executable encoding: security issues

malware wants to modify executables

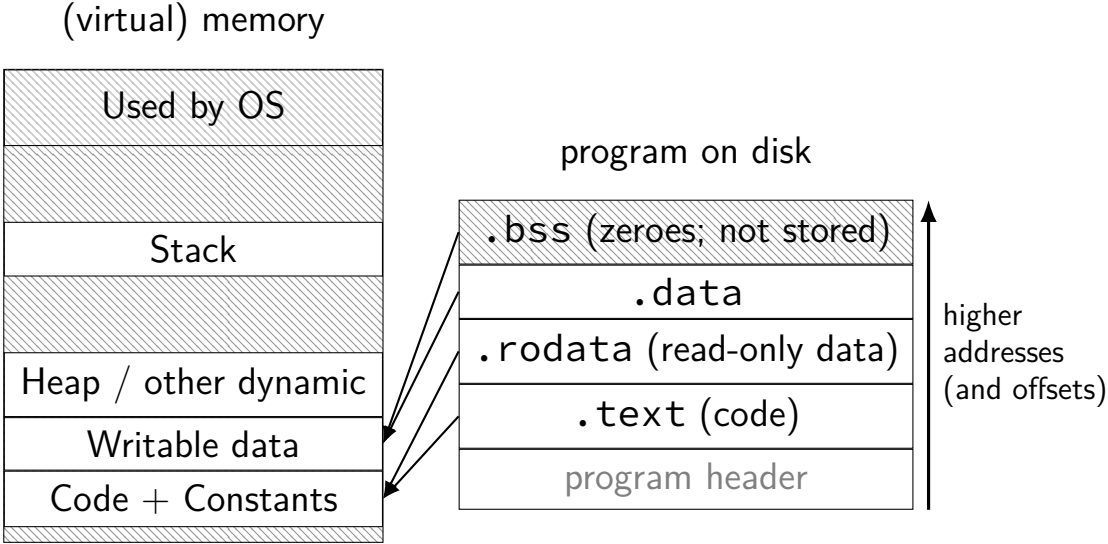
- hide in 'normal' programs (viruses)
- evade program analysis tools by doing weird things

memory vulnerabilities require understanding memory layout

- going from "write memory address X" to "run arbitrary code"
- where are pointers to functions (we could change?)
- where is code (vulnerabilities might want to execute)
- where is data (vulnerabilities might want to read/change)

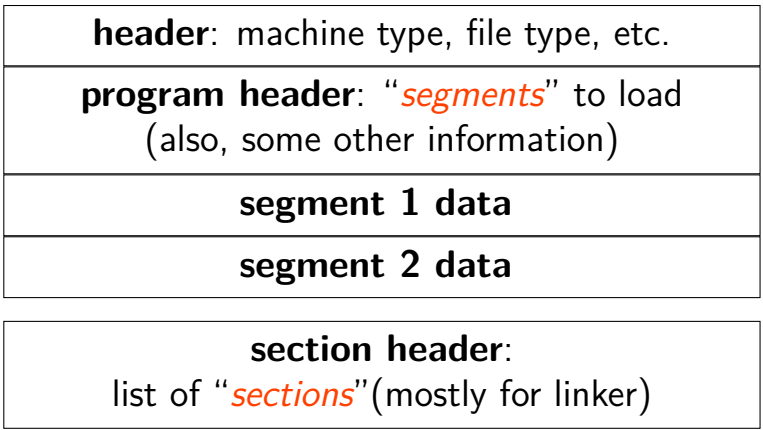
ways we can load+layout programs that are harder to exploit?

memory v. disk



ELF (executable and linking format)

Linux (and some others) executable/object file format



segments versus sections?

note: ELF terminology; may not be true elsewhere!

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

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

segments — executables, used to actually load program

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

section headers

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

sections

tons of “sections”

not actually needed/used to run program

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

- location in executable *and* in memory

some sections aren’t stored (no “CONTENTS” flag)

- just all zeroes

selected sections

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

based on http://people.redhat.com/mpolacek/src/devconf2012.pdf

ELF example

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

`-x`: output all headers

```
/bin/busybox:     file format elf64-x86-64
/bin/busybox
architecture: i386:x86-64, flags 0x00000102:
EXEC_P, D_PAGED
start address 0x0000000000402170

Program Header:
[...]

Sections:
[...]
```

ELF example

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

`-x`: output all headers

```
/bin/busybox:     file format elf64-x86-64
/bin/busybox
architecture: i386:x86-64, flags 0x00000102:
EXEC_P, D_PAGED
start address 0x0000000000402170

Program Header:
[...]

Sections:
[...]
```

ELF example

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

`-x`: output all headers

```
/bin/busybox:     file format elf64-x86-64
/bin/busybox
architecture: i386:x86-64, flags 0x00000102:
EXEC_P, D_PAGED
start address 0x0000000000402170

Program Header:
[...]

Sections:
[...]
```

a program header (1)

```
Program Header:
[...]
LOAD off    0x0001000 vaddr 0x0401000 paddr 0x0401000 align 2**12
     filesz 0x01b04ed memsz 0x01b04ed flags r-x
[...]
LOAD off    0x0207950 vaddr 0x0608950 paddr 0x0608950 align 2**12
     filesz 0x0008f40 memsz 0x000c718 flags rw-
```

load `0x1bd04ed` bytes (read+executable):

- from `0x1000` bytes into the file
- to memory at `0x401000`

load `0x8f40` bytes (read+write):

- from `0x207950` bytes into the file
- to memory at `0x608950`
- plus (`0xc718`–`0x8f40`) bytes of zeroes

a program header (1)

```
Program Header:
[...]
LOAD off    0x0001000 vaddr 0x0401000 paddr 0x0401000 align 2**12
     filesz 0x01b04ed memsz 0x01b04ed flags r-x
[...]
LOAD off    0x0207950 vaddr 0x0608950 paddr 0x0608950 align 2**12
     filesz 0x0008f40 memsz 0x000c718 flags rw-
```

load *0x1bd04ed* bytes (read+executable):

