x86-64 (2)

LEA

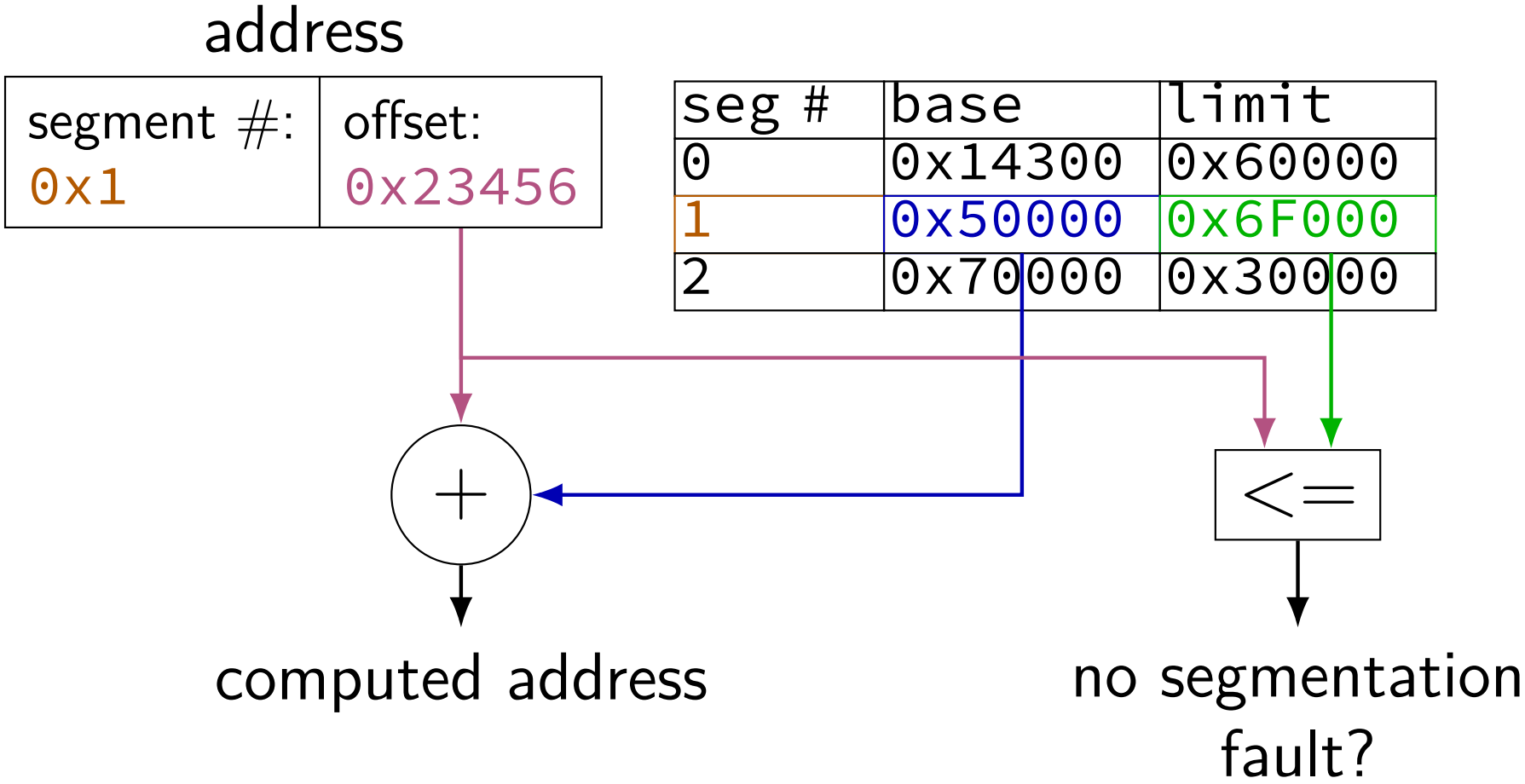
like a `mov` — but stop at finding the memory address

never accesses memory

`lea` `(%rax), %rbx` is **`mov`** `%rax, %rbx`

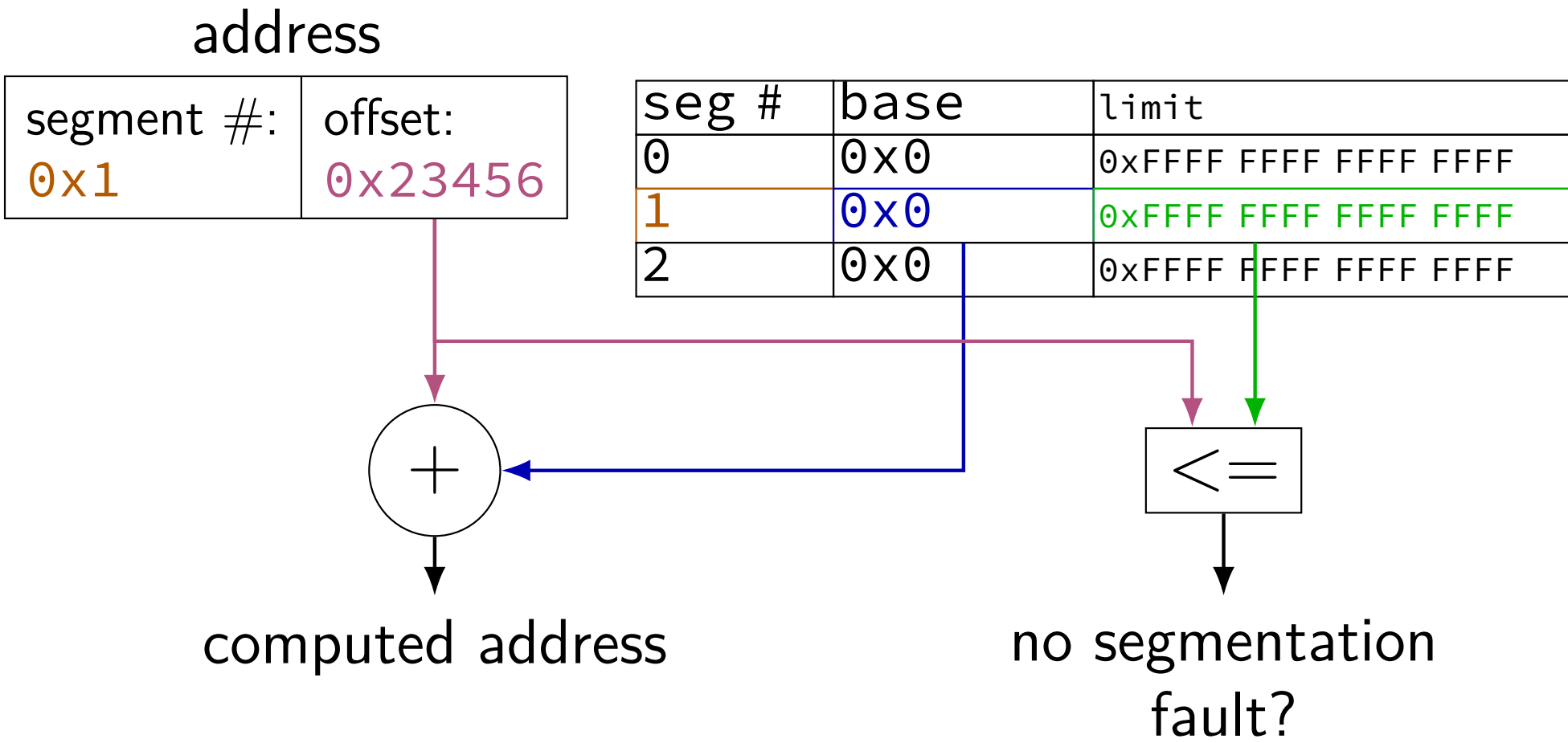
segmentation

before virtual memory, there was segmentation



segmentation

before virtual memory, there was segmentation



x86 segmentation

addresses you've seen are the offsets

but every access uses a segment number!

segment numbers come from registers

- CS — code segment number (jump, call, etc.)
- SS — stack segment number (push, pop, etc.)
- DS — data segment number (mov, add, etc.)
- ES — addt'l data segment (string instructions)
- FS, GS — extra segments (never default)

instructions can have a segment override:

```
movq $42, %fs:100(%rsi)
    // move 42 to segment (# in FS),
    // offset 100 + RSI
```

