CS 3330 — introduction

layers of abstraction

`x += y` “Higher-level” language: C

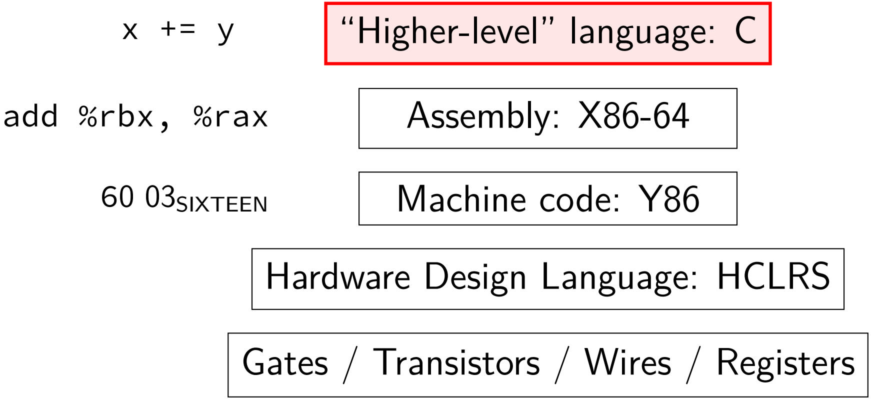
`add %rbx, %rax` Assembly: X86-64

$60\ 03_{\text{SIXTEEN}}$ Machine code: Y86

Hardware Design Language: HCLRS

Gates / Transistors / Wires / Registers

layers of abstraction



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why C?

almost a subset of C++

- notably removes classes, new/delete, iostreams
- other changes, too, so C code often not valid C++ code

direct correspondence to assembly

why C?

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- notably removes classes, new/delete, iostreams
- other changes, too, so C code often not valid C++ code

direct correspondence to assembly

Should help you understand machine!
Manual translation to assembly

why C?

almost a subset of C++

- notably removes classes, new/delete, iostreams
- other changes, too, so C code often not valid C++ code

direct correspondence to assembly

But "clever" (optimizing) compiler might be confusingly indirect instead

homework: C environment

get Unix environment with a C compiler

will have department accounts, hopefully by end of week

- portal.cs.virginia.edu or NX
- instructions off course website (Collab)

some other options:

- Linux (native or VM)
    - 2150 VM image should work
- some assignments can use OS X natively
- some assignments can Windows Subsystem for Linux natively

assignment compatibility

supported platform: department machines

many use laptops

trouble? we'll say to use department machines

most assignments: C and Unix-like environment

also: tool written in Rust — but we'll provide binaries

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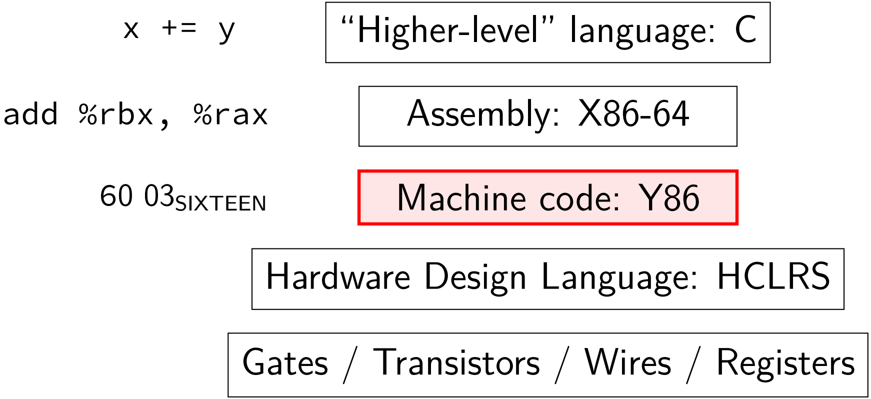
X86-64 assembly

in theory, you know this (CS 2150)

in reality, ...

layers of abstraction



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“Higher-level” language: C

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Assembly: X86-64

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Y86-64??