- from 0x1000 bytes into the file
- to memory at 0x401000

load 0x8f40 bytes (read+write):

- from 0x207950 bytes into the file
- to memory at 0x608950
- plus (0xc718–0x8f40) bytes of zeroes

a program header (1)

```
Program Header:
[...]
LOAD off    0x0001000 vaddr 0x0401000 paddr 0x0401000 align 2**12
     filesz 0x01b04ed memsz 0x01b04ed flags r-x
[...]
LOAD off    0x0207950 vaddr 0x0608950 paddr 0x0608950 align 2**12
     filesz 0x0008f40 memsz 0x000c718 flags rw-
```

load `0x1bd04ed` bytes (*read+executable*):

from `0x1000` bytes into the file

to memory at `0x401000`

load `0x8f40` bytes (read+write):

from `0x207950` bytes into the file

to memory at `0x608950`

plus (`0xc718`–`0x8f40`) bytes of zeroes

a program header (1)

```
Program Header:
[...]
LOAD off    0x0001000 vaddr 0x0401000 paddr 0x0401000 align 2**12
     filesz 0x01b04ed memsz 0x01b04ed flags r-x
[...]
LOAD off    0x0207950 vaddr 0x0608950 paddr 0x0608950 align 2**12
     filesz 0x0008f40 memsz 0x000c718 flags rw-
```

load `0x1bd04ed` bytes (read+executable):

from `0x1000` bytes into the file

to memory at `0x401000`

load `0x8f40` bytes (read+write):

from `0x207950` bytes into the file

to memory at `0x608950`

plus (`0xc718`–`0x8f40`) bytes of zeroes

a program header (2)

```
Program Header:
[...]
    NOTE off    0x0000290 vaddr 0x0400290 paddr 0x0400290 align 2**2
         filesz 0x0000044 memsz 0x0000044 flags r--
     TLS off    0x0207950 vaddr 0x0608950 paddr 0x0608950 align 2**3
         filesz 0x0000030 memsz 0x0000092 flags r--
0x6474e553 off  0x0000270 vaddr 0x0400270 paddr 0x0400270 align 2**3
         filesz 0x0000020 memsz 0x0000020 flags r--
   STACK off    0x0000000 vaddr 0x0000000 paddr 0x0000000 align 2**4
         filesz 0x0000000 memsz 0x0000000 flags rw-
   RELRO off    0x0207950 vaddr 0x0608950 paddr 0x0608950 align 2**0
         filesz 0x00066b0 memsz 0x00066b0 flags r--
[...]
```

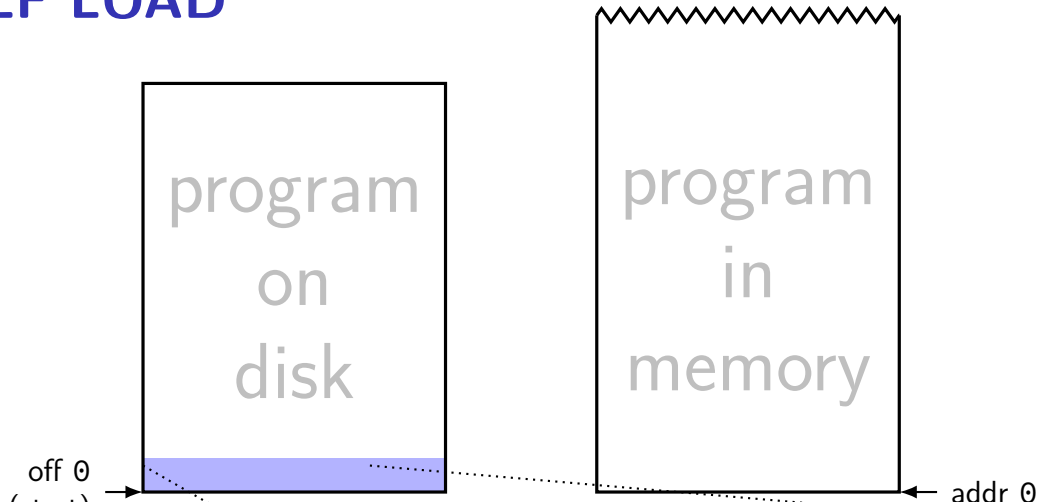
NOTE — comment

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

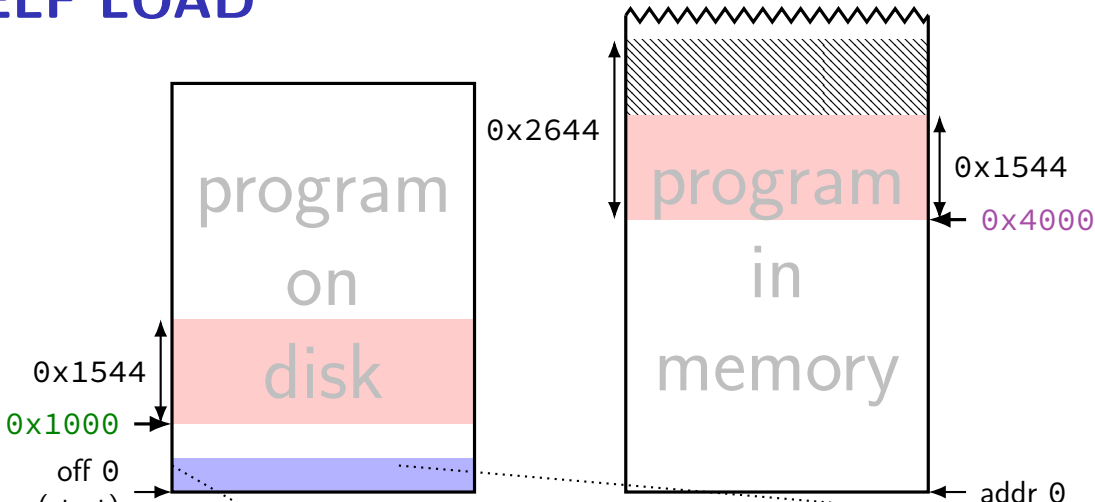
0x6474e553 — ‘GNU_PROPERTY’ — adtl linker/loader info

