

Linking and Loading

Anton Burtsev

What is inside a program?

- What parts do we need to run code?

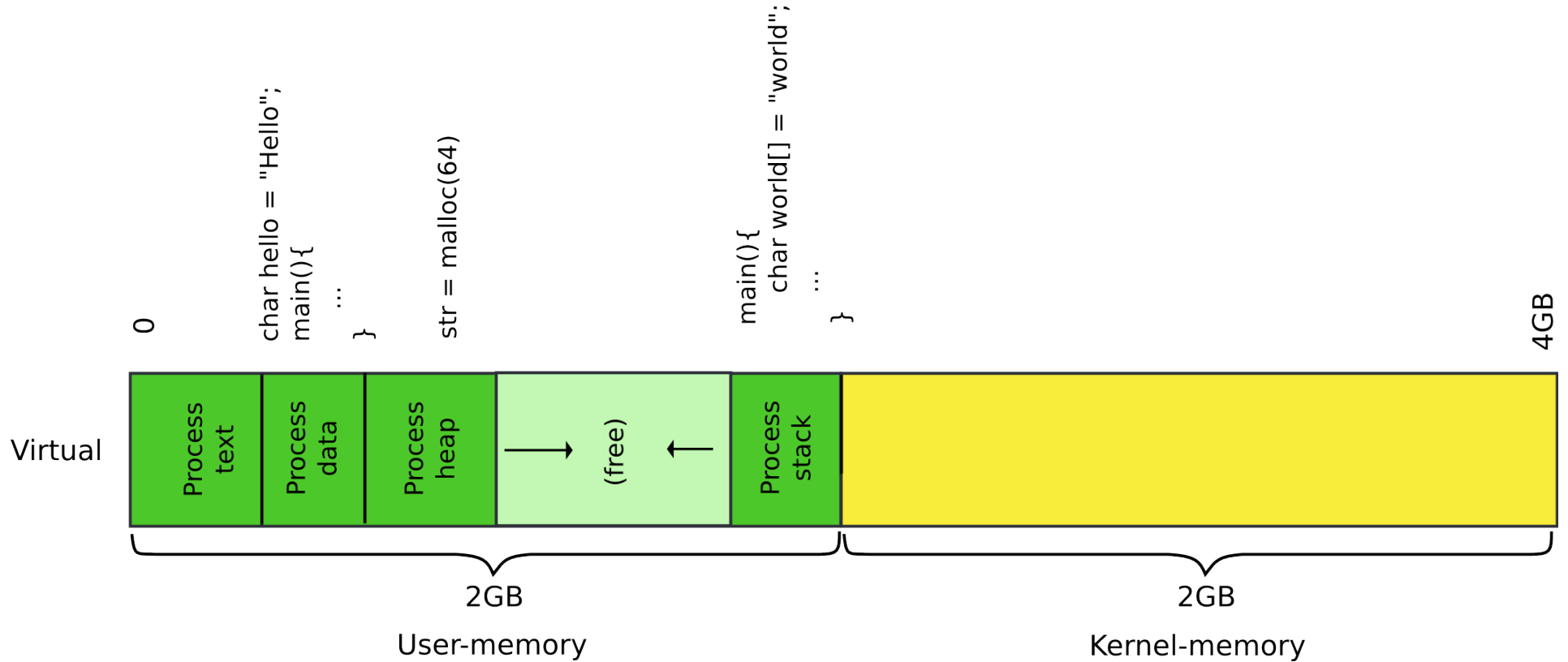
Parts needed to run a program

- Code itself
 - By convention it's called text
- Stack
 - To call functions
- Space for variables

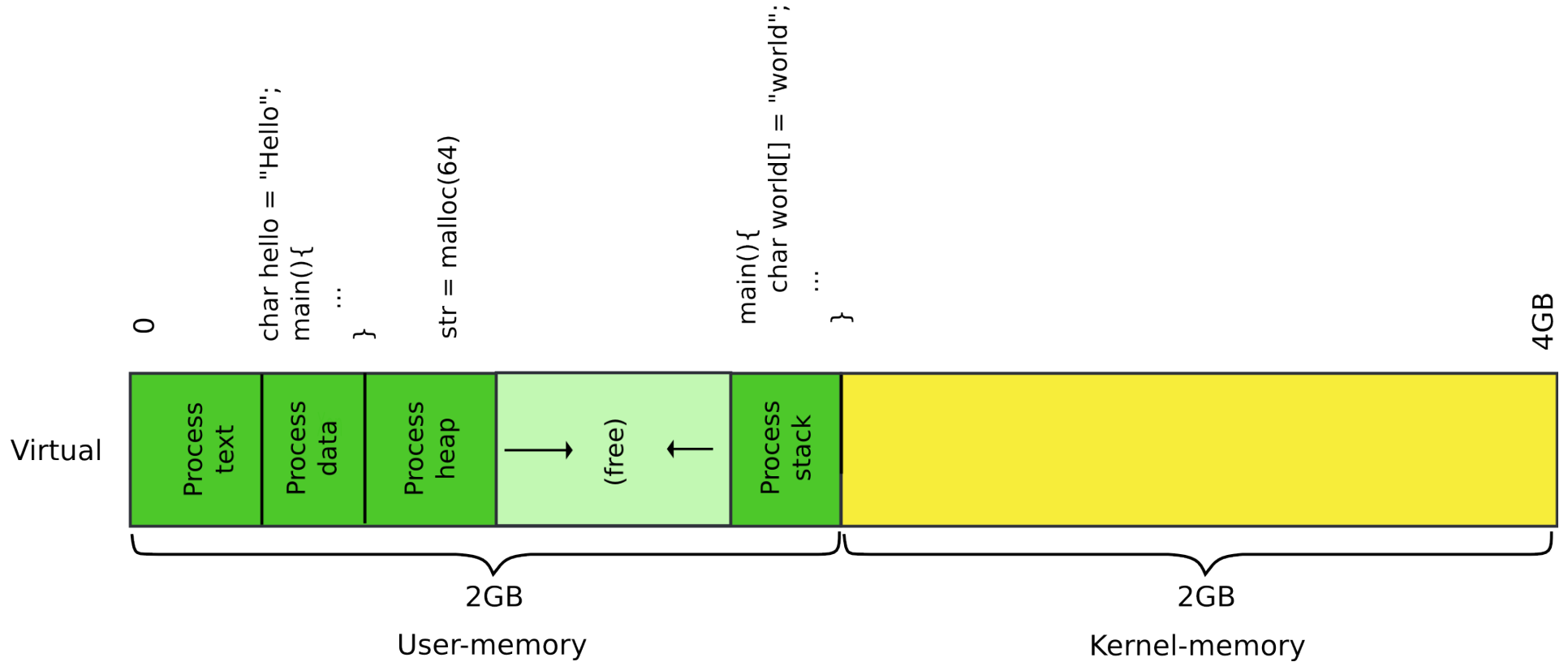
What types of variables do you know?

- Global variables
 - Initialized → data section
 - Uninitialized → BSS
- Local variables
 - Stack
- Dynamic variables
 - Heap

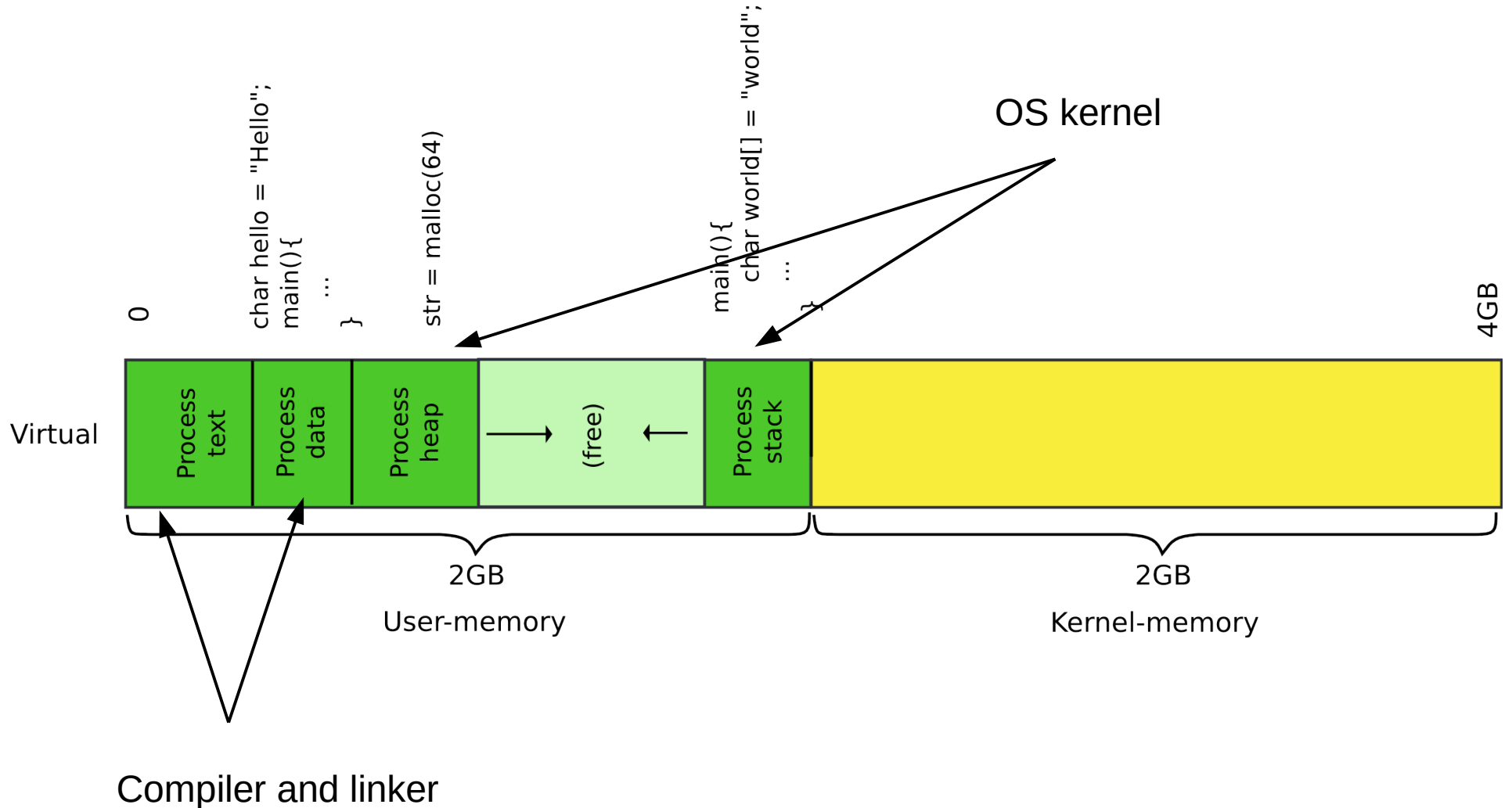
Memory layout of a process



Where do these areas come from?



Memory layout of a process



Example program

- Compute 5 + 6

```
#include <stdio.h>
```

```
int main(int ac, char **av)
{
    int a = 5, b = 6;
    return a + b;
}
```

- We build it like
 - I'm on 64 bit system, but want 32bit code, hence -m32
 - -fno-pic – disables position independent code

```
gcc -m32 -fno-pic hello-int.c
```


a.out: file format elf32-i386

Contents of section .text:

```
80483e0 d0c9e979 ffffffff e973ffff ff5589e5 ...y.....s...U..
80483f0 83ec10c7 45f80500 0000c745 fc060000 ....E.....E....
8048400 008b45fc 8b55f801 d0c9c366 90669090 ..E..U.....f.f..
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8048420 0083ec1c 8b6c2430 8db30cff ffffe861 .....l$0.....a
8048430 feffff8d 8308ffff ff29c6c1 fe0285f6 .....)......
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Contents of section .rodata:

```
8048498 03000000 01000200 .....
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Contents of section .data:

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804a014 00000000 00000000 .....
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Disassembly of section .text:

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...
080483ed <main>:
80483ed:    55          push    %ebp
80483ee:    89 e5      mov     %esp,%ebp
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80483f3:    c7 45 f8 05 00 00 00  movl   $0x5,-0x8(%ebp)
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8048401:    8b 45 fc   mov    -0x4(%ebp),%eax
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objdump -sd a.out

- GCC syntax, i.e.
`mov %esp, %ebp`
`// EBP = ESP`

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8048409:      c9              leave                # Pop the frame ESP = EBP
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8048407:      01 d0      add   %edx,%eax
8048409:      c9        leave
804840a:      c3        ret
804840b:      66 90     xchg  %ax,%ax      # Code alignment
804840d:      66 90     xchg  %ax,%ax      # 2 byte no op
804840f:      90        nop                # 1 byte no op
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`// EBP = ESP`

“Optimizing subroutines in assembly language” by
Agner Fog:

https://www.agner.org/optimize/optimizing_assembly.pdf

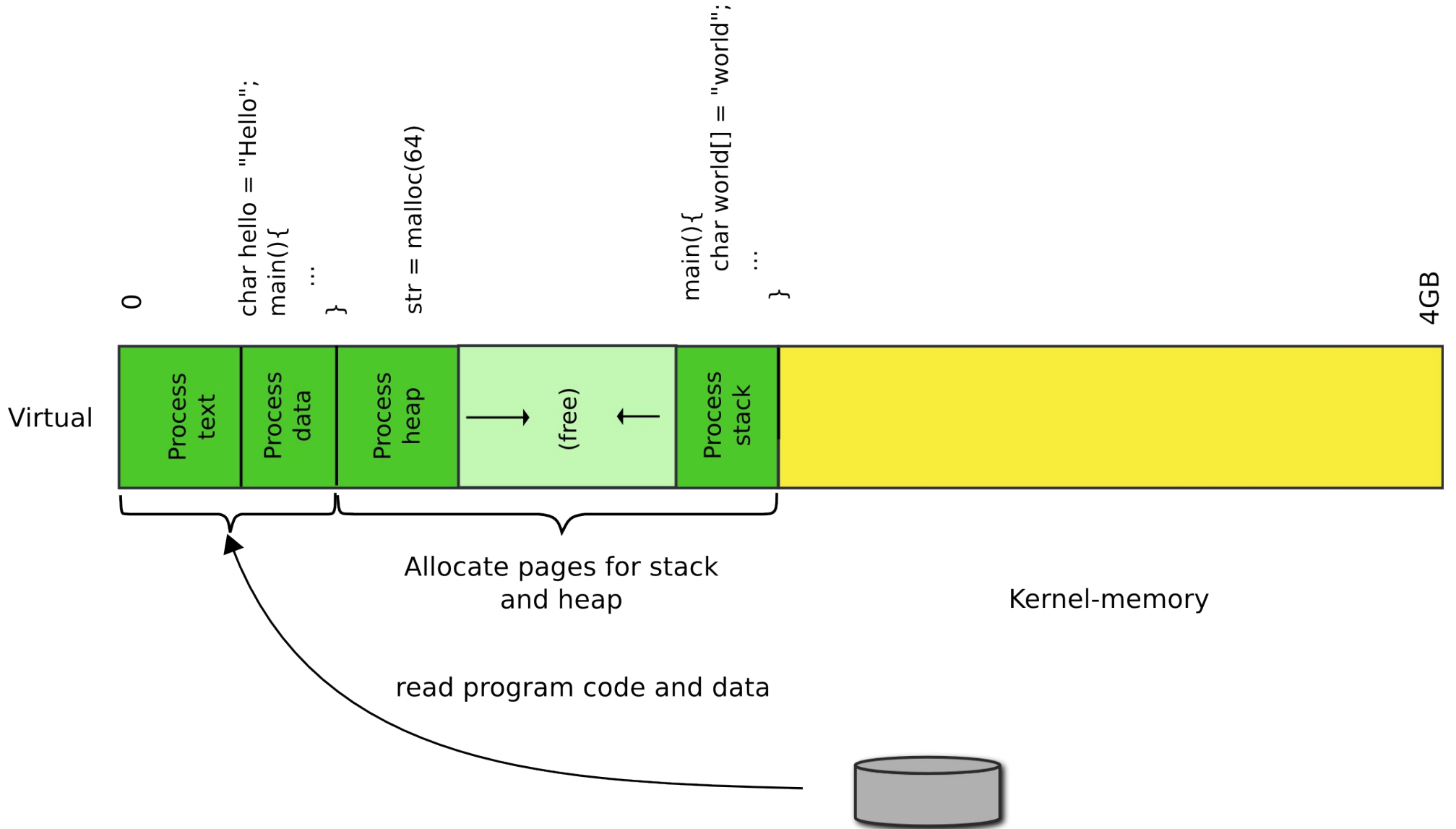
11.5 Alignment of code

Most microprocessors fetch code in aligned 16-byte or 32-byte blocks. If an important subroutine entry or jump label happens to be near the end of a 16-byte block then the microprocessor will only get a few useful bytes of code when fetching that block of code. It may have to fetch the next 16 bytes too before it can decode the first instructions after the label. This can be avoided by aligning important subroutine entries and loop entries by 16.

...

Aligning a subroutine entry is as simple as putting as many NOP 's as needed before the subroutine entry to make the address divisible by 8, 16, 32 or 64, as desired.

