Lecture 05: Linking and Loading

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October, 2021

What is inside a program?

- What parts do we need to run code?

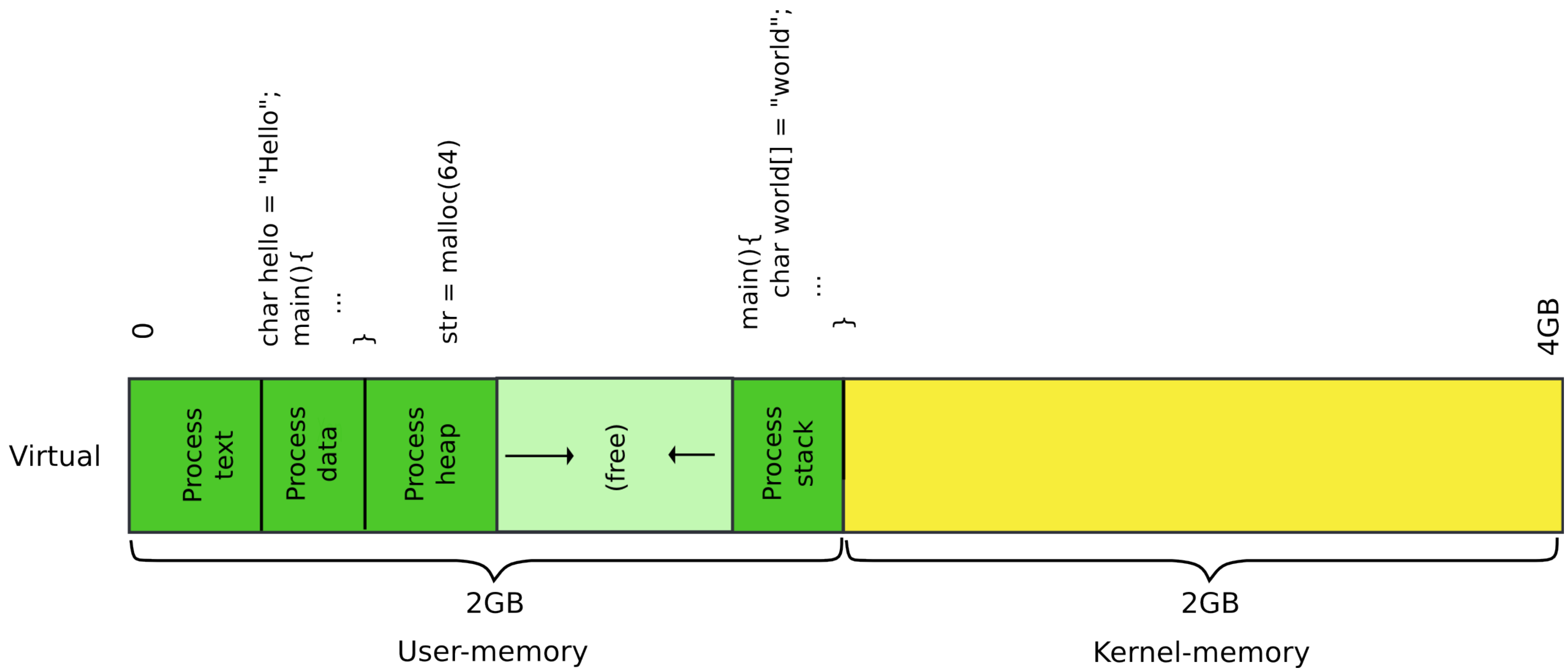
Parts needed to run a program

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

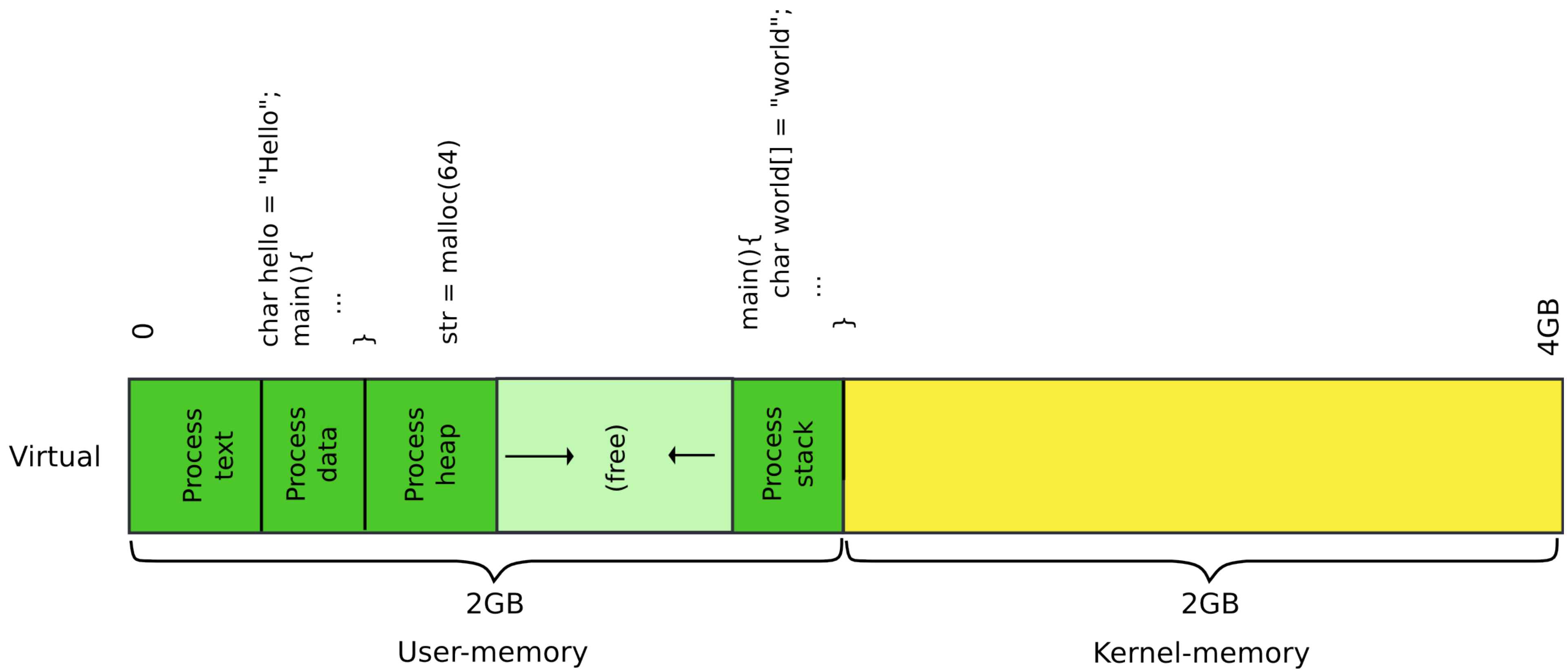
What types of variables do you know?

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

Memory layout of a process



Where do these areas come from?



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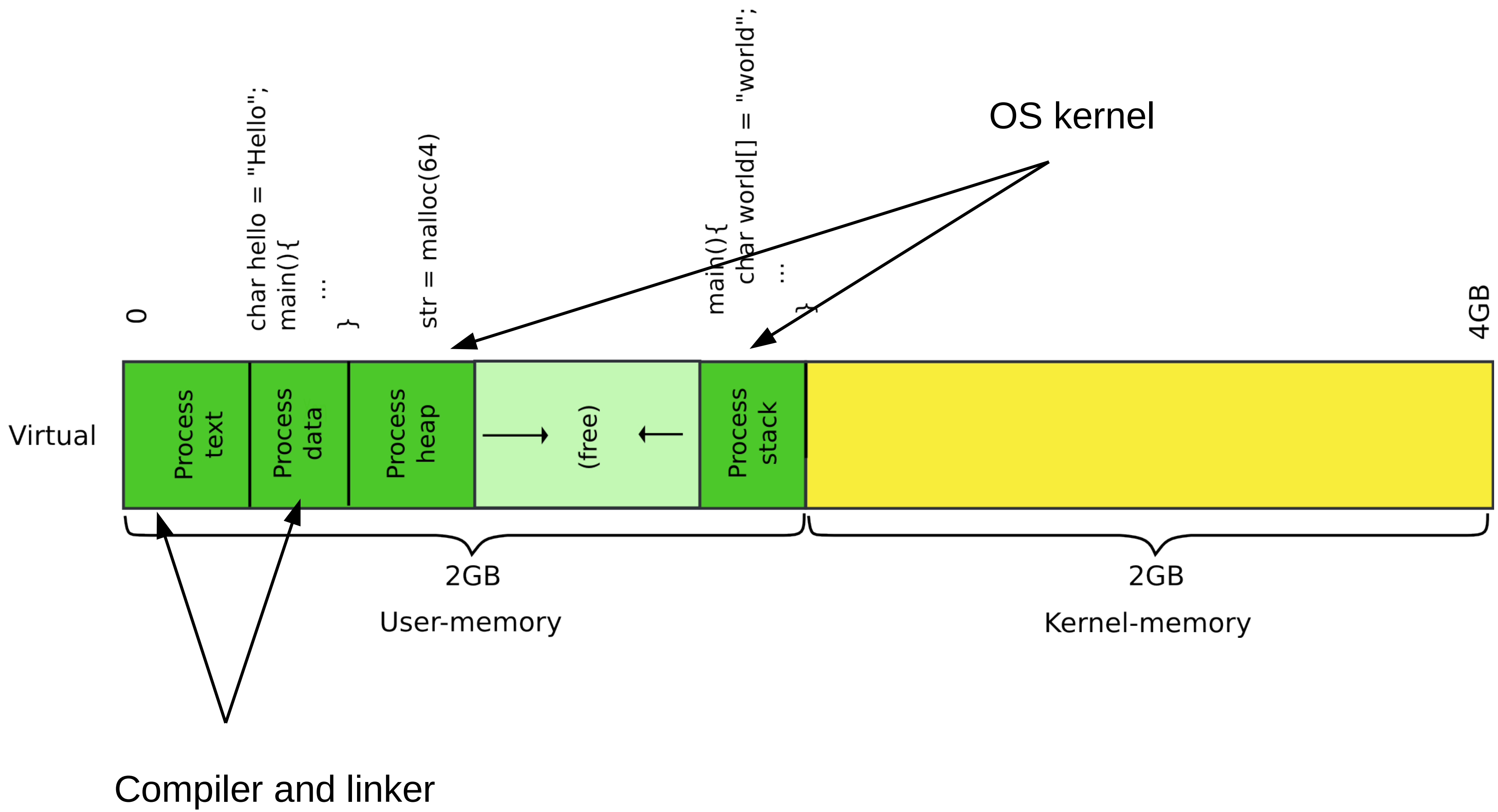

Example program

- 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
```

objdump -sd a.out

```
a.out:     file format elf32-i386

Contents of section .text:
 80483e0 d0c9e979 ffffff90 e973ffff ff5589e5  ...y.....s...U..
 80483f0 83ec10c7 45f80500 0000c745 fc060000  ....E......E....
 8048400 008b45fc 8b55f801 d0c9c366 90669090  ..E..U.....f.f..
 8048410 555731ff 5653e805 ffffff81 c3e51b00  UW1.VS..........
 8048420 0083ec1c 8b6c2430 8db30cff ffffe861  .....l$0.......a
 8048430 feffff8d 8308ffff ff29c6c1 fe0285f6  .........)......
Contents of section .rodata:
 8048498 03000000 01000200                    ........
Contents of section .data:
 804a014 00000000 00000000                    ........
Disassembly of section .text:
…
080483ed <main>:
 80483ed:       55                      push   %ebp
 80483ee:       89 e5                   mov    %esp,%ebp
 80483f0:       83 ec 10                sub    $0x10,%esp
 80483f3:       c7 45 f8 05 00 00 00    movl   $0x5,-0x8(%ebp)
 80483fa:       c7 45 fc 06 00 00 00    movl   $0x6,-0x4(%ebp)
 8048401:       8b 45 fc                mov    -0x4(%ebp),%eax
 8048404:       8b 55 f8                mov    -0x8(%ebp),%edx
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 804840b:       66 90                   xchg   %ax,%ax
 804840d:       66 90                   xchg   %ax,%ax
 804840f:       90                      nop
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- GCC syntax, i.e.

