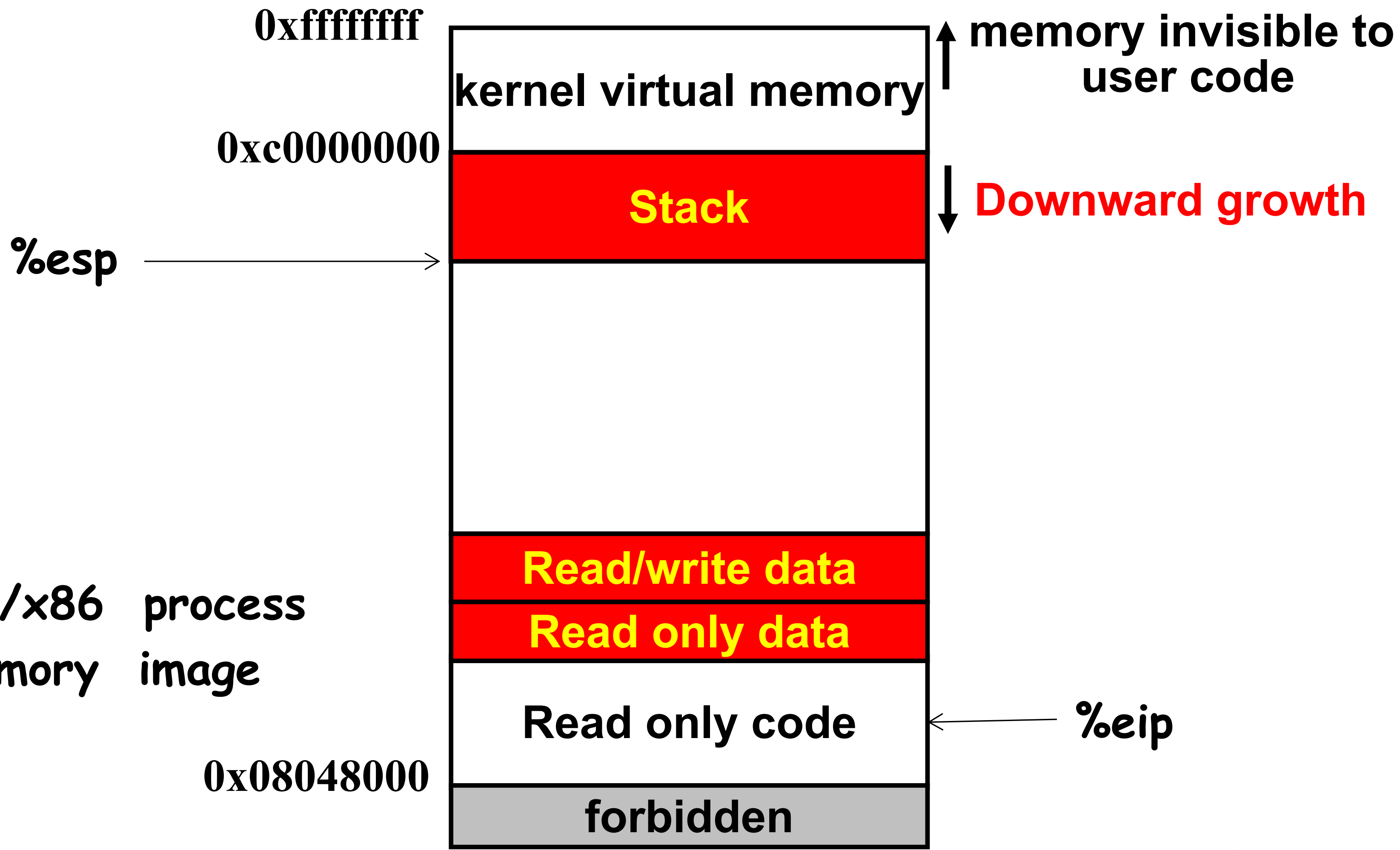
Linux/x86 process memory image



Data layout

- Object model in assembly
  - A large, byte-addressable array
  - No distinctions even between signed or unsigned integers
  - Code, user data, OS data
  - Run-time stack for managing procedure call and return
  - Blocks of memory allocated by user

Data Layout



Linux/x86 process memory image

Example (C Code)

```
#include <stdio.h>

int accum = 0;
```

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

```
int main()
{
   int s;
   s = sum(4,3);
   printf(" %d %d \n", s, accum);
   return 0;
}
```

Example (object Code)

```
08048360 <sum>:
 8048360:   55                      push   %ebp
 8048361:   89 e5                   mov    %esp,%ebp
 8048363:   8b 45 0c                mov    0xc(%ebp),%eax
 8048366:   8b 55 08                mov    0x8(%ebp),%edx
 8048369:   5d                      pop    %ebp
 804836a:   01 d0                   add    %edx,%eax
 804836c:   01 05 f0 95 04 08       add    %eax, 0x80495f0
 8048372:   c3                      ret
```

Example (object Code)

```
08048360 <sum>:
 8048360:   55                      push   %ebp
 8048361:   89 e5                   mov    %esp,%ebp
 8048363:   8b 45 0c                mov    0xc(%ebp),%eax
 8048366:   8b 55 08                mov    0x8(%ebp),%edx
 8048369:   5d                      pop    %ebp
 804836a:   01 d0                   add    %edx,%eax
 804836c:   01 05 f0 95 04 08       add    %eax, 0x80495f0
 8048372:   c3                      ret
```

Example (object Code)

```
08048360 <sum>:
 8048360:   55                    push   %ebp
 8048361:   89 e5                 mov     %esp,%ebp
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 8048366:   8b 55 08              mov     0x8(%ebp),%edx
 8048369:   5d                    pop    %ebp
 804836a:   01 d0                 add    %edx,%eax
 804836c:   01 05 f0 95 04 08     add    %eax, 0x80495f0
 8048372:   c3                    ret
```