Load program in memory



We however build programs from multiple files

Part of the xv6 Makefile

```
bootblock: bootasm.S bootmain.c
```

```
$(CC) $(CFLAGS) -fno-pic -O -nostdinc -I. -c bootmain.c
```

```
$(CC) $(CFLAGS) -fno-pic -nostdinc -I. -c bootasm.S
```

```
$(LD) $(LDFLAGS) -N -e start -Ttext 0x7C00 -o bootblock.o bootasm.o bootmain.o
```

```
$(OBJDUMP) -S bootblock.o > bootblock.asm
```

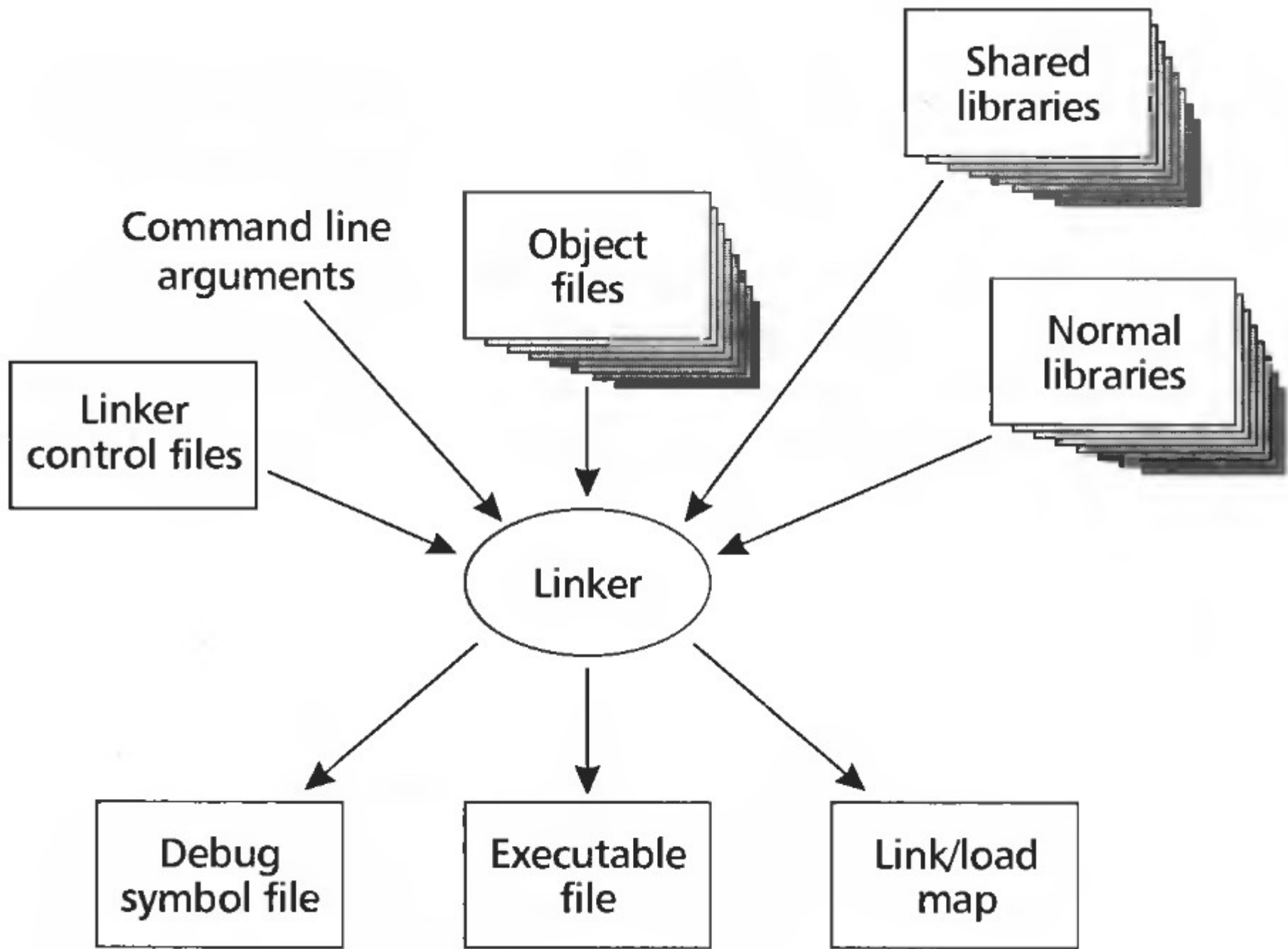
```
$(OBJCOPY) -S -O binary -j .text bootblock.o bootblock
```

```
./sign.pl bootblock
```

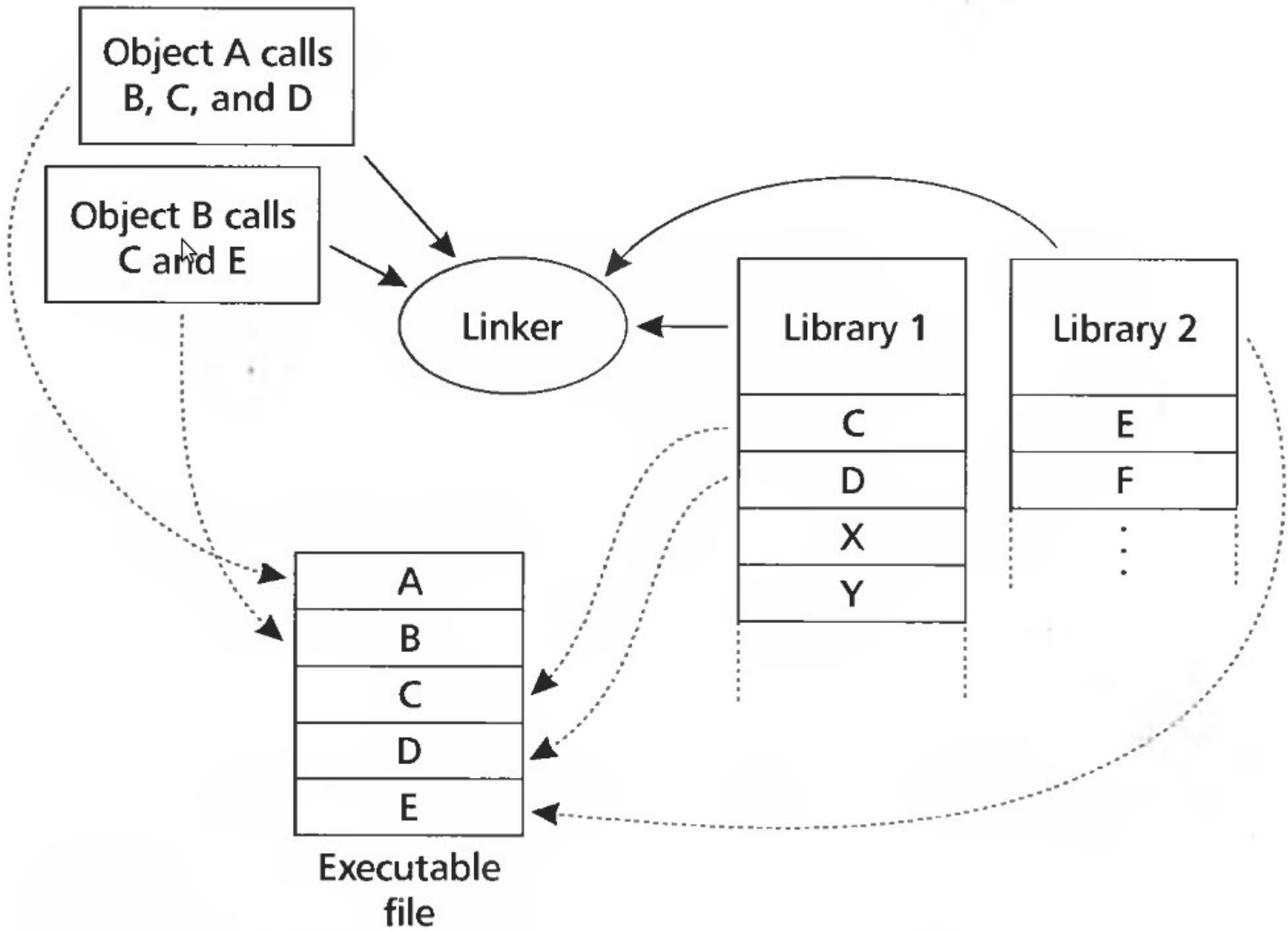
Linking and Loading

Linking and loading

- Linking
 - Combining multiple code modules into a single executable
 - E.g., use standard libraries in your own code
- Loading
 - Process of getting an executable running on the machine



- Input: object files (code modules)
- Each object file contains
 - A set of segments
 - Code
 - Data
 - A symbol table
 - Imported & exported symbols
- Output: executable file, library, etc.



Why linking?

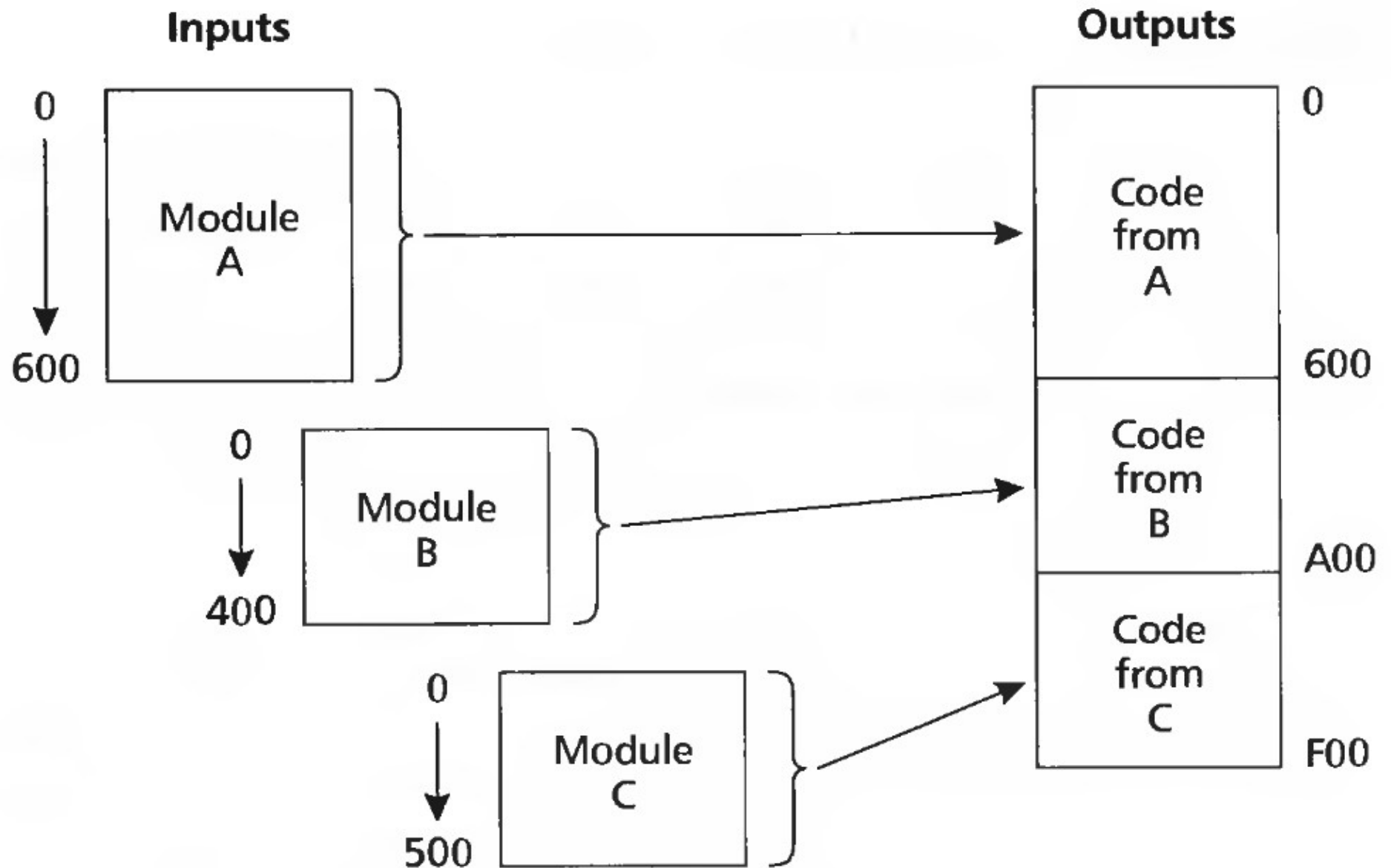
Why linking?

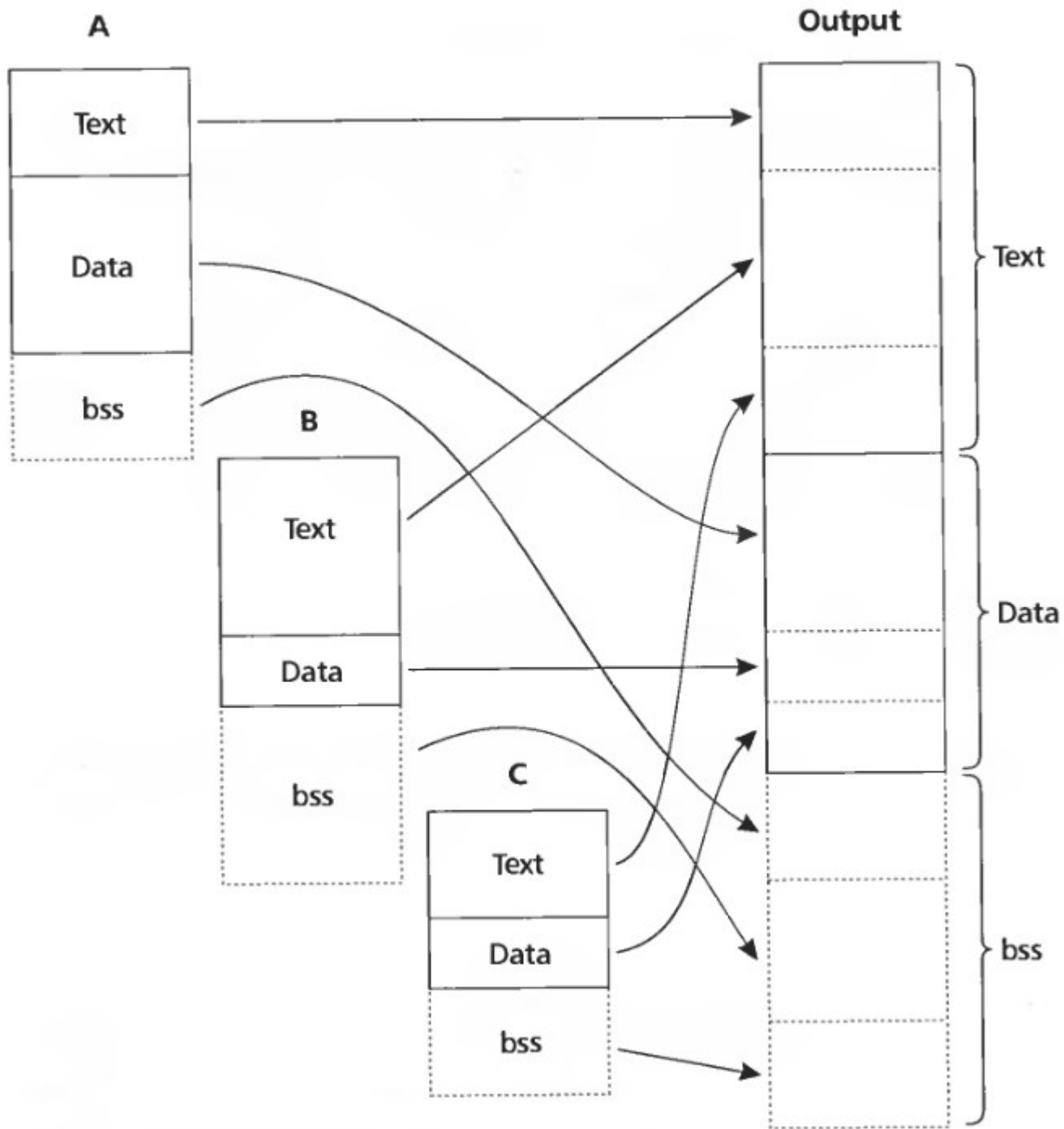
- Modularity
 - Program can be written as a collection of modules
 - We can build libraries of common functions
- Efficiency
 - Code compilation
 - Change one source file, recompile it, and re-link the executable
 - Space efficiency
 - Share common code across executable files
 - On disk and in memory

Two path process

- Path 1: scan input files
 - Identify boundaries of each segment
 - Collect all defined and undefined symbol information
 - Determine sizes and locations of each segment
- Path 2
 - Adjust memory addresses in code and data to reflect relocated segment addresses

Multiple object files





Merging segments

What needs to be done to merge (or move) code in memory?

Relocation

Example

- Save a into b, e.g., $b = a$

```
mov a, %eax
```

```
mov %eax, b
```

- Generated code

- a is defined in the same file at 0x1234, **b is imported**

- Each instruction is 1 byte opcode + 4 bytes address

```
A1 34 12 00 00 mov a, %eax
```

```
A3 00 00 00 00 mov %eax, b
```

Example

- Save a into b, e.g., $b = a$

```
mov a, %eax
```

- 
- 1 byte opcode

generated code

a is defined in the same file at 0x1234, **b is imported**

Each instruction is 1 byte opcode + 4 bytes address

```
A1 34 12 00 00 mov a, %eax
```

```
A3 00 00 00 00 mov %eax, b
```

Example

- Save a into b, e.g., $b = a$

```
mov a, %eax
```

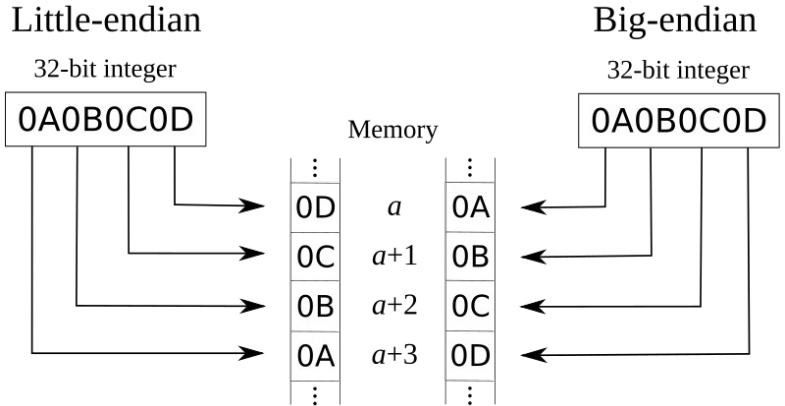
• 4 byte address

Generate code

- a is defined in the same file at 0x1234, **b is imported**
- Each instruction is 1 byte opcode + 4 bytes address

```
A1 34 12 00 00 mov a, %eax
```

```
A3 00 00 00 00 mov %eax, b
```



Example

- Save a into b, e.g., $b = a$

```
mov a, %eax
```

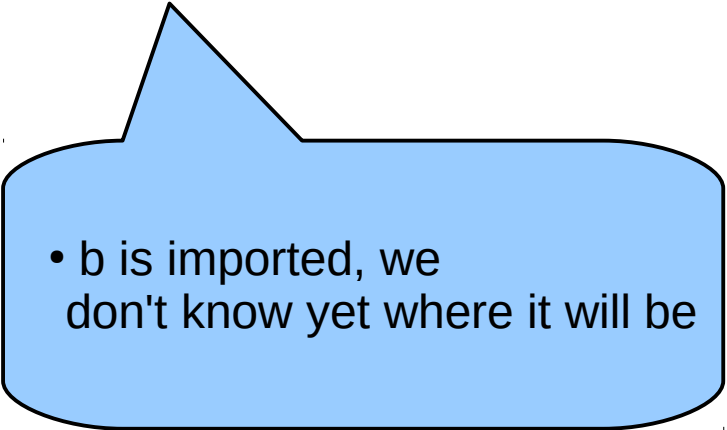
```
mov %eax, b
```

- Generated code

- a is defined in the same file at 0x1234, **b is imported**
- Each instruction is 1 byte opcode + 4 bytes address

```
A1 34 12 00 00 mov a, %eax
```

```
A3 00 00 00 00 mov %eax, b
```