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mov %esp, %ebp
// EBP = ESP
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Disassembly of section .text:
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080483ed <main>:
 80483ed:       55                      push   %ebp      # Maintain the stack frame
 80483ee:       89 e5                   mov    %esp,%ebp
 80483f0:       83 ec 10                sub    $0x10,%esp
 80483f3:       c7 45 f8 05 00 00 00    movl   $0x5,-0x8(%ebp)
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 8048401:       8b 45 fc                mov    -0x4(%ebp),%eax # Move b into %eax
 8048404:       8b 55 f8                mov    -0x8(%ebp),%edx # Move a into %edx
 8048407:       01 d0                   add    %edx,%eax
 8048409:       c9                      leave
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 8048404:       8b 55 f8                mov    -0x8(%ebp),%edx
 8048407:       01 d0                   add    %edx,%eax      # a + b
 8048409:       c9                      leave
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 8048404:       8b 55 f8                mov    -0x8(%ebp),%edx
 8048407:       01 d0                   add    %edx,%eax
 8048409:       c9                      leave                    # Pop the frame ESP = EBP
 804840a:       c3                      ret                      # return
 804840b:       66 90                   xchg   %ax,%ax
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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
```

“Optimizing subroutines in assembly language” by Agner Fog:
https://www.agner.org/optimize/optimizing_assembly.pdf

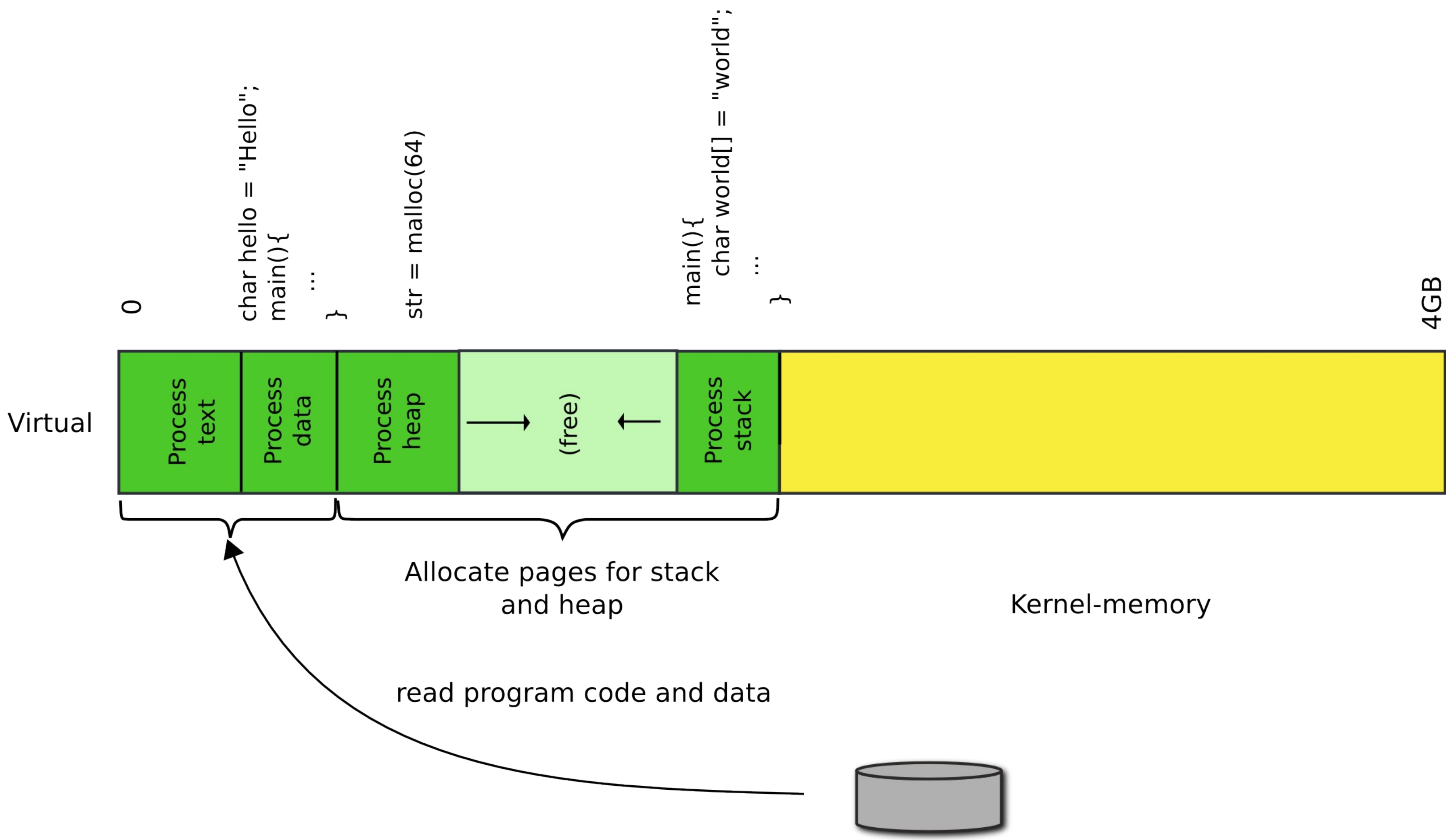
11.5 Alignment of code

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

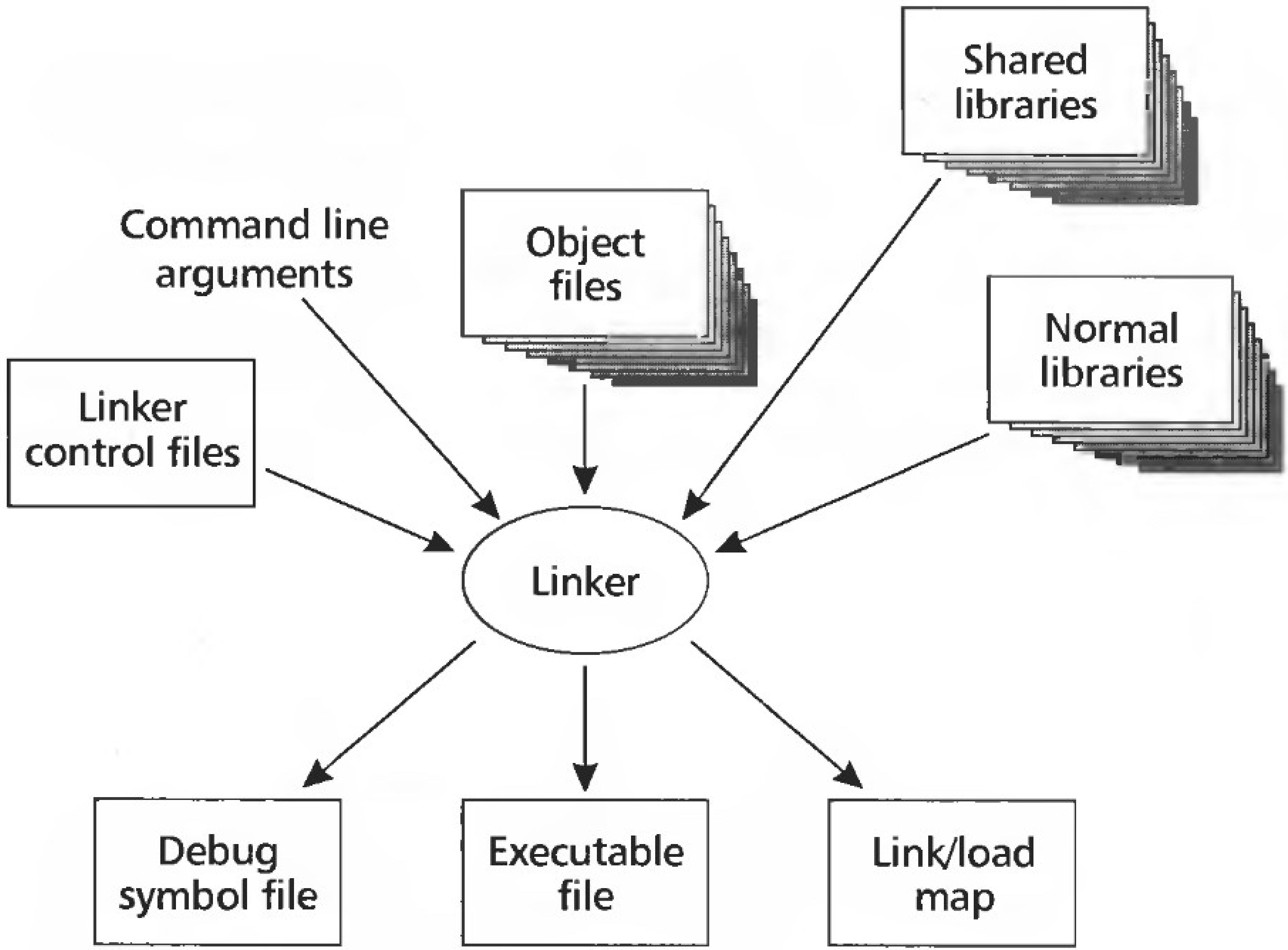
Part of the xv6 Makefile