Y86: our textbook's X86-64 subset

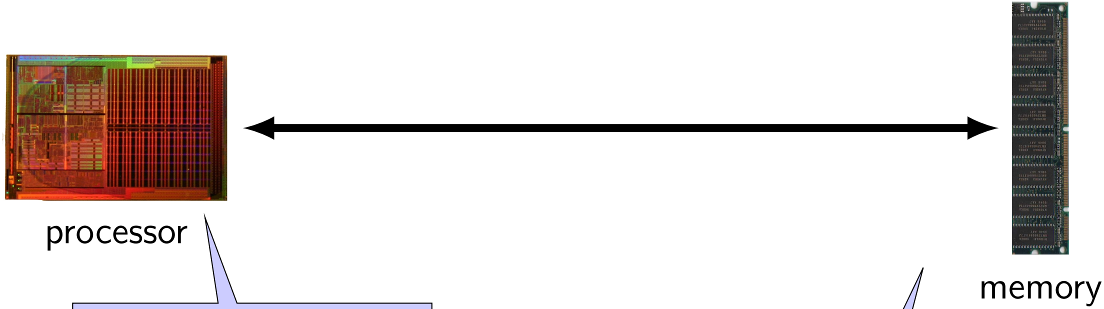
much simpler than real X86-64 encoding

- (which we will not cover)

not as simple as 2150's IBCM

- variable-length encoding
- more than one register
- full conditional jumps
- stack-manipulation instructions

processors and memory

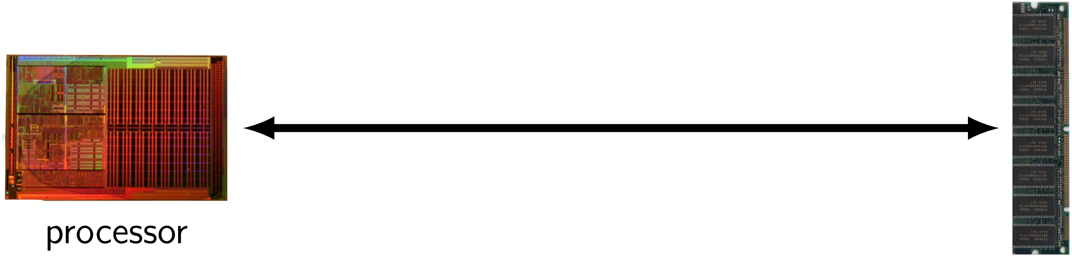


fetch instruction
execute instruction
fetch next instruction
...

stores instructions + data
get read/write request from CPU
return data (if any)
...

Images:
Single core Opteron 8xx die: Dg2fer at the German language Wikipedia, via Wikimedia Commons
SDRAM by Arnaud 25, via Wikimedia Commons

processors and memory



processor

memory

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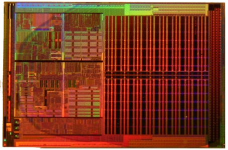

processor

bus
send address + send or get data
(machine code/text/number...)

memory

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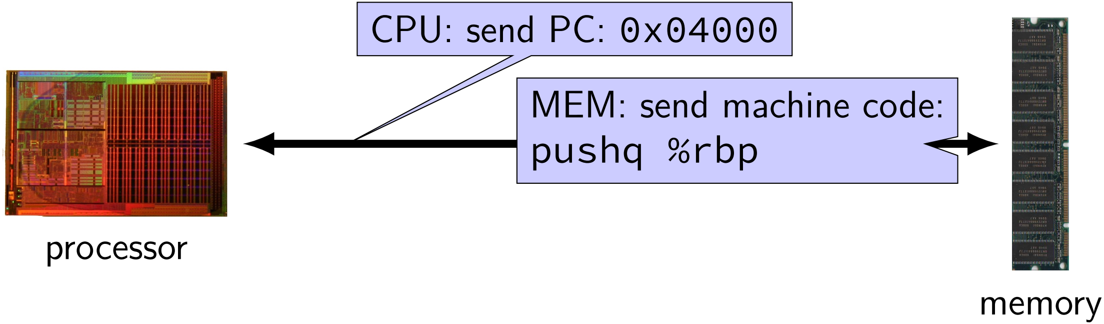