STACK — indicates stack is read/write

ELF LOAD


program
on
disk
program
in
memory
off 0
(start)
addr 0
LOAD off 0x1000 vaddr 0x4000 …
filesz 0x1544 memsz 0x2644 …

ELF LOAD


program
on
disk
0x1544
0x1000
off 0
(start)
0x2644
program
in
memory
0x1544
0x4000
addr 0
LOAD off 0x1000 vaddr 0x4000 …
filesz 0x1544 memsz 0x2644 …

dynamic library headers

```
/lib/x86_64-linux-gnu/libc.so.6:     file format elf64-x86-64
/lib/x86_64-linux-gnu/libc.so.6
architecture: i386:x86-64, flags 0x00000150:
HAS_SYMS, DYNAMIC, D_PAGED
start address 0x00000000000271f0

Program Header:
    PHDR off    0x0000000000000040 vaddr 0x0000000000000040 paddr 0x0000000000000040
         filesz 0x0000000000000310 memsz 0x0000000000000310 flags r--
  INTERP off    0x00000000001c16a0 vaddr 0x00000000001c16a0 paddr 0x00000000001c16a0
         filesz 0x000000000000001c memsz 0x000000000000001c flags r--
    LOAD off    0x0000000000000000 vaddr 0x0000000000000000 paddr 0x0000000000000000
         filesz 0x0000000000024940 memsz 0x0000000000024940 flags r--
...
```

DYNAMIC — instead of EXEC_P

dynamic library headers

```
/lib/x86_64-linux-gnu/libc.so.6:     file format elf64-x86-64
/lib/x86_64-linux-gnu/libc.so.6
architecture: i386:x86-64, flags 0x00000150:
HAS_SYMS, DYNAMIC, D_PAGED
start address 0x00000000000271f0

Program Header:
    PHDR off    0x0000000000000040 vaddr 0x0000000000000040 paddr 0x0000000000000040
         filesz 0x0000000000000310 memsz 0x0000000000000310 flags r--
  INTERP off    0x00000000001c16a0 vaddr 0x00000000001c16a0 paddr 0x00000000001c16a0
         filesz 0x000000000000001c memsz 0x000000000000001c flags r--
    LOAD off    0x0000000000000000 vaddr 0x0000000000000000 paddr 0x0000000000000000
         filesz 0x0000000000024940 memsz 0x0000000000024940 flags r--
...
```

specifies loading starting at address 0
but dynamic linker will actually choose a different starting address

position-independent executables

```
hello.exe:     file format elf64-x86-64
hello.exe
architecture: i386:x86-64, flags 0x00000150:
HAS_SYMS, DYNAMIC, D_PAGED
start address 0x0000000000001080

Program Header:
    PHDR off    0x0000000000000040 vaddr 0x0000000000000040 paddr 0x0000000000000040
         filesz 0x00000000000002d8 memsz 0x00000000000002d8 flags r--
  INTERP off    0x0000000000000318 vaddr 0x0000000000000318 paddr 0x0000000000000318
         filesz 0x000000000000001c memsz 0x000000000000001c flags r--
    LOAD off    0x0000000000000000 vaddr 0x0000000000000000 paddr 0x0000000000000000
         filesz 0x00000000000005f8 memsz 0x00000000000005f8 flags r--
```

executable with headers like dynamic library
“position-independent executable”: can be loaded at any address

position-independent executables

```
hello.exe:     file format elf64-x86-64
hello.exe
architecture: i386:x86-64, flags 0x00000150:
HAS_SYMS, DYNAMIC, D_PAGED
start address 0x0000000000001080

Program Header:
    PHDR off    0x0000000000000040 vaddr 0x0000000000000040 paddr 0x0000000000000040
         filesz 0x00000000000002d8 memsz 0x00000000000002d8 flags r--
  INTERP off    0x0000000000000318 vaddr 0x0000000000000318 paddr 0x0000000000000318
         filesz 0x000000000000001c memsz 0x000000000000001c flags r--
    LOAD off    0x0000000000000000 vaddr 0x0000000000000000 paddr 0x0000000000000000
         filesz 0x00000000000005f8 memsz 0x00000000000005f8 flags r--
```

other executable formats

PE (Portable Executable) — Windows

Mach-O — MacOS X

broadly similar to ELF

differences:

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

simple executable startup

copy segments into memory

jump to start address

executable startup code

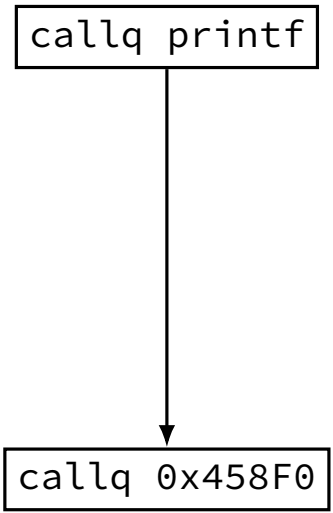
Linux: executables don't start at `main`

why not?