```
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
```

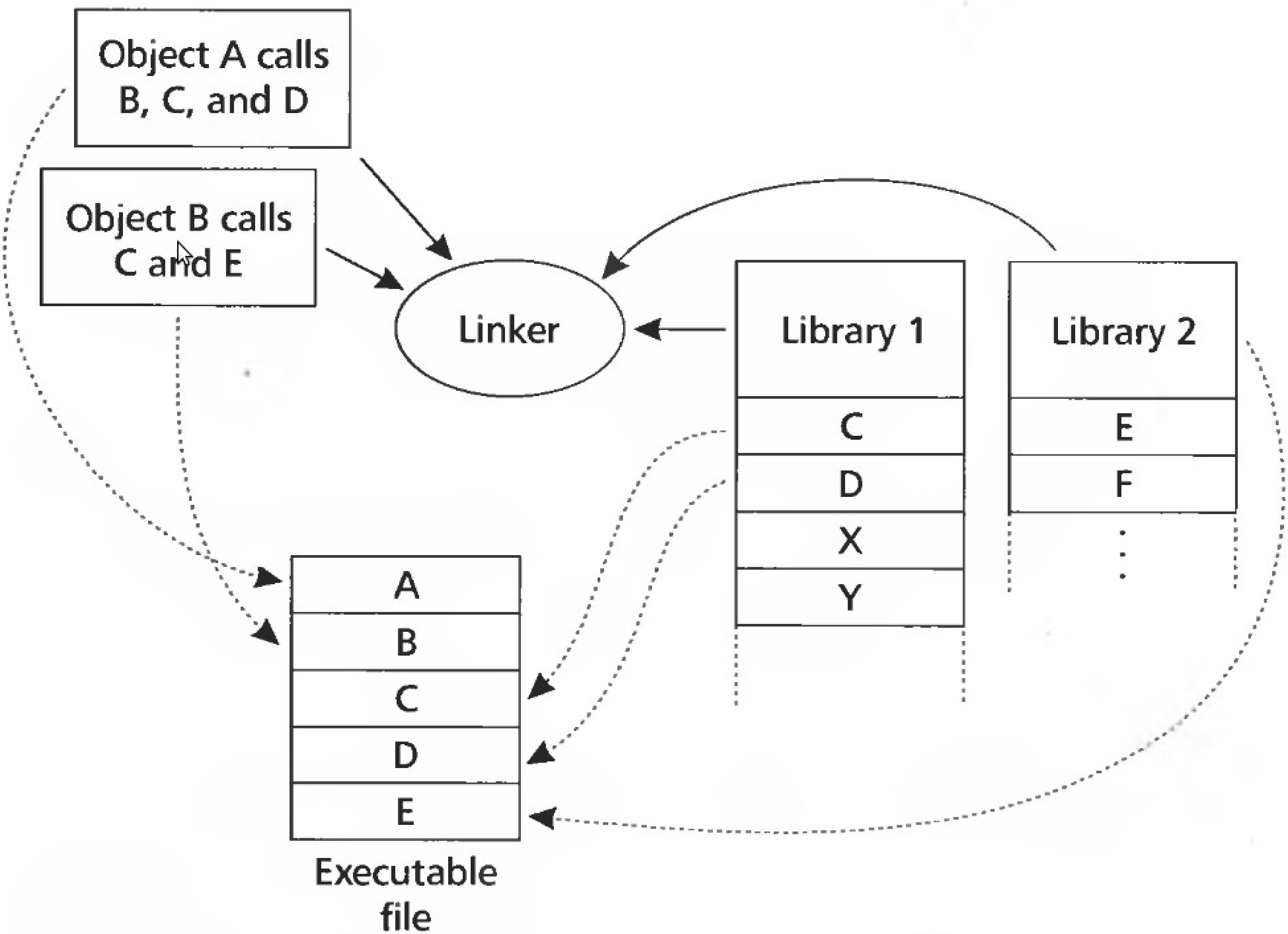
Linking and Loading

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


Shared libraries
Command line arguments
Object files
Normal libraries
Linker control files
Linker
Debug symbol file
Executable file
Link/load map

- 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.


Object A calls B, C, and D
Object B calls C and E
Linker
Library 1
C
D
X
Y
Library 2
E
F
A
B
C
D
E
Executable file

Why linking?

Why linking?

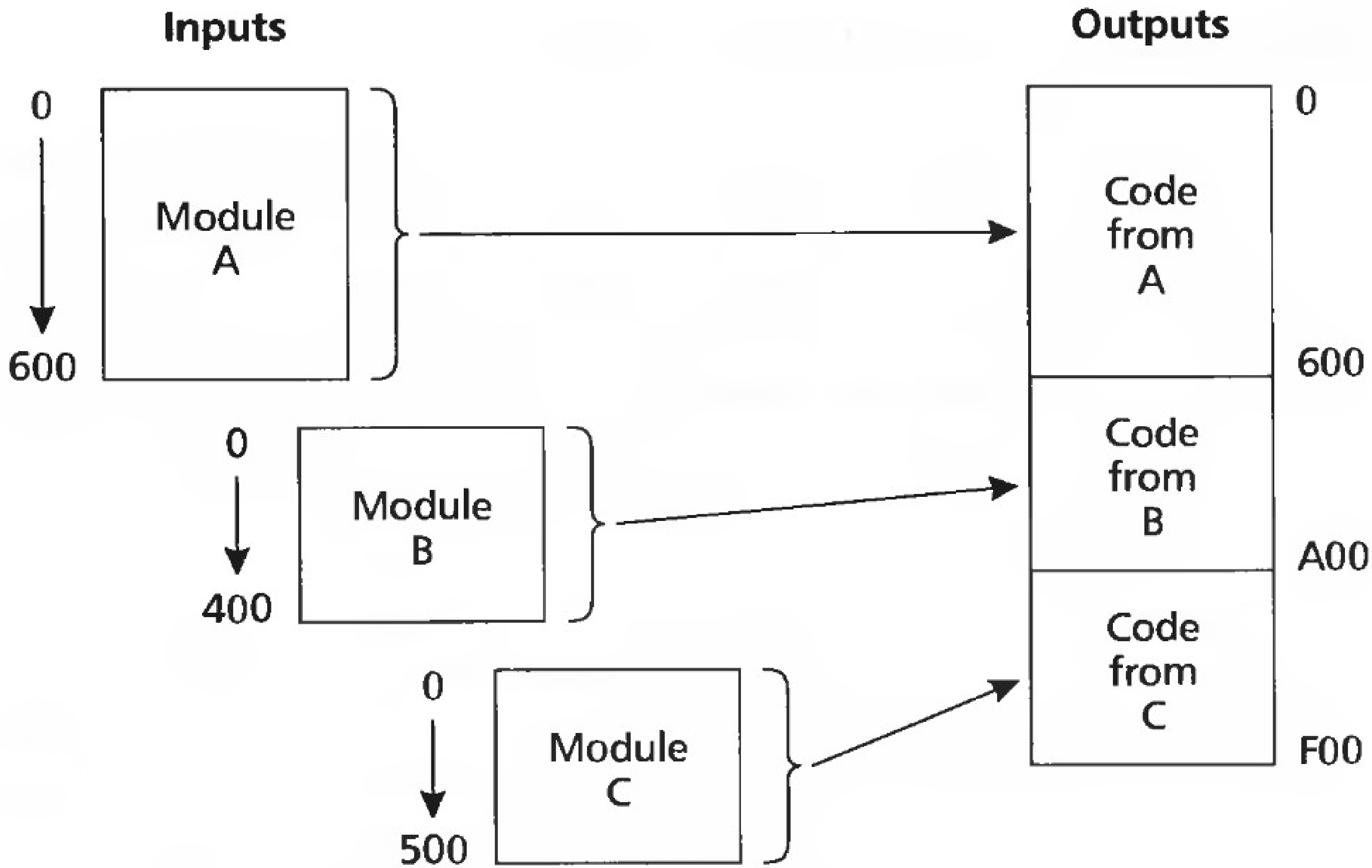
- Modularity
  - Program can be written as a collection of modules
  - We can build libraries of common functions
- Efficiency
  - Code compilation
    - Change one source file, recompile it, and re-link the executable
  - Space efficiency
    - Share common code across executable files
    - On disk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

Two path process

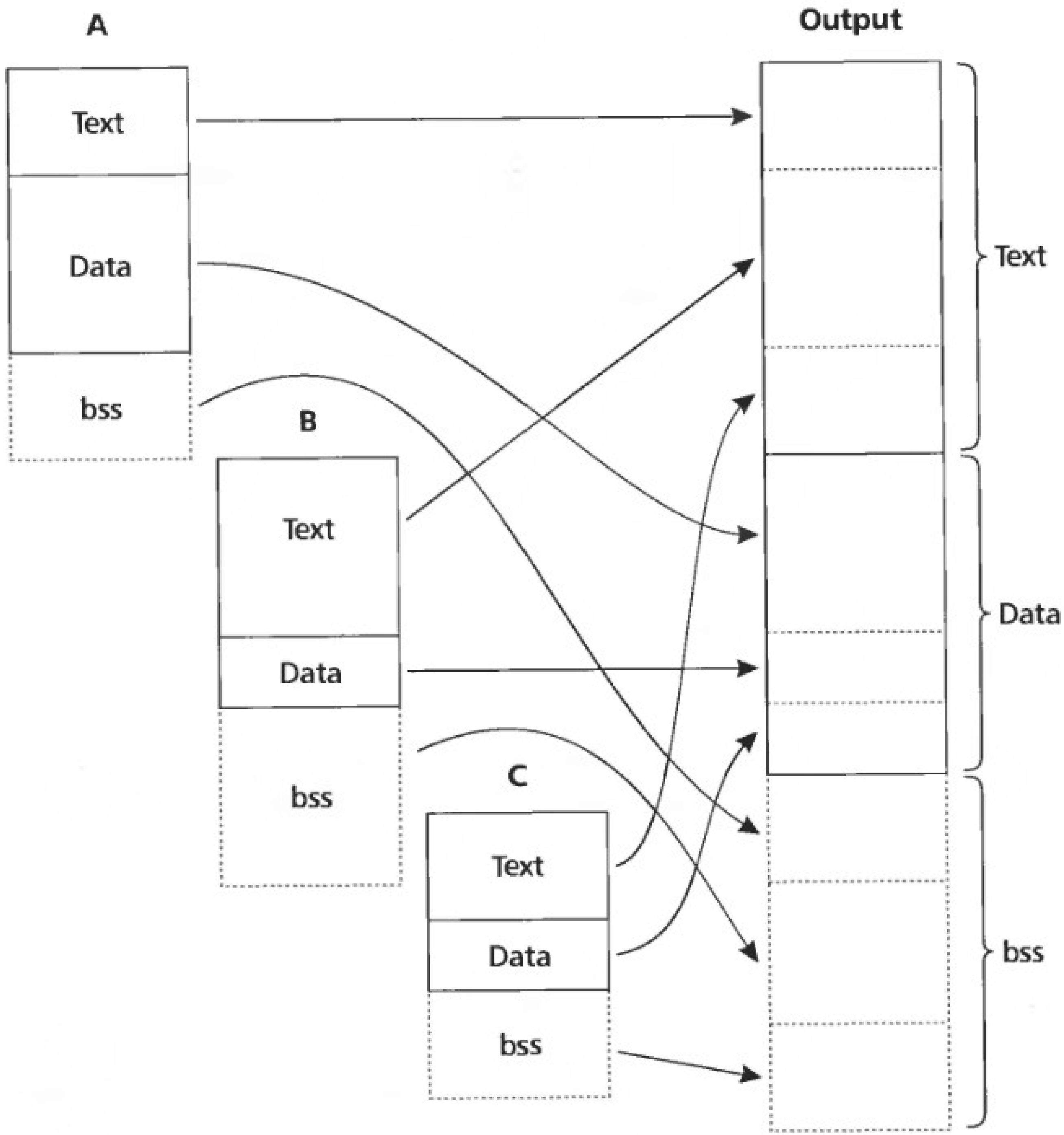
- Path 1: scan input files
  - Identify boundaries of each segment
  - Collect all defined and undefined symbol information
  - Determine sizes and locations of each segment

- 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

nerated 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

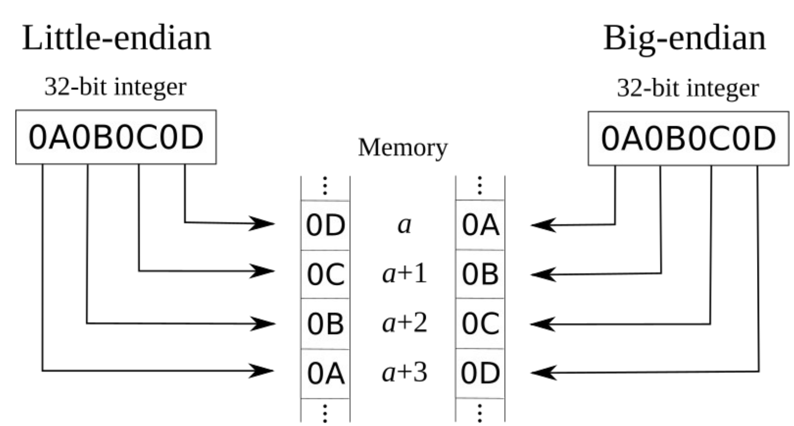
- Save a into b, e.g., b = a

```
mov a, %eax
mov %eax, b
```

- 4 byte address

- 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
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

```c
extern void a(char *);
int main(int ac, char **av)
{
  static char string[] = "Hello, world!\n";
  a(string);
}
```

- Source file a.c

```c
#include <unistd.h>
#include <string.h>
void a(char *s)
{
  write(1, s, strlen(s));
}
```

More realistic example

- Source file m.c

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

- Source file a.c

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

More realistic example

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  a(string);
}
```

- Source file a.c

```c
#include <unistd.h>
#include <string.h>
void a(char *s)
{
  write(1, s, strlen(s));
}
```

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

• Code starts at 0x0

```
Sections:
 Idx Name Size     VMA      LMA      File off Algn
  0 .t             000000 00000000 00000020 2**3
  1 .d             000010 00000010 00000030 2**3
Disassem    ly 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

```c
extern void a(char *);
int main(int ac, char **av)
{
  static char string[] = "Hello, world!\n";
  a(string);
}
```

- Source file a.c

```c
#include <unistd.h>
#include <string.h>
void a(char *s)
{
  write(1, s, strlen(s));
}
```

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

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

- Source file a.c

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

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

```c
extern void a(char *);
int main(int ac, char **av)
{
  static char string[] = "Hello, world!\n";
  a(string);
}
```

- Source file a.c

```c
#include <unistd.h>
#include <string.h>
void a(char *s)
{
  write(1, s, strlen(s));
}
```

More realistic example

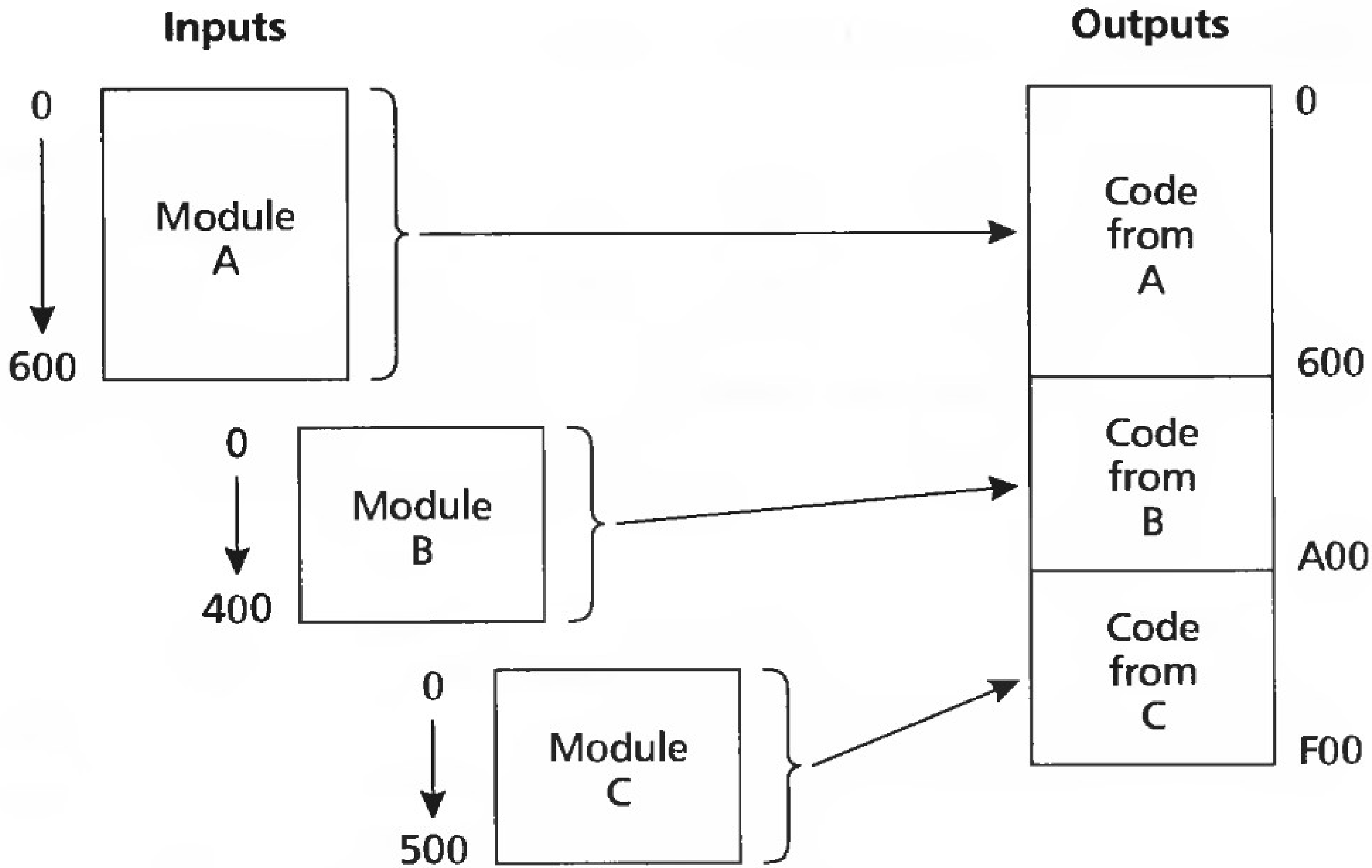
```
Sections:
 Idx Name Size      VMA       LMA       File off Algn
   0 .text 0000001c 00000000 00000000 00000020 2**2
     CONTENTS, ALLOC, LOAD, RELOC, CODE
   1 .data 00000000 0000001c 0000001c 0000003c 2**2
     CONTENTS, ALLOC, LOAD, DATA
Disassembly of section .text:
  00000000 <_a>:
  0: 55              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()