CPU: send PC: `0x04000`

MEM: send machine code: `pushq %rbp`

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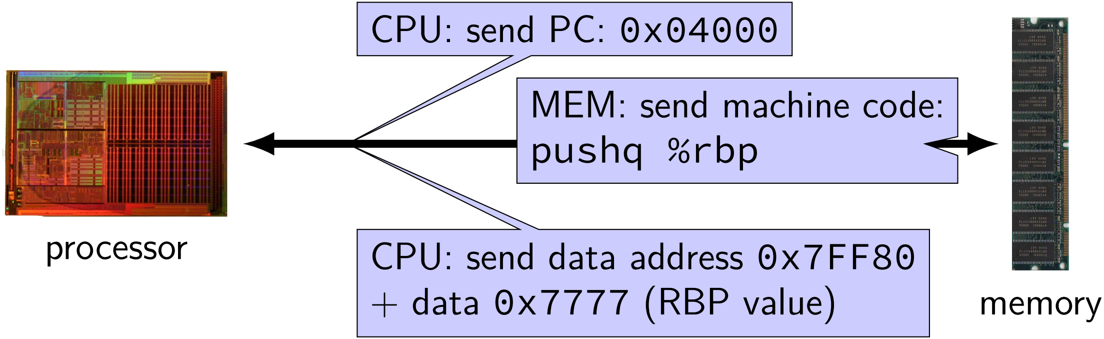

CPU: send PC: `0x04000`

MEM: send machine code: `pushq %rbp`

CPU: send data address `0x7FF80` + data `0x7777` (RBP value)

processor

memory

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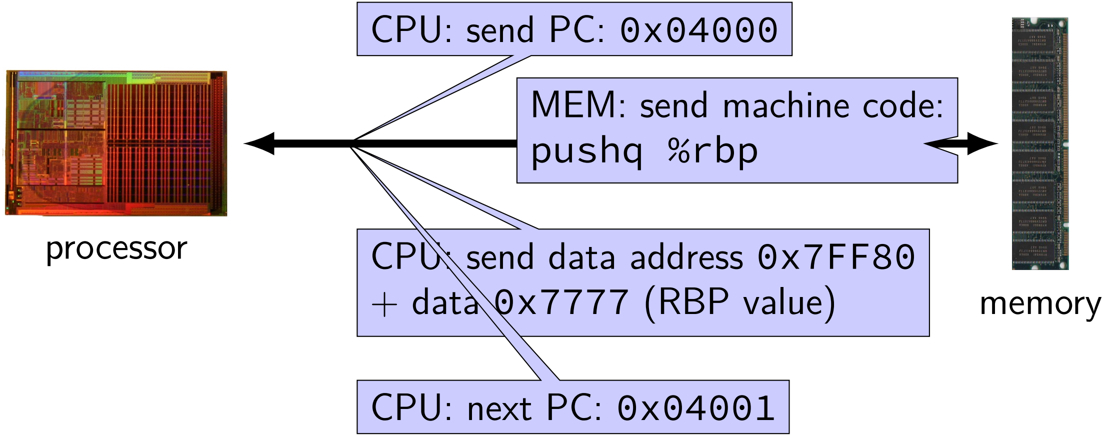
processors and memory



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CPU: next PC: `0x04001`

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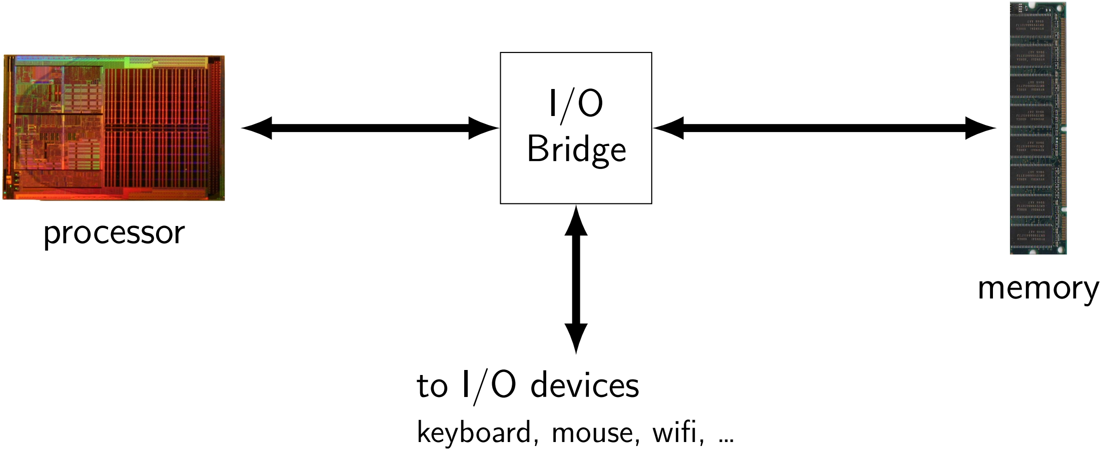
processors and memory