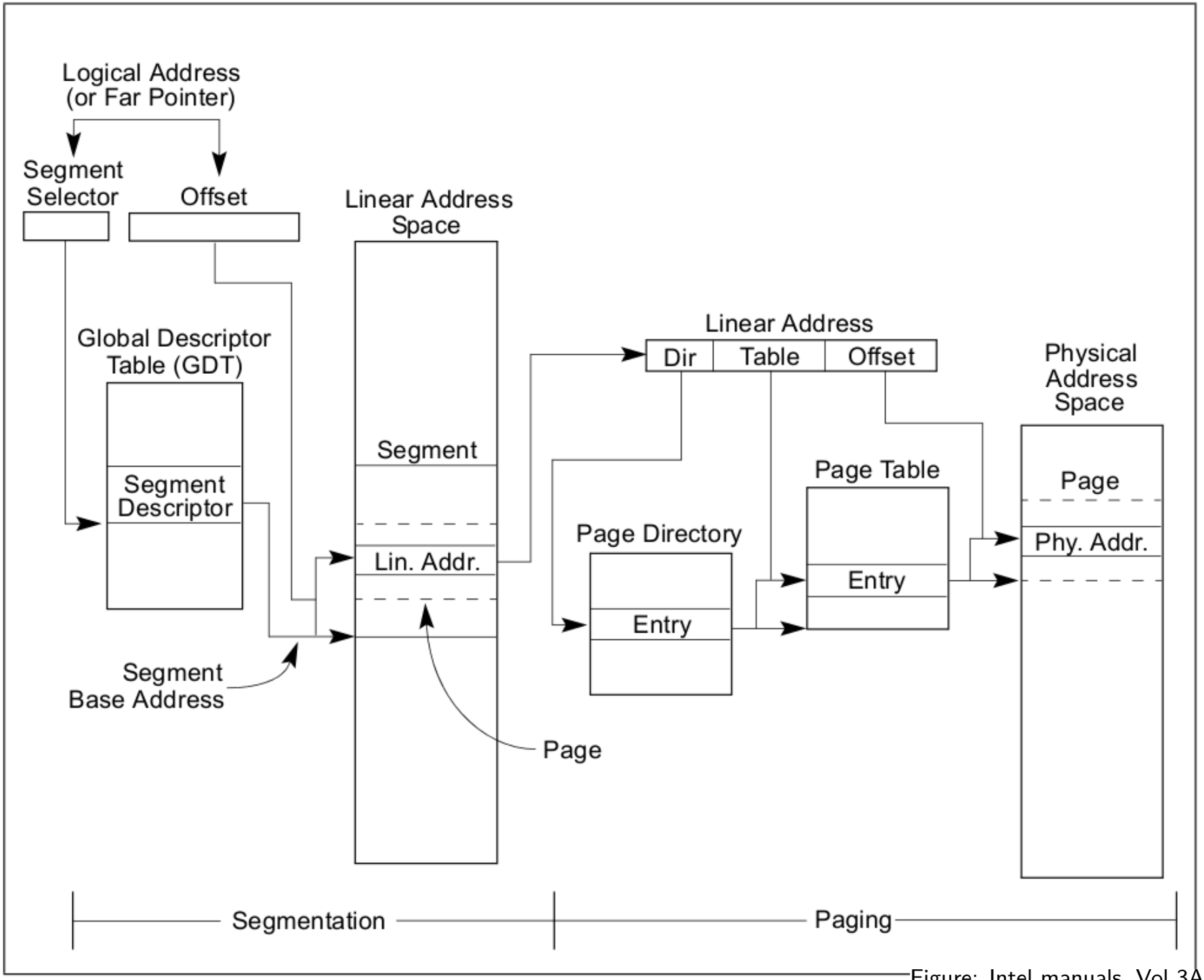


Figure: Intel manuals, Vol 3A

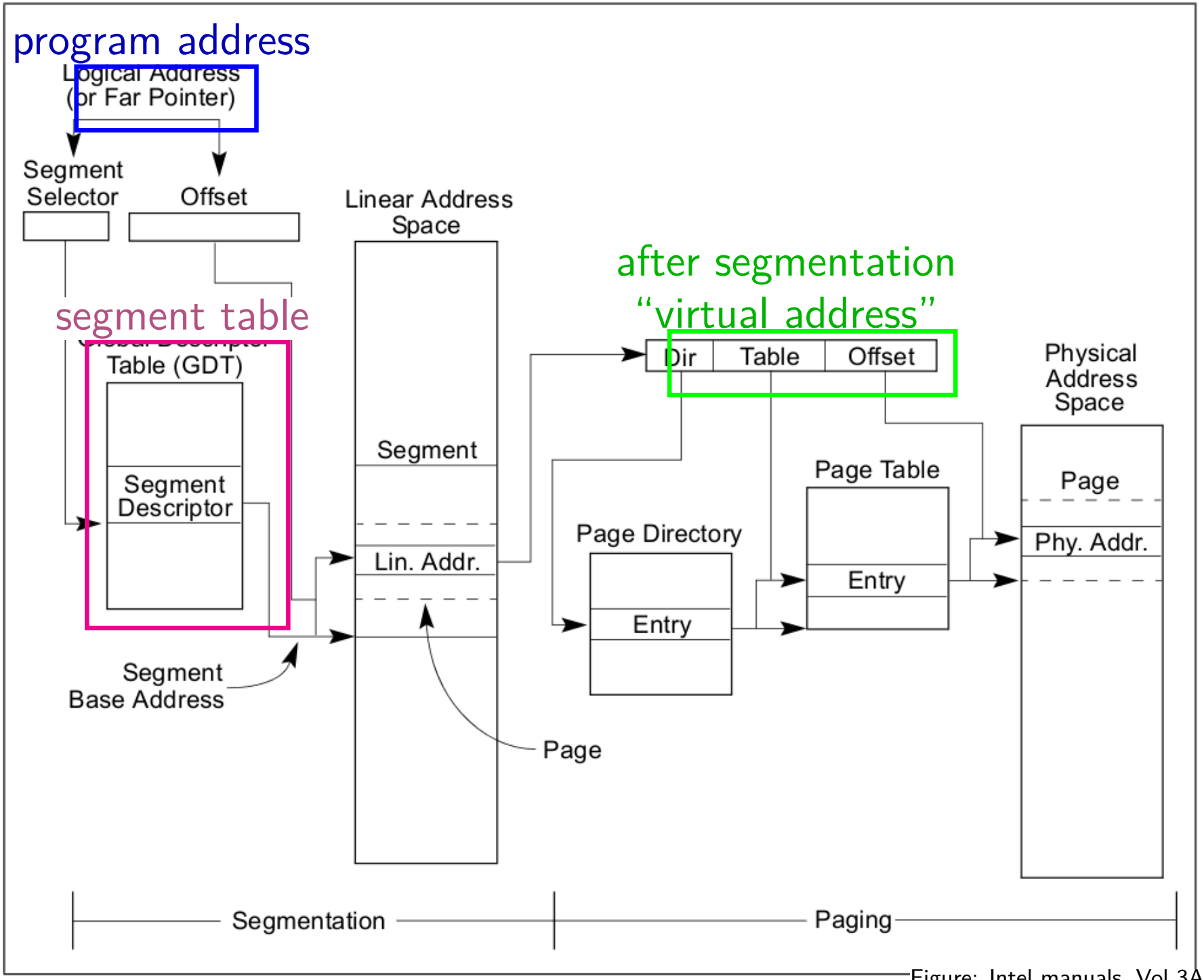


Figure: Intel manuals, Vol 3A

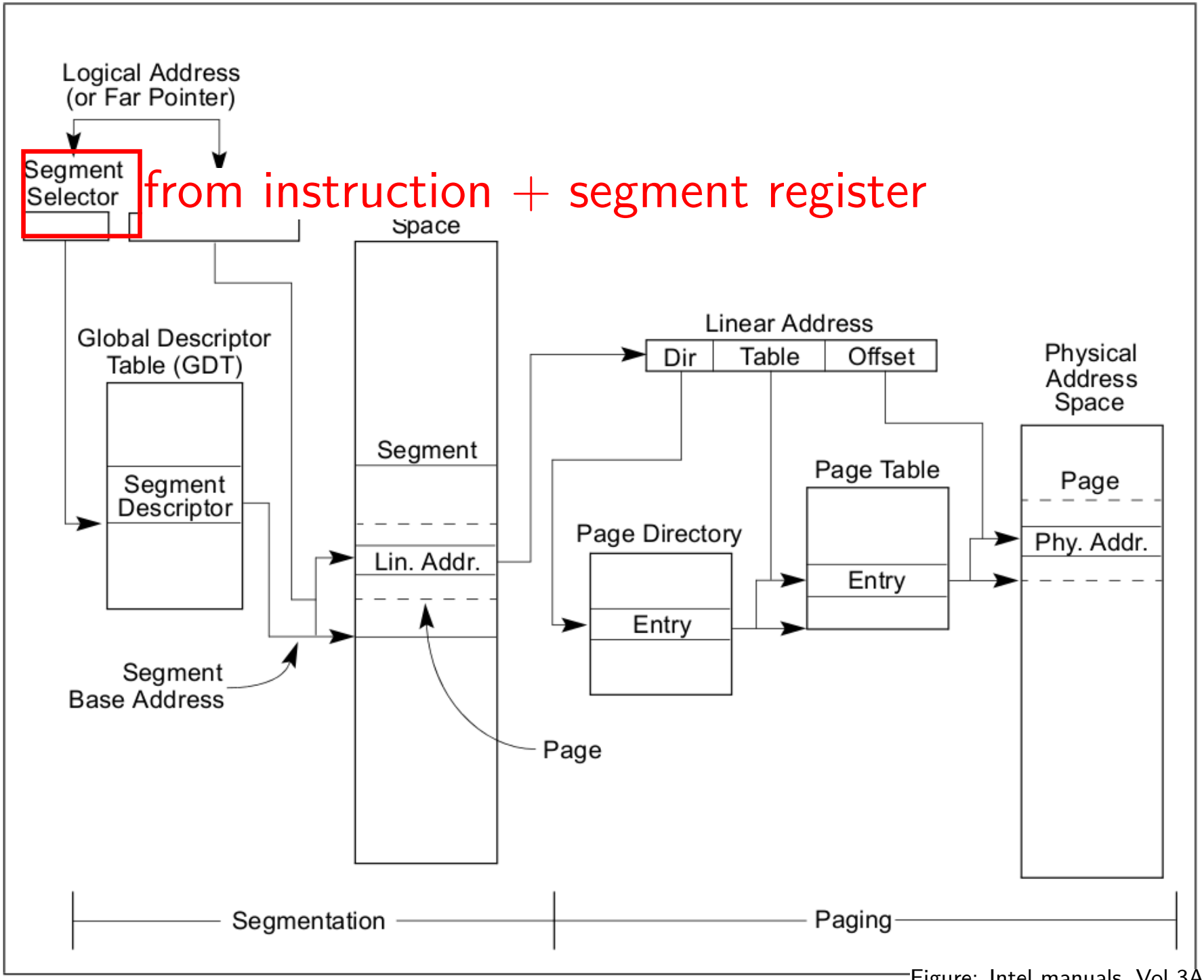
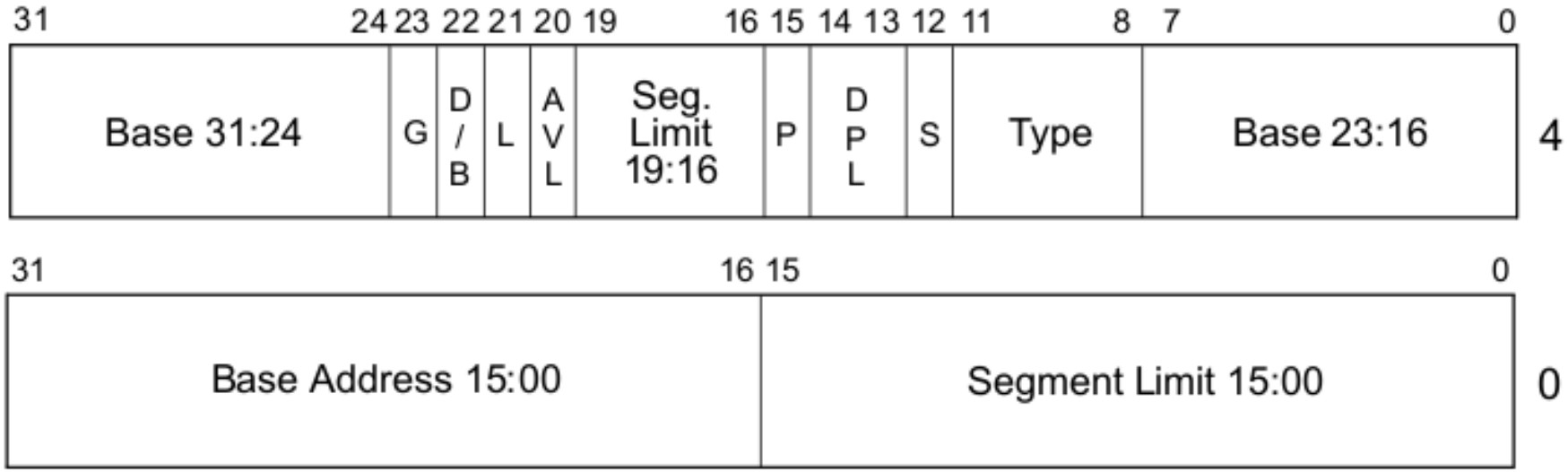