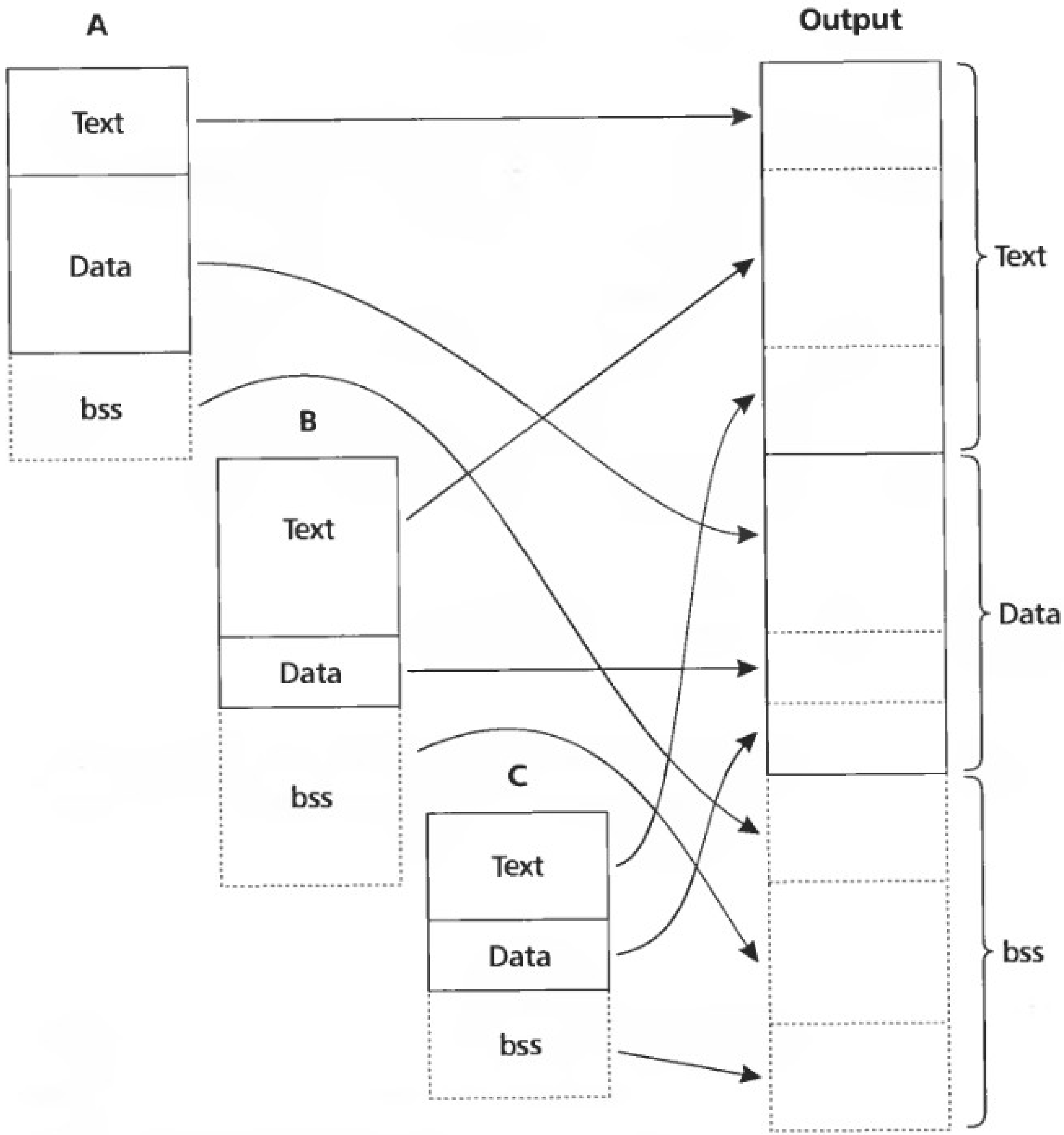
Now we understand how to produce an executable

- 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 10b
  ...
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

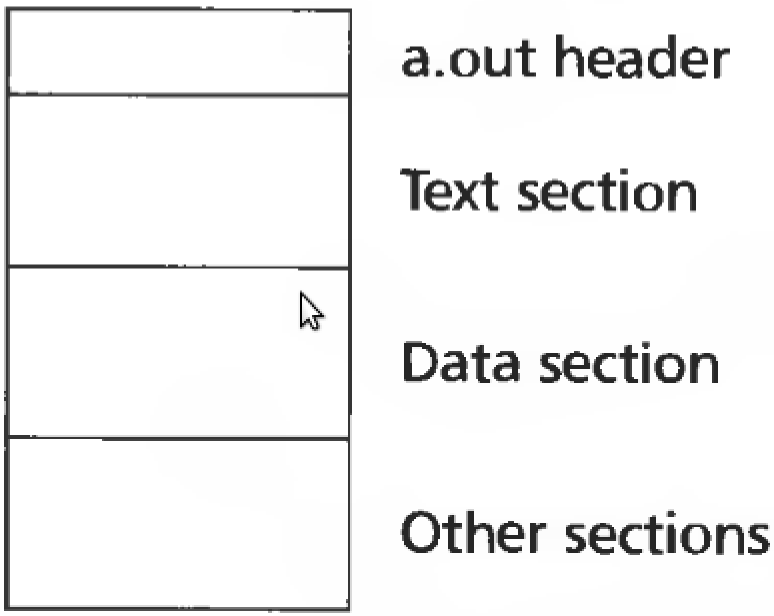
Description
Saves procedure linking information on the stack and branches to the procedure (called procedure) specified with the destination (target) operand. The target operand specifies the address of the first instruction in the called procedure. This operand can be an immediate value, a generalpurpose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

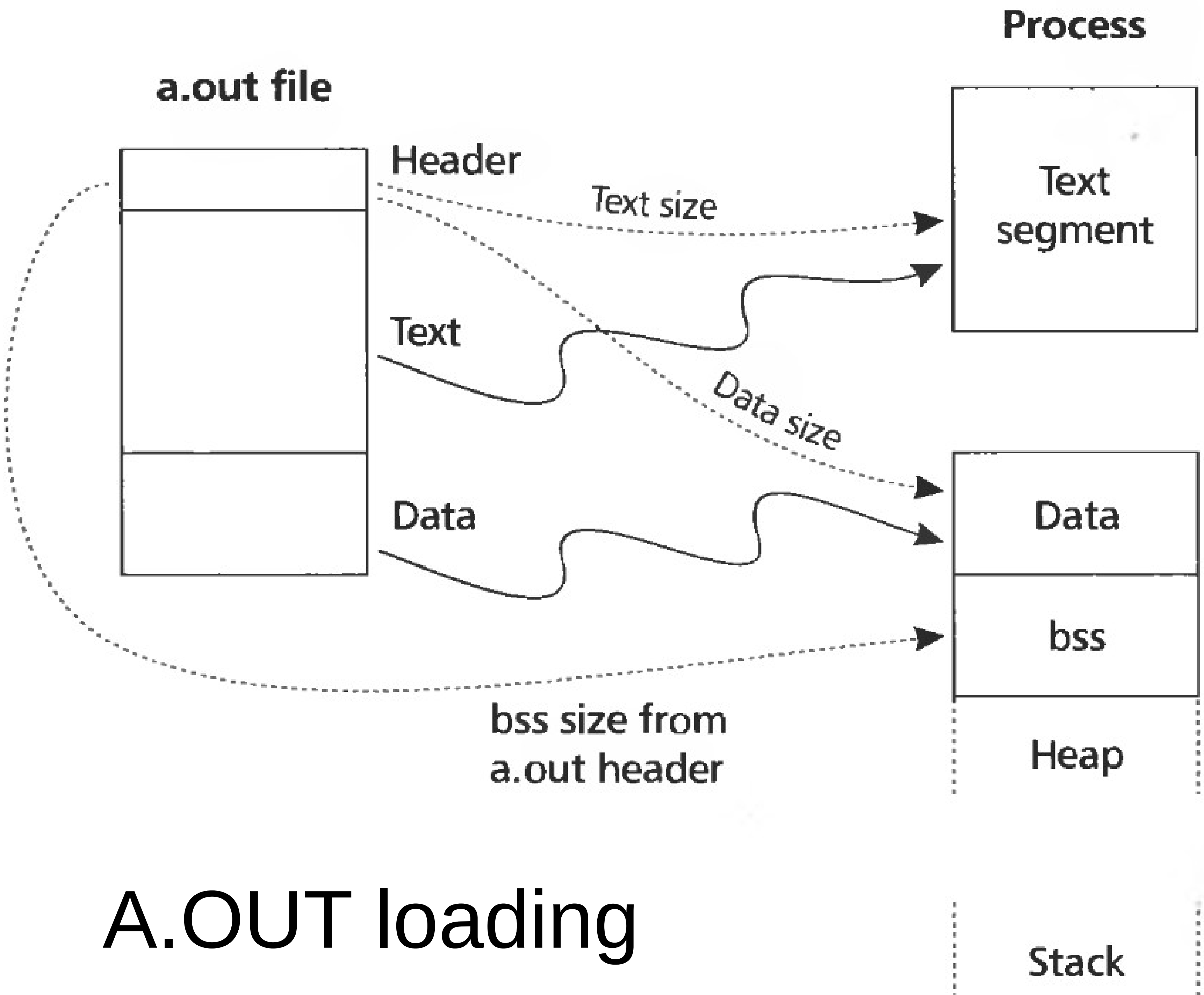
Example: UNIX A.OUT



- 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)