processor

I/O Bridge

memory

to I/O devices

keyboard, mouse, wifi, …

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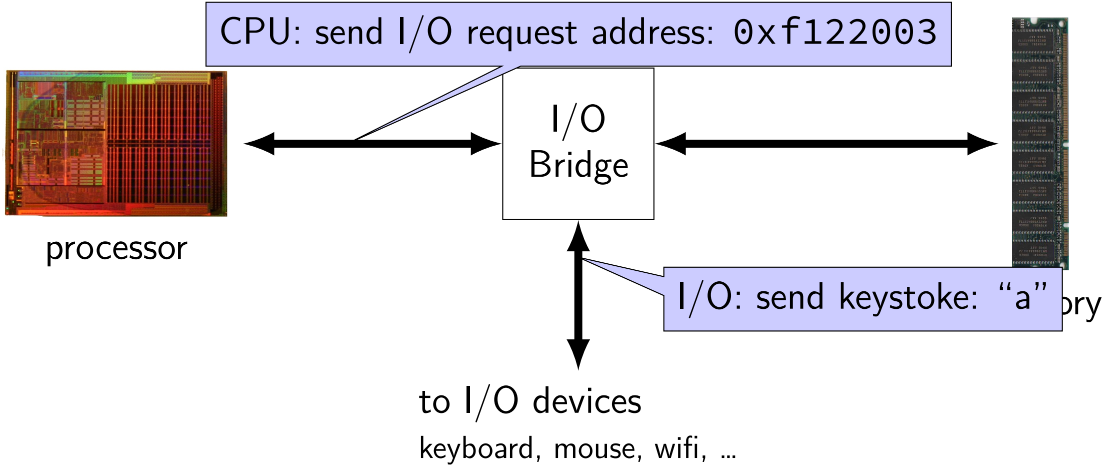
processors and memory



CPU: send I/O request address: `0xf122003`

I/O Bridge

processor

ory

I/O: send keystoke: “a”

to I/O devices

keyboard, mouse, wifi, …

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goals/other topics

understand how hardware works for...

program performance

what compilers are/do

weird program behaviors

goals/other topics

understand how hardware works for...

program performance

what compilers are/do

weird program behaviors

program performance: major issues

parallelism

fast hardware is parallel
does (parts of) multiple instructions at once

caching

accessing things recently accessed is faster
need reuse of data/code

(more in other classes: algorithmic efficiency)

goals/other topics

understand how hardware works for...

program performance

what compilers are/do

weird program behaviors

what compilers are/do

understanding compiler/linker rrors

if you want to make compilers

debugging applications

goals/other topics

understand how hardware works for...

program performance

what compilers are/do

weird program behaviors

weird program behaviors

what is a segmentation fault really?

how does the operating system interact with programs?

if you want to handle them — writing OSs

interlude: powers of two

	...	
2^0	1	
2^1	2	
2^2	4	
2^3	8	
2^4	16	
2^5	32	
2^6	64	
2^7	128	
2^8	256	
2^9	512	
$\mathbf{2}^{10}$	**1 024**	**K** (or Ki)

	...	
2^{11}	2 048	
2^{12}	4 096	
2^{13}	8 192	
2^{14}	16 384	
2^{15}	32 768	
2^{16}	65 536	
	...	
$\mathbf{2^{20}}$	1 048 576	**M** (or Mi)
	...	
$\mathbf{2^{30}}$	1 073 741 824	**G** (or Gi)
2^{31}	2 147 483 648	
2^{32}	4 294 967 296	
	...	

powers of two: forward

2^{35}

2^{21}

2^{9}

2^{14}

powers of two: forward

$2^{35} = 2^5 \cdot 2^{30} = 32G$ (30 = G)

2^{21}

2^{9}

2^{14}

powers of two: forward

$2^{35} = 2^5 \cdot 2^{30} = 32G$ (30 = G)

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powers of two: forward

$2^{35} = 2^5 \cdot 2^{30} = 32G$ (30 = G)

$2^{21} = 2^1 \cdot 2^{20} = 2M$ (20 = M)

2^9

2^{14}

powers of two: forward

$2^{35} = 2^5 \cdot 2^{30} = 32G$ (30 = G)

$2^{21} = 2^1 \cdot 2^{20} = 2M$ (20 = M)

$2^9 = 512$

2^{14}

powers of two: forward

$2^{35} = 2^5 \cdot 2^{30} = 32G$ (30 = G)

$2^{21} = 2^1 \cdot 2^{20} = 2M$ (20 = M)