Figure: Intel manuals, Vol 3A

Figure 3-1. Segmentation and Paging

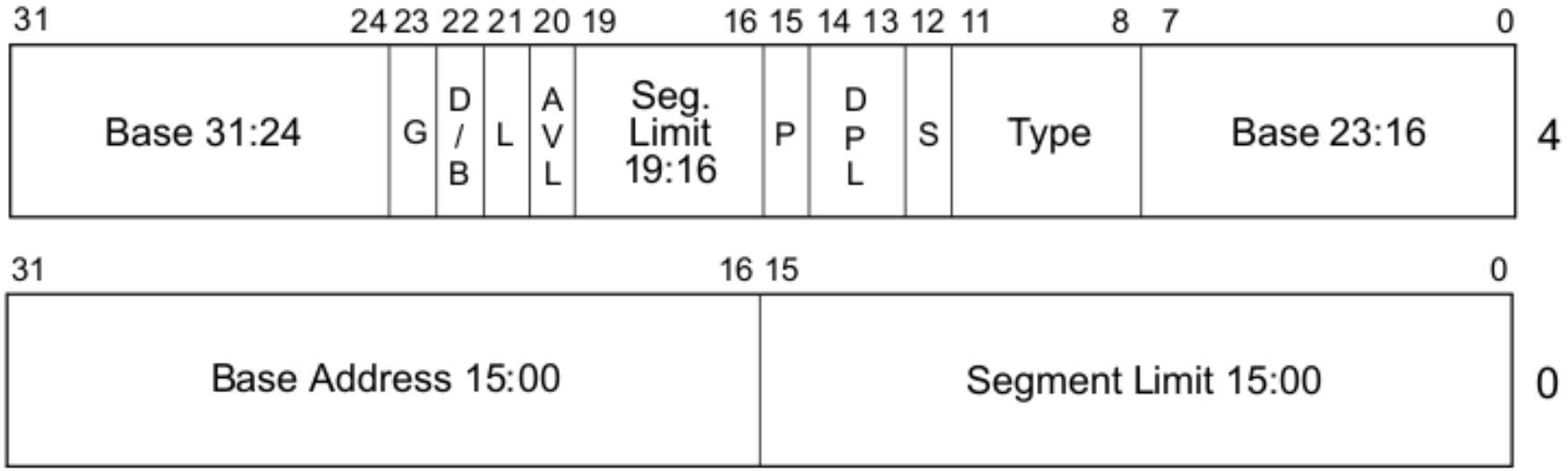
x86 segment descriptor



L — 64-bit code segment (IA-32e mode only)
AVL — Available for use by system software
BASE — Segment base address
D/B — Default operation size (0 = 16-bit segment; 1 = 32-bit segment)
DPL — Descriptor privilege level
G — Granularity
LIMIT — Segment Limit
P — Segment present
S — Descriptor type (0 = system; 1 = code or data)
TYPE — Segment type

Figure: Intel manuals, Volume 3A

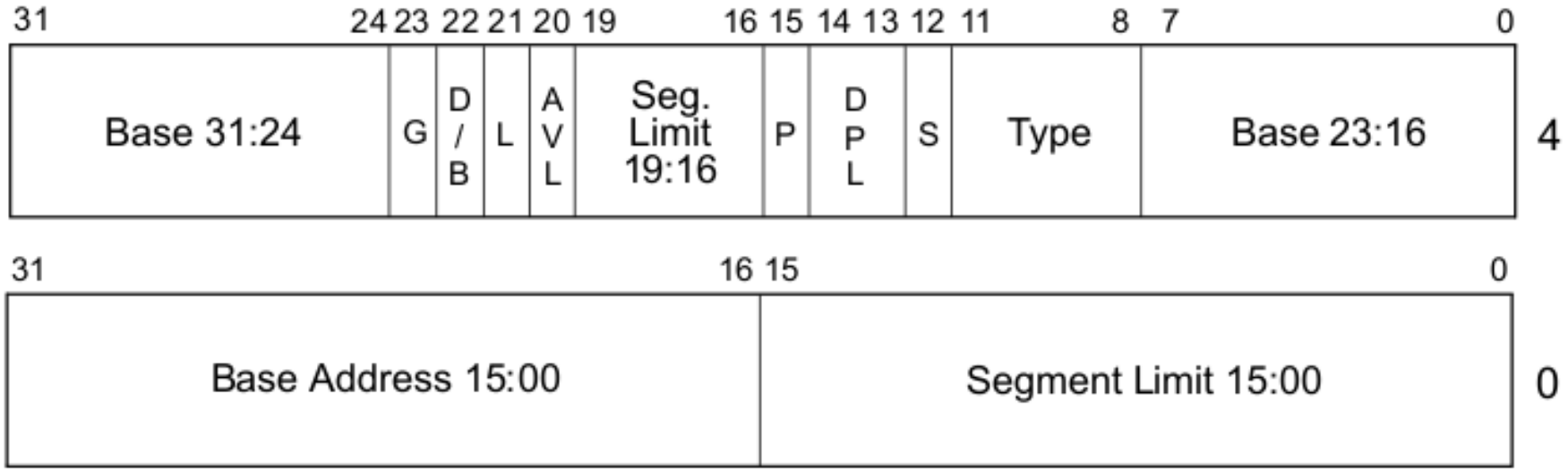
x86 segment descriptor



L — 64-bit code segment (IA-32e mode only)
AVL — Available for use by system software
BASE — Segment base address
D/B — Default operation size (0 = 16-bit segment; 1 = 32-bit segment)
DPL — Descriptor privilege level user or kernel mode? (if code)
G — Granularity
LIMIT — Segment Limit
P — Segment present
S — Descriptor type (0 = system; 1 = code or data)
TYPE — Segment type

Figure: Intel manuals, Volume 3A

x86 segment descriptor



L — 64-bit code segment (IA-32e mode only)
AVL — Available for use by system software
BASE — Segment base address
D/B — Default operation size (0 = 16-bit segment; 1 = 32-bit segment)
DPL — Descriptor privilege level

64-bit or 32-bit or 16-bit mode? (if code)

LIMIT — Segment Limit
P — Segment present
S — Descriptor type (0 = system; 1 = code or data)
TYPE — Segment type

Figure: Intel manuals, Volume 3A

64-bit segmentation

in 64-bit mode:

limits are ignored

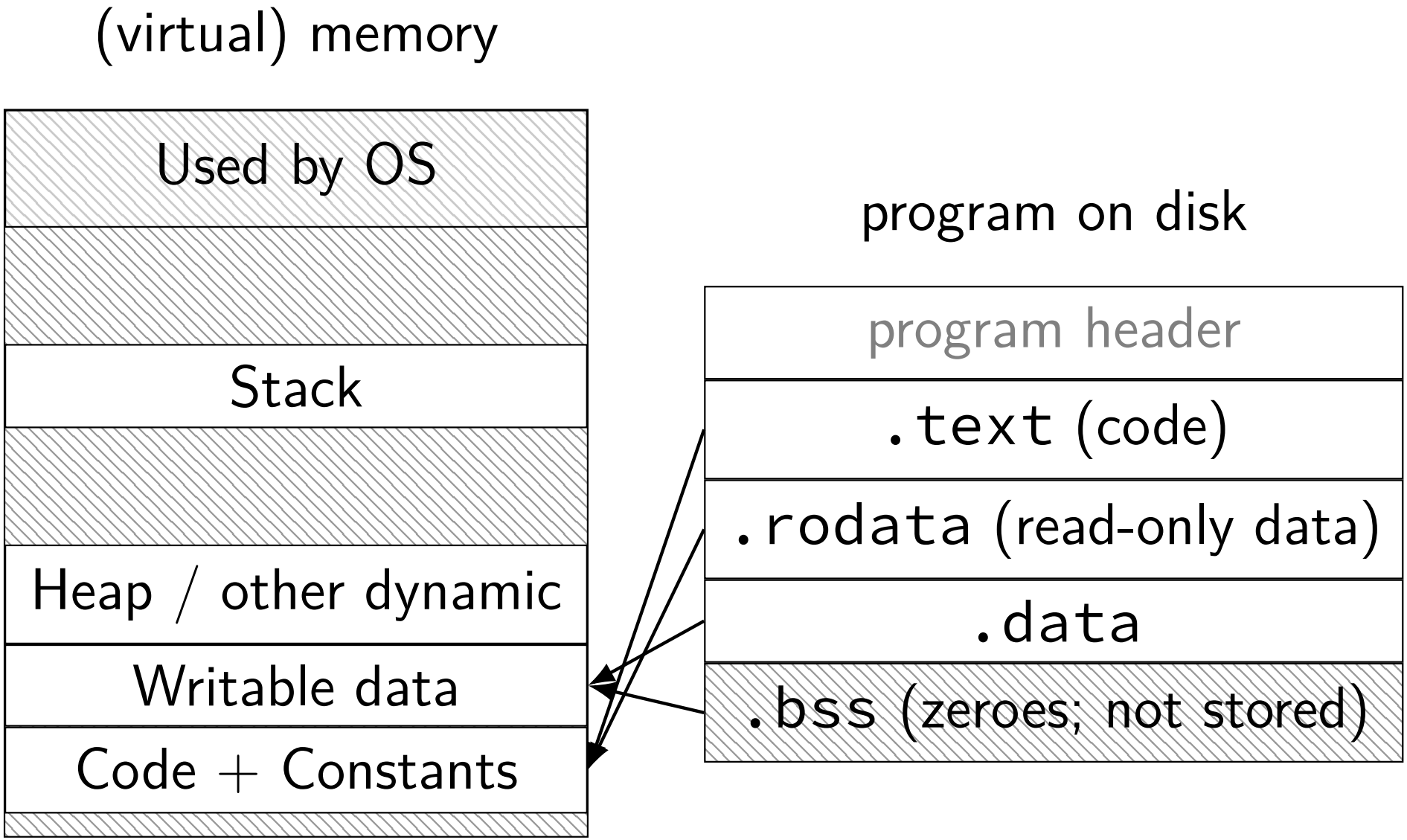
base addresses are ignored

...except for `%fs`, `%gs`

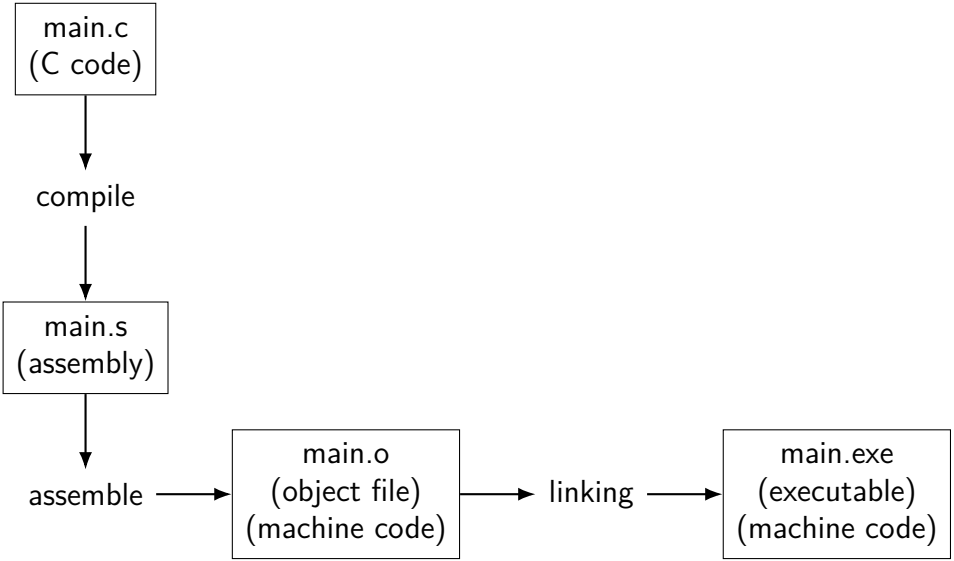
when explicit segment override is used

effectively: extra pointer register

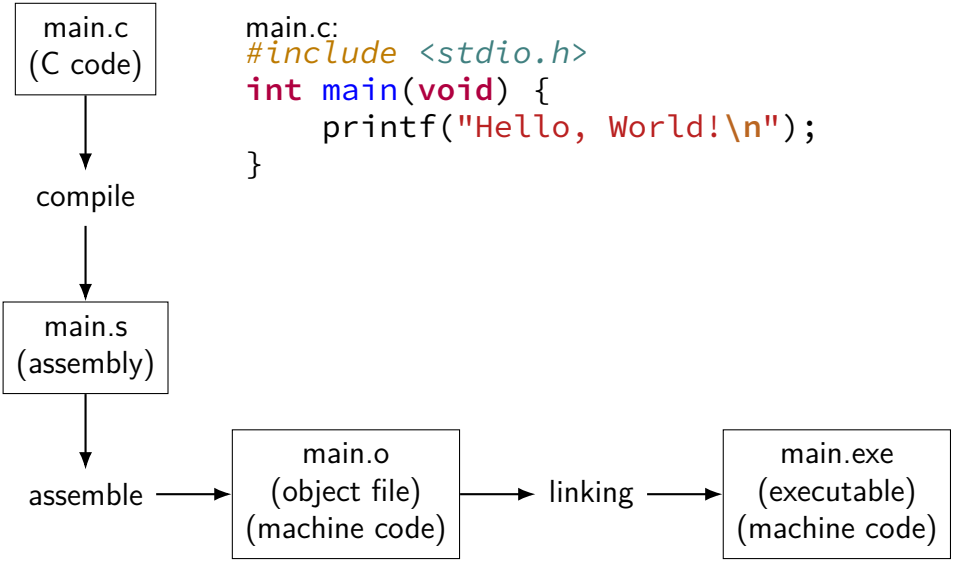
memory v. disk



compilation pipeline



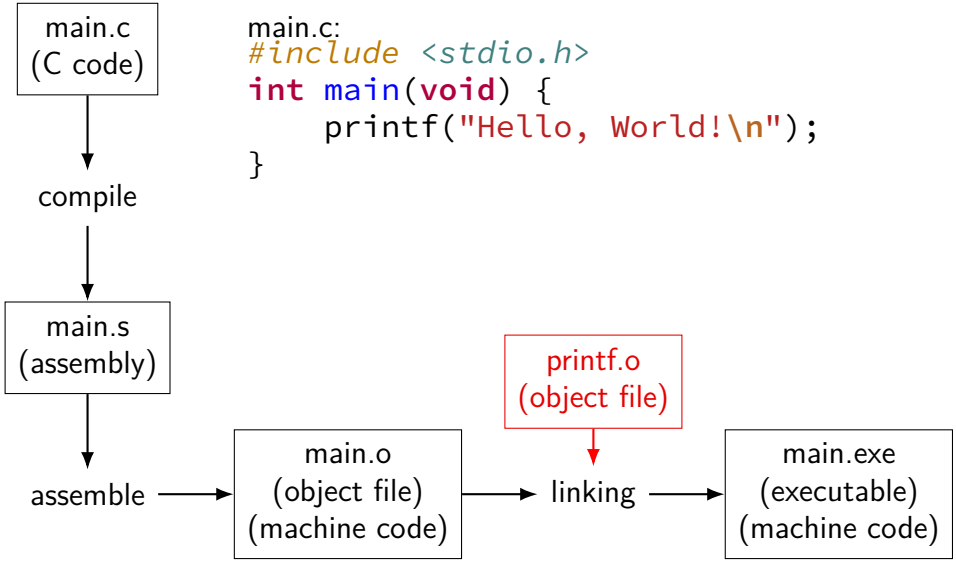
compilation pipeline



main.c:

```c
#include <stdio.h>
int main(void) {
    printf("Hello, World!\n");
}
```

compilation pipeline



main.c:

```c
#include <stdio.h>
int main(void) {
    printf("Hello, World!\n");
}
```

compilation commands

compile:	`gcc -S file.c`	$\Rightarrow$	`file.s` (assembly)
assemble:	`gcc -c file.s`	$\Rightarrow$	`file.o` (object file)
link:	`gcc -o file file.o`	$\Rightarrow$	`file` (executable)
c+a:	`gcc -c file.c`	$\Rightarrow$	`file.o`
c+a+l:	`gcc -o file file.c`	$\Rightarrow$	`file`

...

what's in those files?

hello.c

```c
#include <stdio.h>
int main(void) {
  puts("Hello, World!");
  return 0;
}
```

what's in those files?

hello.c

```c
#include <stdio.h>
int main(void) {
  puts("Hello, World!");
  return 0;
}
```

hello.s

```
    .text
    .global main
main:
    sub  $8, %rsp
    mov  $.Lstr, %rdi
    call puts
    xor  %eax, %eax
    add  $8, %rsp
    ret

    .data
.Lstr: .string "Hello, World!"
```

what's in those files?

hello.c

```c
#include <stdio.h>
int main(void) {
  puts("Hello, World!");
  return 0;
}
```

hello.s

```
    .text
    .global main
main:
    sub  $8, %rsp
    mov  $.Lstr, %rdi
    call puts
    xor  %eax, %eax
    add  $8, %rsp
    ret

    .data
.Lstr: .string "Hello, World!"
```

hello.s (Intel syntax)

```
.text
main:
  sub RSP, 8
  mov RDI, .Lstr
  call puts
  xor EAX, EAX
  add RSP, 8
  ret

.data
.Lstr: .string "Hello, Worl
```

what's in those files?

hello.c

```c
#include <stdio.h>
int main(void) {
  puts("Hello, World!");
  return 0;
}
```

hello.s

```
    .text
    .global main
main:
    sub  $8, %rsp
    mov  $.Lstr, %rdi
    call puts
    xor  %eax, %eax
    add  $8, %rsp
    ret

    .data
.Lstr: .string "Hello, World!"
```

Linux x86-64 calling convention: stack addr. must be multiple of 16

what's in those files?

hello.c

```c
#include <stdio.h>
int main(void) {
  puts("Hello, World!");
  return 0;
}
```

hello.s

```
    .text
    .global main
main:
    sub  $8, %rsp
    mov  $.Lstr, %rdi
    call puts
    xor  %eax, %eax
    add  $8, %rsp
    ret

    .data
.Lstr: .string "Hello, World!"
```

sets eax to 0 (shorter machine code than mov)

what's in those files?

hello.c

```c
#include <stdio.h>
int main(void) {
  puts("Hello, World!");
  return 0;
}
```

hello.s

```
    .text
    .global main
main:
    sub  $8, %rsp
    mov  $.Lstr, %rdi
    call puts
    xor  %eax, %eax
    add  $8, %rsp
    ret

    .data
.Lstr: .string "Hello, World!"
```

mark used by other files

what's in those files?

hello.c

```c
#include <stdio.h>
int main(void) {
  puts("Hello, World!");
  return 0;
}
```

hello.s

```
    .text
    .global main
main:
    sub  $8, %rsp
    mov  $.Lstr, %rdi
    call puts
    xor  %eax, %eax
    add  $8, %rsp
    ret

    .data
.Lstr: .string "Hello, World!"
```

hello.o

text (code) segment:

```
48 83 EC 08 BF 00 00 00 00 E8 00 00
00 00 31 C0 48 83 C4 08 C3
```

what's in those files?