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

compiler links in startup code

linking



static v. dynamic linking

static linking — linking *to create executable*

dynamic linking — linking *when executable is run*

static v. dynamic linking

static linking — linking *to create executable*

dynamic linking — linking *when executable is run*

conceptually: no difference in how they work

reality — very different mechanisms

linking data structures

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

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

relocation table: offset ⇒ (name, kind)

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

hello.s

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

hello.o (pre-static or dynamic linking)

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

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

hello.o (pre-static or dynamic linking)

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

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

undefined symbol: look for `puts` elsewhere

hello.o (pre-static or dynamic linking)

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

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

insert address of puts, format for `call`

hello.o (pre-static or dynamic linking)

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

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

insert address of string, format for `movq`

hello.o (pre-static or dynamic linking)

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

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

different ways to represent address
32S — signed 32-bit value
PC32 — 32-bit difference from current address

hello.o (pre-static or dynamic linking)

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

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

g: global — used by other files
l: local

hello.o (pre-static or dynamic linking)

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

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

`.text` segment beginning plus 0 bytes

hello.o / statically linked, no PIE

hello.o:

```
Disassembly of section .text:

0000000000000000 <main>:
   0:   48 c7 c7 00 00 00 00    mov    $0x0,%rdi
                        3: R_X86_64_32S .data
   7:   e8 00 00 00 00          call   c <main+0xc>
                        8: R_X86_64_PLT32       puts-0x4
   c:   c3                      ret
```

hello.exe (gcc -static -no-pie):

```
Disassembly of section .text:
...
 00000000004016c3 <main>:
   4016c3:►      48 c7 c7 b5 16 40 00 ►  mov    $0x4016b5,%rdi
   4016ca:►      e8 e1 a9 00 00       ►  call   40c0b0 <_IO_puts>
   4016cf:►      c3                   ►  ret
...
```

symbols in executable

```
SYMBOL TABLE:
0000000000000000 l    df *ABS*  0000000000000000 crt1.o
00000000004002b4 l     O .note.ABI-tag  0000000000000020 __ab
0000000000000000 l    df *ABS*  0000000000000000 assert.o
0000000000498530 l     O .rodata        0000000000000013 errs
0000000000401100 l     F .text  000000000000000f __assert_fai
```

...

by default, symbol information in statically-linked executable

...but not actually used to run it!

can be stripped (-s linker option or strip command) isntead:

```
SYMBOL TABLE:
no symbols
```

exercise: finding without symbols?

how can I find where functions are without symbols?

ideally: some *automated* way to do this?

interlude: strace

`strace` — system call tracer

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

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

statically linked hello.exe

`gcc -no-pie -static -o hello-static.exe hello.s`

`strace ./hello-static.exe`:

```
execve("./hello-static.exe", ["./hello-static.exe"], [/* 46 vars */]) = 0
uname(sysname="Linux", nodename="reiss-lenovo", ...) = 0
brk(NULL)                               = 0x20a5000
brk(0x20a61c0)                          = 0x20a61c0
arch_prctl(ARCH_SET_FS, 0x20a5880)      = 0
readlink("/proc/self/exe", "/home/cr4bd/spring2017/cs4630/sl"..., 4096) = 62
brk(0x20c71c0)                          = 0x20c71c0
brk(0x20c8000)                          = 0x20c8000
access("/etc/ld.so.nohwcap", F_OK)      = -1 ENOENT (No such file or directory)
fstat(1, st_mode=S_IFCHR|0620, st_rdev=makedev(136, 1), ...) = 0
write(1, "Hello, World!\n", 14)         = 14
exit_group(14)                          = ?
+++ exited with 14 +++
```

statically linked hello.exe

`gcc -no-pie -static -o hello-static.exe hello.s`

`strace ./hello-static.exe`:

```
execve("./hello-static.exe", ["./hello-static.exe"], [/* 46 vars */]) = 0
uname(sysname="Linux", nodename="reiss-lenovo", ...) = 0
brk(NULL)                               = 0x20a5000
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arch_prctl(ARCH_SET_FS, 0x20a5880)      = 0
readlink("/proc/self/exe", "/home/cr4bd/spring2017/cs4630/sl"..., 4096) = 62
brk(0x20c71c0)                          = 0x20c71c0
brk(0x20c8000)                          = 0x20c8000
access("/etc/ld.so.nohwcap", F_OK)      = -1 ENOENT (No such file or directory)
fstat(1, st_mode=S_IFCHR|0620, st_rdev=makedev(136, 1), ...) = 0
write(1, "Hello, World!\n", 14)         = 14
exit_group(14)                          = ?
+++ exited with 14 +++
```

standard library startup

statically linked hello.exe

`gcc -no-pie -static -o hello-static.exe hello.s`

`strace ./hello-static.exe`:

```
execve("./hello-static.exe", ["./hello-static.exe"], [/* 46 vars */]) = 0
uname(sysname="Linux", nodename="reiss-lenovo", ...) = 0
brk(NULL)                               = 0x20a5000
brk(0x20a61c0)                          = 0x20a61c0
arch_prctl(ARCH_SET_FS, 0x20a5880)      = 0
readlink("/proc/self/exe", "/home/cr4bd/spring2017/cs4630/sl"..., 4096) = 62
brk(0x20c71c0)                          = 0x20c71c0
brk(0x20c8000)                          = 0x20c8000
access("/etc/ld.so.nohwcap", F_OK)      = -1 ENOENT (No such file or directory)
fstat(1, st_mode=S_IFCHR|0620, st_rdev=makedev(136, 1), ...) = 0
write(1, "Hello, World!\n", 14)         = 14
exit_group(14)                          = ?
+++ exited with 14 +++
```

memory allocation

statically linked hello.exe

`gcc -no-pie -static -o hello-static.exe hello.s`

`strace ./hello-static.exe`:

```
execve("./hello-static.exe", ["./hello-static.exe"], [/* 46 vars */]) = 0
uname(sysname="Linux", nodename="reiss-lenovo", ...) = 0
brk(NULL)                               = 0x20a5000
brk(0x20a61c0)                          = 0x20a61c0
arch_prctl(ARCH_SET_FS, 0x20a5880)      = 0
readlink("/proc/self/exe", "/home/cr4bd/spring2017/cs4630/sl"..., 4096) = 62
brk(0x20c71c0)                          = 0x20c71c0
brk(0x20c8000)                          = 0x20c8000
access("/etc/ld.so.nohwcap", F_OK)      = -1 ENOENT (No such file or directory)
fstat(1, st_mode=S_IFCHR|0620, st_rdev=makedev(136, 1), ...) = 0
write(1, "Hello, World!\n", 14)         = 14
exit_group(14)                          = ?
+++ exited with 14 +++
```

implementation of puts

statically linked hello.exe

```
gcc -no-pie -static -o hello-static.exe hello.s
```