- 
- b is imported, we don't know yet where it will be

Example

- Save a into b, e.g., $b = a$

```
mov a, %eax
```

```
mov %eax, b
```

- Generated code

- a is defined in the same file at 0x1234, **b is imported**

- Each instruction is 1 byte opcode + 4 bytes address

```
A1 34 12 00 00 mov a, %eax
```

```
A3 00 00 00 00 mov %eax, b
```

- Assume that a is relocated by 0x10000 bytes, and b is found at 0x9a12

```
A1 34 12 01 00 mov a, %eax
```

```
A3 12 9A 00 00 mov %eax, b
```


Example

- Save a into b, e.g., $b = a$

```
mov a, %eax
```

```
mov %eax, b
```

- Generated code

- a is defined in the same file at 0x1234, **b is imported**

- Each instruction is 1 byte opcode + 4 bytes address

```
A1 34 12 00 00 mov a, %eax
```

```
A3 00 00 00 00 mov %eax, b
```

- Assume that a is relocated by 0x10000 bytes, and b is found at 0x9a12

```
A1 34 12 01 00 mov a, %eax
```

```
A3 12 9A 00 00 mov %eax, b
```

More realistic example

- Source file m.c

```
1  extern void a(char *);
2  int main(int ac, char **av)
3  {
4      static char string[] = "Hello, world!\n";
5      a(string);
6  }
```

- Source file a.c

```
1  #include <unistd.h>
2  #include <string.h>
3  void a(char *s)
4  {
5      write(1, s, strlen(s));
6  }
```

More realistic example

- Source file m.c

```
1  extern void a(char *);
2  int main(int ac, char **av)
3  {
4      static char string[] = "Hello, world!\n";
5      a(string);
6  }
```

- Source file a.c

```
1  #include <unistd.h>
2  #include <string.h>
3  void a(char *s)
4  {
5      write(1, s, strlen(s));
6  }
```

More realistic example

- Source file m.c

```
1  extern void a(char *);
2  int main(int ac, char **av)
3  {
4      static char string[] = "Hello, world!\n";
5      a(string);
6  }
```

- Source file a.c

```
1  #include <unistd.h>
2  #include <string.h>
3  void a(char *s)
4  {
5      write(1, s, strlen(s));
6  }
```

More realistic example

Sections:

Idx	Name	Size	VMA	LMA	File off	Algn
0	.text	00000010	00000000	00000000	00000020	2**3
1	.data	00000010	00000010	00000010	00000030	2**3

Disassembly of section .text:

00000000 <_main>:

```
0: 55                pushl %ebp
1: 89 e5             movl %esp,%ebp
3: 68 10 00 00 00    pushl $0x10
4: 32 .data
8: e8 f3 ff ff ff    call 0
9: DISP32 _a
d: c9                leave
e: c3                ret
...
```

More realistic example

- Two sections:
 - Text (0x10 – 16 bytes)
 - Data (16 bytes)

Sections:

Idx	Name	Size	VMA	LMA	File off	Algn
0	.text	00000010	00000000	00000000	00000020	2**3
1	.data	00000010	00000010	00000010	00000030	2**3

Disassembly of section .text:

00000000 <_main>:

```
0: 55                pushl %ebp
1: 89 e5             movl %esp,%ebp
3: 68 10 00 00 00    pushl $0x10
4: 32 .data
8: e8 f3 ff ff ff    call 0
9: DISP32 _a
d: c9                leave
e: c3                ret
...
```

More realistic example

- Two sections:
 - Text starts at 0x0
 - Data starts at 0x10

Sections:

Idx	Name	Size	VMA	LMA	File off	Algn
0	.text	00000010	00000000	00000000	00000020	2**3
1	.data	00000010	00000010	00000010	00000030	2**3

Disassembly of section .text:

00000000 <_main>:

```
0: 55                pushl %ebp
1: 89 e5             movl %esp,%ebp
3: 68 10 00 00 00    pushl $0x10
4: 32 .data
8: e8 f3 ff ff ff    call 0
9: DISP32 _a
d: c9                leave
e: c3                ret
...
```

More realistic example

Sections:

Idx	Name	Size	VMA	LMA	File off	Algn
0	.text		00000000	00000000	00000020	2**3
1	.data		00000010	00000010	00000030	2**3

• Code starts at 0x0

Disassembly of section .text:

00000000 <_main>:

```
0: 55                pushl %ebp
1: 89 e5             movl %esp,%ebp
3: 68 10 00 00 00   pushl $0x10
4: 32 .data
8: e8 f3 ff ff ff   call 0
9: DISP32 _a
d: c9                leave
e: c3                ret
...
```


More realistic example

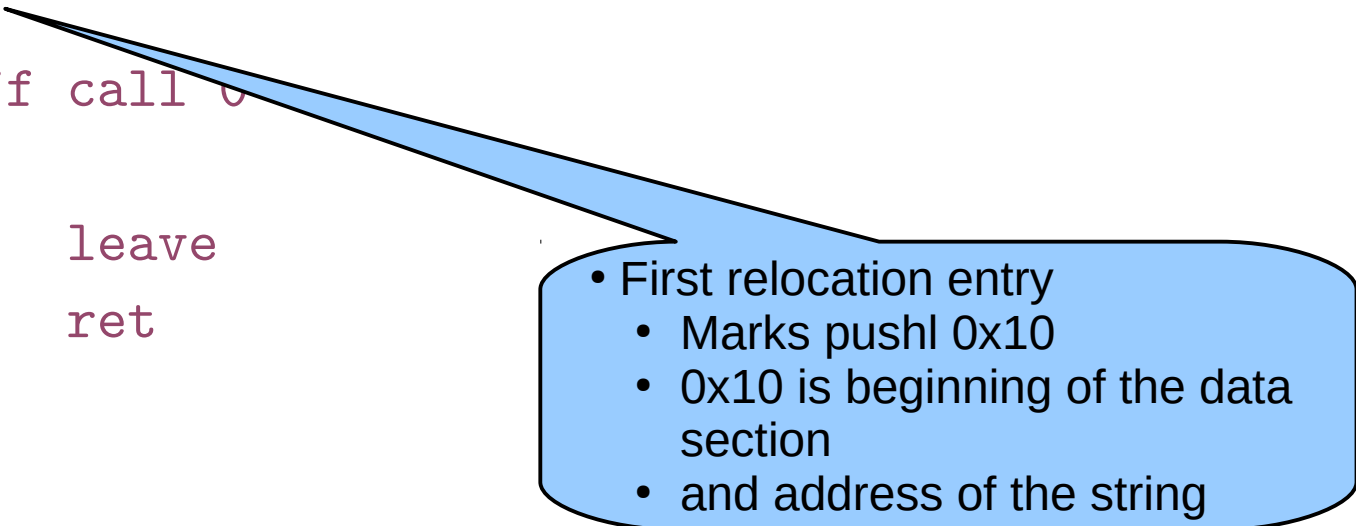
Sections:

Idx	Name	Size	VMA	LMA	File off	Algn
0	.text	00000010	00000000	00000000	00000020	2**3
1	.data	00000010	00000010	00000010	00000030	2**3

Disassembly of section .text:

00000000 <_main>:

```
0: 55                pushl %ebp
1: 89 e5             movl %esp,%ebp
3: 68 10 00 00 00    pushl $0x10 # push string on the stack
4: 32 .data
8: e8 f3 ff ff ff    call 0
9: DISP32 _a
d: c9                leave
e: c3                ret
...
```

- 
- First relocation entry
 - Marks pushl 0x10
 - 0x10 is beginning of the data section
 - and address of the string

More realistic example

- Source file m.c

```
1  extern void a(char *);
2  int main(int ac, char **av)
3  {
4      static char string[] = "Hello, world!\n";
5      a(string);
6  }
```

- Source file a.c

```
1  #include <unistd.h>
2  #include <string.h>
3  void a(char *s)
4  {
5      write(1, s, strlen(s));
6  }
```

More realistic example

Sections:

Idx	Name	Size	VMA	LMA	File off	Algn
0	.text	00000010	00000000	00000000	00000020	2**3
1	.data	00000010	00000010	00000010	00000030	2**3

Disassembly of section .text:

00000000 <_main>:

```
0: 55                pushl %ebp
1: 89 e5             movl %esp,%ebp
3: 68 10 00 00 00    pushl $0x10
4: 32 .data
8: e8 f3 ff ff ff    call 0
9: DISP32 _a
d: c9                leave
e: c3                ret
...
```

- Second relocation entry
 - Marks call
 - 0x0 – address is unknown

More realistic example

- Source file m.c

```
1  extern void a(char *);
2  int main(int ac, char **av)
3  {
4      static char string[] = "Hello, world!\n";
5      a(string);
6  }
```

- Source file a.c

```
1  #include <unistd.h>
2  #include <string.h>
3  void a(char *s)
4  {
5      write(1, s, strlen(s));
6  }
```

More realistic example

Sections:

Idx	Name	Size	VMA	LMA	File off	Algn
0	.text	0000001c	00000000	00000000	00000020	2**2
	CONTENTS, ALLOC, LOAD, RELOC, CODE					
1	.data	00000000	0000001c	0000001c	0000003c	2**2
	CONTENTS, ALLOC, LOAD, DATA					

Disassembly of section .text:

```
00000000 <_a>:
0: 55                pushl %ebp
1: 89 e5            movl %esp,%ebp
3: 53                pushl %ebx
4: 8b 5d 08        movl 0x8(%ebp),%ebx
7: 53                pushl %ebx
8: e8 f3 ff ff ff  call 0
9: DISP32 _strlen
d: 50                pushl %eax
e: 53                pushl %ebx
f: 6a 01            pushl $0x1
11: e8 ea ff ff ff  call 0
12: DISP32 _write
16: 8d 65 fc        leal -4(%ebp),%esp
19: 5b                popl %ebx
1a: c9                leave
1b: c3                ret
```

- Two sections:
 - Text (0 bytes)
 - Data (28 bytes)

More realistic example

- Source file m.c

```
1  extern void a(char *);
2  int main(int ac, char **av)
3  {
4      static char string[] = "Hello, world!\n";
5      a(string);
6  }
```

- Source file a.c

```
1  #include <unistd.h>
2  #include <string.h>
3  void a(char *s)
4  {
5      write(1, s, strlen(s));
6  }
```

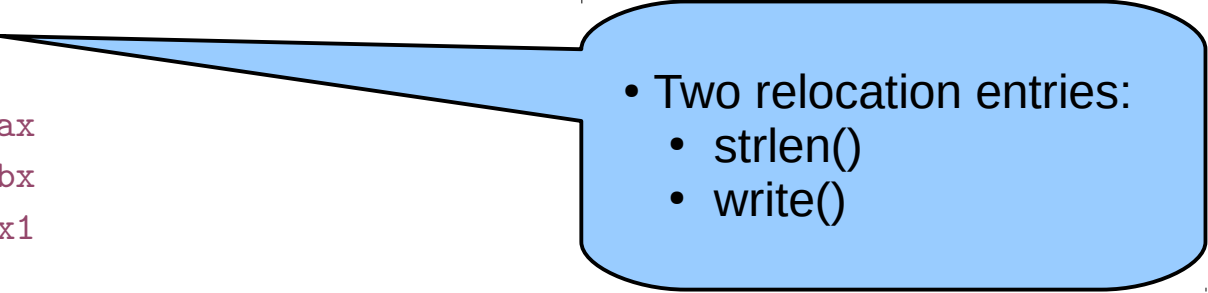
More realistic example

Sections:

```
Idx Name Size      VMA      LMA      File off Algn
 0 .text 0000001c 00000000 00000000 00000020 2**2
    CONTENTS, ALLOC, LOAD, RELOC, CODE
 1 .data 00000000 0000001c 0000001c 0000003c 2**2
    CONTENTS, ALLOC, LOAD, DATA
```

Disassembly of section .text:

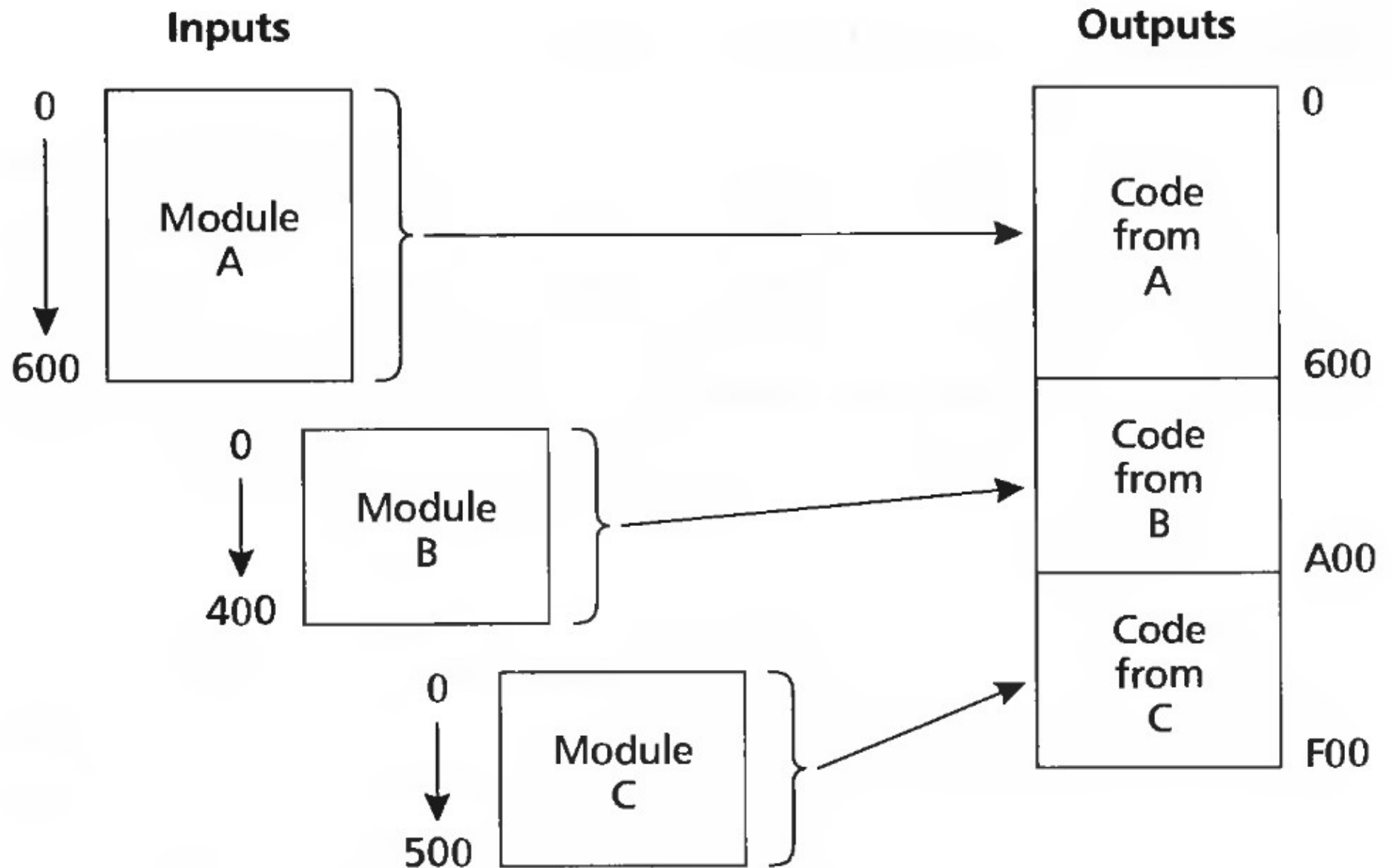
```
00000000 <_a>:
0: 55                pushl %ebp
1: 89 e5            movl %esp,%ebp
3: 53              pushl %ebx
4: 8b 5d 08        movl 0x8(%ebp),%ebx
7: 53              pushl %ebx
8: e8 f3 ff ff ff  call 0
 9: DISP32 _strlen
d: 50              pushl %eax
e: 53              pushl %ebx
f: 6a 01          pushl $0x1
11: e8 ea ff ff ff call 0
12: DISP32 _write
16: 8d 65 fc        leal -4(%ebp),%esp
19: 5b              popl %ebx
1a: c9              leave
1b: c3              ret
```

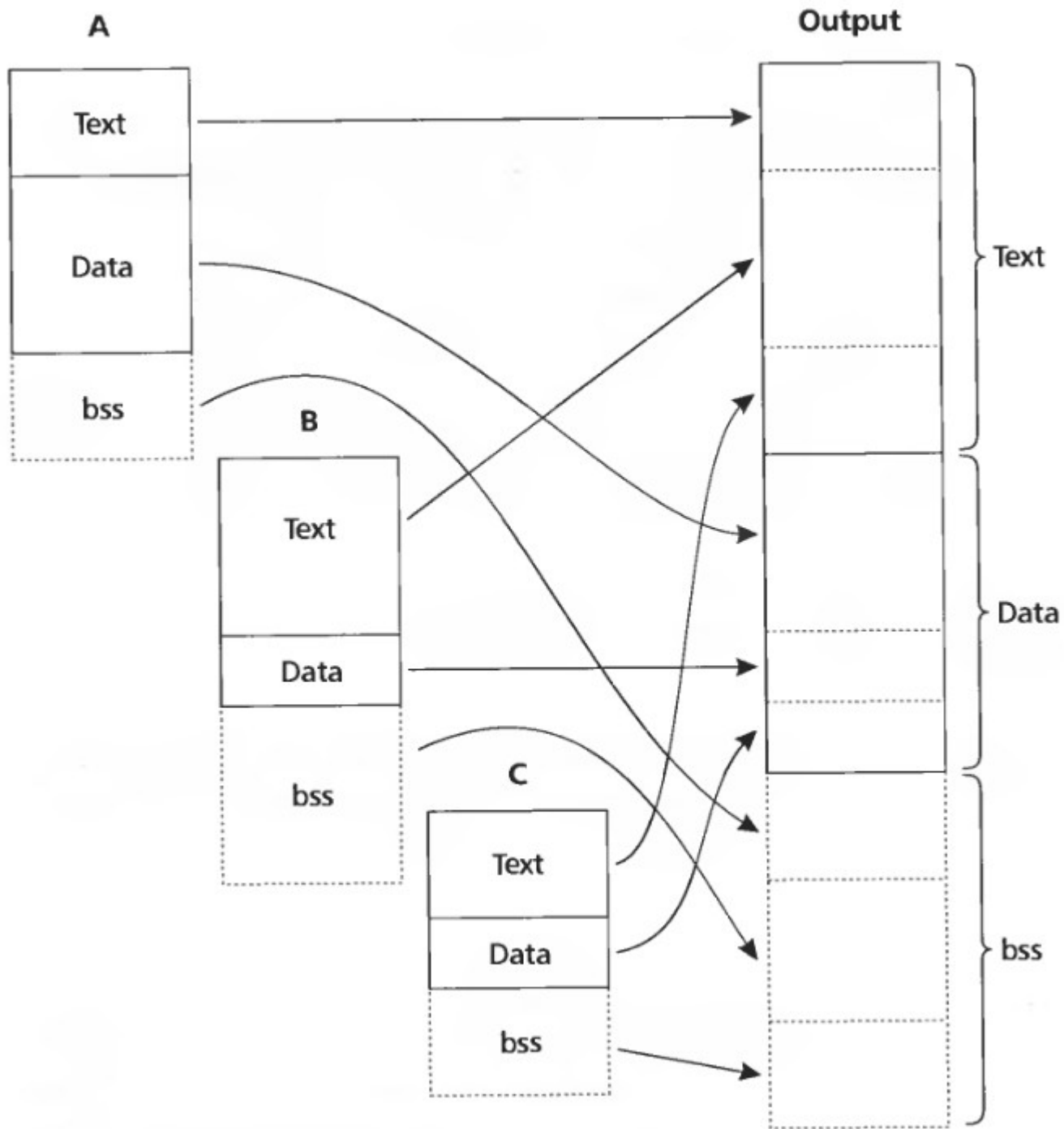
- 
- Two relocation entries:
 - strlen()
 - write()

Now we understand how to produce an executable

- Combine corresponding segments from each object file
 - Combined text segment
 - Combined data segment
- (Optional) pad each segment to 4KB to match the page size

Multiple object files





Merging segments

Sections:

Idx	Name	Size	VMA	LMA	File off	Algn
0	.text	00000fe0	00001020	00001020	00000020	2**3
1	.data	00001000	00002000	00002000	00001000	2**3
2	.bss	00000000	00003000	00003000	00000000	2**3

Disassembly of section .text:

00001020 <start-c>:

...