$2^9 = 512$

$2^{14} = 2^4 \cdot 2^{10} = 16K$

powers of two: backward

16G

128K

4M

256T

powers of two: backward

16G $= 16 \cdot 2^{30} = 2^{30+4} = 2^{34}$

128K

4M

256T

powers of two: backward

16G $= 16 \cdot 2^{30} = 2^{30+4} = 2^{34}$

128K $= 128 \cdot 2^{10} = 2^{10+7} = 2^{17}$

4M

256T

powers of two: backward

16G $= 16 \cdot 2^{30} = 2^{30+4} = 2^{34}$

128K $= 128 \cdot 2^{10} = 2^{10+7} = 2^{17}$

4M $= 4 \cdot 2^{20} = 2^{20+2} = 2^{22}$

256T $= 256 \cdot 2^{40} = 2^{40+8} = 2^{48}$

lecturers

Graham and I co-teaching

- two lecture sections
- mostly alternating: one week me, one week Graham

same(ish) lecture in each section

coursework

labs — grading: did you make reasonable progress?

- collaboration permitted

homework assignments — introduced by lab (mostly)

- due Tuesday night before next lab
- complete individually

exams

weekly quizzes

on lecture/lab/HW synchronization

labs/HWs not quite synchronized with lectures

main problem: want to cover material **before you need it** in lab/HW

quizzes?

linked off course website (demo)

after each week

primarily based on lecture material from previous week

some questions from reading for next week

one quiz dropped

first quiz — after this week

quiz demo

attendance?

lecture: strongly recommended.

we will try to record lectures

best-effort — sometimes technical difficulties

lab: generally electronic, remote-possible submission

late policy

exceptional circumstance? contact us.

otherwise, for homeworks only:

- -10% 0 to 48 hours late
- -15% 48 to 72 hours late
- -100% otherwise

late quizzes, labs: no

- we release answers
- talk to us if illness, etc.

TAs/Office Hours

office hours will be posted on calendar on the website

should be plenty

use them

your TODO list

department account and/or C environment working

department accounts should happen by this weekend

before lab next week

grading

Quizzes: 10%

Midterms (2): 30%

Final Exam (cumulative): 20%

Homework + Labs: 40%

quiz demo

memory

address	value
0xFFFFFFFF	0x14
0xFFFFFFFE	0x45
0xFFFFFFFD	0xDE
…	…
0x00042006	0x06
0x00042005	0x05
0x00042004	0x04
0x00042003	0x03
0x00042002	0x02
0x00042001	0x01
0x00042000	0x00
0x00041FFF	0x03
0x00041FFE	0x60
…	…
0x00000002	0xFE
0x00000001	0xE0
0x00000000	0xA0

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array of bytes (byte = 8 bits)
CPU interprets based on how accessed

memory

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0x00042003	0x03
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0x00042005	0x05
0x00042006	0x06
…	…
0xFFFFFFFD	0xDE
0xFFFFFFFE	0x45
0xFFFFFFFF	0x14