`strace ./hello-static.exe`:

```
execve("./hello-static.exe", ["./hello-static.exe"], [/* 46 vars */]) = 0
uname(sysname="Linux", nodename="reiss-lenovo", ...) = 0
brk(NULL)                               = 0x20a5000
brk(0x20a61c0)                          = 0x20a61c0
arch_prctl(ARCH_SET_FS, 0x20a5880)      = 0
readlink("/proc/self/exe", "/home/cr4bd/spring2017/cs4630/sl"..., 4096) = 62
brk(0x20c71c0)                          = 0x20c71c0
brk(0x20c8000)                          = 0x20c8000
access("/etc/ld.so.nohwcap", F_OK)      = -1 ENOENT (No such file or directory)
fstat(1, st_mode=S_IFCHR|0620, st_rdev=makedev(136, 1), ...) = 0
write(1, "Hello, World!\n", 14)         = 14
exit_group(14)                          = ?
+++ exited with 14 +++
```

standard library shutdown

dynamically linked hello.exe

```
gcc -no-pie -o hello.exe hello.s
```

strace ./hello.exe:

```
execve("./hello.exe", ["./hello.exe"], [/* 46 vars */]) = 0
...
mmap(NULL, 8192, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) = 0x7fdfeeb39000
access("/etc/ld.so.preload", R_OK)      = -1 ENOENT (No such file or directory)
open("/etc/ld.so.cache", O_RDONLY|O_CLOEXEC) = 3
fstat(3, st_mode=S_IFREG|0644, st_size=137808, ...) = 0
...
open("/lib/x86_64-linux-gnu/libc.so.6", O_RDONLY|O_CLOEXEC) = 3
read(3, "\177ELF\2\1\1\3\0\0\0\0\0\0\0\0\3\0>\0\1\0\0\0P\t\2\0\0\0\0"..., 832) = 832
fstat(3, st_mode=S_IFREG|0755, st_size=1864888, ...) = 0
mmap(NULL, 3967392, PROT_READ|PROT_EXEC, ..., 3, 0) = 0x7fdfee54d000
mprotect(0x7fdfee70c000, 2097152, PROT_NONE) = 0
mmap(0x7fdfee90c000, 24576, PROT_READ|PROT_WRITE, ..., 3, 0x1bf000) = 0x7fdfee90c000
mmap(0x7fdfee912000, 14752, PROT_READ|PROT_WRITE, ..., -1, 0) = 0x7fdfee912000
close(3)                                = 0
...
write(1, "Hello, World!\n", 14)         = 14
exit_group(14)                          = ?
+++ exited with 14 +++
```

dynamically linked hello.exe

```
gcc -no-pie -o hello.exe hello.s
```

strace ./hello.exe:

```
execve("./hello.exe", ["./hello.exe"], [/* 46 vars */]) = 0
...
mmap(NULL, 8192, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) = 0x7fdfeeb39000
access("/etc/ld.so.preload", R_OK)      = -1 ENOENT (No such file or directory)
open("/etc/ld.so.cache", O_RDONLY|O_CLOEXEC) = 3
fstat(3, st_mode=S_IFREG|0644, st_size=137808, ...) = 0
...
open("/lib/x86_64-linux-gnu/libc.so.6", O_RDONLY|O_CLOEXEC) = 3
read(3, "\177ELF\2\1\1\3\0\0\0\0\0\0\0\0\3\0>\0\1\0\0\0P\t\2\0\0\0\0"..., 832) = 832
fstat(3, st_mode=S_IFREG|0755, st_size=1864888, ...) = 0
mmap(NULL, 3967392, PROT_READ|PROT_EXEC, ..., 3, 0) = 0x7fdfee54d000
mprotect(0x7fdfee70
mmap(0x7fdfee90c000                                                    0x7fdfee90c000
mmap(0x7fdfee912000                                                    ee912000
close(3)                                = 0
...
write(1, "Hello, World!\n", 14)          = 14
exit_group(14)                          = ?
+++ exited with 14 +++
```

the standard C library (includes puts)

dynamically linked hello.exe

```
gcc -no-pie -o hello.exe hello.s
```

strace ./hello.exe:

```
execve("./hello.exe", ["./hello.exe"], [/* 46 vars */]) = 0
...
mmap(NULL, 8192, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) = 0x7fdfeeb39000
access("/etc/ld.so.preload", R_OK)      = -1 ENOENT (No such file or directory)
open("/etc/ld.so.cache", O_RDONLY|O_CLOEXEC) = 3
fstat(3, st_mode=S_IFREG|0644, st_size=137808, ...) = 0
...
open("/lib/x86_64-linux-gnu/libc.so.6", O_RDONLY|O_CLOEXEC) = 3
read(3, "\177ELF\2\1\1\3\0\0\0\0\0\0\0\0\3\0>\0\1\0\0\0P\t\2\0\0\0\0"..., 832) = 832
fstat(3, st_mode=S_IFREG|0755, st_size=1864888, ...) = 0
mmap(NULL, 3967392, PROT_READ|PROT_EXEC, ..., 3, 0) = 0x7fdfee54d000
mprotect(0x7fdfee70c
mmap(0x7fdfee90c000,                                                    0x7fdfee90c000
mmap(0x7fdfee912000,                                                    fee912000
close(3)                                = 0
...
write(1, "Hello, World!\n", 14)          = 14
exit_group(14)                          = ?
+++ exited with 14 +++
```

memory allocation (different method)