1092: e8 0d 00 00 00 call 10a4 <_main>

...

000010a4 <_main>:

10a7: 68 24 20 00 00 pushl \$0x2024

10ac: e8 03 00 00 00 call 10b4 <_a>

...

000010b4 <_a>:

10bc: e8 37 00 00 00 call 10f8 <_strlen>

...

10c3: 6a 01 pushl \$0x1

10c5: e8 a2 00 00 00 call 116c <_write>

...

000010f8 <_strlen>:

...

0000116c <_write>:

...

Linked executable

Sections:

Idx	Name	Size	VMA	LMA	File off	Algn
0	.text	00000fe0	00001020	00001020	00000020	2**3
1	.data	00001000	00002000	00002000	00001000	2**3
2	.bss	00000000	00003000	00003000	00000000	2**3

Disassembly of section .text:

00001020 <start-c>:

...

1092: e8 0d 00 00 00 call 10a4 <_main>

...

000010a4 <_main>:

10a7: 68 24 20 00 00 pushl \$0x2024

10ac: e8 03 00 00 00 call 10b4 <_a>

...

000010b4 <_a>:

10bc: e8 37 00 00 00 call 10f8 <_strlen>

...

10c3: 6a 01 pushl \$0x1

10c5: e8 a2 00 00 00 call 116c <_write>

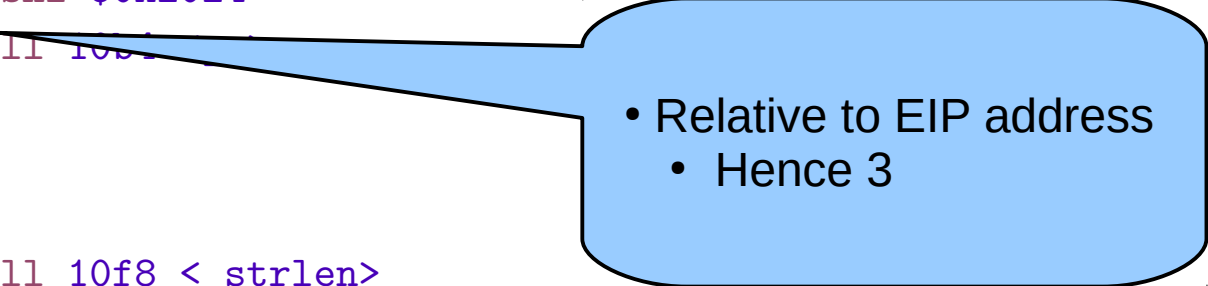
...

000010f8 <_strlen>:

...

0000116c <_write>:

...

- 
- Relative to EIP address
 - Hence 3

Linked executable

x86 Call instruction

x86 Instruction Set Reference

CALL

Call Procedure

Opcode	Mnemonic	Description
E8 cw	CALL rel16	Call near, relative, displacement relative to next instruction
E8 cd	CALL rel32	Call near, relative, displacement relative to next instruction
FF /2	CALL r/m16	Call near, absolute indirect, address given in r/m16
FF /2	CALL r/m32	Call near, absolute indirect, address given in r/m32
9A cd	CALL ptr16:16	Call far, absolute, address given in operand
9A cp	CALL ptr16:32	Call far, absolute, address given in operand
FF /3	CALL m16:16	Call far, absolute indirect, address given in m16:16
FF /3	CALL m16:32	Call far, absolute indirect, address given in m16:32

Description

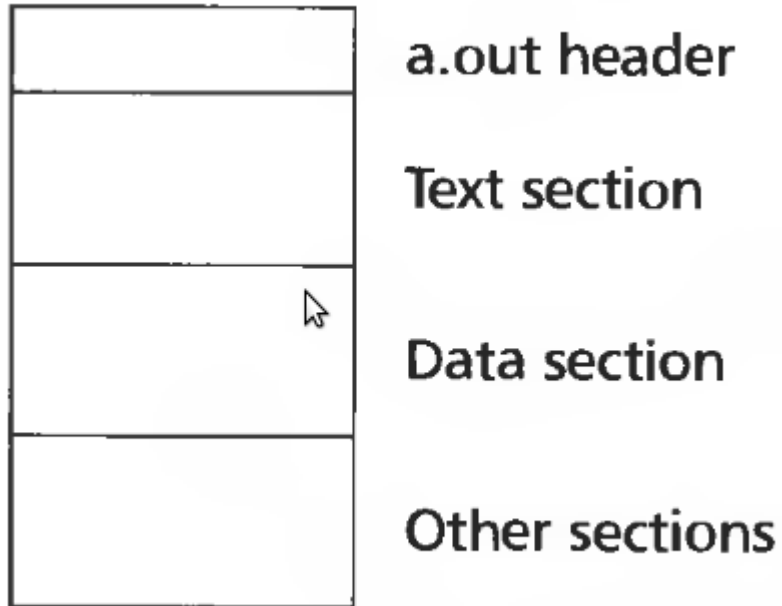
Saves procedure linking information on the stack and branches to the procedure (called procedure) specified with the destination (target) operand. The target operand specifies the address of the first instruction in the called procedure. This operand can be an immediate value, a generalpurpose register, or a memory location.

Object files (.o)

Object files

- Conceptually: five kinds of information
 - Header: code size, name of the source file, creation date
 - Object code: binary instruction and data generated by the compiler
 - Relocation information: list of places in the object code that need to be patched
 - Symbols: global symbols defined by this module
 - Symbols to be imported from other modules
 - Debugging information: source file and file number information, local symbols, data structure description

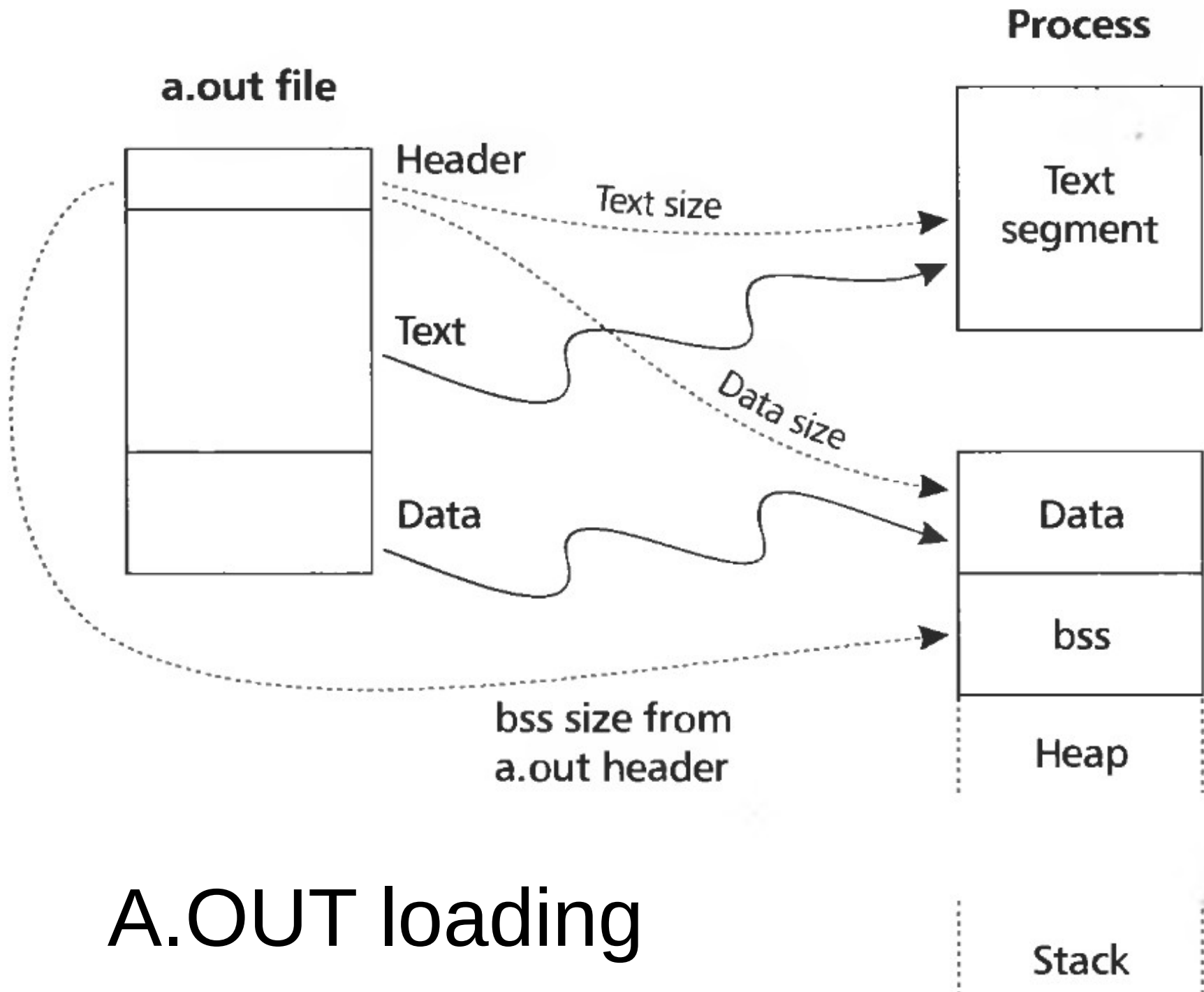
Example: UNIX A.OUT



- Small header
- Text section
 - Executable code
- Data section
 - Initial values for static data

- A.OUT header

```
int a_magic; // magic number
int a_text; // text segment size
int a_data; // initialized data size
int a_bss; // uninitialized data size
int a_syms; // symbol table size
int a_entry; // entry point
int a_trsize; // text relocation size
int a_drsize; // data relocation size
```



A.OUT loading

A.OUT loading

- Read the header to get segment sizes
- Check if there is a shareable code segment for this file
 - If not, create one,
 - Map into the address space,
 - Read segment from a file into the address space
- Create a private data segment
 - Large enough for data and BSS
 - Read data segment, zero out the BSS segment
- Create and map stack segment
 - Place arguments from the command line on the stack
- Jump to the entry point

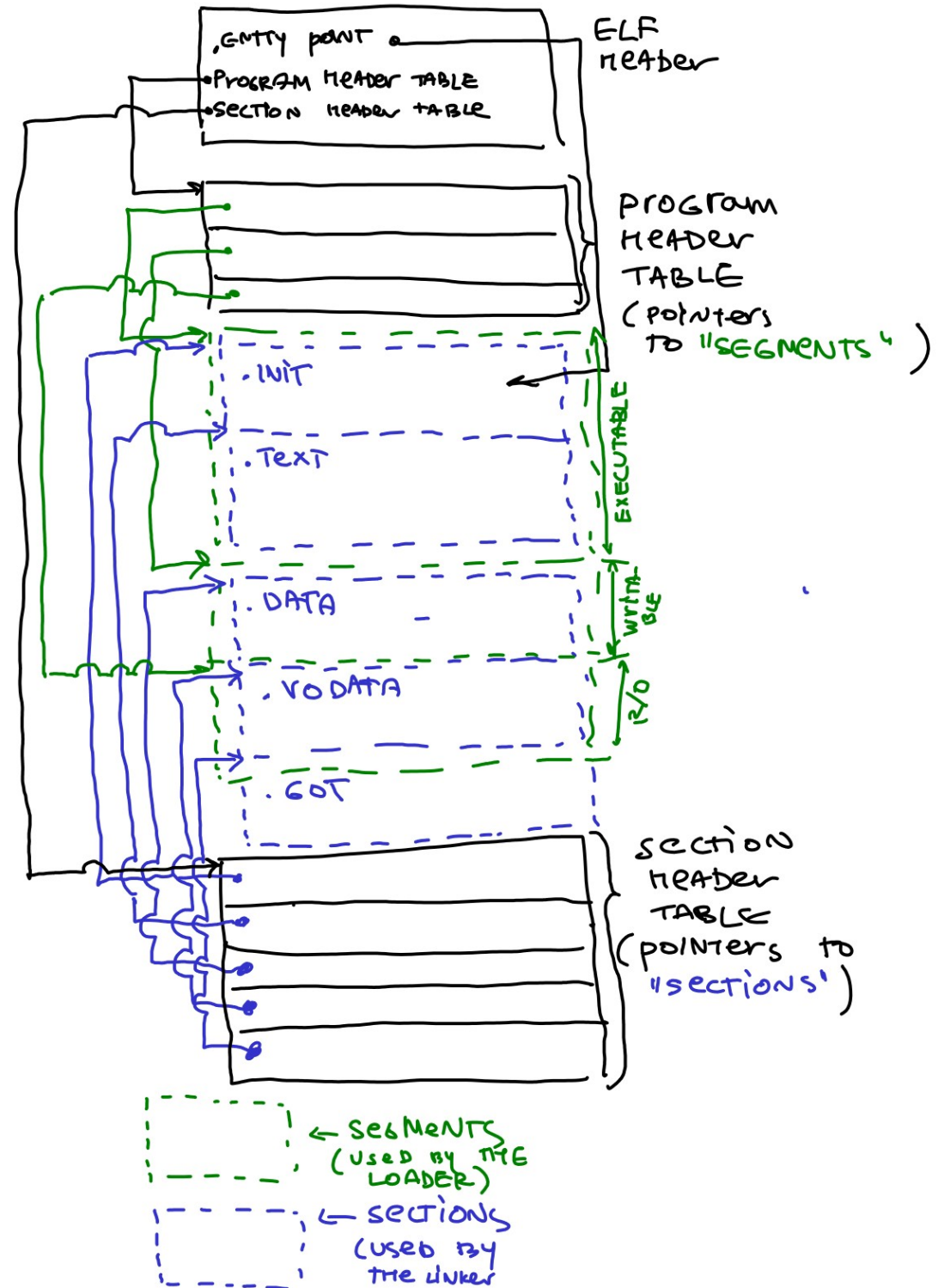
Executable and Linkable Format (ELF)

Types of object files

- Relocatable object files (.o)
 - Static libraries (.a)
 - Shared libraries (.so)
 - Executable files
-
- We looked at A.OUT, but Unix has a general format capable to hold all of these files
 - ELF

ELF

- Header
 - Magic number
 - Entry point
 - Pointers to two tables
 - Program header table
 - Section header table



- `gcc -c -fno-pic -static -fno-builtin -ggdb -m32 -fno-omit-frame-pointer hello-elf.c`
- `ld -m elf_i386 -N -e main -Ttext 0 -o a.out hello-elf.o`
- `readelf -a a.out`