hello.c

```c
#include <stdio.h>
int main(void) {
  puts("Hello, World!");
  return 0;
}
```

hello.s

```
    .text
    .global main
main:
    sub  $8, %rsp
    mov  $.Lstr, %rdi
    call puts
    xor  %eax, %eax
    add  $8, %rsp
    ret

    .data
.Lstr: .string "Hello, World!"
```

hello.o

text (code) segment:

```
48 83 EC 08 BF 00 00 00 00 E8 00 00
00 00 31 C0 48 83 C4 08 C3
```

data segment:

```
48 65 6C 6C 6F 2C 20 57 6F 72 6C 00
```

what's in those files?

hello.c

```c
#include <stdio.h>
int main(void) {
  puts("Hello, World!");
  return 0;
}
```

hello.s

```
    .text
    .global main
main:
    sub  $8, %rsp
    mov  $.Lstr, %rdi
    call puts
    xor  %eax, %eax
    add  $8, %rsp
    ret

    .data
.Lstr: .string "Hello, World!"
```

hello.o

text (code) segment:

```
48 83 EC 08 BF 00 00 00 00 E8 00 00
00 00 31 C0 48 83 C4 08 C3
```

data segment:

```
48 65 6C 6C 6F 2C 20 57 6F 72 6C 00
```

what's in those files?

hello.c

```c
#include <stdio.h>
int main(void) {
  puts("Hello, World!");
  return 0;
}
```

hello.s

```
    .text
    .global main
main:
    sub  $8, %rsp
    mov  $.Lstr, %rdi
    call puts
    xor  %eax, %eax
    add  $8, %rsp
    ret

    .data
.Lstr: .string "Hello, World!"
```

hello.o

text (code) segment:

```
48 83 EC 08 BF 00 00 00 00 E8 00 00
00 00 31 C0 48 83 C4 08 C3
```

data segment:

```
48 65 6C 6C 6F 2C 20 57 6F 72 6C 00
```

relocations:

take 0s at	*and replace with*
text, byte 5 ( )	data segment, byte 0
text, byte 10 ( )	address of puts

what's in those files?

hello.c

```c
#include <stdio.h>
int main(void) {
  puts("Hello, World!");
  return 0;
}
```

hello.s

```
    .text
    .global main
main:
    sub  $8, %rsp
    mov  $.Lstr, %rdi
    call puts
    xor  %eax, %eax
    add  $8, %rsp
    ret

    .data
.Lstr: .string "Hello, World!"
```

hello.o

text (code) segment:

```
48 83 EC 08 BF 00 00 00 00 E8 00 00
00 00 31 C0 48 83 C4 08 C3
```

data segment:

```
48 65 6C 6C 6F 2C 20 57 6F 72 6C 00
```

relocations:

take 0s at	*and replace with*
text, byte 5 ( )	data segment, byte 0
text, byte 10 ( )	address of puts

symbol table:

main	text byte 0

what's in those files?

hello.c

```c
#include <stdio.h>
int main(void) {
  puts("Hello, World!");
  return 0;
}
```

hello.s

```
    .text
    .global main
main:
    sub  $8, %rsp
    mov  $.Lstr, %rdi
    call puts
    xor  %eax, %eax
    add  $8, %rsp
    ret

    .data
.Lstr: .string "Hello, World!"
```

hello.o

text (code) segment:

```
48 83 EC 08 BF 00 00 00 00 E8 00 00
00 00 31 C0 48 83 C4 08 C3
```

data segment:

```
48 65 6C 6C 6F 2C 20 57 6F 72 6C 00
```

relocations:

take 0s at	*and replace with*
text, byte 5 ( )	data segment, byte 0
text, byte 10 ( )	address of puts

symbol table:

main text byte 0

`.Lstr` location specified w/o name
and not usable by other files
so no symbol table entry needed

(convention: .L…labels always local)

what's in those files?

hello.c

```c
#include <stdio.h>
int main(void) {
  puts("Hello, World!");
  return 0;
}
```

hello.s

```
    .text
    .global main
main:
    sub  $8, %rsp
    mov  $.Lstr, %rdi
    call puts
    xor  %eax, %eax
    add  $8, %rsp
    ret

    .data
.Lstr: .string "Hello, World!"
```

hello.o

text (code) segment:

```
48 83 EC 08 BF 00 00 00 00 E8 00 00
00 00 31 C0 48 83 C4 08 C3
```

data segment:

```
48 65 6C 6C 6F 2C 20 57 6F 72 6C 00
```

relocations:

take 0s at	*and replace with*
text, byte 5 ( )	data segment, byte 0
text, byte 10 ( )	address of puts

symbol table:

main text byte 0

+ stdio.o

hello.exe

(actually binary, but shown as hexadecimal) …

```
48 83 EC 08 BF A7 02 04 00
E8 08 4A 00 00 31 C0 48
83 C4 08 C3 …
```

…(code from stdio.o) …

```
48 65 6C 6C 6F 2C 20 57 6F
72 6C 00 …
```

…(data from stdio.o) …

hello.s

```
        .section        .rodata.str1.1,"aMS",@progbi
.LC0:
        .string "Hello, World!"
        .text
        .globl  main
main:
        subq    $8, %rsp
        movl    $.LC0, %edi
        call    puts
        movl    $0, %eax
        addq    $8, %rsp
        ret
```

exercise (1)

main.c:

```c
#include <stdio.h>
void sayHello(void) {
    puts("Hello, World!");
}
int main(void) {
    sayHello();
}
```

Which files contain the **memory address** of `sayHello`?

A. main.s (assembly)
B. main.o (object)
C. main.exe (executable)
D. B and C
E. A, B and C
F. something else

exercise (2)

main.c:

```c
#include <stdio.h>
void sayHello(void) {
    puts("Hello, World!");
}
int main(void) {
    sayHello();
}
```

Which files contain the **literal ASCII string** of `Hello, World!`?

A. main.s (assembly)
B. main.o (object)
C. main.exe (executable)
D. B and C
E. A, B and C
F. something else

dynamic linking (very briefly)

dynamic linking — done when application is loaded

idea: don't have N copies of `printf` on disk

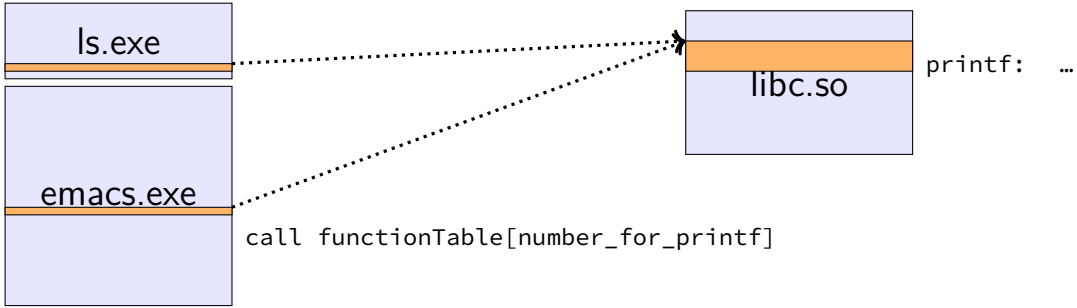
other type of linking: *static* (`gcc -static`)

load executable file + its libraries into memory when app starts

often extra indirection:

```
call functionTable[number_for_printf]
```

linker fills in `functionTable` instead of changing `calls`



ldd /bin/ls

```
$ ldd /bin/ls
    linux-vdso.so.1 =>  (0x00007ffcca9d8000)
    libselinux.so.1 => /lib/x86_64-linux-gnu/libselinux.so.1
            (0x00007f851756f000)
    libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6
            (0x00007f85171a5000)
    libpcre.so.3 => /lib/x86_64-linux-gnu/libpcre.so.3
            (0x00007f8516f35000)
    libdl.so.2 => /lib/x86_64-linux-gnu/libdl.so.2
            (0x00007f8516d31000)
    /lib64/ld-linux-x86-64.so.2 (0x00007f8517791000)
    libpthread.so.0 => /lib/x86_64-linux-gnu/libpthread.so.0
            (0x00007f8516b14000)
```

relocation types

machine code doesn't always use addresses as is

"call function 4303 bytes later"

linker needs to compute "4303"

- extra field on relocation list

ELF (executable and linking format)

Linux (and some others) executable/object file format

header: machine type, file type, etc.
program header: "segments" to load (also, some other information)
segment 1 data
segment 2 data

section header: list of "sections"(mostly for linker)

segments versus sections?

note: ELF terminology; may not be true elsewhere!

sections — object files (and usually executables), used by linker

- have information on intended purpose
- linkers combine these to create executables
- linkers might omit unneeded sections

segments — executables, used to actually load program

- program loader is dumb — doesn't know what segments are for

ELF example

`objdump -x /bin/busybox` (on my laptop)

`-x`: output all headers

```
/bin/busybox:     file format elf64-x86-64
/bin/busybox
architecture: i386:x86-64, flags 0x00000102:
EXEC_P, D_PAGED
start address 0x0000000000401750

Program Header:
[...]

Sections:
[...]
```

ELF example

`objdump -x /bin/busybox` (on my laptop)

`-x`: output all headers

```
/bin/busybox:     file format elf64-x86-64
/bin/busybox
architecture: i386:x86-64, flags 0x00000102:
EXEC_P, D_PAGED
start address 0x0000000000401750

Program Header:
[...]

Sections:
[...]
```

a program header (1)

```
Program Header:
[...]
LOAD off    0x0000000 vaddr 0x0400000 paddr 0x0400000 align 2**21
     filesz 0x01db697 memsz 0x01db697 flags r-x
LOAD off    0x01dbea8 vaddr 0x07dbea8 paddr 0x07dbea8 align 2**21
     filesz 0x00021ee memsz 0x0007d18 flags rw-
[...]
```

load `0x1db697` bytes:

- from `0x0` bytes into the file
- to memory at `0x40000`
- readable and executable

load `0x21ee` bytes:

- from `0x1dbea8`
- to memory at `0x7dbea8`
- plus (`0x7d18`–`0x21ee`) bytes of zeroes
- readable and writable

a program header (1)

```
Program Header:
[...]
LOAD off    0x0000000 vaddr 0x0400000 paddr 0x0400000 align 2**21
     filesz 0x01db697 memsz 0x01db697 flags r-x
LOAD off    0x01dbea8 vaddr 0x07dbea8 paddr 0x07dbea8 align 2**21
     filesz 0x00021ee memsz 0x0007d18 flags rw-
[...]
```

load `0x1db697` bytes:

- from `0x0` bytes into the file
- to memory at `0x40000`
- readable and executable

load `0x21ee` bytes:

- from `0x1dbea8`
- to memory at `0x7dbea8`
- plus (`0x7d18`–`0x21ee`) bytes of zeroes
- readable and writable

a program header (1)

```
Program Header:
[...]
LOAD off    0x0000000 vaddr 0x0400000 paddr 0x0400000 align 2**21
     filesz 0x01db697 memsz 0x01db697 flags r-x
LOAD off    0x01dbea8 vaddr 0x07dbea8 paddr 0x07dbea8 align 2**21
     filesz 0x00021ee memsz 0x0007d18 flags rw-
[...]
```

load `0x1db697` bytes:

- from `0x0` bytes into the file
- to memory at `0x40000`
- readable and executable

load `0x21ee` bytes:

- from `0x1dbea8`
- to memory at `0x7dbea8`
- plus (`0x7d18`–`0x21ee`) bytes of zeroes
- readable and writable

a program header (1)

```
Program Header:
[...]
LOAD off    0x0000000 vaddr 0x0400000 paddr 0x0400000 align 2**21
     filesz 0x01db697 memsz 0x01db697 flags r-x
LOAD off    0x01dbea8 vaddr 0x07dbea8 paddr 0x07dbea8 align 2**21
     filesz 0x00021ee memsz 0x0007d18 flags rw-
[...]
```

load `0x1db697` bytes:

- from `0x0` bytes into the file
- to memory at `0x40000`
- readable and executable

load `0x21ee` bytes:

- from `0x1dbea8`
- to memory at `0x7dbea8`
- plus (`0x7d18`–`0x21ee`) bytes of zeroes
- readable and writable

a program header (2)

```
Program Header:
[...]
 NOTE off    0x0000190 vaddr 0x0400190 paddr 0x0400190 align 2**2
      filesz 0x0000044 memsz 0x0000044 flags r--
  TLS  off    0x01dbea8 vaddr 0x07dbea8 paddr 0x07dbea8 align 2**3
      filesz 0x0000030 memsz 0x000007a flags r--
STACK off    0x0000000 vaddr 0x0000000 paddr 0x0000000 align 2**4
      filesz 0x0000000 memsz 0x0000000 flags rw-
RELRO off    0x01dbea8 vaddr 0x07dbea8 paddr 0x07dbea8 align 2**0
      filesz 0x0000158 memsz 0x0000158 flags r--
[...]
```

NOTE — comment

TLS — thread-local storage region (used via `%fs`)

STACK — indicates stack is read/write

RELRO — make this read-only after runtime linking

section headers

```
Sections:
Idx Name          Size      VMA               LMA               File off  Algn
  0 .note.ABI-tag 00000020  0000000000400190  0000000000400190  00000190  2**2
                  CONTENTS, ALLOC, LOAD, READONLY, DATA
  1 .note.gnu.build-id 00000024  00000000004001b0  00000000004001b0  000001b0  2**2
                  CONTENTS, ALLOC, LOAD, READONLY, DATA
  2 .rela.plt     00000210  00000000004001d8  00000000004001d8  000001d8  2**3
                  CONTENTS, ALLOC, LOAD, READONLY, DATA
  3 .init         0000001a  00000000004003e8  00000000004003e8  000003e8  2**2
                  CONTENTS, ALLOC, LOAD, READONLY, CODE
  4 .plt          00000160  0000000000400410  0000000000400410  00000410  2**4
                  CONTENTS, ALLOC, LOAD, READONLY, CODE
  5 .text         0017ff1d  0000000000400570  0000000000400570  00000570  2**4
                  CONTENTS, ALLOC, LOAD, READONLY, CODE
  6 __libc_freeres_fn 00002032  0000000000580490  0000000000580490  00180490  2**4
                  CONTENTS, ALLOC, LOAD, READONLY, CODE
  7 __libc_thread_freeres_fn 0000021b  00000000005824d0  00000000005824d0  001824d0  2**4
                  CONTENTS, ALLOC, LOAD, READONLY, CODE
  8 .fini         00000009  00000000005826ec  00000000005826ec  001826ec  2**2
                  CONTENTS, ALLOC, LOAD, READONLY, CODE
  9 .rodata       00044ac8  0000000000582700  0000000000582700  00182700  2**6
                  CONTENTS, ALLOC, LOAD, READONLY, DATA
 10 __libc_subfreeres 000000c0  00000000005c71c8  00000000005c71c8  001c71c8  2**3
                  CONTENTS, ALLOC, LOAD, READONLY, DATA
 11 .stapsdt.base 00000001  00000000005c7288  00000000005c7288  001c7288  2**0
                  CONTENTS, ALLOC, LOAD, READONLY, DATA
 12 __libc_atexit 00000008  00000000005c7290  00000000005c7290  001c7290  2**3
                  CONTENTS, ALLOC, LOAD, READONLY, DATA
 13 __libc_thread_subfreeres 00000018  00000000005c7298  00000000005c7298  001c7298  2**3
                  CONTENTS, ALLOC, LOAD, READONLY, DATA
 14 .eh_frame     000141dc  00000000005c72b0  00000000005c72b0  001c72b0  2**3
                  CONTENTS, ALLOC, LOAD, READONLY, DATA
 15 .gcc_except_table 0000020b  00000000005db48c  00000000005db48c  001db48c  2**0
```

sections

tons of "sections"

not actually needed/used to run program

size, file offset, flags (code/data/etc.)

- location in executable *and* in memory

some sections aren't stored (no "CONTENTS" flag)

- just all zeroes

selected sections

`.text`	program code
`.bss`	initially zero data (block started by symbol)
`.data`	other writeable data
`.rodata`	read-only data
`.init`/`.fini`	global constructors/destructors
`.got`/`.plt`	linking related
`.eh_frame`	try/catch related

other executable formats

PE (Portable Executable) — Windows

Mach-O — MacOS X

broadly similar to ELF

differences:

- whether segment/section distinction exists
- how linking/debugging info represented
- how program start info represented

simple executable startup

copy segments into memory

jump to start address

executable startup code

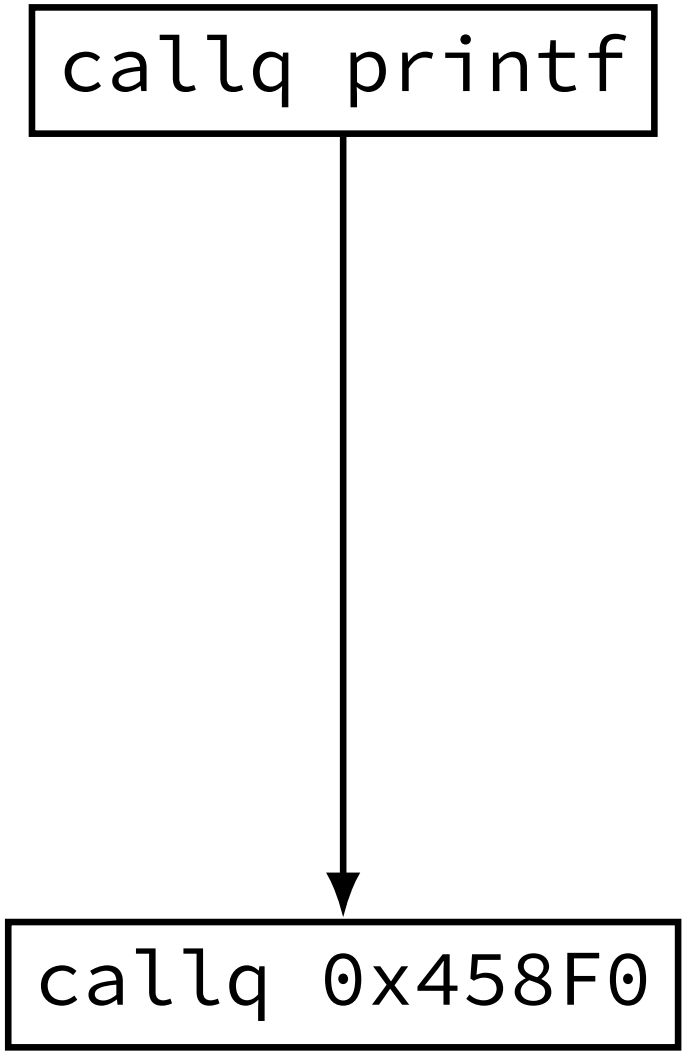
Linux: executables don't start at `main`

why not?

- need to initialize `printf`, `cout`, `malloc`, etc. data structures
- `main` needs to return somewhere

compiler links in startup code

linking



static v. dynamic linking

static linking — linking to create executable

dynamic linking — linking when executable is run

static v. dynamic linking

static linking — linking to create executable

dynamic linking — linking when executable is run

conceptually: no difference in how they work

reality — very different mechanisms

linking data structures

symbol table: `name` ⇒ (section, offset)

- example: `main:` in assembly adds symbol table entry for `main`

relocation table: offset ⇒ (name, kind)