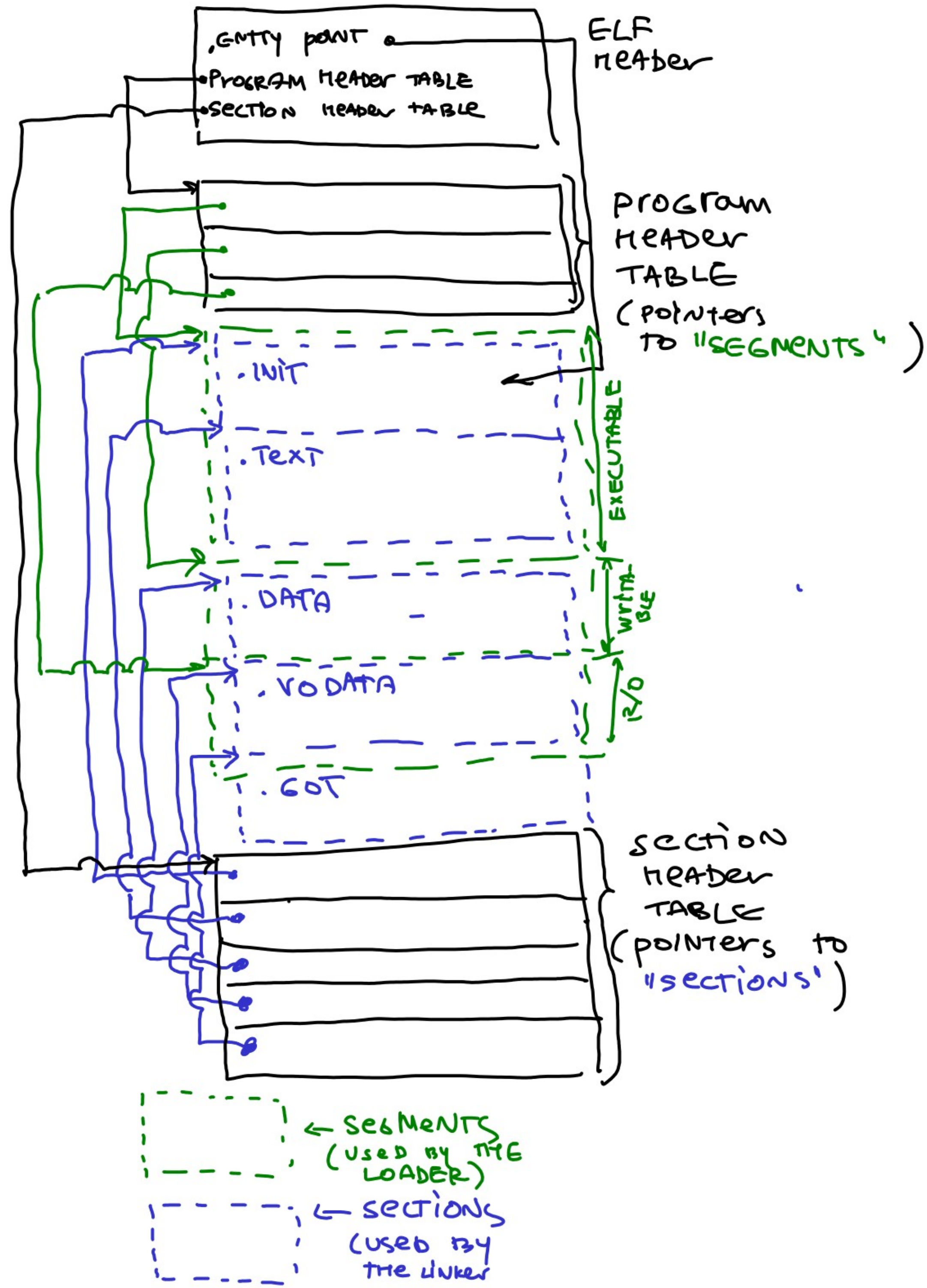
Types of object files

- 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



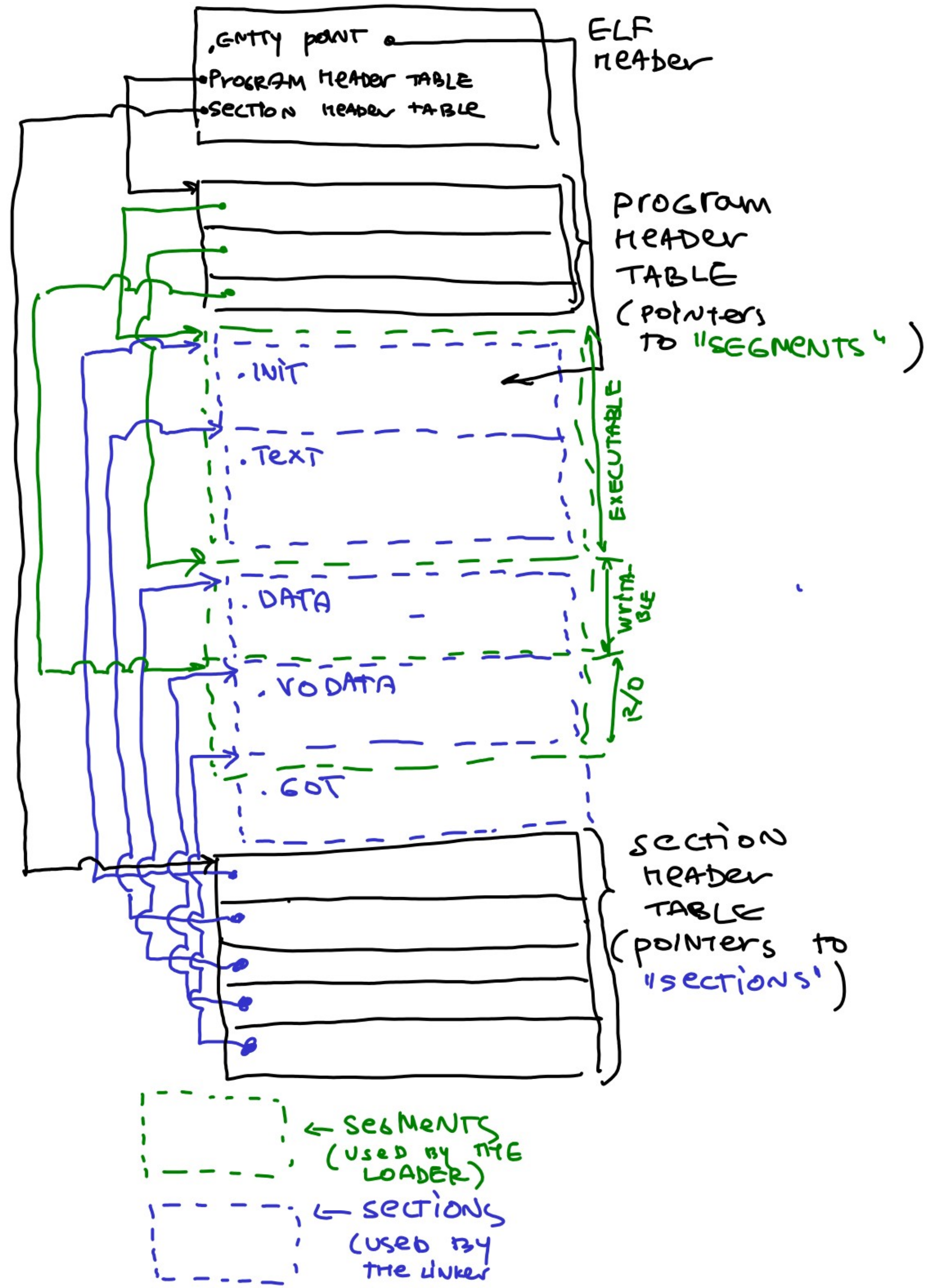
- gcc -c -fno-pic -static -fno-builtin -ggdb -m32 -fno-omit-frame-pointer hello-elf.c
- ld -m elf_i386 -N -e main -Ttext 0 -o a.out hello-elf.o
- readelf -a a.out

```
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

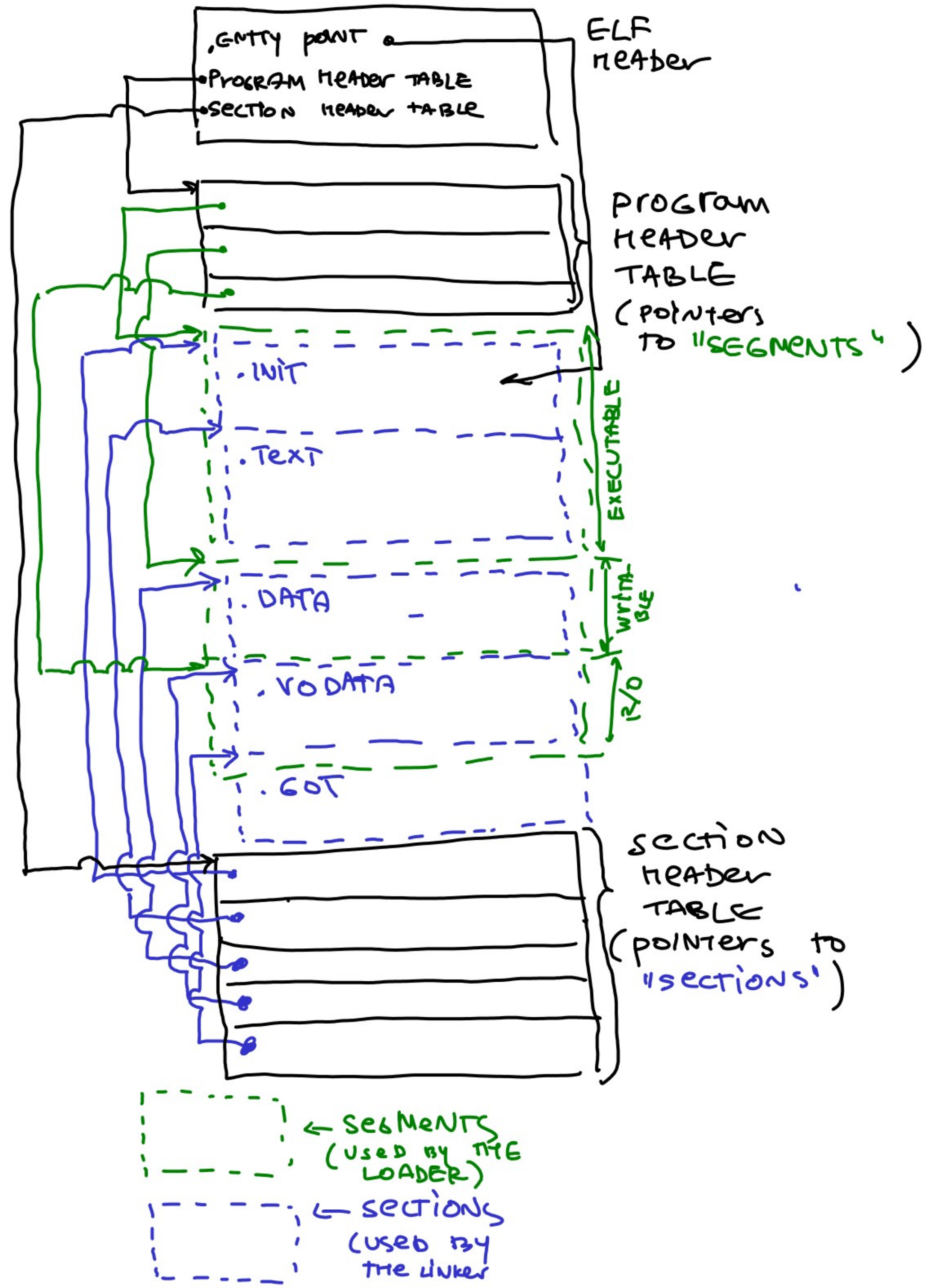
- `gcc -c -fno-pic -static -fno-builtin -ggdb -m32 -fno-omit-frame-pointer hello-elf.c`
- `ld -m elf_i386 -N -e main -Ttext 0 -o a.out hello-elf.o`
- `readelf -a a.out`