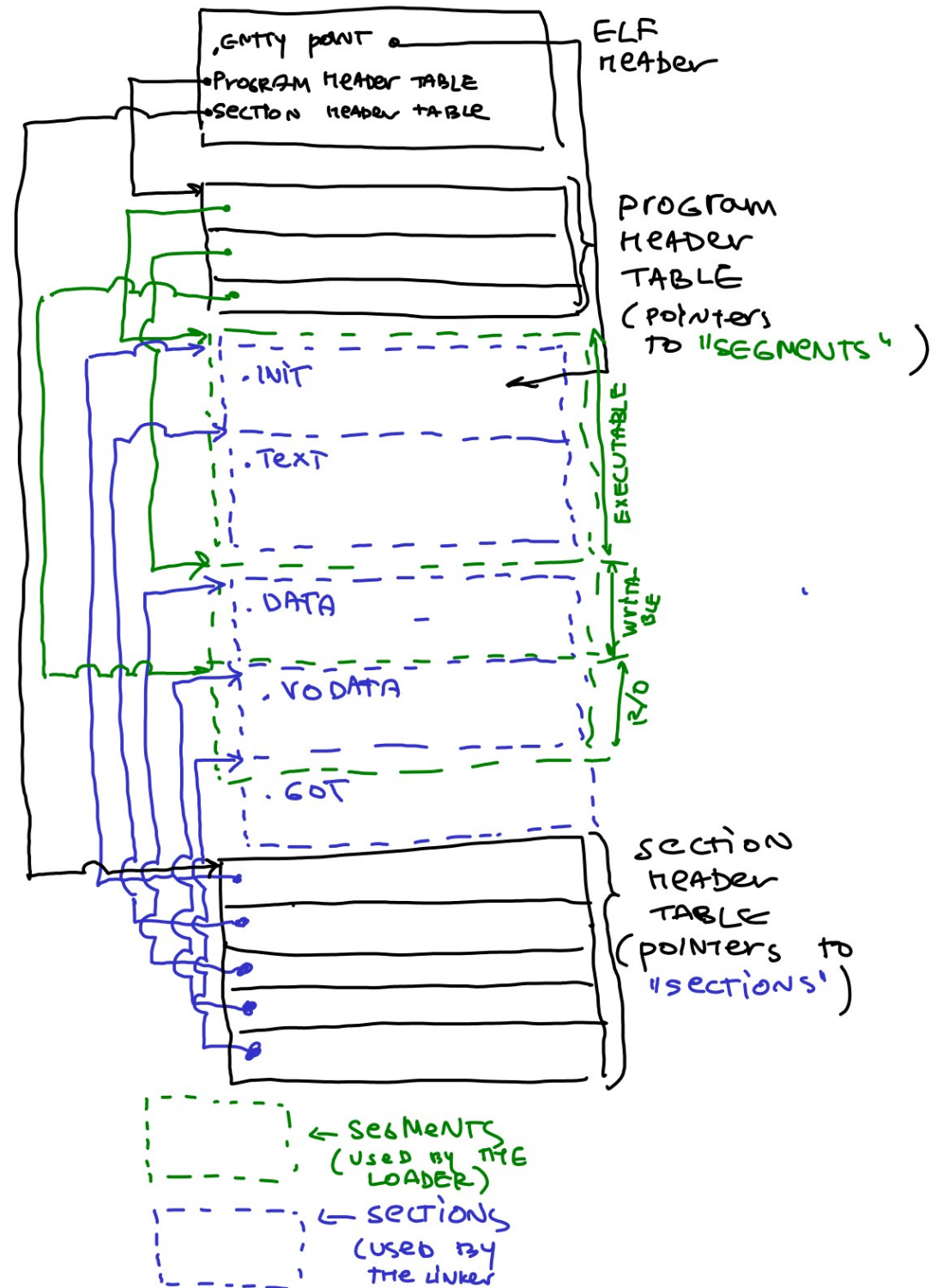
ELF Header:

```
Magic: 7f 45 4c 46 01 01 01 00 00 00 00 00 00 00 00 00
Class: ELF32
Data: 2's complement, little endian
Version: 1 (current)
OS/ABI: UNIX - System V
ABI Version: 0
Type: EXEC (Executable file)
Machine: Intel 80386
Version: 0x1
Entry point address: 0x0
Start of program headers: 52 (bytes into file)
Start of section headers: 2980 (bytes into file)
Flags: 0x0
Size of this header: 52 (bytes)
Size of program headers: 32 (bytes)
Number of program headers: 2
Size of section headers: 40 (bytes)
Number of section headers: 15
Section header string table index: 14
```

ELF header

Program header table

- Used by the loader
 - Take all "segments" marked as LOAD and load them into memory



Program header table

- `gcc -c -fno-pic -static -fno-builtin -ggdb -m32 -fno-omit-frame-pointer hello-elf.c`
- `ld -m elf_i386 -N -e main -Ttext 0 -o a.out hello-elf.o`
- `readelf -a a.out`

Program Headers:

Type	Offset	VirtAddr	PhysAddr	FileSiz	MemSiz	Flg	Align
LOAD	0x000074	0x00000000	0x00000000	0x00068	0x0006c	RWE	0x4
GNU_STACK	0x000000	0x00000000	0x00000000	0x00000	0x00000	RW	0x10

Section to Segment mapping:

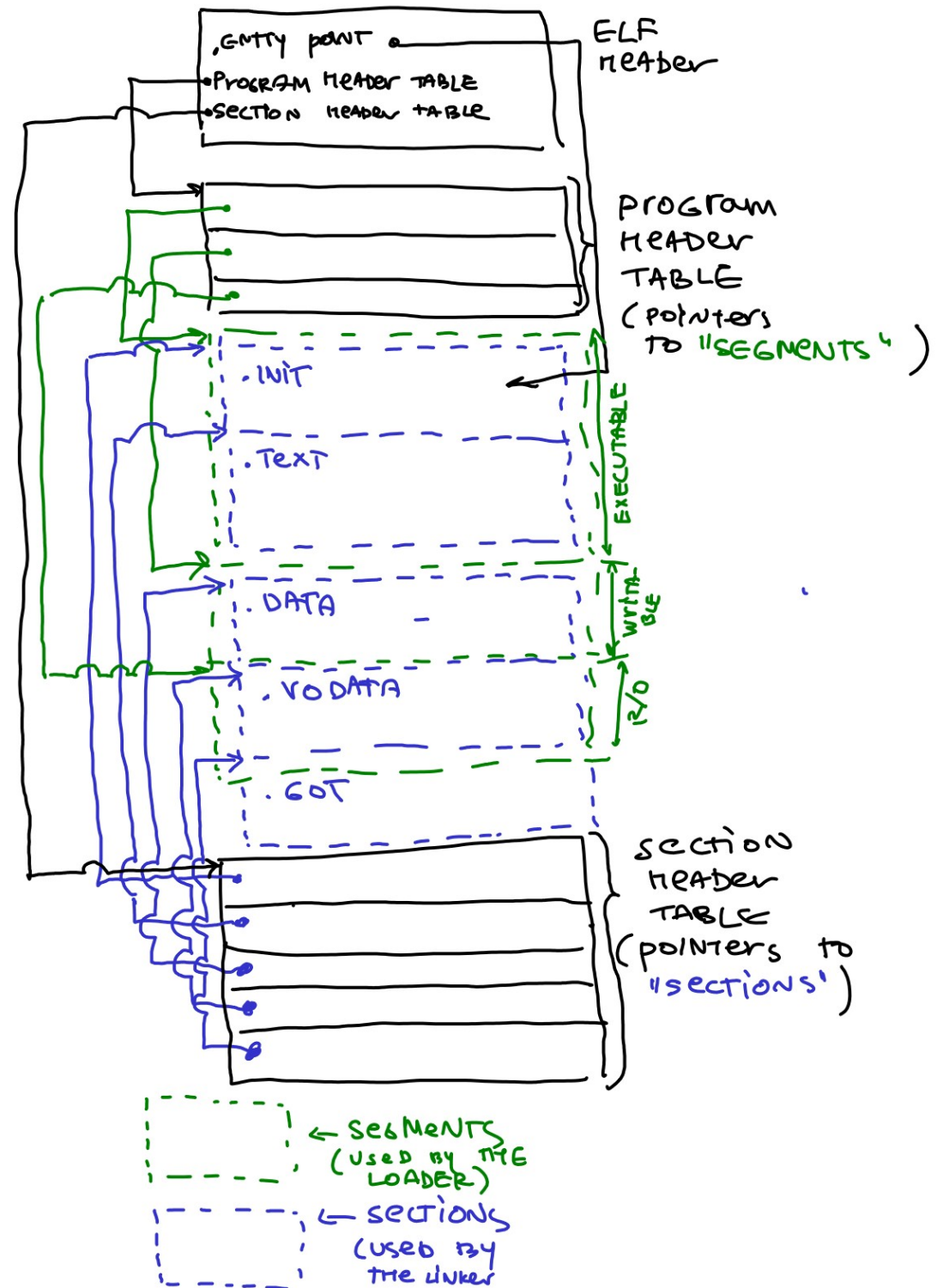
Segment Sections...

00 .text .rodata .eh_frame .data .bss

01

Section header table

- Used by the linker
 - Merging (linking) code and data sections together
 - .text
 - Code of the program
 - .data
 - Initialized global variables
 - .rodata
 - Initialized R/O global variables
 - .bss
 - Better Save Space
 - Uninitialized global variables



• readelf -a a.out

Section Headers:

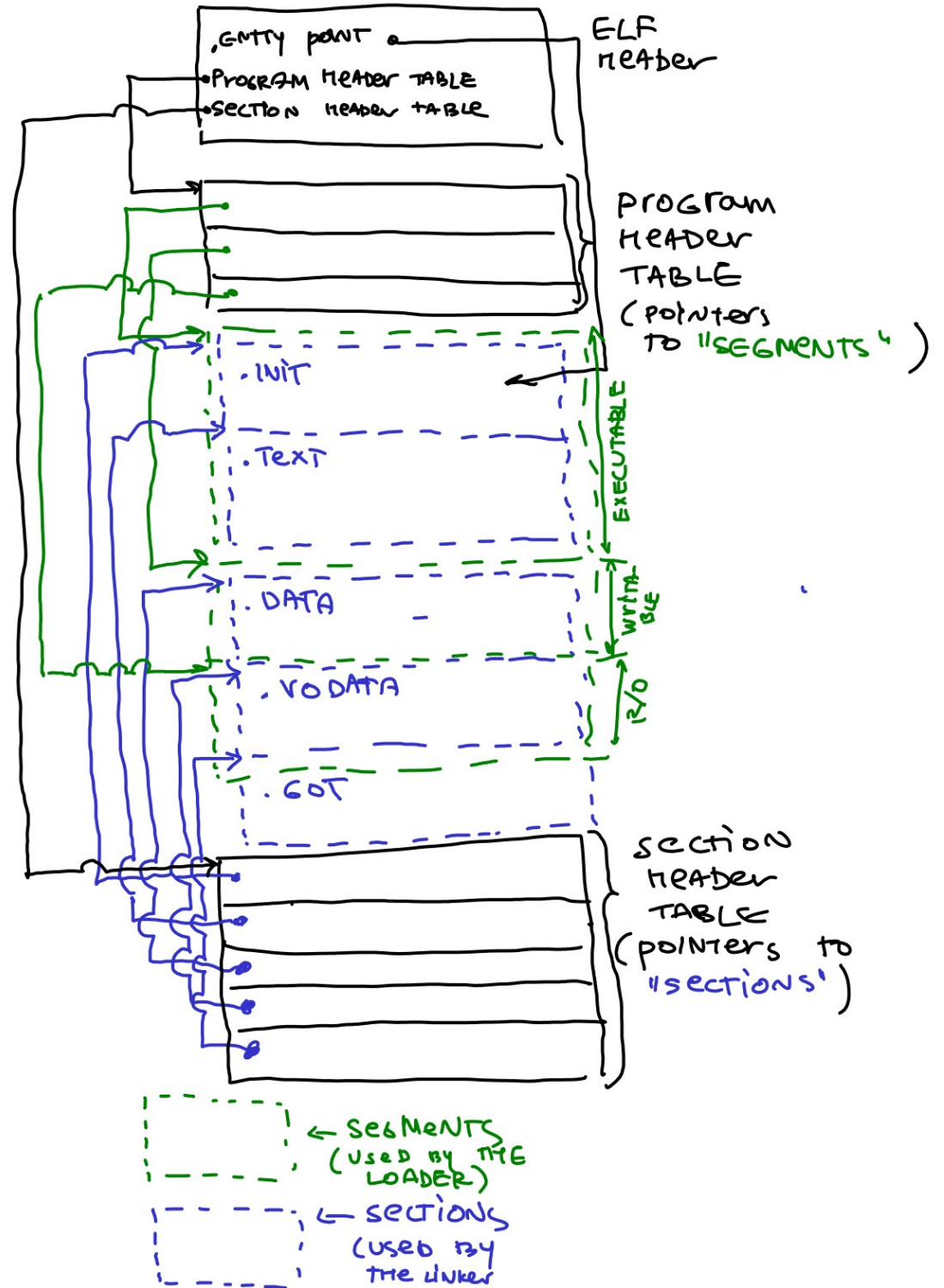
[Nr]	Name	Type	Addr	Off	Size	ES	Flg	Lk	Inf	Al
[0]		NULL	00000000	000000	000000	00		0	0	0
[1]	.text	PROGBITS	00000000	000074	000028	00	WAX	0	0	1
[2]	.rodata	PROGBITS	00000028	00009c	000004	00	A	0	0	4
[3]	.eh_frame	PROGBITS	0000002c	0000a0	000038	00	A	0	0	4
[4]	.data	PROGBITS	00000064	0000d8	000004	00	WA	0	0	4
[5]	.bss	NOBITS	00000068	0000dc	000004	00	WA	0	0	4
[6]	.comment	PROGBITS	00000000	0000dc	000029	01	MS	0	0	1
[7]	.debug_aranges	PROGBITS	00000000	000105	000020	00		0	0	1
[8]	.debug_info	PROGBITS	00000000	000125	000389	00		0	0	1
[9]	.debug_abbrev	PROGBITS	00000000	0004ae	000113	00		0	0	1
[10]	.debug_line	PROGBITS	00000000	0005c1	0000c2	00		0	0	1
[11]	.debug_str	PROGBITS	00000000	000683	00032c	01	MS	0	0	1
[12]	.symtab	SYMTAB	00000000	0009b0	000140	10		13	13	4
[13]	.strtab	STRTAB	00000000	000af0	00002c	00		0	0	1
[14]	.shstrtab	STRTAB	00000000	000b1c	000087	00		0	0	1

Key to Flags:

W (write), A (alloc), X (execute), M (merge), S (strings), I (info),
L (link order), O (extra OS processing required), G (group), T (TLS),
C (compressed), x (unknown), o (OS specific), E (exclude),
p (processor specific)

Section header table

Loading ELF

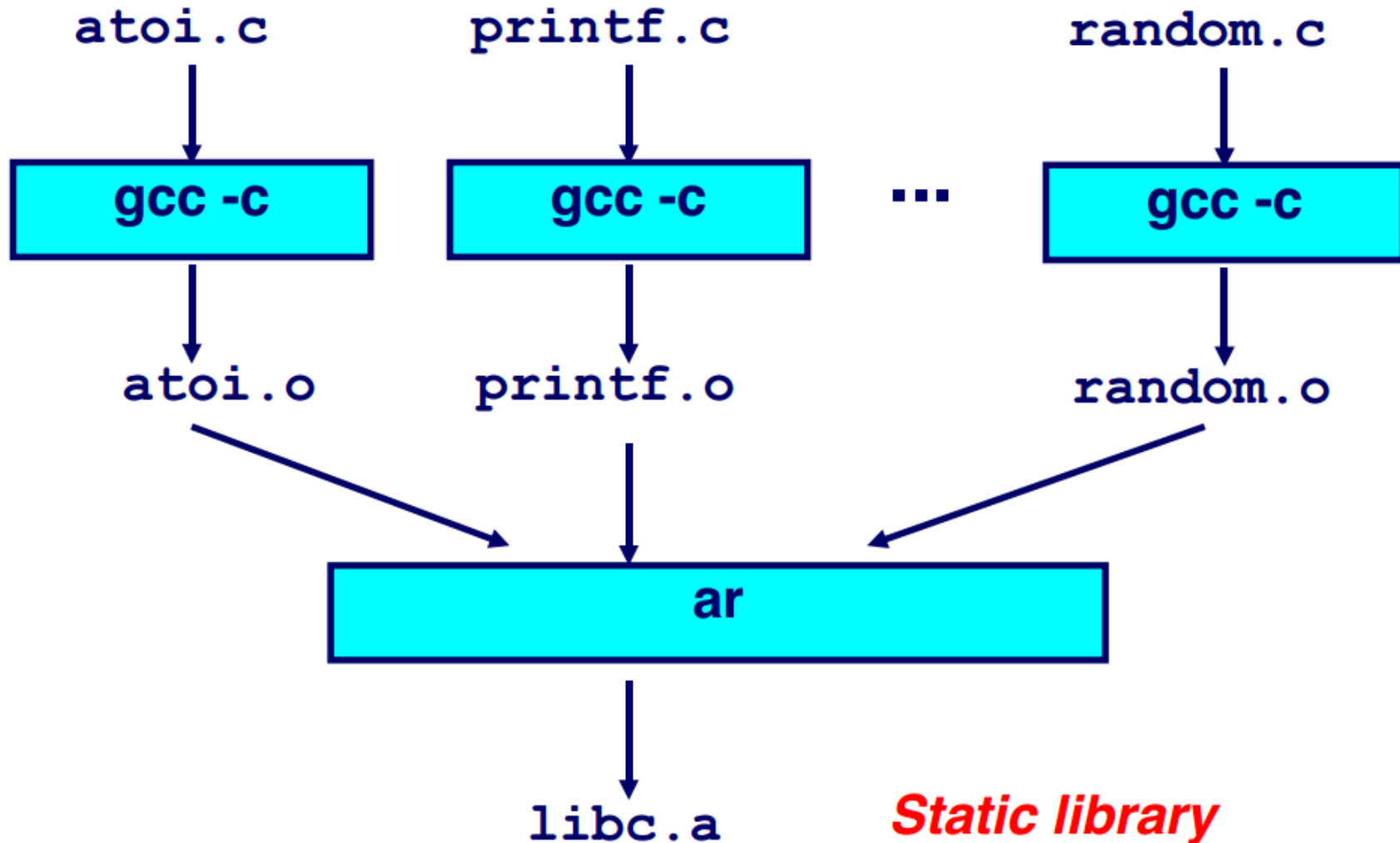


Static libraries (.a)

Libraries

- Conceptually a library is
 - Collection of object files
- UNIX uses an archive format
 - Remember the `ar` tool
 - Can support collections of any objects
 - Rarely used for anything instead of libraries

Creating a static library



Example

- Create a library

```
ar rcs libclass.a class1.o class2.o class3.o
```

- Linking (linker can read ar files)
 - C compiler calls linker

```
gcc main.c libclass.a
```

- or (if libclass.a is placed in standard library path, like /usr/local/lib)

```
gcc main.c -lclass
```

- or (during linking)

```
ld ... main.o -lclass ...
```

- is the same as:

```
gcc main.c class1.o class2.o class3.o
```


Searching libraries

- First linker path needs resolve symbol names into function locations
- To improve the search library formats add an index
 - Map names to member positions

Shared libraries
(.so or .dll on Windows)

Motivation

- 1000 programs in a typical UNIX system
- 1000 copies of printf

- **How big is printf() actually?**

Motivation

- Disk space
 - 2504 programs in /usr/bin on my Linux laptop
 - `ls /usr/bin | wc -l`
 - **printf() is a large function**
 - **Handles conversion of multiple types to strings**
 - **5-10K**
 - This means 10-25MB of disk can be wasted just on `printf()`
- Runtime memory costs are
 - 5-10K times the number of running programs
 - 250 programs running on my Linux laptop
 - `ps -aux | wc -l`
 - 1MB-2.5MB – huge number for most systems 15-20 years ago

Motivation for shared libraries

Example: size of a statically vs dynamically linked program

- On Ubuntu 16.04 (gcc 5.4.0, libc 2.23)
 - Statically linked trivial example
 - `gcc -m32 -static hello-int.c -o test`
 - 725KB
 - Dynamically linked trivial example
 - `gcc -m32 hello-int.c -o test`
 - 7KB

Shared libraries

- Motivation
 - Share code of a library across all processes
 - E.g. libc is linked by all processes in the system
 - Code section should remain identical
 - To be shared read-only
 - What if library is loaded at different addresses?
 - Remember it needs to be relocated

Position independent code

(Parts adapted from Eli Bendersky)

<https://eli.thegreenplace.net/2011/11/03/position-independent-code-pic-in-shared-libraries/>

Position independent code (PIC)

- Main idea:
 - Generate code in such a way that it can work no matter where it is located in the address space
 - Share code across all address spaces

What needs to be changed?