endianness

address	value
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```
int *x = (int*)0x42000;
cout << *x << endl;
// or printf("%d\n", *x);
```

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int *x = (int*)0x42000;
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0x03020100 = 50462976

0x00010203 = 66051

endianness

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little endian
(least significant byte has lowest address)

0x00010203 = 66051

big endian
(most significant byte has lowest address)

endianness

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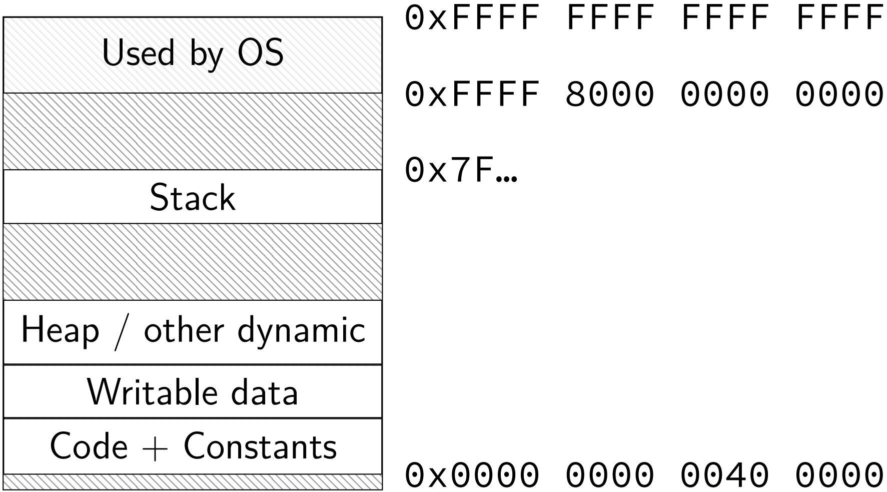
program memory (x86-64 Linux)



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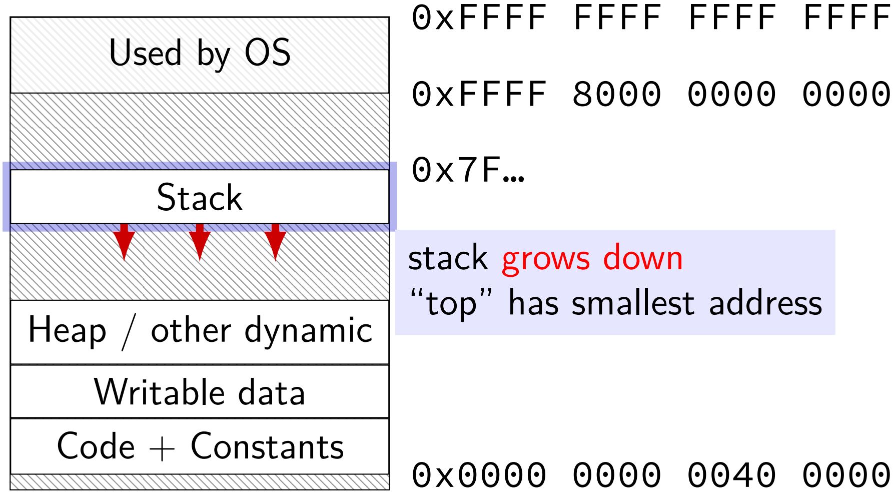
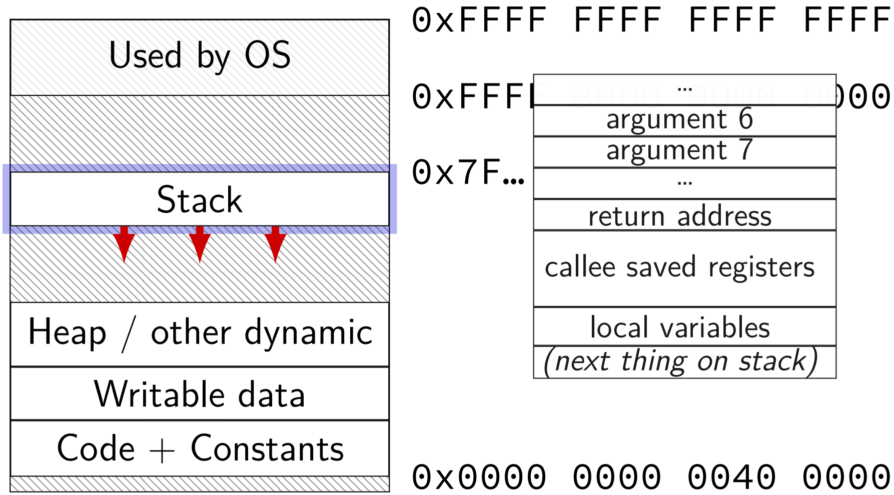


stack grows down
"top" has smallest address

program memory (x86-64 Linux)