- example: `call printf` adds relocation for name `printf`
- kind depends on how instruction encodes address

hello.s

```
.data
string: .asciz "Hello,␣World!"
.text
.globl main
main:
    movq $string, %rdi
    call puts
    ret
```

hello.o

```
SYMBOL TABLE:
0000000000000000 l    d  .text  0000000000000000 .text
0000000000000000 l    d  .data  0000000000000000 .data
0000000000000000 l    d  .bss   0000000000000000 .bss
0000000000000000 l       .data  0000000000000000 string
0000000000000000 g       .text  0000000000000000 main
0000000000000000         *UND*  0000000000000000 puts

RELOCATION RECORDS FOR [.text]:
OFFSET           TYPE              VALUE
0000000000000003 R_X86_64_32S      .data
0000000000000008 R_X86_64_PC32     puts-0x0000000000000004
```

hello.o

```
SYMBOL TABLE:
0000000000000000 l    d  .text  0000000000000000 .text
0000000000000000 l    d  .data  0000000000000000 .data
0000000000000000 l    d  .bss   0000000000000000 .bss
0000000000000000 l       .data  0000000000000000 string
0000000000000000 g       .text  0000000000000000 main
0000000000000000         *UND*  0000000000000000 puts

RELOCATION RECORDS FOR [.text]:
OFFSET           TYPE              VALUE
0000000000000003 R_X86_64_32S      .data
0000000000000008 R_X86_64_PC32     puts-0x0000000000000004
```

undefined symbol: look for `puts` elsewhere

hello.o

```
SYMBOL TABLE:
0000000000000000 l    d  .text  0000000000000000 .text
0000000000000000 l    d  .data  0000000000000000 .data
0000000000000000 l    d  .bss   0000000000000000 .bss
0000000000000000 l       .data  0000000000000000 string
0000000000000000 g       .text  0000000000000000 main
0000000000000000         *UND*  0000000000000000 puts

RELOCATION RECORDS FOR [.text]:
OFFSET           TYPE              VALUE
0000000000000003 R_X86_64_32S      .data
0000000000000008 R_X86_64_PC32     puts-0x0000000000000004
```

insert address of puts, format for `call`

hello.o

```
SYMBOL TABLE:
0000000000000000 l    d  .text  0000000000000000 .text
0000000000000000 l    d  .data  0000000000000000 .data
0000000000000000 l    d  .bss   0000000000000000 .bss
0000000000000000 l       .data  0000000000000000 string
0000000000000000 g       .text  0000000000000000 main
0000000000000000         *UND*  0000000000000000 puts

RELOCATION RECORDS FOR [.text]:
OFFSET           TYPE              VALUE
0000000000000003 R_X86_64_32S      .data
0000000000000008 R_X86_64_PC32     puts-0x0000000000000004
```

insert address of string, format for movq

hello.o

```
SYMBOL TABLE:
0000000000000000 l    d  .text  0000000000000000 .text
0000000000000000 l    d  .data  0000000000000000 .data
0000000000000000 l    d  .bss   0000000000000000 .bss
0000000000000000 l       .data  0000000000000000 string
0000000000000000 g       .text  0000000000000000 main
0000000000000000         *UND*  0000000000000000 puts

RELOCATION RECORDS FOR [.text]:
OFFSET           TYPE              VALUE
0000000000000003 R_X86_64_32S      .data
0000000000000008 R_X86_64_PC32     puts-0x0000000000000004
```

different ways to represent address

32S — signed 32-bit value

PC32 — 32-bit difference from current address

hello.o

```
SYMBOL TABLE:
0000000000000000 l    d  .text  0000000000000000 .text
0000000000000000 l    d  .data  0000000000000000 .data
0000000000000000 l    d  .bss   0000000000000000 .bss
0000000000000000 l       .data  0000000000000000 string
0000000000000000 g       .text  0000000000000000 main
0000000000000000         *UND*  0000000000000000 puts

RELOCATION RECORDS FOR [.text]:
OFFSET           TYPE              VALUE
0000000000000003 R_X86_64_32S      .data
0000000000000008 R_X86_64_PC32     puts-0x0000000000000004
```

g: global — used by other files
l: local

hello.o

```
SYMBOL TABLE:
0000000000000000 l    d  .text  0000000000000000 .text
0000000000000000 l    d  .data  0000000000000000 .data
0000000000000000 l    d  .bss   0000000000000000 .bss
0000000000000000 l       .data  0000000000000000 string
0000000000000000 g       .text  0000000000000000 main
0000000000000000         *UND*  0000000000000000 puts

RELOCATION RECORDS FOR [.text]:
OFFSET           TYPE              VALUE
0000000000000003 R_X86_64_32S      .data
0000000000000008 R_X86_64_PC32     puts-0x0000000000000004
```

`.text` segment beginning plus 0 bytes

interlude: strace

`strace` — system call tracer

- on Linux, some other Unices
- OS X approx. equivalent: `dtruss`
- Windows approx. equivalent: Process Monitor

indicates what system calls (operating system services) used by a program

statically linked hello.exe

```
gcc -static -o hello-static.exe hello.s
```

strace ./hello-static.exe:

```
execve("./hello-static.exe", ["./hello-static.exe"], [/* 46 vars */]) = 0
uname(sysname="Linux", nodename="reiss-lenovo", ...) = 0
brk(NULL)                                   = 0x20a5000
brk(0x20a61c0)                              = 0x20a61c0
arch_prctl(ARCH_SET_FS, 0x20a5880)          = 0
readlink("/proc/self/exe", "/home/cr4bd/spring2017/cs4630/sl"..., 4096) =
brk(0x20c71c0)                              = 0x20c71c0
brk(0x20c8000)                              = 0x20c8000
access("/etc/ld.so.nohwcap", F_OK)          = -1 ENOENT (No such file or direc
fstat(1, st_mode=S_IFCHR|0620, st_rdev=makedev(136, 1), ...) = 0
write(1, "Hello, World!\n", 14)             = 14
exit_group(14)                              = ?
+++ exited with 14 +++
```

statically linked hello.exe

```
gcc -static -o hello-static.exe hello.s
```

strace ./hello-static.exe:

```
execve("./hello-static.exe", ["./hello-static.exe"], [/* 46 vars */]) = 0
uname(sysname="Linux", nodename="reiss-lenovo", ...) = 0
brk(NULL)                                   = 0x20a5000
brk(0x20a61c0)                              = 0x20a61c0
arch_prctl(ARCH_SET_FS, 0x20a5880)          = 0
readlink("/proc/self/exe", "/home/cr4bd/spring2017/cs4630/sl"..., 4096) =
brk(0x20c71c0)                              = 0x20c71c0
brk(0x20c8000)                              = 0x20c8000
access("/etc/ld.so.nohwcap", F_OK)          = -1 ENOENT (No such file or direc
fstat(1, st_mode=S_IFCHR|0620, st_rdev=makedev(136, 1), ...) = 0
write(1, "Hello, World!\n", 14)             = 14
exit_group(14)                              = ?
+++ exited with 14 +++
```

standard library startup

statically linked hello.exe

```
gcc -static -o hello-static.exe hello.s
```

strace ./hello-static.exe:

```
execve("./hello-static.exe", ["./hello-static.exe"], [/* 46 vars */]) = 0
uname(sysname="Linux", nodename="reiss-lenovo", ...) = 0
brk(NULL)                                   = 0x20a5000
brk(0x20a61c0)                              = 0x20a61c0
arch_prctl(ARCH_SET_FS, 0x20a5880)          = 0
readlink("/proc/self/exe", "/home/cr4bd/spring2017/cs4630/sl"..., 4096) =
brk(0x20c71c0)                              = 0x20c71c0
brk(0x20c8000)                              = 0x20c8000
access("/etc/ld.so.nohwcap", F_OK)          = -1 ENOENT (No such file or direc
fstat(1, st_mode=S_IFCHR|0620, st_rdev=makedev(136, 1), ...) = 0
write(1, "Hello, World!\n", 14)             = 14
exit_group(14)                              = ?
+++ exited with 14 +++
```

memory allocation

statically linked hello.exe

```
gcc -static -o hello-static.exe hello.s
```

strace ./hello-static.exe:

```
execve("./hello-static.exe", ["./hello-static.exe"], [/* 46 vars */]) = 0
uname(sysname="Linux", nodename="reiss-lenovo", ...) = 0
brk(NULL)                                   = 0x20a5000
brk(0x20a61c0)                              = 0x20a61c0
arch_prctl(ARCH_SET_FS, 0x20a5880)          = 0
readlink("/proc/self/exe", "/home/cr4bd/spring2017/cs4630/sl"..., 4096) =
brk(0x20c71c0)                              = 0x20c71c0
brk(0x20c8000)                              = 0x20c8000
access("/etc/ld.so.nohwcap", F_OK)          = -1 ENOENT (No such file or direc
fstat(1, st_mode=S_IFCHR|0620, st_rdev=makedev(136, 1), ...) = 0
write(1, "Hello, World!\n", 14)             = 14
exit_group(14)                              = ?
+++ exited with 14 +++
```

implementation of puts

statically linked hello.exe

```
gcc -static -o hello-static.exe hello.s
```

strace ./hello-static.exe:

```
execve("./hello-static.exe", ["./hello-static.exe"], [/* 46 vars */]) = 0
uname(sysname="Linux", nodename="reiss-lenovo", ...) = 0
brk(NULL)                                   = 0x20a5000
brk(0x20a61c0)                              = 0x20a61c0
arch_prctl(ARCH_SET_FS, 0x20a5880)          = 0
readlink("/proc/self/exe", "/home/cr4bd/spring2017/cs4630/sl"..., 4096) =
brk(0x20c71c0)                              = 0x20c71c0
brk(0x20c8000)                              = 0x20c8000
access("/etc/ld.so.nohwcap", F_OK)          = -1 ENOENT (No such file or direc
fstat(1, st_mode=S_IFCHR|0620, st_rdev=makedev(136, 1), ...) = 0
write(1, "Hello, World!\n", 14)             = 14
exit_group(14)                              = ?
+++ exited with 14 +++
```

standard library shutdown

dynamically linked hello.exe

```
gcc -o hello.exe hello.s
```

strace ./hello.exe:

```
execve("./hello.exe", ["./hello.exe"], [/* 46 vars */]) = 0
...
mmap(NULL, 8192, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) =
access("/etc/ld.so.preload", R_OK)      = -1 ENOENT (No such file or direc
open("/etc/ld.so.cache", O_RDONLY|O_CLOEXEC) = 3
fstat(3, st_mode=S_IFREG|0644, st_size=137808, ...) = 0
...
open("/lib/x86_64-linux-gnu/libc.so.6", O_RDONLY|O_CLOEXEC) = 3
read(3, "\177ELF\2\1\1\3\0\0\0\0\0\0\0\0\3\0>\0\1\0\0\0P\t\2\0\0\0\0\0"...
fstat(3, st_mode=S_IFREG|0755, st_size=1864888, ...) = 0
mmap(NULL, 3967392, PROT_READ|PROT_EXEC, ..., 3, 0) = 0x7fdfee54d000
mprotect(0x7fdfee70c000, 2097152, PROT_NONE) = 0
mmap(0x7fdfee90c000, 24576, PROT_READ|PROT_WRITE, ..., 3, 0x1bf000) = 0x7f
mmap(0x7fdfee912000, 14752, PROT_READ|PROT_WRITE, ..., -1, 0) = 0x7fdfee91
close(3)                                = 0
...
write(1, "Hello, World!\n", 14)         = 14
exit_group(14)                          = ?
+++ exited with 14 +++
```