- Can stay untouched
 - Local jumps and calls are relative
 - Stack data is relative to the stack
- Needs to be modified
 - Global variables
 - Imported functions

Example

```
000010a4 <_main>:
  10a4: 55                pushl %ebp
  10a5: 89 e5            movl %esp,%ebp
  10a7: 68 10 00 00 00  pushl $0x10
  10a8: 32 .data
  10ac: e8 03 00 00 00  call 10b4 <_a>
  ...
000010b4 <_a>:
  10bc: e8 37 00 00 00  call 10f8 <_strlen>
  ...
  10c3: 6a 01          pushl $0x1
  10c5: e8 a2 00 00 00  call 116c <_write>
  ...
```

- Reference to a data section
 - Code and data sections can be moved around

Example

```
000010a4 <_main>:
  10a4: 55                pushl %ebp
  10a5: 89 e5            movl %esp,%ebp
  10a7: 68 10 00 00 00  pushl $0x10
    10a8: 32 .data
  10ac: e8 03 00 00 00  call 10b4 <_a>
...
000010b4 <_a>:
  10bc: e8 37 00 00 00  call 10f8 <_strlen>
...
  10c3: 6a 01          pushl $0x1
  10c5: e8 a2 00 00 00  call 116c <_write>
...
```

- Local function invocations use relative addresses
 - No need to relocate

Position independent code

- How would you build it?

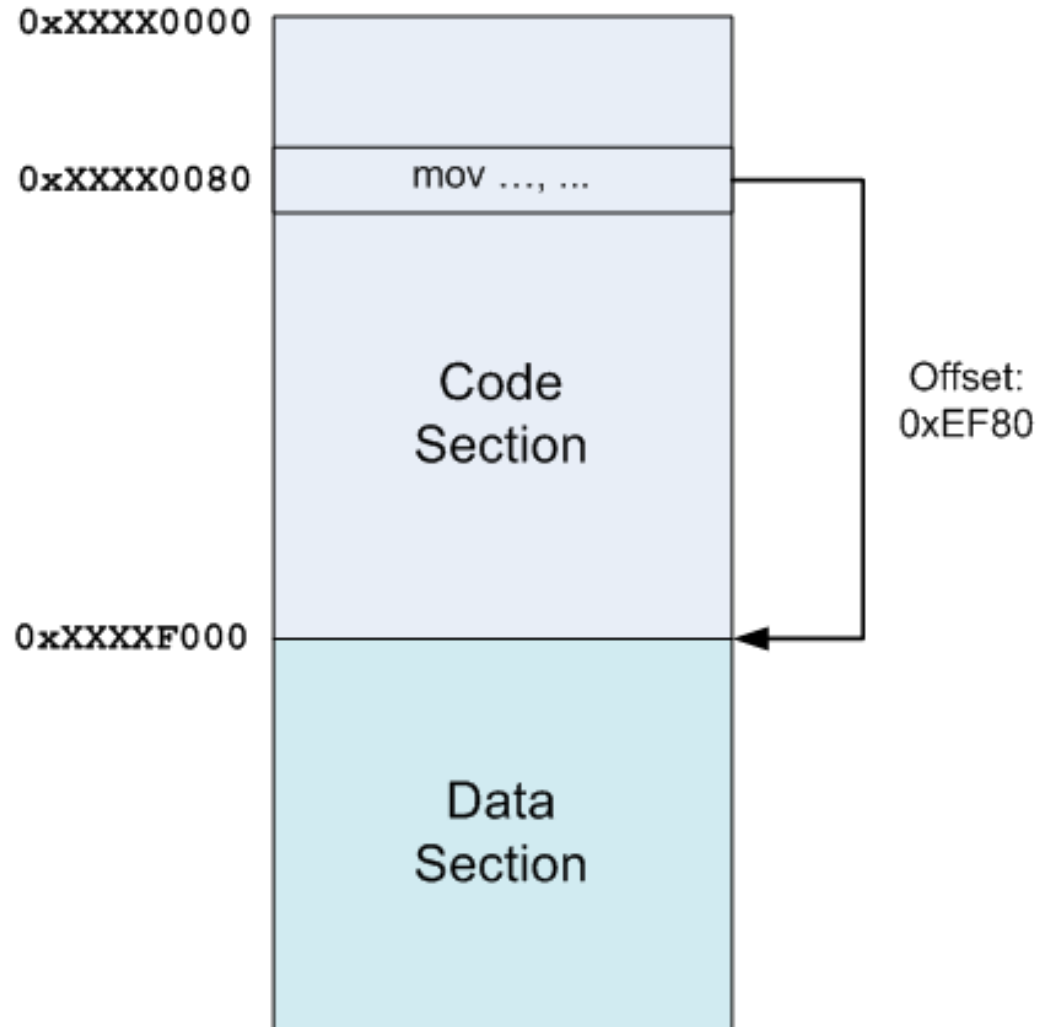
Position independent code

- How would you build it?
- Main idea:
 - Add additional layer of indirection for all references to
 - Global data
 - Imported functions

Position independent code

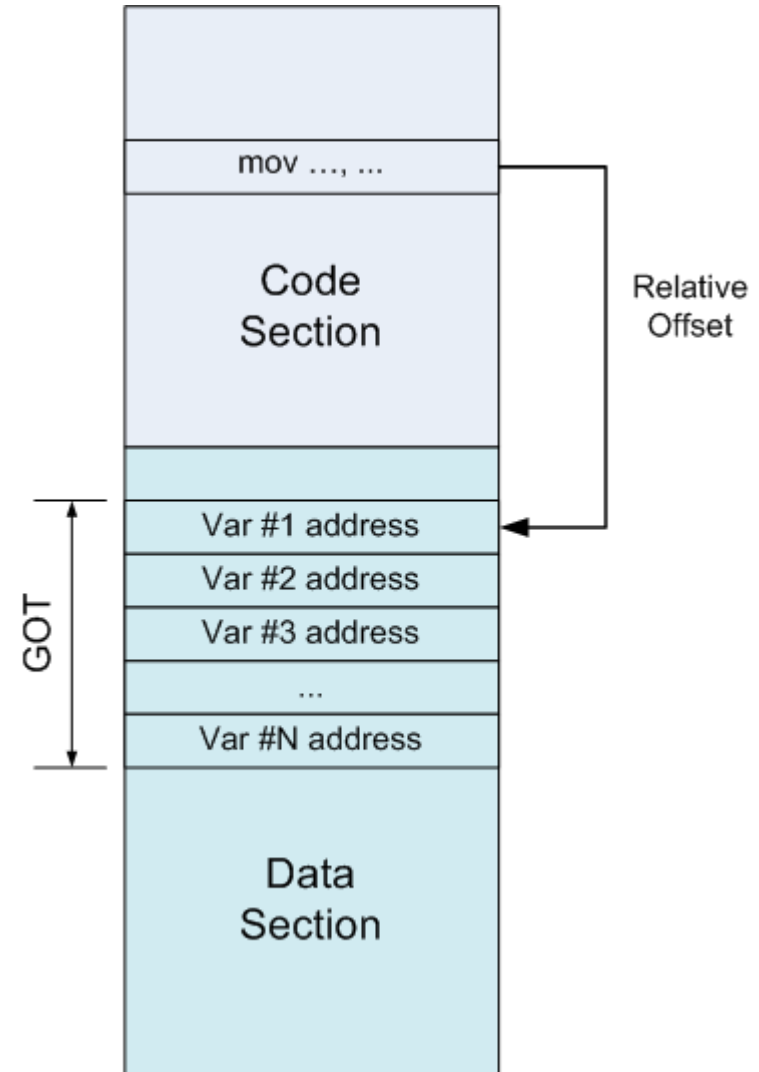
- Main insight
 - Code sections are followed by data sections
 - The distance between code and data **remains constant even if code is relocated**
 - Linker knows the distance
 - Even if it combines multiple code sections together

Insight 1: Constant offset between text and data sections



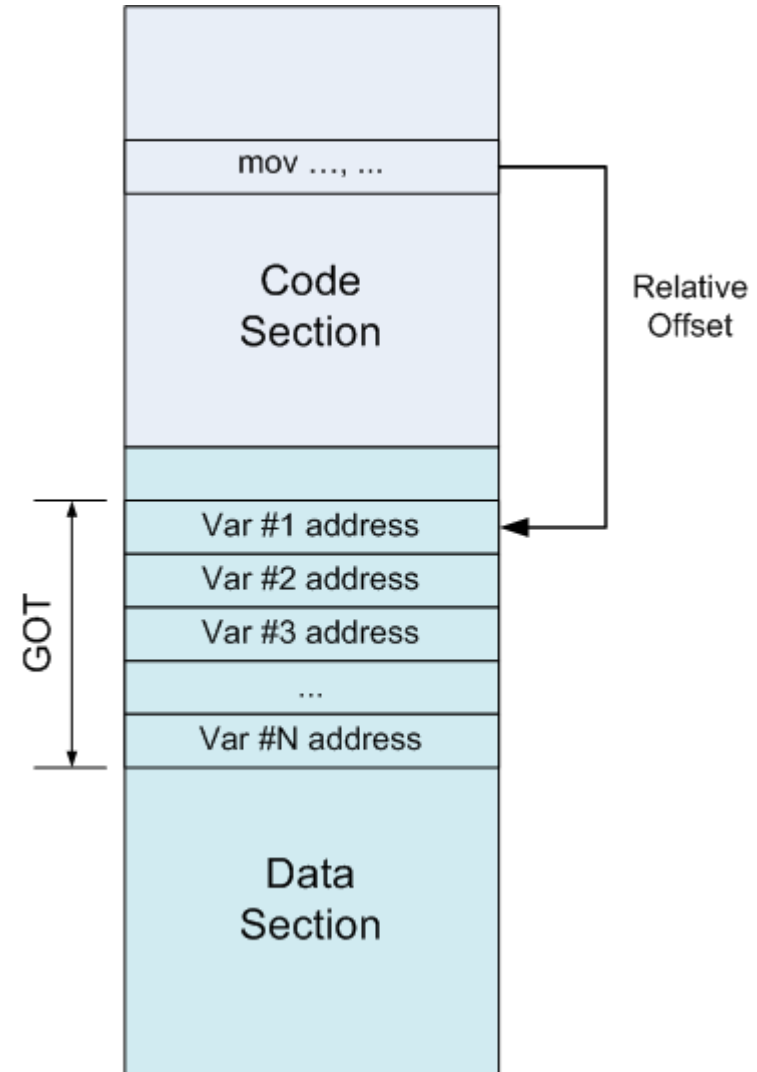
Global offset table (GOT)

- Insight #2:
 - Instead of referring to a variable by its absolute address
 - Which would require a relocation
 - Refer through GOT



Global offset table (GOT)

- GOT
 - Table of addresses
 - Each entry contains absolute address of a variable
 - GOT is patched by the linker at relocation time



How to find position of the code in memory at run time?

How to find position of the code in memory at run time?

- Is there an x86 instruction that does this?
 - i.e., give me my current code address
- x86 32bit architecture requires absolute addresses for `mov` instructions
 - No relative addresses allowed
- There is no instruction to learn the value of EIP
 - Instruction pointer

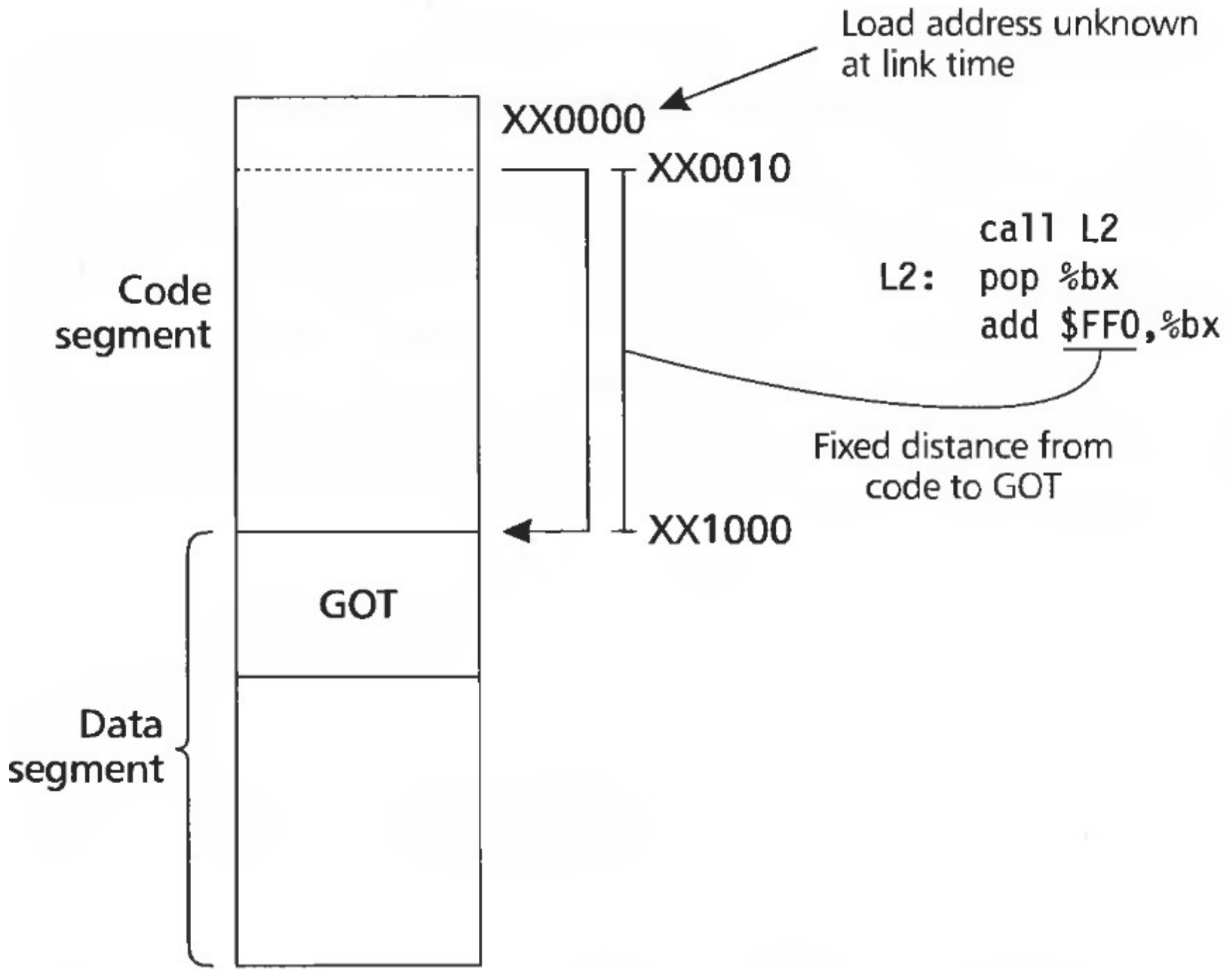
How to find position of the code in memory at run time?