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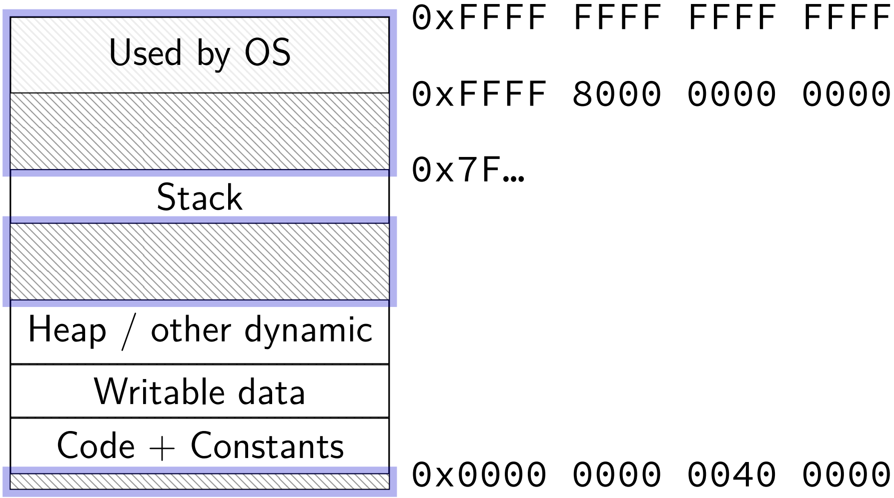
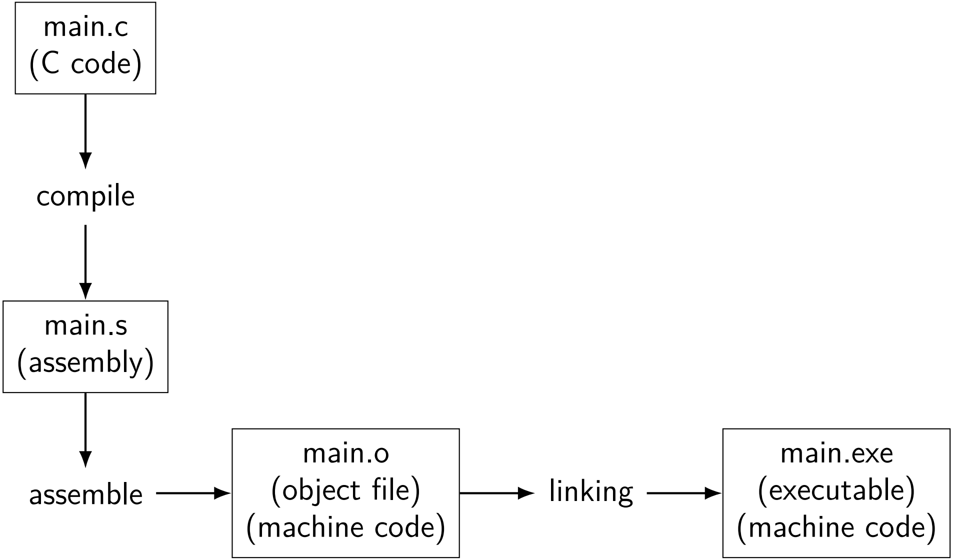


compilation pipeline



main.c
(C code)

compile

main.s
(assembly)

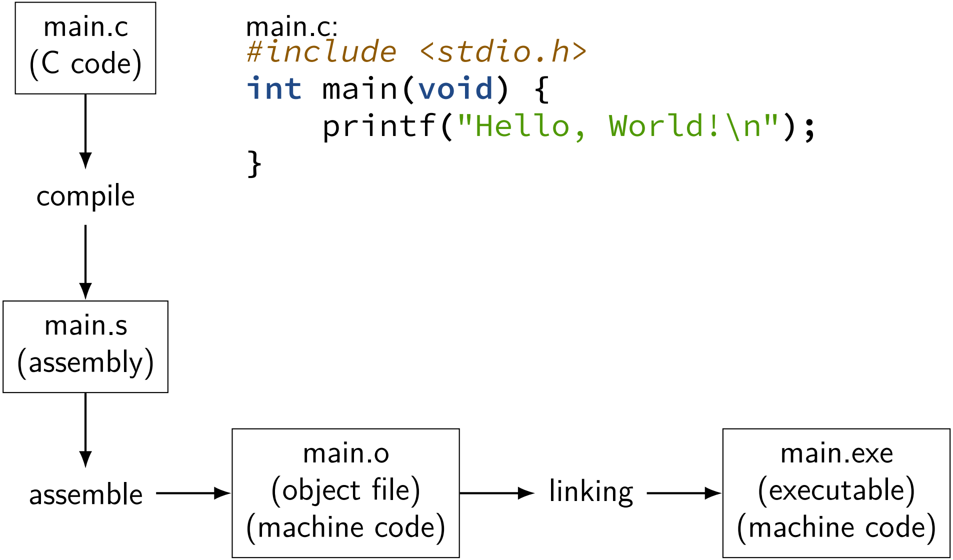
assemble

main.o
(object file)
(machine code)

linking

main.exe
(executable)
(machine code)

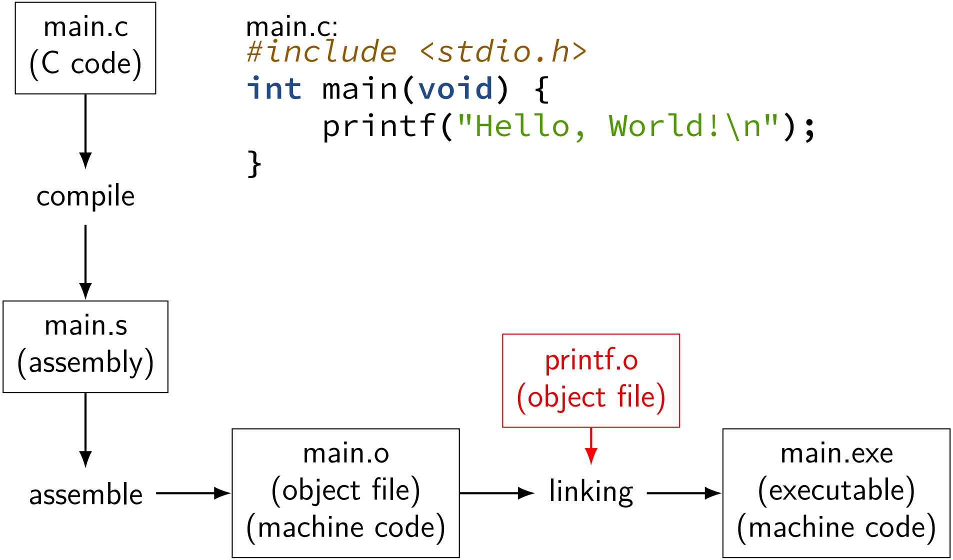
compilation pipeline



main.c:

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

compilation pipeline



main.c:
```
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int main(void) {
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}
```

compilation commands

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

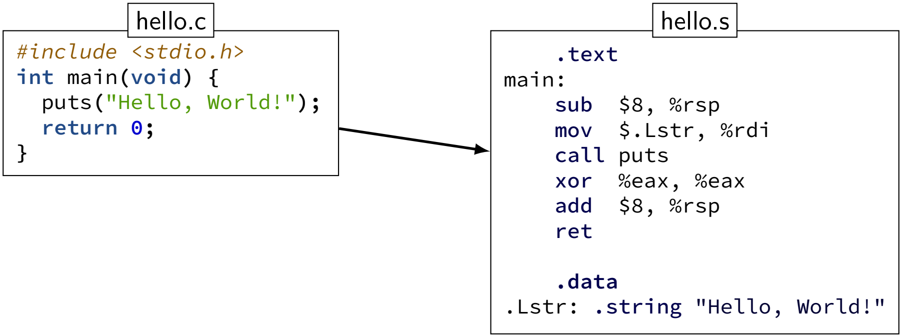
…

what’s in those files?

hello.c

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

what's in those files?



hello.c