dynamically linked hello.exe

```
gcc -no-pie -o hello.exe hello.s
```

strace ./hello.exe:

```
execve("./hello.exe", ["./hello.exe"], [/* 46 vars */]) = 0
...
mmap(NULL, 8192, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) = 0x7fdfeeb39000
access("/etc/ld.so.preload", R_OK)      = -1 ENOENT (No such file or directory)
open("/etc/ld.so.cache", O_RDONLY|O_CLOEXEC) = 3
fstat(3, st_mode=S_IFREG|0644, st_size=137808, ...) = 0
...
open("/lib/x86_64-linux-gnu/libc.so.6", O_RDONLY|O_CLOEXEC) = 3
read(3, "\177ELF\2\1\1\3\0\0\0\0\0\0\0\0\3\0>\0\1\0\0\0P\t\2\0\0\0\0"..., 832) = 832
fstat(3, st_mode=S_IFREG|0755, st_size=1864888, ...) = 0
mmap(NULL, 3967392, PROT_READ|PROT_EXEC, ..., 3, 0) = 0x7fdfee54d000
mprotect(0x7fdfee70c000,
mmap(0x7fdfee90c000, 245                                    00) = 0x7fdfee90c000
mmap(0x7fdfee912000, 147                                    0x7fdfee912000
close(3)                                = 0
...
write(1, "Hello, World!\n", 14)          = 14
exit_group(14)                          = ?
+++ exited with 14 +++
```

read standard C library header

dynamically linked hello.exe

```
gcc -no-pie -o hello.exe hello.s
```

strace ./hello.exe:

```
execve("./hello.exe", ["./hello.exe"], [/* 46 vars */]) = 0
...
mmap(NULL, 8192, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) = 0x7fdfeeb39000
access("/etc/ld.so.preload", R_OK)      = -1 ENOENT (No such file or directory)
open("/etc/ld.so.cache", O_RDONLY|O_CLOEXEC) = 3
fstat(3, st_mode=S_IFREG|0644, st_size=137808, ...) = 0
...
open("/lib/x86_64-linux-gnu/libc.so.6", O_RDONLY|O_CLOEXEC) = 3
read(3, "\177ELF\2\1\1\3\0\0\0\0\0\0\0\0\3\0>\0\1\0\0\0P\t\2\0\0\0\0"..., 832) = 832
fstat(3, st_mode=S_IFREG|0755, st_size=1864888, ...) = 0
mmap(NULL, 3967392, PROT_READ|PROT_EXEC, ..., 3, 0) = 0x7fdfee54d000
mprotect(0x7fdfee7
mmap(0x7fdfee90c00                                                    x7fdfee90c000
mmap(0x7fdfee91200                                                    e912000
close(3)                                = 0
...
write(1, "Hello, World!\n", 14)          = 14
exit_group(14)                          = ?
+++ exited with 14 +++
```

load standard C library (3 = opened file)

dynamically linked hello.exe

```
gcc -no-pie -o hello.exe hello.s
```

strace ./hello.exe:

```
execve("./hello.exe", ["./hello.exe"], [/* 46 vars */]) = 0
...
mmap(NULL, 8192, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) = 0x7fdfeeb39000
access("/etc/ld.so.preload", R_OK)      = -1 ENOENT (No such file or directory)
open("/etc/ld.so.cache", O_RDONLY|O_CLOEXEC) = 3
fstat(3, st_mode=S_IFREG|0644, st_size=137808, ...) = 0
...
open("/lib/x86_64-linux-gnu/libc.so.6", O_RDONLY|O_CLOEXEC) = 3
read(3, "\177ELF\2\1\1\3\0\0\0\0\0\0\0\0\3\0>\0\1\0\0\0P\t\2\0\0\0\0\0"..., 832) = 832
fstat(3, st_mode=S_IFREG|0755, st_size=1864888, ...) = 0
mmap(NULL, 3967392, PROT_READ|PROT_EXEC, ..., 3, 0) = 0x7fdfee54d000
mprotect(0x7
mmap(0x7fdfe                                                    ee90c000
mmap(0x7fdfe                                                    00
close(3)                                = 0
...
write(1, "Hello, World!\n", 14)          = 14
exit_group(14)                          = ?
+++ exited with 14 +++
```

allocate zero-initialized data segment for C library

where's the linker

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

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

where's the linker

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

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

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

on Linux: contains loading code instead of core OS

- OS loads it instead of program

objdump — the interpreter

excerpt from `objdump -sx hello.exe`:

```
Program Header:
...
  INTERP off    0x0000238 vaddr 0x0400318 paddr 0x0400238 align 2**0
         filesz 0x000001c memsz 0x000001c flags r--
...
Contents of section .interp:
 400318 2f6c6962 36342f6c 642d6c69 6e75782d  /lib64/ld-linux-
 400328 7838362d 36342e73 6f2e3200           x86-64.so.2.
```

dynamic linking: what to load? (1)

excerpt from `objdump -sx hello.exe`:

```
Program Header:
...
 DYNAMIC off    0x0000000000002e20 vaddr 0x0000000000403e20 paddr 0x0000000000403e
         filesz 0x00000000000001d0 memsz 0x00000000000001d0 flags rw-
...
Dynamic Section:
  NEEDED               libc.so.6
  INIT                 0x0000000000401000
  ...
  STRTAB               0x0000000000400420
  ...
```

program header: identifies where dynamic linking info is

dynamic linking info: array of key-value pairs

- needed libraries
- constructor locations (‘INIT’)
- string table location

dynamic linking: what to load? (2)

excerpt from `objdump -sx hello.exe`:

```
Program Header:
...
 DYNAMIC off    0x0000000000002e20 vaddr 0x0000000000403e20 paddr 0x0000000000403e
         filesz 0x00000000000001d0 memsz 0x00000000000001d0 flags rw-
...
Dynamic Section:
  NEEDED               libc.so.6
  INIT                 0x0000000000401000
  ...
  STRTAB               0x0000000000400420
  ...
...
 403e20 01000000 00000000 01000000 00000000  ................
 403e30 0c000000 00000000 00104000 00000000  ..............@...
```

type *0x1 = "DT_NEEDED"* (from ELF manual)

value 0x1 = string table entry 1

type 0xC = "DT_INIT"

value 0x401000

dynamic linking: what to load? (2)