- Simple trick

```
call L2
```

```
L2: popl %ebx
```

- Call next instruction
 - Saves EIP on the stack
 - EIP holds current position of the code
 - Use popl to fetch EIP into a register



Examples of position independent code

```
int myglob = 42;
```

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

PIC example

```
0000043c <ml_func>:
```

```
43c: 55          push    ebp
43d: 89 e5       mov     ebp,esp
43f: e8 16 00 00 00 call   45a <__i686.get_pc_thunk.cx>
444: 81 c1 b0 1b 00 00 add    ecx,0x1bb0
44a: 8b 81 f0 ff ff ff mov    eax,DWORD PTR [ecx-0x10]
450: 8b 00       mov    eax,DWORD PTR [eax]
452: 03 45 08   add    eax,DWORD PTR [ebp+0x8]
455: 03 45 0c   add    eax,DWORD PTR [ebp+0xc]
458: 5d         pop    ebp
459: c3        ret
```

```
0000045a <__i686.get_pc_thunk.cx>:
```

```
45a: 8b 0c 24   mov    ecx,DWORD PTR [esp]
45d: c3        ret
```



```
int myglob = 42;
```

```
int ml_func(int a, int b)
{
    return myglob + a + b;
}
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```
0000043c <ml_func>:
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43c:	55	push	ebp
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444:	81 c1 b0 1b 00 00	add	ecx,0x1bb0
44a:	8b 81 f0 ff ff ff	mov	eax,DWORD PTR [ecx-0x10]
450:	8b 00	mov	eax,DWORD PTR [eax]
452:	03 45 08	add	eax,DWORD PTR [ebp+0x8]
455:	03 45 0c	add	eax,DWORD PTR [ebp+0xc]
458:	5d	pop	ebp
459:	c3	ret	

```
0000045a <__i686.get_pc_thunk.cx>:
```

45a:	8b 0c 24	mov	ecx,DWORD PTR [esp]
45d:	c3	ret	

PIC example

- Access a global variable `myglob`

```
int myglob = 42;
```

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

PIC example

- Save EIP into ECX

```
0000043c <ml_func>:
```

```
43c: 55          push    ebp
43d: 89 e5       mov     ebp,esp
43f: e8 16 00 00 00 call   45a <__i686.get_pc_thunk.cx>
444: 81 c1 b0 1b 00 00 add    ecx,0x1bb0
44a: 8b 81 f0 ff ff ff mov    eax,DWORD PTR [ecx-0x10]
450: 8b 00       mov    eax,DWORD PTR [eax]
452: 03 45 08   add    eax,DWORD PTR [ebp+0x8]
455: 03 45 0c   add    eax,DWORD PTR [ebp+0xc]
458: 5d        pop    ebp
459: c3        ret
```

```
0000045a <__i686.get_pc_thunk.cx>:
```

```
45a: 8b 0c 24   mov    ecx,DWORD PTR [esp]
45d: c3        ret
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```

```
int ml_func(int a, int b)
{
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}
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0000043c <ml_func>:
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```
43c: 55          push    ebp
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444: 81 c1 b0 1b 00 00 add    ecx,0x1bb0
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450: 8b 00      mov    eax,DWORD PTR [eax]
452: 03 45 08   add    eax,DWORD PTR [ebp+0x8]
455: 03 45 0c   add    eax,DWORD PTR [ebp+0xc]
458: 5d        pop    ebp
459: c3        ret
```

```
0000045a <__i686.get_pc_thunk.cx>:
```

```
45a: 8b 0c 24   mov    ecx,DWORD PTR [esp]
45d: c3        ret
```

PIC example

- Add offset to GOT
 - 0x1bb0

```
int myglob = 42;
```

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

PIC example

- Access address of a specific GOT entry (address of `myglob`)
- Save it in EAX

```
0000043c <ml_func>:
```

```
43c: 55          push    ebp
43d: 89 e5      mov     ebp,esp
43f: e8 16 00 00 00 call   45a <__i686.get_pc_thunk.cx>
444: 81 c1 b0 1b 00 00 add    ecx,0x1bb0
44a: 8b 81 f0 ff ff ff mov    eax,DWORD PTR [ecx-0x10]
450: 8b 00      mov    eax,DWORD PTR [eax]
452: 03 45 08   add    eax,DWORD PTR [ebp+0x8]
455: 03 45 0c   add    eax,DWORD PTR [ebp+0xc]
458: 5d        pop    ebp
459: c3        ret
```

```
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45a: 8b 0c 24   mov    ecx,DWORD PTR [esp]
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```
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```
int ml_func(int a, int b)
{
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}
```

```
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```

43c:	55	push	ebp
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444:	81 c1 b0 1b 00 00	add	ecx,0x1bb0
44a:	8b 81 f0 ff ff ff	mov	eax,DWORD PTR [ecx-0x10]
450:	8b 00	mov	eax,DWORD PTR [eax]
452:	03 45 08	add	eax,DWORD PTR [ebp+0x8]
455:	03 45 0c	add	eax,DWORD PTR [ebp+0xc]
458:	5d	pop	ebp
459:	c3	ret	

```
0000045a <__i686.get_pc_thunk.cx>:
```

45a:	8b 0c 24	mov	ecx,DWORD PTR [esp]
45d:	c3	ret	

PIC example

- Load the value of the variable at the address pointed by EAX
 - i.e., load `myglob` into EAX

What about function calls?

What about function calls?

- Same approach can work
- But this is not how it is done

Late binding

- When a shared library refers to some function, the real address of that function is not known until load time
 - Resolving this address is called binding

Lazy procedure binding

- In large libraries many routines are never called
 - Libc has over 600
 - **The number of functions is much larger than the number of global variables**
 - It's ok to bind all routines when the program is **statically linked**
 - Binding is done offline, no runtime costst
 - But with **dynamic linking** run-time overhead is too high
 - **Lazy approach, i.e., linking only when used, works better**

Procedure linkage table (PLT)

Code:

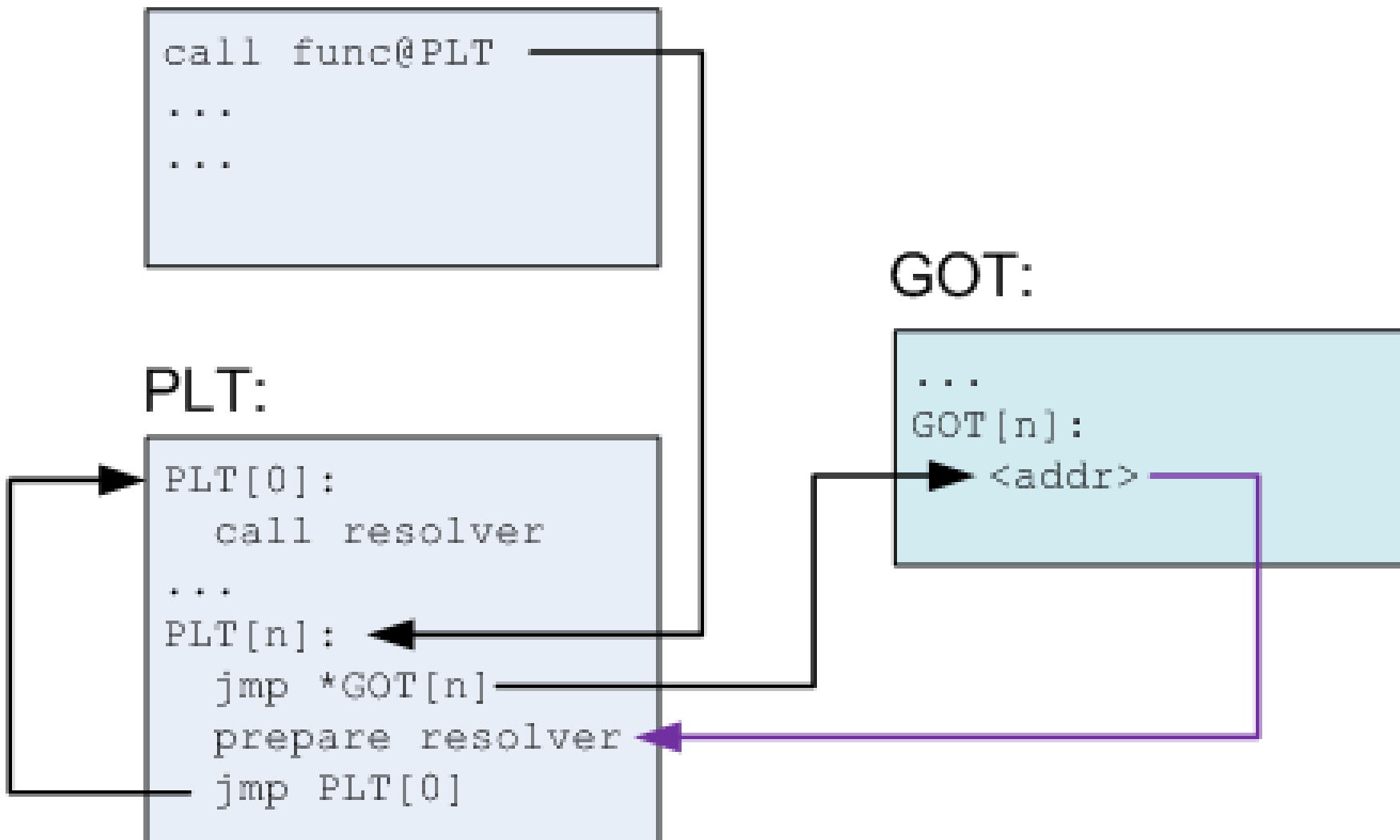
```
call func@PLT  
...  
...
```

PLT:

```
PLT[0]:  
  call resolver  
  ...  
PLT[n]:  
  jmp *GOT[n]  
  prepare resolver  
  jmp PLT[0]
```

GOT:

```
...  
GOT[n]:  
  <addr>
```



Procedure linkage table (PLT)

- PLT is part of the executable text section
 - A set of entries
 - A special first entry
 - One for each external function
- Each PLT entry
 - Is a short chunk of executable code
 - Has a corresponding entry in the GOT
 - Contains an actual offset to the function
 - Only after it is resolved by the dynamic loader

- Each PLT entry but the first consists of these parts:
 - A jump to a location which is specified in a corresponding GOT entry
 - Preparation of arguments for a "resolver" routine
 - Call to the resolver routine, which resides in the first entry of the PLT

Before function is resolved

- Nth GOT entry points to after the jump

Code:

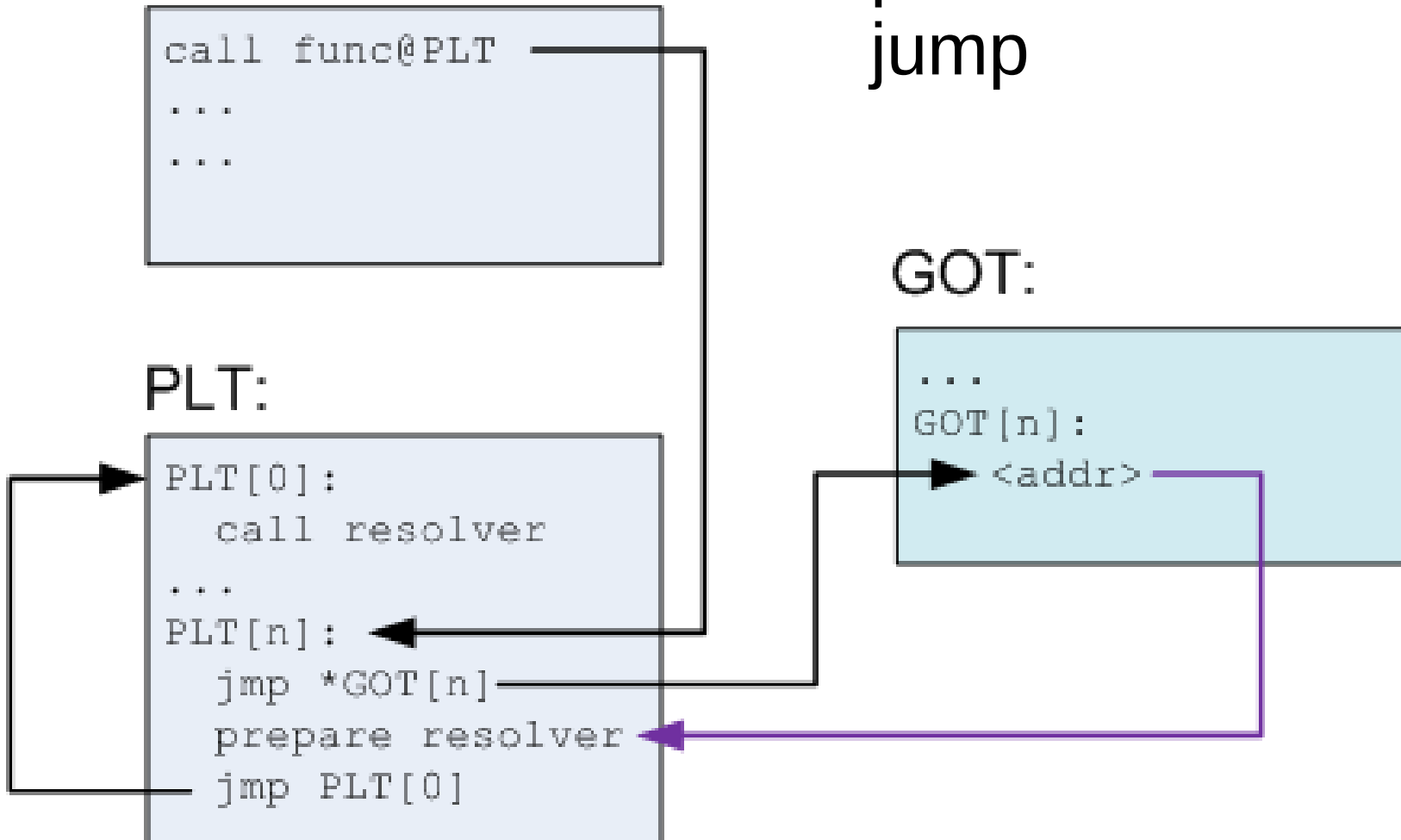
```
call func@PLT
...
...
```

PLT:

```
PLT[0]:
  call resolver
...
PLT[n]:
  jmp *GOT[n]
  prepare resolver
  jmp PLT[0]
```

GOT:

```
...
GOT[n]:
  <addr>
```



PLT after the function is resolved

- Nth GOT entry points to the actual function

Code:

```
call func@PLT
...
...
```

PLT:

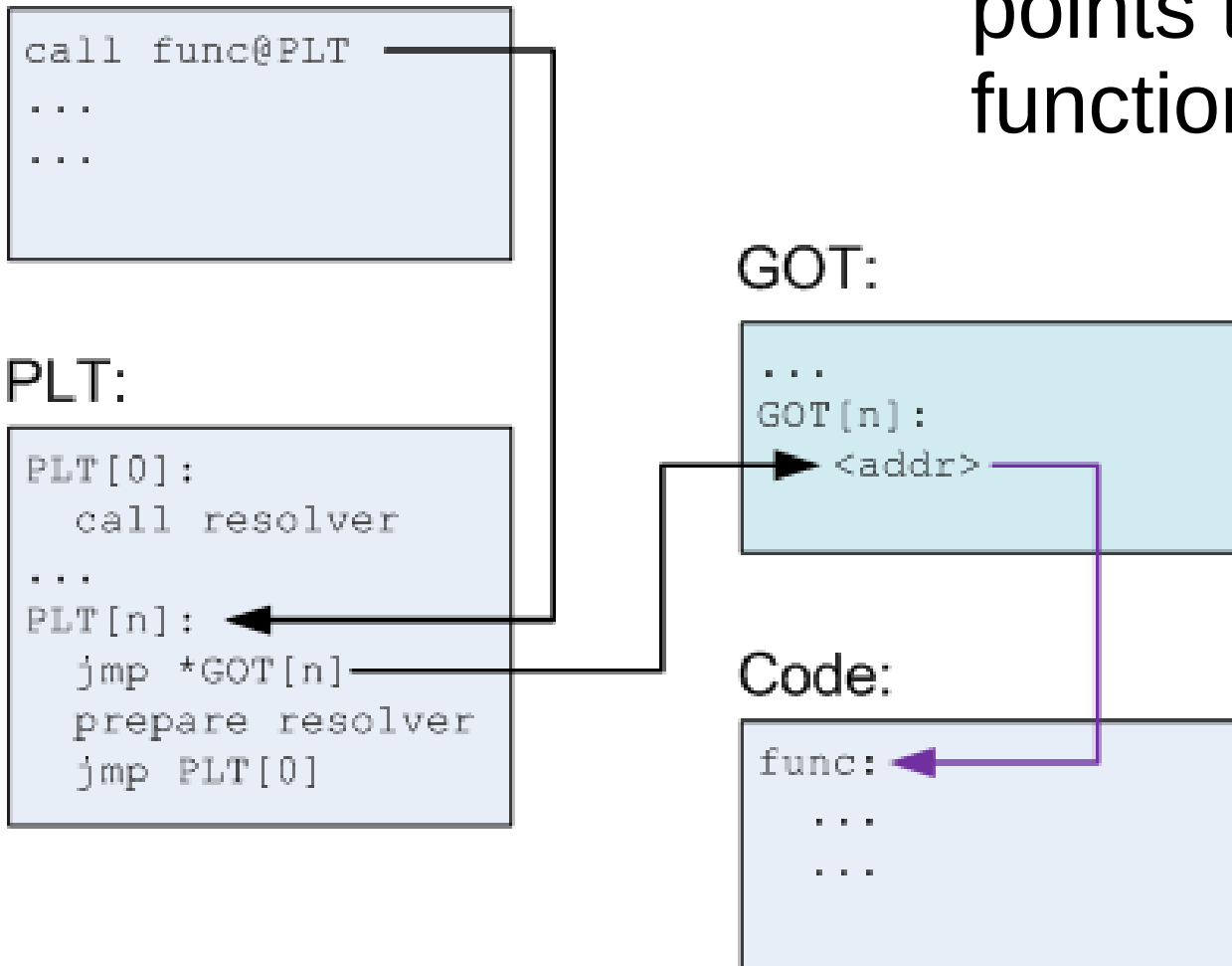
```
PLT[0]:
  call resolver
...
PLT[n]: ←
  jmp *GOT[n]
  prepare resolver
  jmp PLT[0]
```

GOT:

```
...
GOT[n]:
  → <addr>
```

Code:

```
func: ←
...
...
```



PIC example (functions)

```
int ml_util_func(int a)
{
    return a + 1;
}
int ml_func(int a, int b)
{
    int c = b + ml_util_func(a);
    myglob += c;
    return b + myglob;
}
```

00000477 <ml_func>:

```
477:  55                push   ebp
478:  89 e5             mov    ebp,esp
47a:  53                push   ebx
47b:  83 ec 24          sub    esp,0x24
47e:  e8 e4 ff ff ff   call  467 <__i686.get_pc_thunk.bx>
483:  81 c3 71 1b 00 00 add    ebx,0x1b71
489:  8b 45 08          mov    eax,DWORD PTR [ebp+0x8]
48c:  89 04 24          mov    DWORD PTR [esp],eax
48f:  e8 0c ff ff ff   call  3a0 <ml_util_func@plt>
...
```

000003a0 <ml_util_func@plt>:

```
3a0:  ff a3 14 00 00 00 jmp    DWORD PTR [ebx+0x14]
3a6:  68 10 00 00 00   push  0x10
3ab:  e9 c0 ff ff ff   jmp    370 <_init+0x30>
```

PIC example (functions)

```
int ml_util_func(int a)
{
    return a + 1;
}
int ml_func(int a, int b)
{
    int c = b + ml_util_func(a);
    myglob += c;
    return b + myglob;
}
```

- Resolve the address of GOT
- First learn EIP
 - Saved in EBX
- Then add offset to EBX

00000477 <ml_func>:

```
477: 55          push    ebp
478: 89 e5      mov     ebp,esp
47a: 53        push    ebx
47b: 83 ec 24   sub     esp,0x24
47e: e8 e4 ff ff ff  call   467 <__i686.get_pc_thunk.bx>
483: 81 c3 71 1b 00 00  add    ebx,0x1b71
489: 8b 45 08   mov     eax,DWORD PTR [ebp+0x8]
48c: 89 04 24   mov     DWORD PTR [esp],eax
48f: e8 0c ff ff ff  call   3a0 <ml_util_func@plt>
...
```

000003a0 <ml_util_func@plt>:

```
3a0: ff a3 14 00 00 00  jmp   DWORD PTR [ebx+0x14]
3a6: 68 10 00 00 00    push  0x10
3ab: e9 c0 ff ff ff    jmp   370 <_init+0x30>
```


PIC example (functions)

- Push the argument a on the stack