```
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

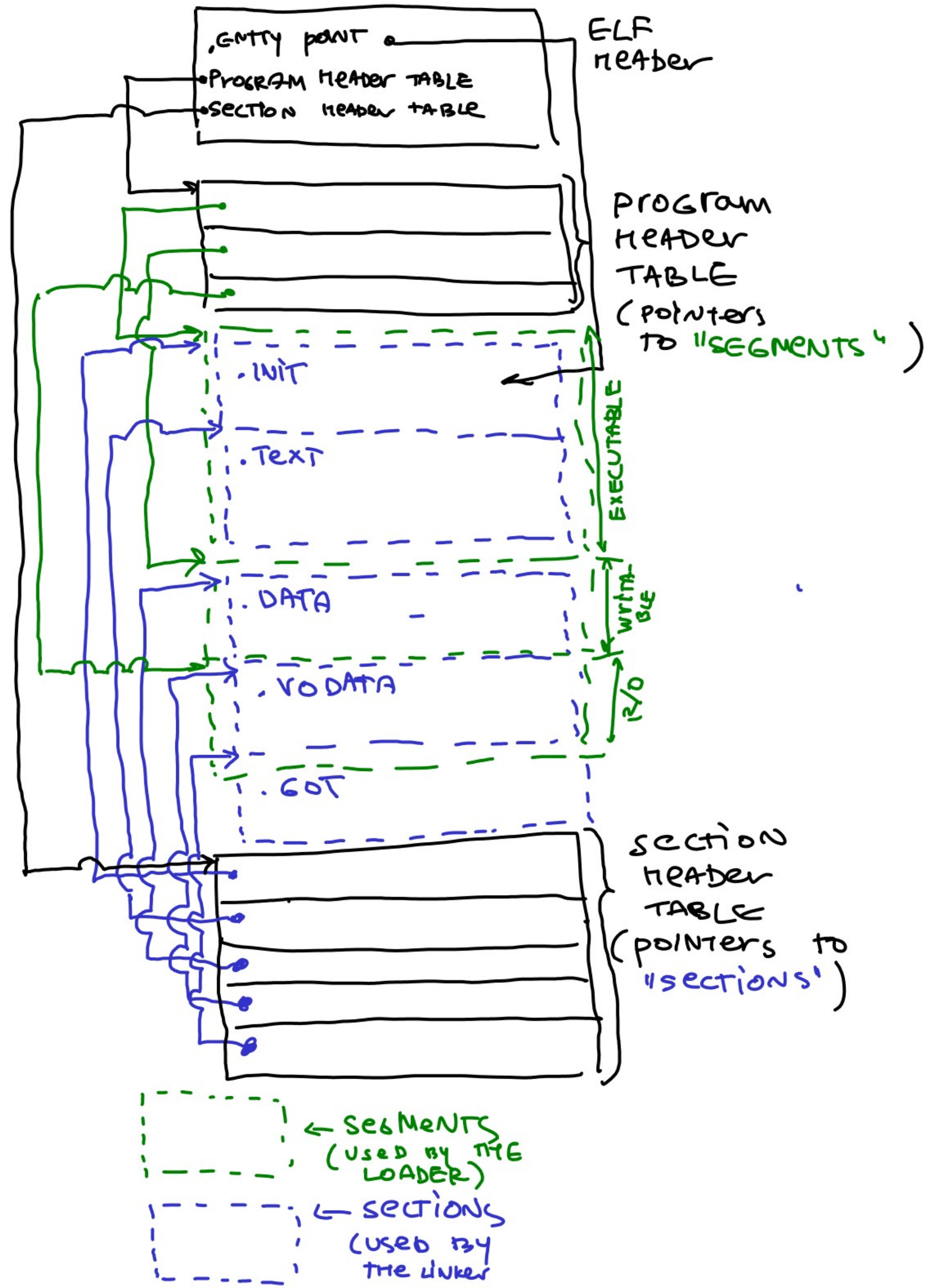


- readelf -a a.out

```
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



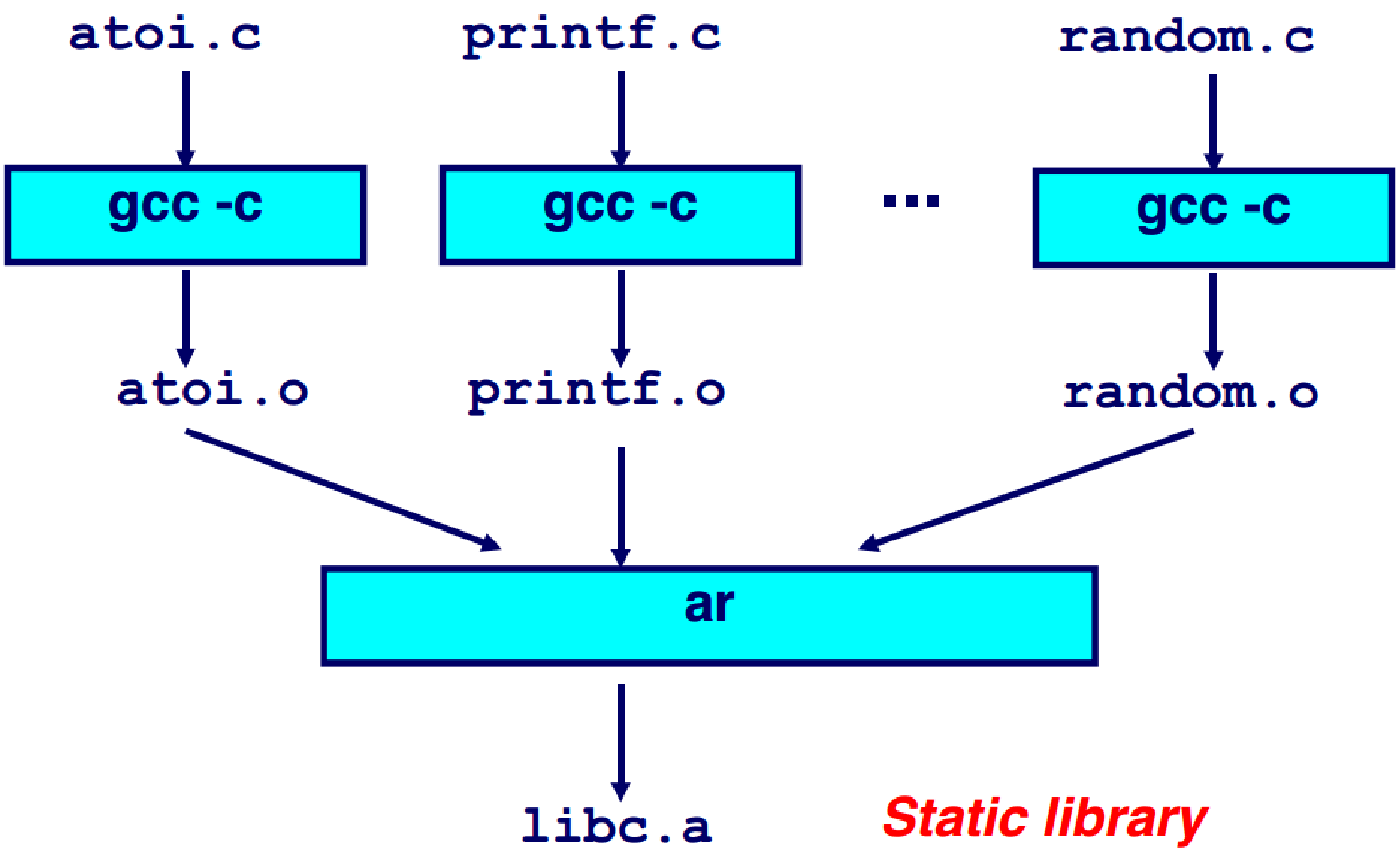
ENTRY POINT
PROGRAM HEADER TABLE
SECTION HEADER TABLE
ELF HEADER
PROGRAM HEADER TABLE (POINTERS TO "SEGMENTS")
.INIT
.TEXT
EXECUTABLE
.DATA
WRITABLE
.RODATA
R/O
.GOT
SECTION HEADER TABLE (POINTERS TO "SECTIONS")
← SEGMENTS (USED BY THE LOADER)
← SECTIONS (USED BY THE LINKER)

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
  - Dyncamically 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?

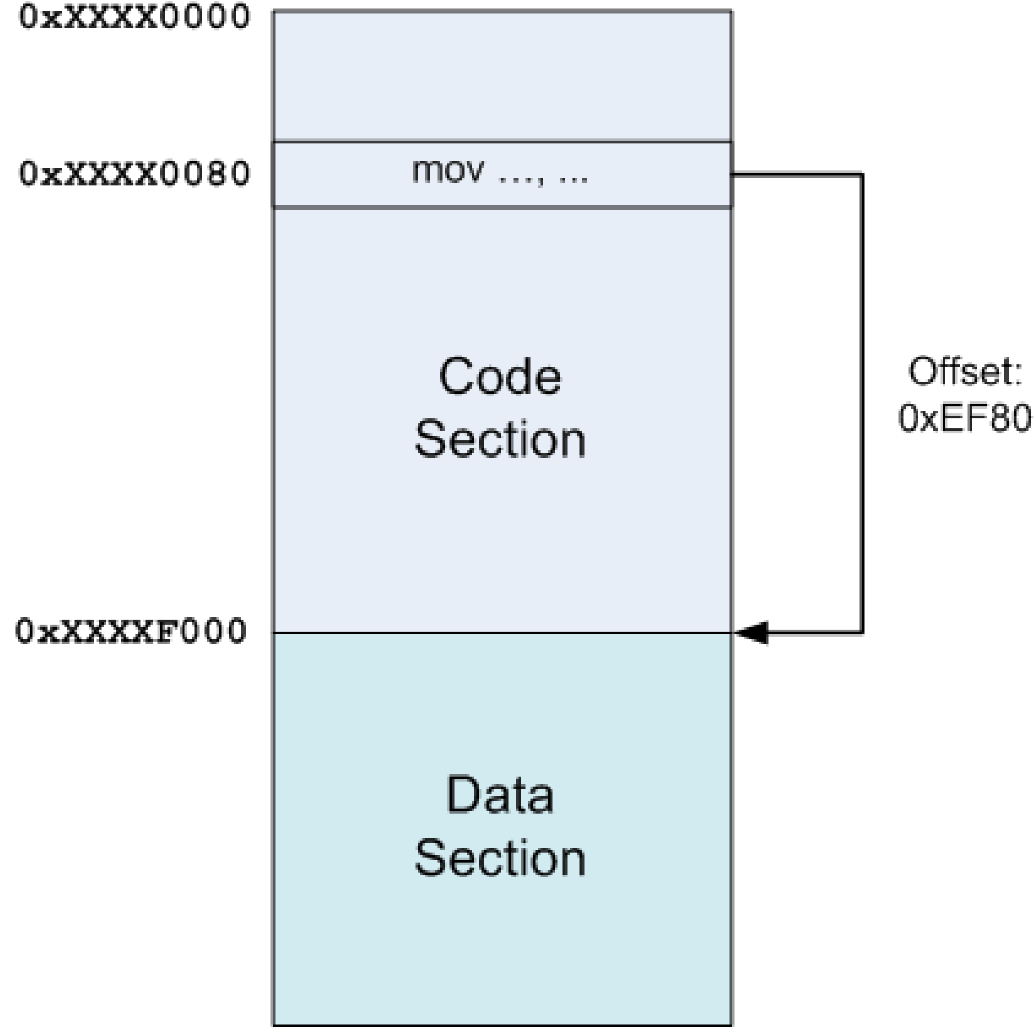
Position independent code

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

Position independent code

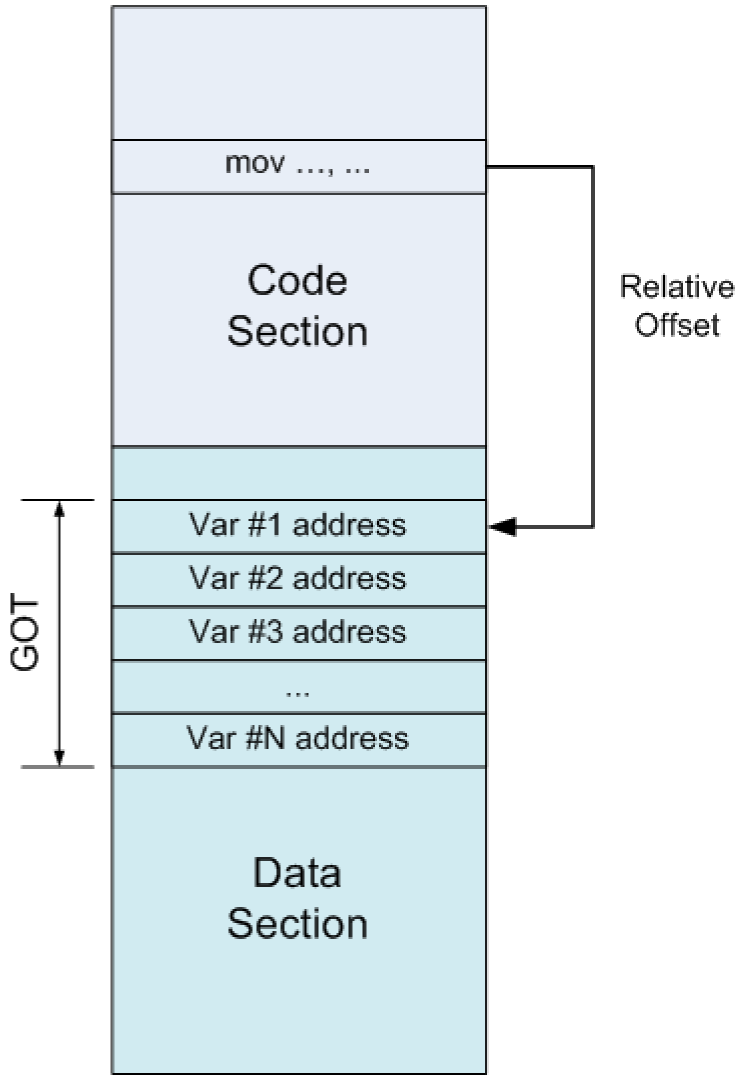
- Main insight
  - Code sections are followed by data sections
  - The distance between code and data **remains constant even if code is relocated**
    - Linker knows the distance
    - Even if it combines multiple code sections together

Insight 1: Constant offset between text and data sections



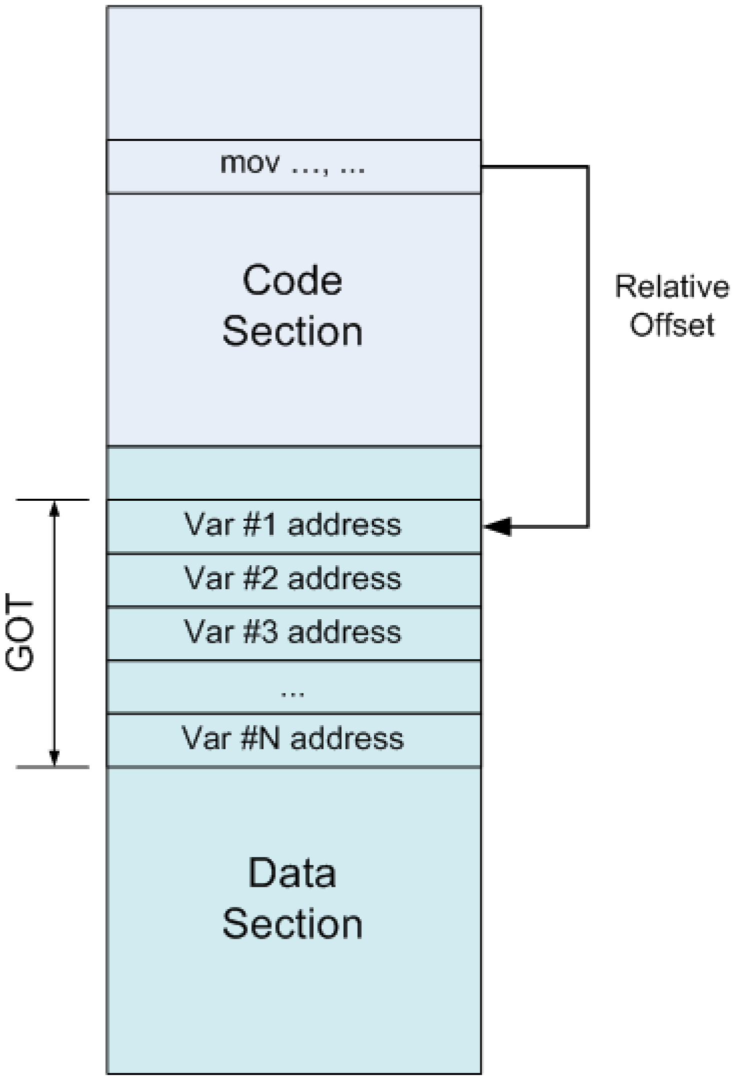
Global offset table (GOT)

- 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?

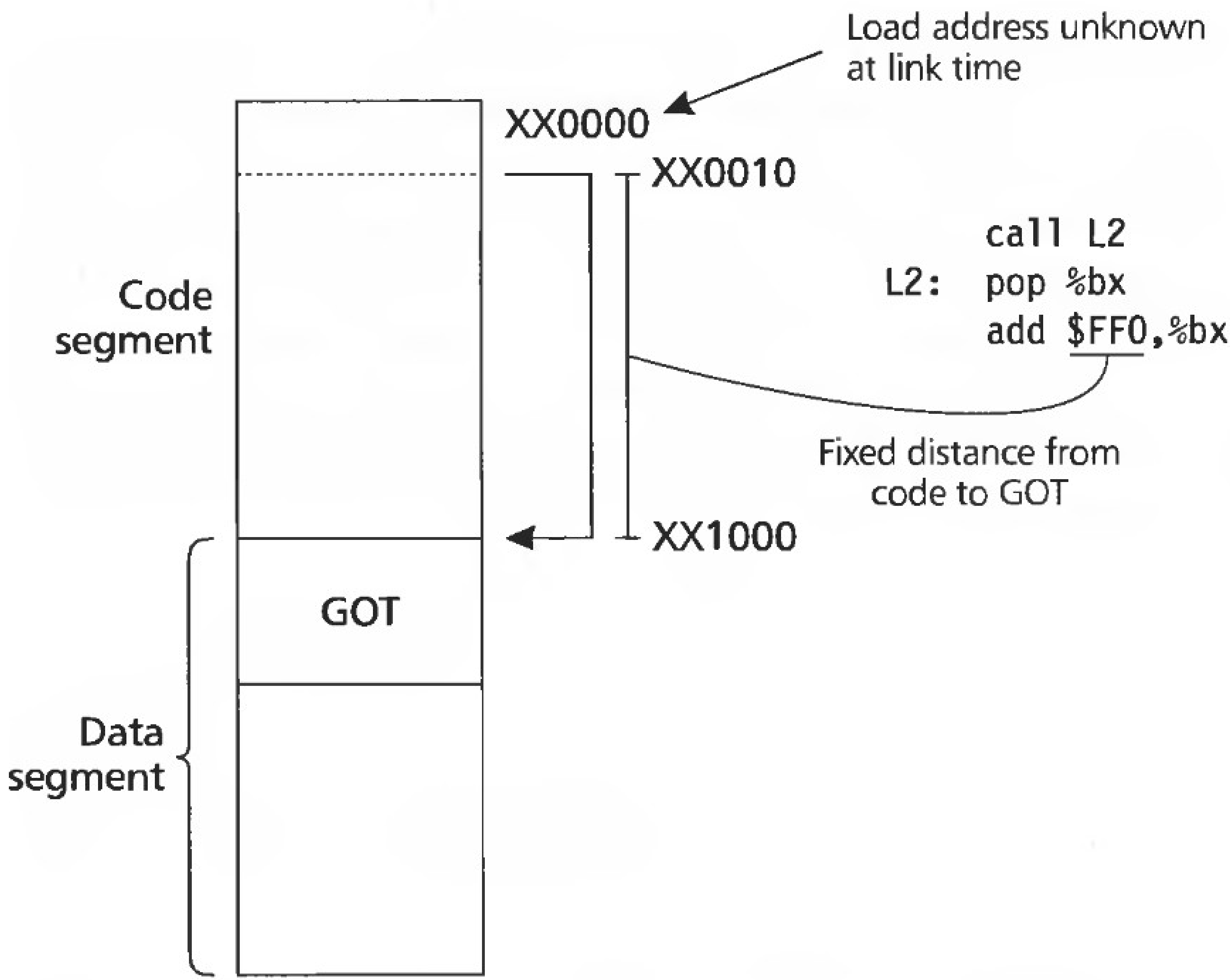
- Is there an x86 instruction that does this?
  - i.e., give me my current code address
- x86 32bit architecture requires absolute addresses for `mov` instructions
  - No relative addresses allowed
- There is no instruction to learn the value of EIP
  - Instruction pointer

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


Load address unknown
at link time
XX0000
XX0010
call L2
L2: pop %bx
add $FF0,%bx
Code
segment
Fixed distance from
code to GOT
XX1000
GOT
Data
segment

Examples of position independent code

PIC example