excerpt from `objdump -sx hello.exe`:

```
Program Header:
...
 DYNAMIC off    0x0000000000002e20 vaddr 0x0000000000403e20 paddr 0x0000000000403e
         filesz 0x00000000000001d0 memsz 0x00000000000001d0 flags rw-
...
Dynamic Section:
  NEEDED               libc.so.6
  INIT                 0x0000000000401000
  ...
  STRTAB               0x0000000000400420
  ...
...
 403e20 01000000 00000000 01000000 00000000  ................
 403e30 0c000000 00000000 00104000 00000000  ..............@...
```

type 0x1 = “DT_NEEDED” (from ELF manual)

value *0x1 = string table entry 1*

type 0xC = “DT_INIT”

value 0x401000

dynamic linking: what to load? (2)

excerpt from `objdump -sx hello.exe`:

```
Program Header:
...
 DYNAMIC off    0x0000000000002e20 vaddr 0x0000000000403e20 paddr 0x0000000000403e
         filesz 0x00000000000001d0 memsz 0x00000000000001d0 flags rw-
...
Dynamic Section:
  NEEDED               libc.so.6
  INIT                 0x0000000000401000
  ...
  STRTAB               0x0000000000400420
  ...
...
 403e20 01000000 00000000 01000000 00000000  ................
 403e30 0c000000 00000000 00104000 00000000  ..............:...
```

type 0x1 = “DT_NEEDED” (from ELF manual)

value 0x1 = string table entry 1

type *0xC = “DT_INIT”*

value *0x401000*

adding linker stubs

program.s

```
main:
    ...
    call puts
    ...
```

program.exe

```
GLOBAL_LOOKUP_TABLE:
    ... // placeholders

puts@plt:
    jmp *GLOBAL_LOOKUP_TABLE[index]
    ...
...
main:
    ...
    call puts@plt
    ...
```

+ something that says where `puts` in the lookup table

dynamic linking information

symbol table in libraries: list of functions/variables to find

- with their locations in the library

relocation records in programs: list of functions/variables

- with locations (probably in lookup table) to fill in

dynamically linked puts (non-lazy)

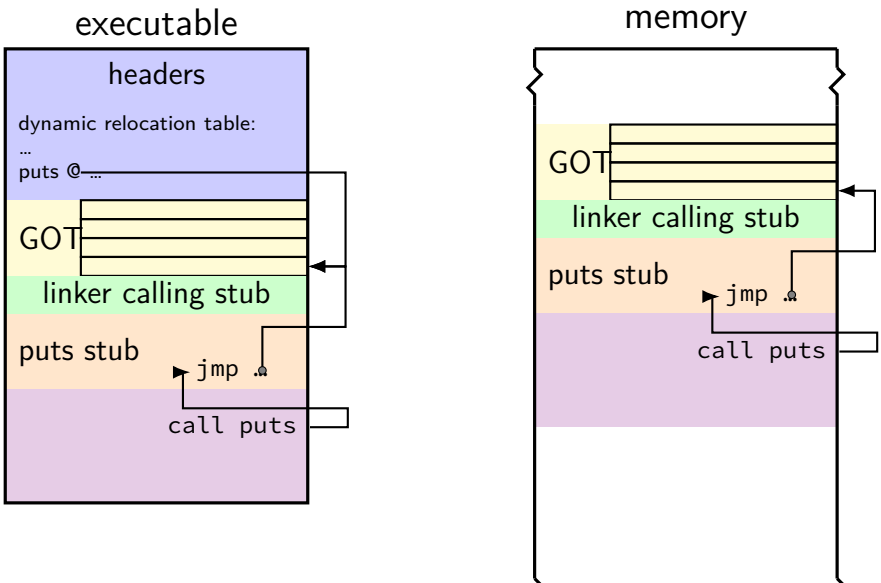
```
DYNAMIC RELOCATION RECORDS
OFFSET           TYPE              VALUE
0000000000403ff0 R_X86_64_GLOB_DAT  __libc_start_main@GLIBC_2.34
0000000000403ff8 R_X86_64_GLOB_DAT  __gmon_start__@Base
0000000000403fe8 R_X86_64_JUMP_SLOT  puts@GLIBC_2.2.5

...

Text:
0000000000401030 <puts@plt>:
  401030:       ff 25 b2 2f 00 00       jmp    *0x2fb2(%rip)        # 403fe8 <puts
```

stub reads pointer from 0x403fe8, jump to location

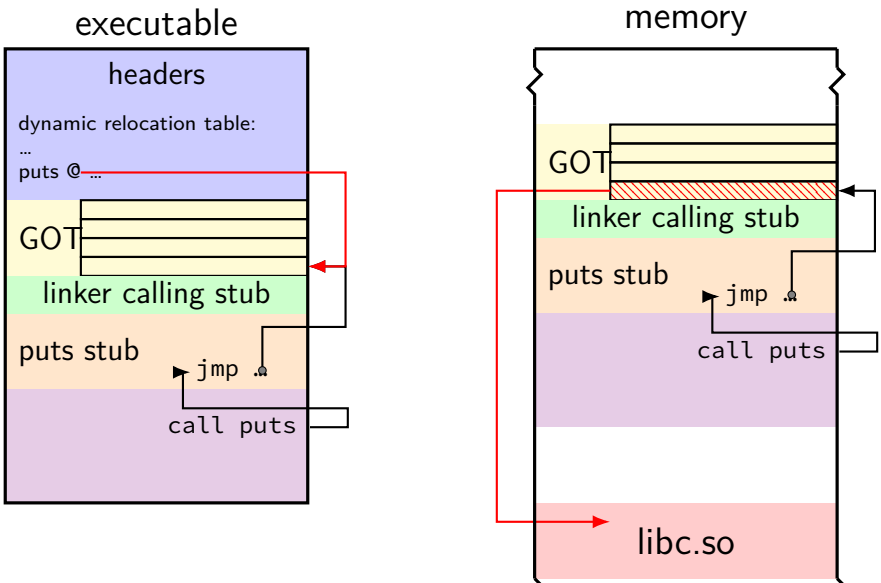
`0x403fe8` part of 'global offset table' (GOT)