```
int ml_util_func(int a)
{
    return a + 1;
}
int ml_func(int a, int b)
{
    int c = b + ml_util_func(a);
    myglob += c;
    return b + myglob;
}
```

```
00000477 <ml_func>:
477:  55                push   ebp
478:  89 e5             mov    ebp,esp
47a:  53                push   ebx
47b:  83 ec 24          sub    esp,0x24
47e:  e8 e4 ff ff ff   call  467 <__i686.get_pc_thunk.bx>
483:  81 c3 71 1b 00 00 add    ebx,0x1b71
489:  8b 45 08           mov    eax,DWORD PTR [ebp+0x8]
48c:  89 04 24           mov    DWORD PTR [esp],eax
48f:  e8 0c ff ff ff   call  3a0 <ml_util_func@plt>
...
```

```
000003a0 <ml_util_func@plt>:
3a0:  ff a3 14 00 00 00 jmp    DWORD PTR [ebx+0x14]
3a6:  68 10 00 00 00   push  0x10
3ab:  e9 c0 ff ff ff   jmp    370 <_init+0x30>
```

PIC example (functions)

- Call the PLT entry for the `ml_util_func()`

```
int ml_util_func(int a)
{
    return a + 1;
}
int ml_func(int a, int b)
{
    int c = b + ml_util_func(a);
    myglob += c;
    return b + myglob;
}
```

00000477 <ml_func>:

```
477:  55                push   ebp
478:  89 e5             mov    ebp,esp
47a:  53                push   ebx
47b:  83 ec 24         sub    esp,0x24
47e:  e8 e4 ff ff ff   call   467 <__i686.get_pc_thunk.bx>
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48c:  89 04 24         mov    DWORD PTR [esp],eax
48f:  e8 0c ff ff ff   call   3a0 <ml_util_func@plt>
...
```

000003a0 <ml_util_func@plt>:

```
3a0:  ff a3 14 00 00 00 jmp    DWORD PTR [ebx+0x14]
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```

PIC example (functions)

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int ml_util_func(int a)
{
    return a + 1;
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{
    int c = b + ml_util_func(a);
    myglob += c;
    return b + myglob;
}
```

00000477 <ml_func>:

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47a:  53                push   ebx
47b:  83 ec 24         sub    esp,0x24
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...
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000003a0 <ml_util_func@plt>:

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3a0:  ff a3 14 00 00 00  jmp    DWORD PTR [ebx+0x14]
3a6:  68 10 00 00 00    push   0x10
3ab:  e9 c0 ff ff ff    jmp    370 <_init+0x30>
```

- Jump to an address specified in GOT
 - [ebx+0x14] contains address 0x3a6
 - i.e., effectively we jump to the next instruction via GOT

PIC example (functions)

- Prepare arguments for the resolver

```
int ml_util_func(int a)
{
    return a + 1;
}
int ml_func(int a, int b)
{
    int c = b + ml_util_func(a);
    myglob += c;
    return b + myglob;
}
```

00000477 <ml_func>:

```
477: 55          push    ebp
478: 89 e5       mov     ebp,esp
47a: 53          push    ebx
47b: 83 ec 24    sub     esp,0x24
47e: e8 e4 ff ff call    467 <__i686.get_pc_thunk.bx>
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489: 8b 45 08    mov     eax,DWORD PTR [ebp+0x8]
48c: 89 04 24    mov     DWORD PTR [esp],eax
48f: e8 0c ff ff call    3a0 <ml_util_func@plt>
...
```

000003a0 <ml_util_func@plt>:

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3a0: ff a3 14 00 00 00 jmp     DWORD PTR [ebx+0x14]
3a6: 68 10 00 00 00 push   0x10
3ab: e9 c0 ff ff jmp     370 <_init+0x30>
```

PIC example (functions)

- Call resolver

```
int ml_util_func(int a)
{
    return a + 1;
}
int ml_func(int a, int b)
{
    int c = b + ml_util_func(a);
    myglob += c;
    return b + myglob;
}
```

00000477 <ml_func>:

```
477:  55                push   ebp
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47e:  e8 e4 ff ff ff   call  467 <__i686.get_pc_thunk.bx>
483:  81 c3 71 1b 00 00 add    ebx,0x1b71
489:  8b 45 08         mov    eax,DWORD PTR [ebp+0x8]
48c:  89 04 24         mov    DWORD PTR [esp],eax
48f:  e8 0c ff ff ff   call  3a0 <ml_util_func@plt>
...
```

000003a0 <ml_util_func@plt>:

```
3a0:  ff a3 14 00 00 00 jmp    DWORD PTR [ebx+0x14]
3a6:  68 10 00 00 00   push  0x10
3ab:  e9 c0 ff ff ff   jmp    370 <_init+0x30>
```

PIC example (functions)

```
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}
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000003a0 <ml_util_func@plt>:

```
3a0: ff a3 14 00 00 00 jmp    DWORD PTR [ebx+0x14]
3a6: 68 10 00 00 00 push  0x10
3ab: e9 c0 ff ff ff jmp    370 <_init+0x30>
```

- After the address of `ml_util_func()` is resolved
 - i.e., on the next invocation
- This jump goes to the function entry

What did we gain?

- Processes can share code
- Each have private GOT
- Why is it better?
 - GOT is in the data section, private to each process anyway
 - We saved memory
 - We saved some linking time too
 - GOT is patched per variable, not per variable reference
 - There are many references to the same variable in the code
 - It takes some time to relocate
 - We saved this time

PIC: Advantages and disadvantages

- Any ideas?

PIC: Advantages and disadvantages

- Bad
 - Code gets slower
 - One register is wasted to keep GOT pointer
 - x86 has 7 registers (plus maybe EBP is used to maintain the frame, so maybe 6)
 - Losing one of them is bad
 - One more memory dereference
 - GOT can be large (lots of global variables)
 - Extra memory dereferences can have a high cost due to cache misses
 - One more call to find GOT
- Good
 - Share memory of common libraries
 - Address space randomization

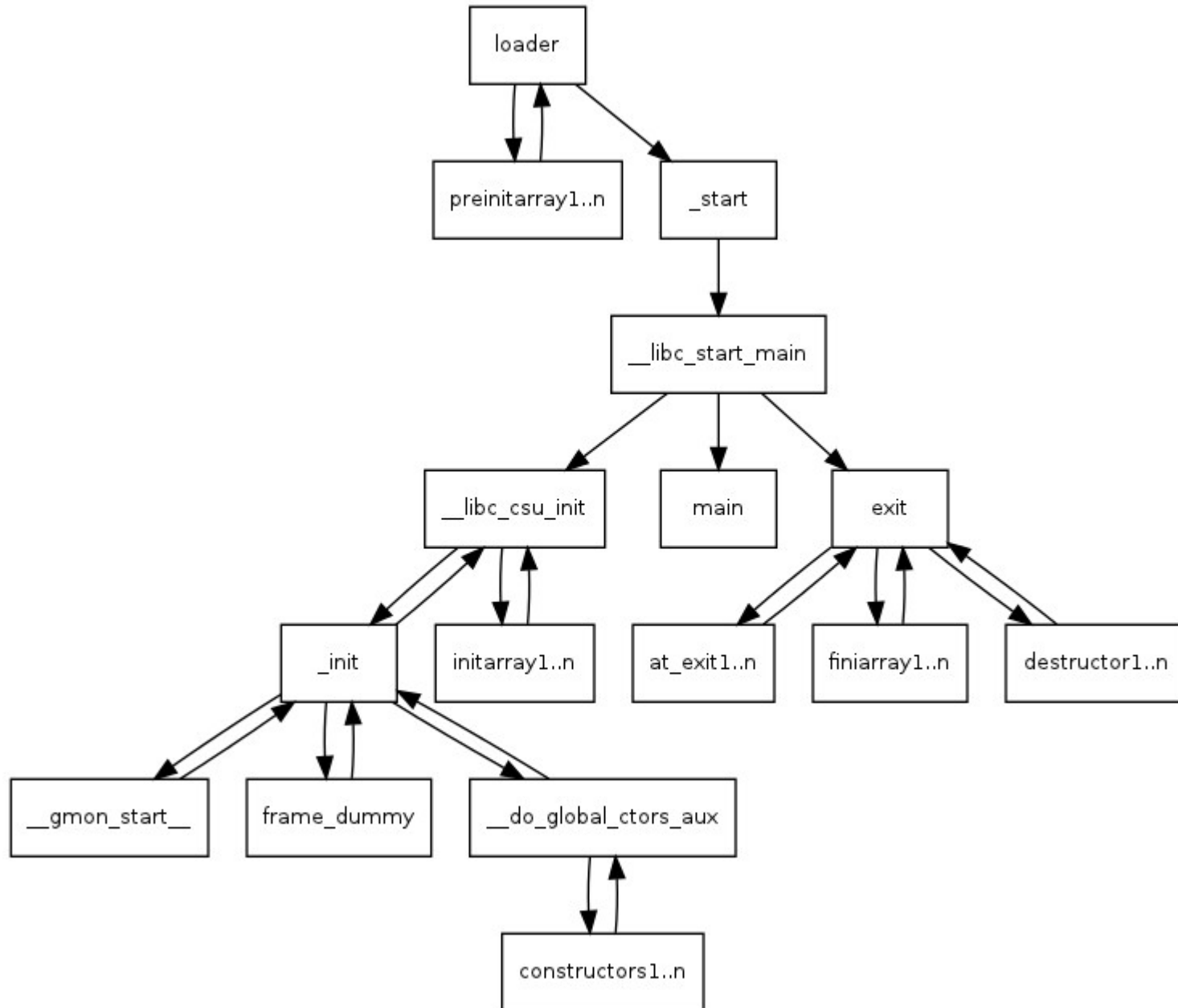
Loading and starting programs

Starting statically linked programs

Remember we call `execv()`

- Kernel reads the program from disk
- Kernel can handle multiple executable formats
 - It tries all of them one by one until it succeeds
 - E.g. it can execute scripts by noticing that the program starts with
 - `#!`
- We'll concentrate on ELF

A bit of work before `main()`



To see the backtrace before `main()`

- Execute this command in GDB

```
(gdb) set backtrace past-main on
```

- Example for our homework

```
Breakpoint 1, main () at main.c:26
```

```
26     s = sum(100);
```

```
Missing separate debuginfos, use: debuginfo-install glibc-2.17-292.el7.i686
```

```
(gdb) set backtrace past-main on
```

```
(gdb) bt
```

```
#0  main () at main.c:26
```

```
#1  0xf7dfb2a3 in __libc_start_main () from /lib/libc.so.6
```

```
#2  0x08048331 in _start ()
```

```
(gdb)
```

Alternatively set a breakpoint on `__start`

- Use `readelf`

```
readelf -a hello
```

- Example for our homework

```
ELF Header:
```

```
Magic:  7f 45 4c 46 01 01 01 00 00 00 00 00 00 00 00 00
Class:                               ELF32
Data:                                 2's complement, little endian
Version:                             1 (current)
OS/ABI:                               UNIX - System V
ABI Version:                          0
Type:                                 EXEC (Executable file)
Machine:                              Intel 80386
Version:                              0x1
Entry point address:              0x8048310
Start of program headers:             52 (bytes into file)
Start of section headers:             6880 (bytes into file)
Flags:                                 0x0
Size of this header:                  52 (bytes)
Size of program headers:              32 (bytes)
Number of program headers:            9
Size of section headers:              40 (bytes)
Number of section headers:            36
Section header string table index:    35
```

Initializers and finalizers

- C++ needs a segment for invoking constructors for static variables
 - List of pointers to startup routines
 - Startup code in every module is put into an anonymous startup routine
 - Put into a segment called `.init`
- Problem
 - Order matters
 - Ideally you should track dependencies
 - This is not done
 - Simple hack
 - System libraries go first (`.init`), then user (`.ctor`)

Example of a constructor

```
#include <stdio.h>

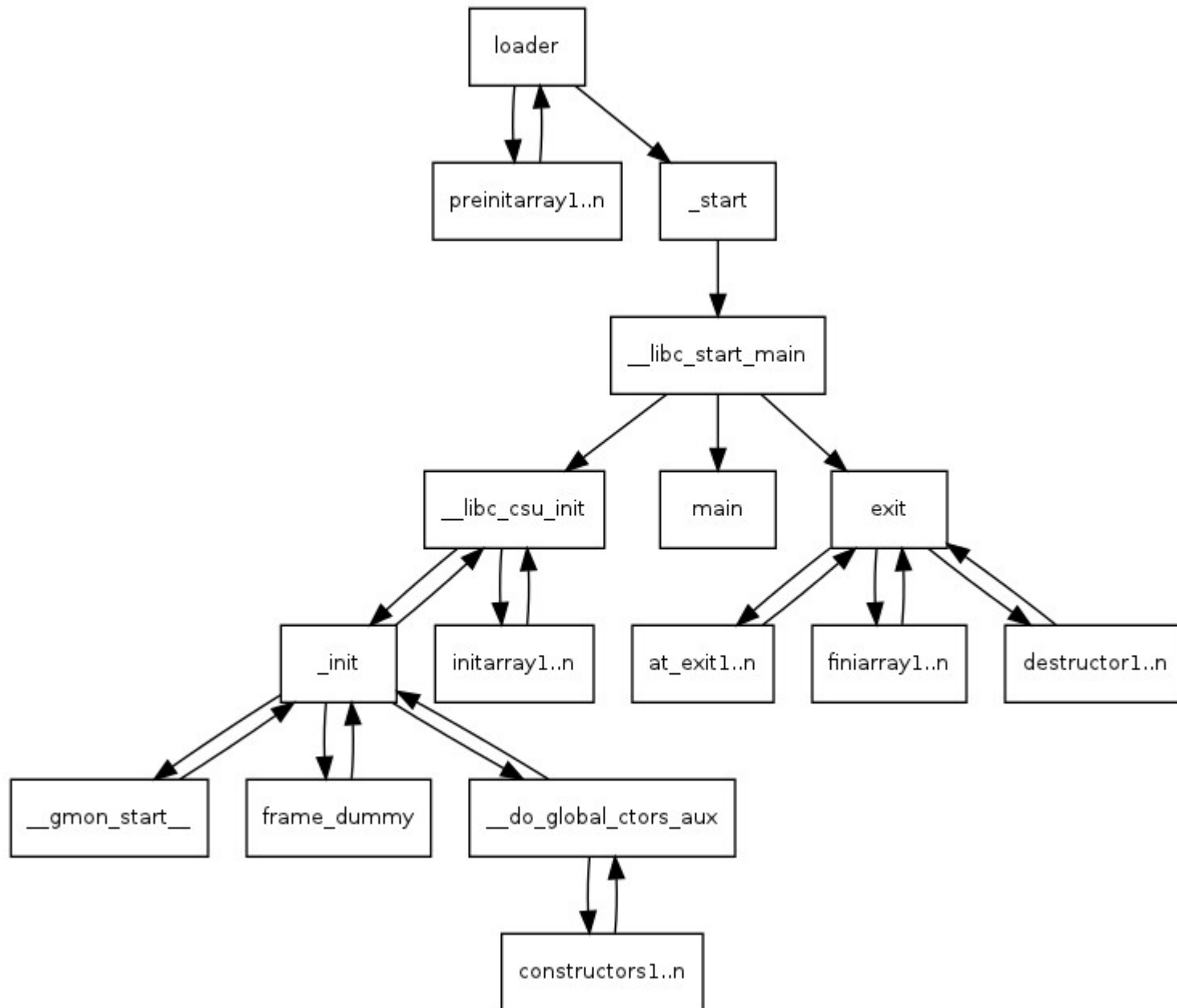
void __attribute__((constructor)) a_constructor() {
    printf("%s\n", __FUNCTION__);
}

int
main()
{
    printf("%s\n", __FUNCTION__);
}
```

- Run it

```
$ ./hello
a_constructor
main
$
```

Starting main()



Starting dynamically linked programs

Loading a dynamically linked ELF program

- Map ELF sections into memory
- Note the interpreter section
 - Usually ld.so
- Map ld.so into memory
 - Start ld.so instead of the program
- Linker (ld.so) initializes itself
- Finds the names of shared libraries required by the program
 - DT_NEEDED entries

Starting dynamically linked programs

Runtime linker: ld-linux.so

- The kernel checks if `PT_INTERP` is present in the ELF file
 - Reads the filename of the interpreter
 - Reads the interpreter and loads it in program's memory
 - It's an ELF executable itself
 - Sets to start the program at the entry point of the interpreter
 - `execv()` completes starting interpreter

Finding libraries in the file system

- DT_RPATH symbol
 - Can be linked into a file by a normal linker at link time
- LD_LIBRARY_PATH
- Library cache file
 - /etc/ld.so.conf
 - This is the most normal way to resolve library paths
- Default library path
 - /usr/lib

Loading more libraries

- When the library is found it is loaded into memory
 - Linker adds its symbol table to the linked list of symbol tables
 - Recursively searches if the library depends on other libraries
 - Loads them if needed

Shared library initialization

- Remember PIC needs relocation in the data segment and GOT
 - ld.so linker performs this relocation

Conclusion

- You understand linking and loading
 - Relocation
 - Assign load address to each object file
 - Patch the code
 - Symbol resolution
 - Resolve symbols imported from other object files

Resources

- How statically linked programs run on Linux by Eli Bendersky

<https://eli.thegreenplace.net/2012/08/13/how-statically-linked-programs-run-on-linux>

- Linux x86 Program Start Up or - How the heck do we get to main()? by Patrick Horgan

<http://dbp-consulting.com/tutorials/debugging/linuxProgramStartup.html>

- <https://lwn.net/Articles/630727/>
- <https://lwn.net/Articles/631631/>

Thank you!

Weak vs strong symbols

- Virtually every program uses printf
 - Printf can convert floating-point numbers to strings
 - Printf uses fcvt()
 - Does this mean that every program needs to link against floating-point libraries?
- Weak symbols allow symbols to be undefined
 - If program uses floating numbers, it links against the floating-point libraries
 - fcvt() is defined and everything is fine
 - If program doesn't use floating-point libraries
 - fcvt() remains NULL but is never called

nm a.out

```
0804a01c B __bss_start
0804a01c b completed.6591
0804a014 D __data_start
0804a014 W data_start
...
0804a01c D _edata
0804a020 B _end
08048484 T _fini
...
08048294 T _init
...
080483ed T main
...
080482f0 T _start
...
```