```
int myglob = 42;

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

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
```

PIC example

- Access a global variable myglob

```
int myglob = 42;

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

```
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
```

PIC example

- Save EIP into ECX

```
int myglob = 42;

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

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
```

PIC example

- Add offset to GOT
  - 0x1bb0

```
int myglob = 42;

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

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
```

PIC example

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

```
int myglob = 42;

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

```
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
```

PIC example

```c
int myglob = 42;

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

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

0000045a <__i686.get_pc_thunk.cx>:
 45a:   8b 0c 24                mov    ecx,DWORD PTR [esp]
 45d:   c3                      ret
```

What about function calls?

What about function calls?

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

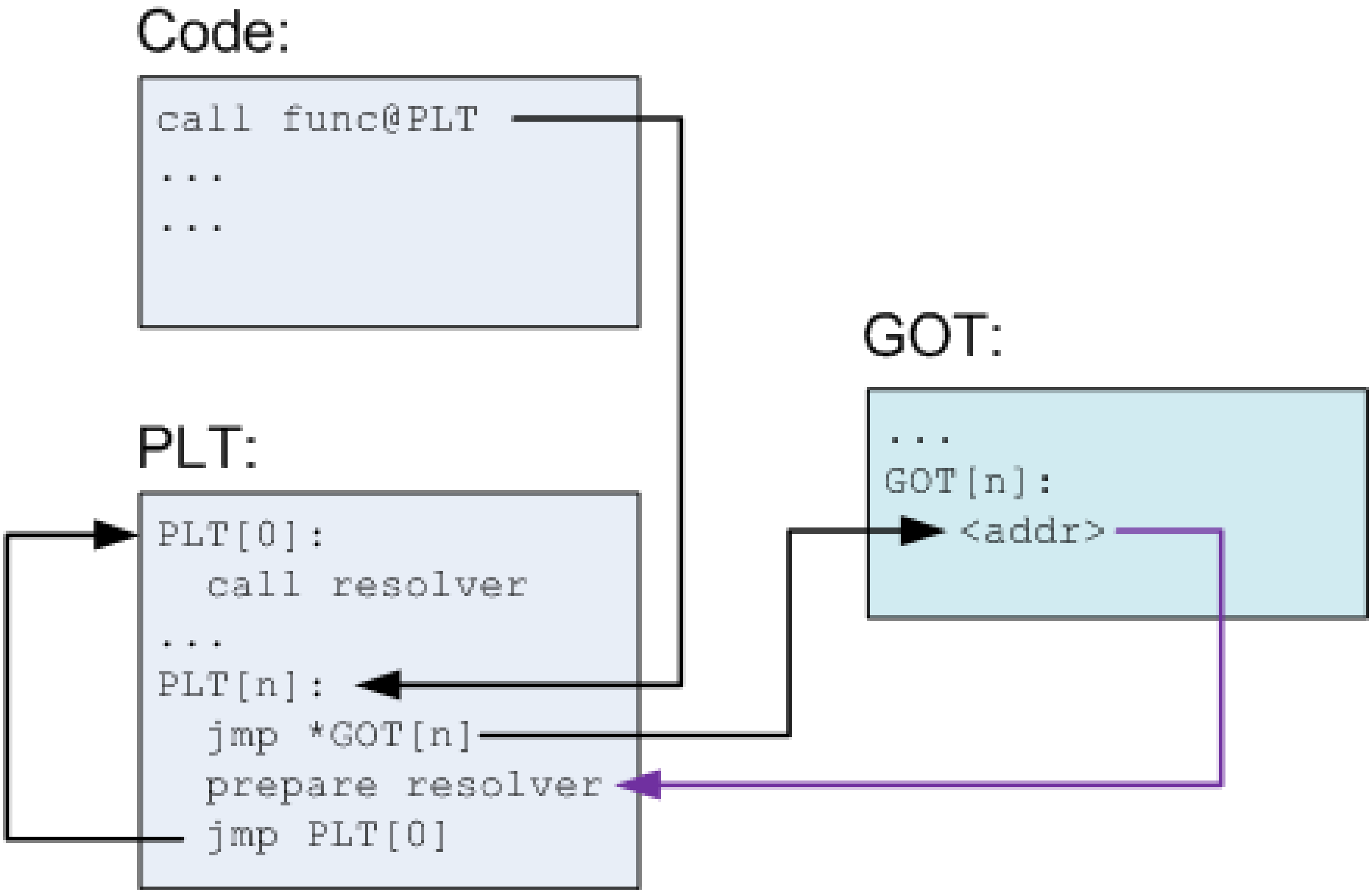
Late binding

- 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)



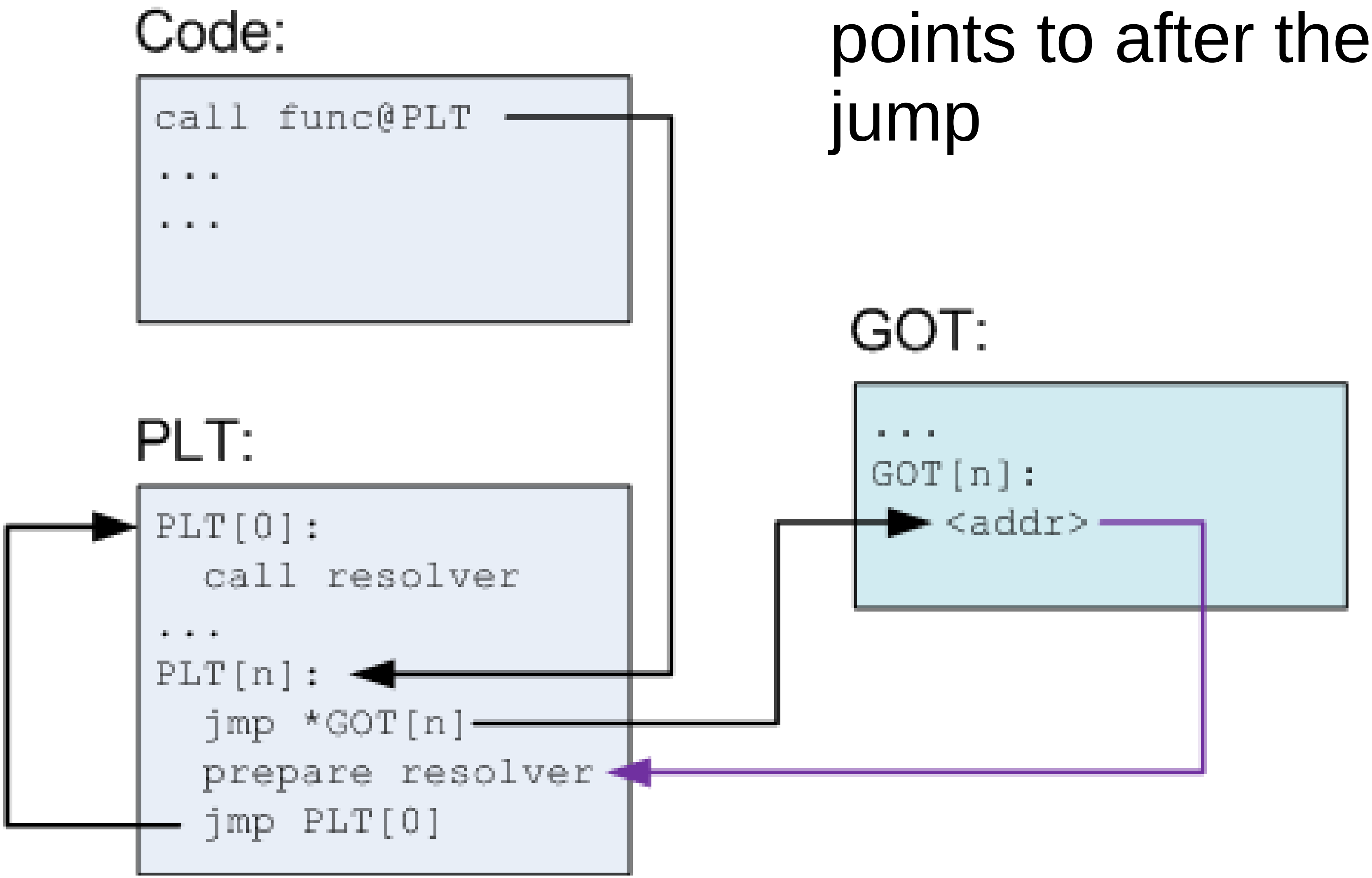
Procedure linkage table (PLT)

- 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

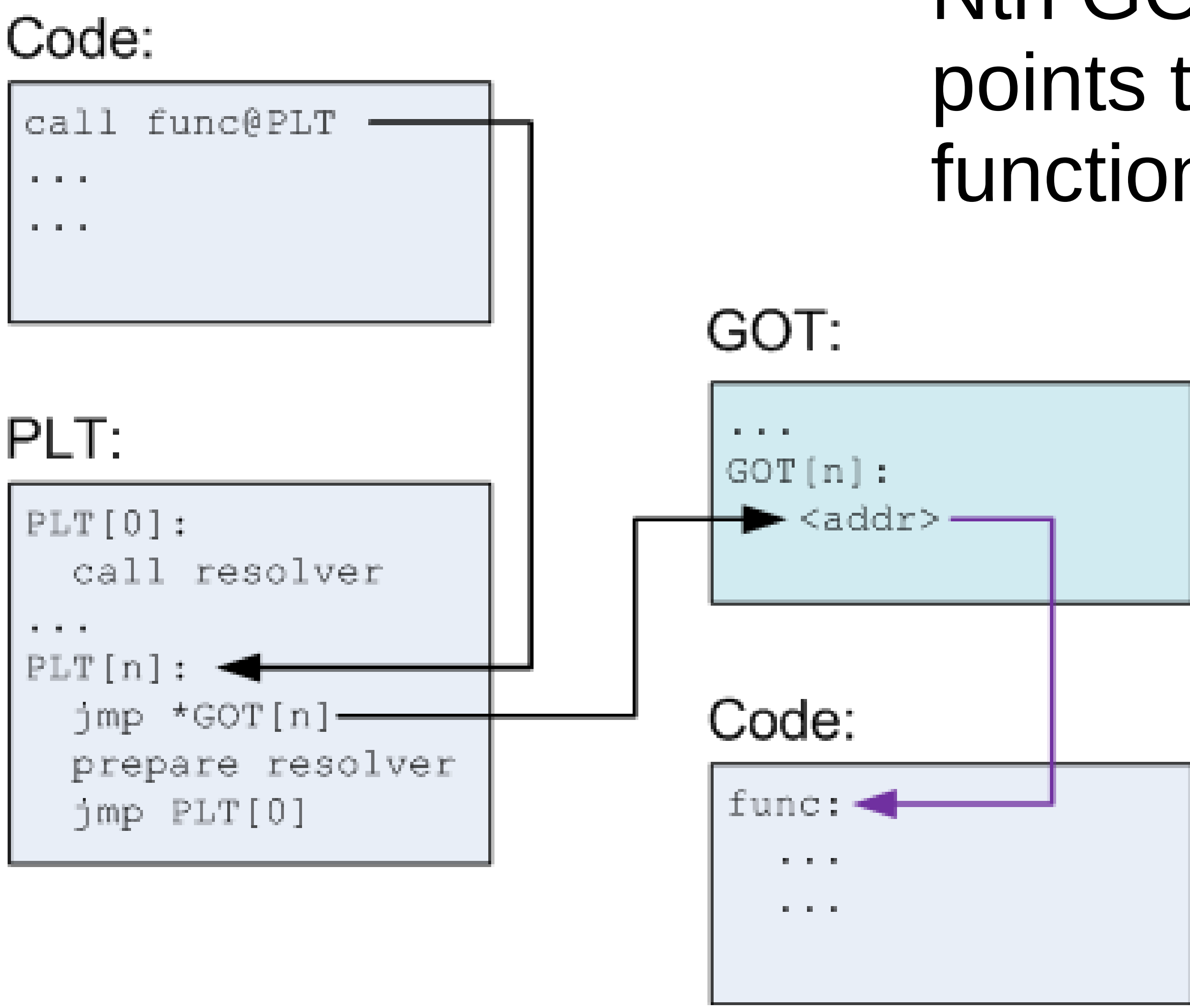
Before function is resolved

- Nth GOT entry points to after the jump



PLT after the function is resolved

- Nth GOT entry points to the actual function



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)

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