relocation table entry indicates where puts pointer goes

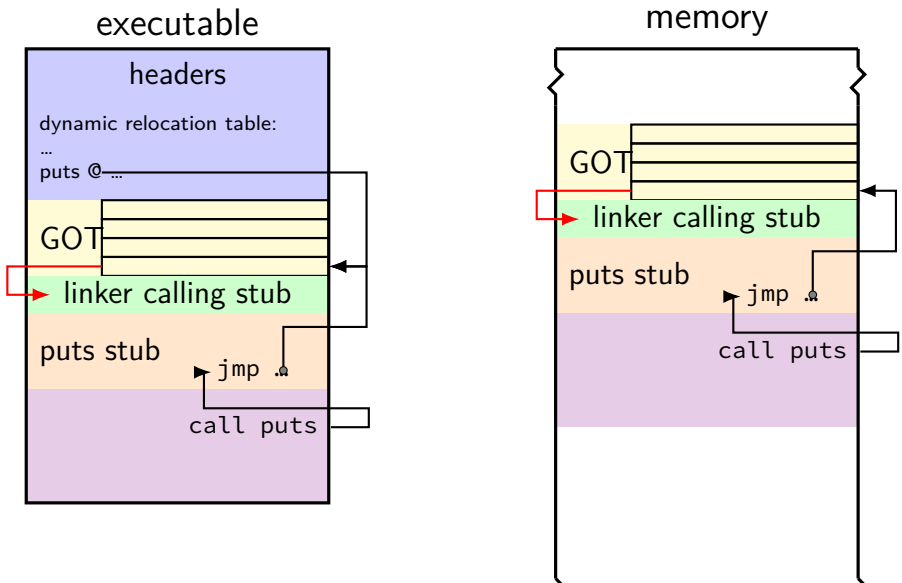
dynamic puts (picture)



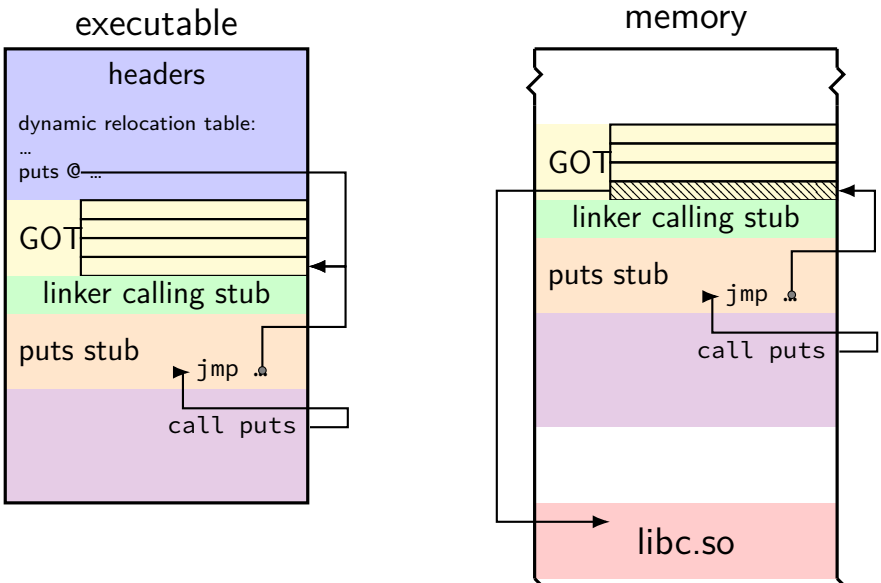
dynamic puts (picture)



dynamic puts (picture)



dynamic puts (picture)



lazy binding

```
0000000000401030 <puts@plt>:
  401030:       ff 25 62 22 00 00       jmp    *0x2262(%rip)        # 403298 <puts@GLIBC_2.2
...
Contents of section .got.plt:
 403280 a0304000 00000000 00000000 00000000  .0@.............
 403290 00000000 00000000 36104000 00000000  ........6.@.....
```

initial contents of `0x403298` = `0x401036` (in .got.plt)

not part of standard library????

lazy binding

```
0000000000401030 <puts@plt>:
  401030:       ff 25 62 22 00 00       jmp    *0x2262(%rip)        # 403298 <puts@GLIBC_2.2
...
Contents of section .got.plt:
 403280 a0304000 00000000 00000000 00000000  .0@.............
 403290 00000000 00000000 36104000 00000000  ........6.@.....
```

initial contents of `0x403298` = `0x401036` (in .got.plt)

not part of standard library????

code found at 0x401036 is routine to invoke dynamic linker code:

```
  401020:       ff 35 62 22 00 00       push   0x2262(%rip)
    # 403288 <_GLOBAL_OFFSET_TABLE_+0x8>
  401026:       ff 25 64 22 00 00       jmp    *0x2264(%rip)
    # 403290 <_GLOBAL_OFFSET_TABLE_+0x10>
...
  401036:       68 00 00 00 00          push   $0x0
  40103b:       e9 e0 ff ff ff          jmp    401020 <_init+0x20>
```

lazy binding

with lazy binding turned on (not always done)

GOT loaded with address of linker routine hard-coded in executable

first call to puts:

- invoke dynamic linker routine pointed to by GOT
- linker routine fills in puts address in `0x404018`
- then jumps to puts

second (and later) call to puts

- 0x404018 contains real address of puts, no indirection

lazy binding pro/con

advantages:

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

disadvantages:

- can move errors (missing functions, etc.) to runtime
- possibly more total overhead
- means global offset table needs to be writable?

preview: exploits and dynamic linking

later we'll talk about memory error exploits

- buffer overflows, etc.

common goal: convert memory overwrite to running code

- bug that "just" allows overwriting memory somewhere
- easy to cause crashes...
- but not so easy to do something in particular

global offset table: function pointers in known location

- useful to overwrite in exploits