dynamically linked hello.exe

```
gcc -o hello.exe hello.s
```

strace ./hello.exe:

```
execve("./hello.exe", ["./hello.exe"], [/* 46 vars */]) = 0
...
mmap(NULL, 8192, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) =
access("/etc/ld.so.preload", R_OK)      = -1 ENOENT (No such file or direc
open("/etc/
fstat(3, st
...
open("/lib/x86_64-linux-gnu/libc.so.6", O_RDONLY|O_CLOEXEC) = 3
read(3, "\177ELF\2\1\1\3\0\0\0\0\0\0\0\0\3\0>\0\1\0\0\0P\t\2\0\0\0\0\0"...
fstat(3, st_mode=S_IFREG|0755, st_size=1864888, ...) = 0
mmap(NULL, 3967392, PROT_READ|PROT_EXEC, ..., 3, 0) = 0x7fdfee54d000
mprotect(0x7fdfee70c000, 2097152, PROT_NONE) = 0
mmap(0x7fdfee90c000, 24576, PROT_READ|PROT_WRITE, ..., 3, 0x1bf000) = 0x7f
mmap(0x7fdfee912000, 14752, PROT_READ|PROT_WRITE, ..., -1, 0) = 0x7fdfee91
close(3)                                = 0
...
write(1, "Hello, World!\n", 14)         = 14
exit_group(14)                          = ?
+++ exited with 14 +++
```

the standard C library (includes puts

dynamically linked hello.exe

```
gcc -o hello.exe hello.s
```

strace ./hello.exe:

```
execve("./hello.exe", ["./hello.exe"], [/* 46 vars */]) = 0
...
mmap(NULL, 8192, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) =
access("/etc/ld.so.preload", R_OK)      = -1 ENOENT (No such file or direc
open("/etc/
fstat(3, st
...
open("/lib/x86_64-linux-gnu/libc.so.6", O_RDONLY|O_CLOEXEC) = 3
read(3, "\177ELF\2\1\1\3\0\0\0\0\0\0\0\0\3\0>\0\1\0\0\0P\t\2\0\0\0\0\0"...
fstat(3, st_mode=S_IFREG|0755, st_size=1864888, ...) = 0
mmap(NULL, 3967392, PROT_READ|PROT_EXEC, ..., 3, 0) = 0x7fdfee54d000
mprotect(0x7fdfee70c000, 2097152, PROT_NONE) = 0
mmap(0x7fdfee90c000, 24576, PROT_READ|PROT_WRITE, ..., 3, 0x1bf000) = 0x7f
mmap(0x7fdfee912000, 14752, PROT_READ|PROT_WRITE, ..., -1, 0) = 0x7fdfee91
close(3)                                = 0
...
write(1, "Hello, World!\n", 14)         = 14
exit_group(14)                          = ?
+++ exited with 14 +++
```

memory allocation (different method)

dynamically linked hello.exe

```
gcc -o hello.exe hello.s
```

strace ./hello.exe:

```
execve("./hello.exe", ["./hello.exe"], [/* 46 vars */]) = 0
...
mmap(NULL, 8192, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) =
access("/etc/ld.so.preload", R_OK)      = -1 ENOENT (No such file or direc
open("/etc/ld.so
fstat(3, st_mode
...
open("/lib/x86_64-linux-gnu/libc.so.6", O_RDONLY|O_CLOEXEC) = 3
read(3, "\177ELF\2\1\1\3\0\0\0\0\0\0\0\0\3\0>\0\1\0\0\0P\t\2\0\0\0\0\0"...
fstat(3, st_mode=S_IFREG|0755, st_size=1864888, ...) = 0
mmap(NULL, 3967392, PROT_READ|PROT_EXEC, ..., 3, 0) = 0x7fdfee54d000
mprotect(0x7fdfee70c000, 2097152, PROT_NONE) = 0
mmap(0x7fdfee90c000, 24576, PROT_READ|PROT_WRITE, ..., 3, 0x1bf000) = 0x7f
mmap(0x7fdfee912000, 14752, PROT_READ|PROT_WRITE, ..., -1, 0) = 0x7fdfee91
close(3)                                = 0
...
write(1, "Hello, World!\n", 14)         = 14
exit_group(14)                          = ?
+++ exited with 14 +++
```

read standard C library header

dynamically linked hello.exe

```
gcc -o hello.exe hello.s
```

strace ./hello.exe:

```
execve("./hello.exe", ["./hello.exe"], [/* 46 vars */]) = 0
...
mmap(NULL, 8192, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) =
access("/etc/ld.so.preload", R_OK)      = -1 ENOENT (No such file or direc
open("/et
fstat(3,
...
open("/lib/x86_64-linux-gnu/libc.so.6", O_RDONLY|O_CLOEXEC) = 3
read(3, "\177ELF\2\1\1\3\0\0\0\0\0\0\0\0\3\0>\0\1\0\0\0P\t\2\0\0\0\0\0"...
fstat(3, st_mode=S_IFREG|0755, st_size=1864888, ...) = 0
mmap(NULL, 3967392, PROT_READ|PROT_EXEC, ..., 3, 0) = 0x7fdfee54d000
mprotect(0x7fdfee70c000, 2097152, PROT_NONE) = 0
mmap(0x7fdfee90c000, 24576, PROT_READ|PROT_WRITE, ..., 3, 0x1bf000) = 0x7f
mmap(0x7fdfee912000, 14752, PROT_READ|PROT_WRITE, ..., -1, 0) = 0x7fdfee91
close(3)                                = 0
...
write(1, "Hello, World!\n", 14)         = 14
exit_group(14)                          = ?
+++ exited with 14 +++
```

load standard C library (3 = opened file)

dynamically linked hello.exe

```
gcc -o hello.exe hello.s
```

strace ./hello.exe:

```
execve("./hello.exe", ["./hello.exe"], [/* 46 vars */]) = 0
...
mmap(NULL, 8192, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) =
access("/etc/ld.so.preload", R_OK)      = -1 ENOENT (No such file or direc
open
fsta
...
open("/lib/x86_64-linux-gnu/libc.so.6", O_RDONLY|O_CLOEXEC) = 3
read(3, "\177ELF\2\1\1\3\0\0\0\0\0\0\0\0\3\0>\0\1\0\0\0P\t\2\0\0\0\0\0"...
fstat(3, st_mode=S_IFREG|0755, st_size=1864888, ...) = 0
mmap(NULL, 3967392, PROT_READ|PROT_EXEC, ..., 3, 0) = 0x7fdfee54d000
mprotect(0x7fdfee70c000, 2097152, PROT_NONE) = 0
mmap(0x7fdfee90c000, 24576, PROT_READ|PROT_WRITE, ..., 3, 0x1bf000) = 0x7f
mmap(0x7fdfee912000, 14752, PROT_READ|PROT_WRITE, ..., -1, 0) = 0x7fdfee91
close(3)                                = 0
...
write(1, "Hello, World!\n", 14)         = 14
exit_group(14)                          = ?
+++ exited with 14 +++
```

allocate zero-initialized data segment for C library

dynamic linking

load and link (find address of `puts`) runtime

advantages:

- smaller executables
- easier upgrades
- less memory usage (load one copy of library for multiple programs)

disadvantages:

- library upgrades breaking programs
- programs less compatible between OS versions
- possibly slower

where's the linker

Where's the code that calls `open("...libc.so.6")`?

Could check `hello.exe` — it's not there!

where's the linker

Where's the code that calls
`open("...libc.so.6")`?

Could check `hello.exe` — it's not there!

instead: "interpreter"
`/lib64/ld-linux-x86-64.so.2`

on Linux: contains loading code instead of core OS

- OS loads it instead of program

objdump — the interpreter

excerpt from `objdump -sx hello.exe`:

```
Program Header:
...
  INTERP off    0x0000238 vaddr 0x0400238 paddr 0x0400238 align 2**0
         filesz 0x000001c memsz 0x000001c flags r--
...
Contents of section .interp:
 400238 2f6c6962 36342f6c 642d6c69 6e75782d  /lib64/ld-linux-
 400248 7838362d 36342e73 6f2e3200           x86-64.so.2.
```

dynamic linking information

symbol table — works the same, but in executable

could use same relocations — but these are expensive

rather just copy data from disk without changes

solutions: global lookup table!

dynamically linked puts

```
0000000000400400 <puts@plt>:
  400400:        ff 25 12 0c 20 00            jmpq   *0x200c12(%rip)
                    /* 0x200c12+RIP = _GLOBAL_OFFSET_TABLE_+0x18 */
... later in main: ...
  40052d:        e8 ce fe ff ff               callq  400400 <puts@plt>
                        /* instead of call puts */
```

replace `puts` with stub `puts@plt`

- plt = procedure linkage table

stub: jump to `*_GLOBAL_OFFSET_TABLE[3]`

dynamic linker changes table instead of code

- could change code — just would be less efficient

lazy binding

```
0000000000400400 <puts@plt>:
  400400:        ff 25 12 0c 20 00              jmpq   *0x200c12(%rip)
                    /* 0x200c12+RIP = _GLOBAL_OFFSET_TABLE_+0x18 */
  400406:        68 00 00 00 00                 pushq  $0x0
  40040b:        e9 e0 ff ff ff                 jmpq   4003f0 <_init+0x28>
```

could fill global offset table immediately

alternative: fill on demand

extra code (`pushq` then `jmpq`) runs "fixup code"

- reads symbol tables to find function
- edits global offset table
- jumps to function

called "lazy binding"

lazy binding pro/con

advantages:

- faster program loading
- no overhead for unused code (often a lot of stuff)

disadvantages:

- can move errors (missing functions, etc.) to runtime
- possibly more total overhead

8086 evolution

Intel 8086 — 1979, 16-bit registers

Intel (80)386 — 1986, 32-bit registers

AMD K8 — 2003, 64-bit registers

x86 modes

x86 has multiple modes

maintains compatiblity

e.g.: modern x86 processor can work like 8086

called "real mode"

different mode for 32-bit/64-bit

same basic encoding; some sizes change