```
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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 47a:   53                      push   ebx
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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>
 ...

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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>
```

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>
 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)

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

```
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)

- 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 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 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 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)

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

```
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>
```

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 fraim, so maybe 6)
      - Loosing 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

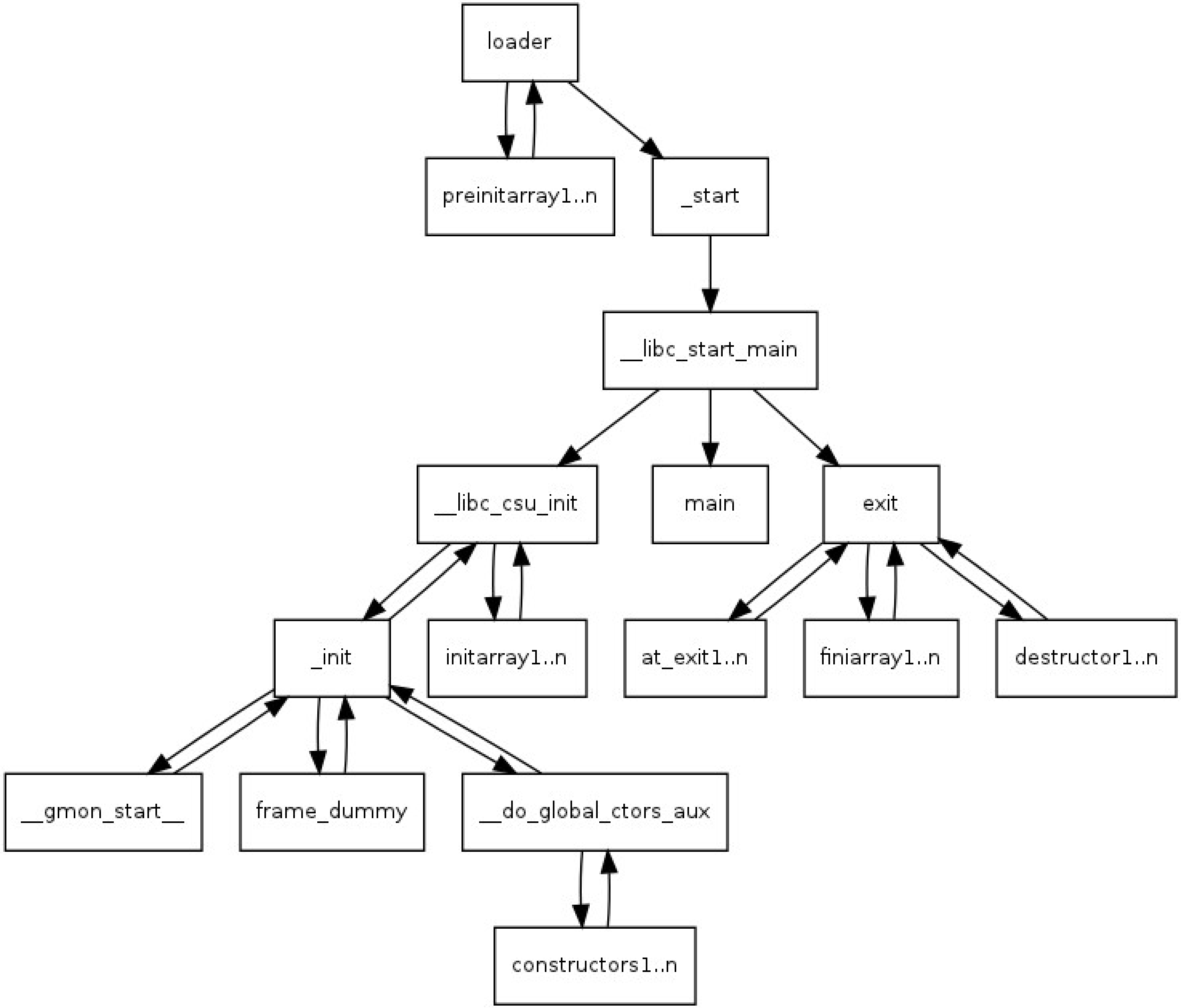
Loading and starting programs

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)

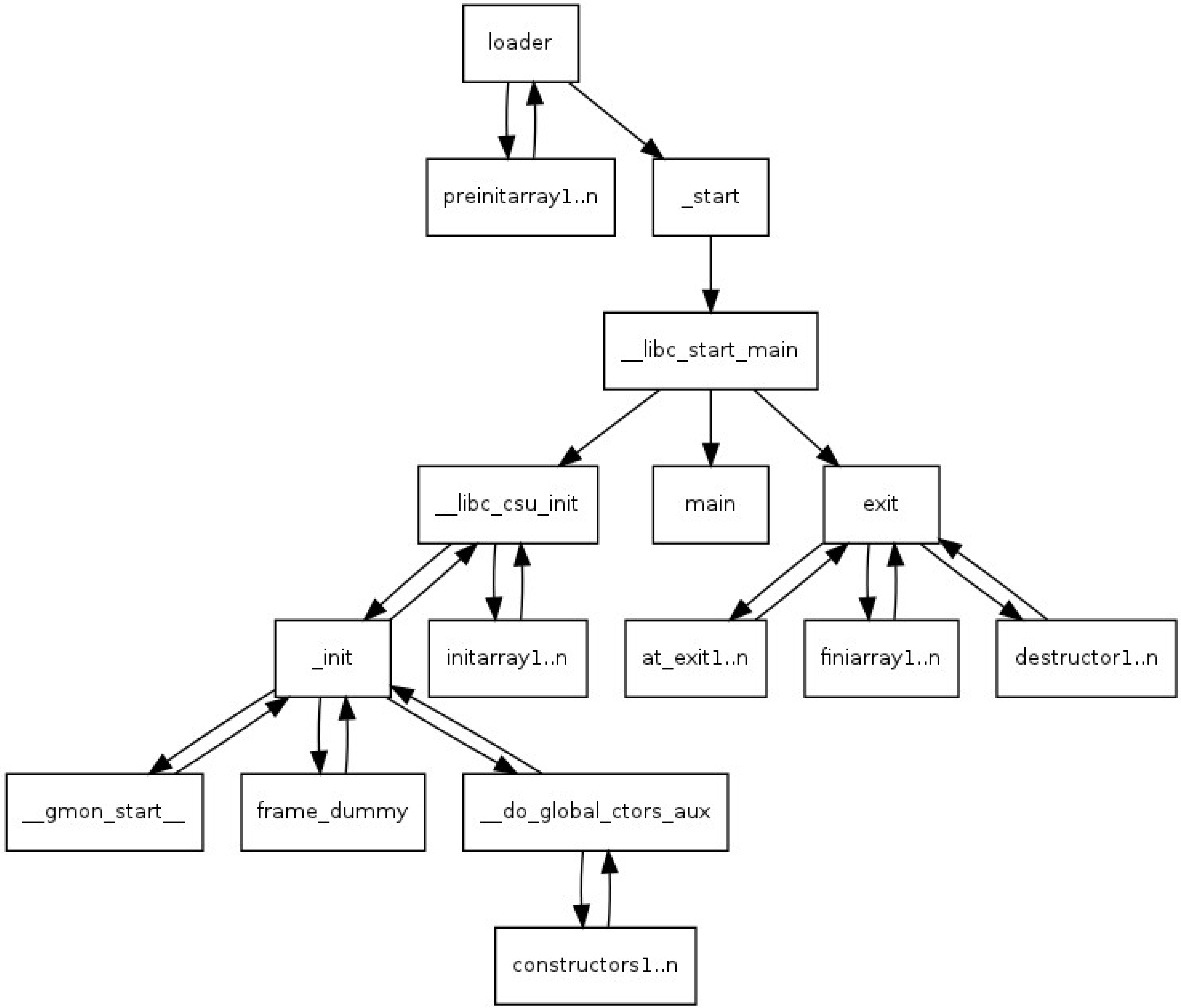
Example of a constructor

```
#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) intializes 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 an 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
...
```