```c
#include <stdio.h>
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  return 0;
}
```
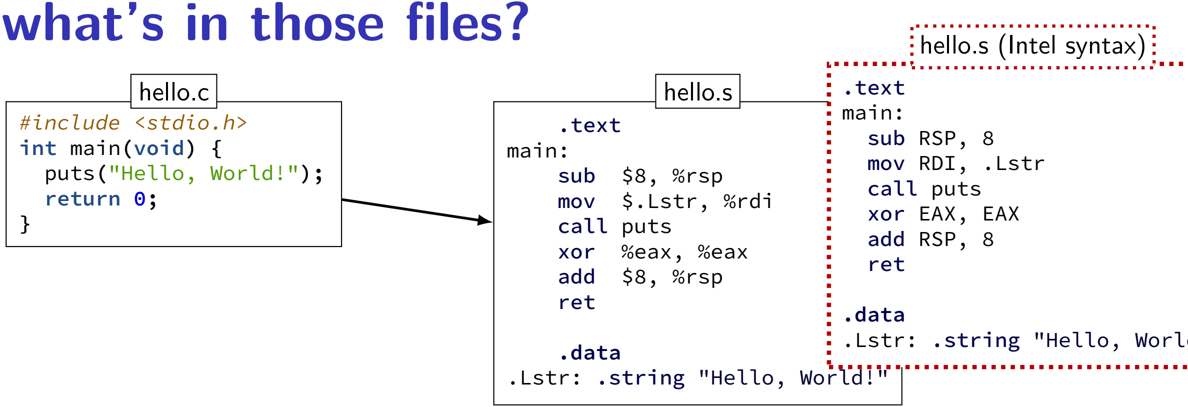

hello.s

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

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

what's in those files?



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    sub   $8, %rsp
    mov   $.Lstr, %rdi
    call  puts
    xor   %eax, %eax
    add   $8, %rsp
    ret

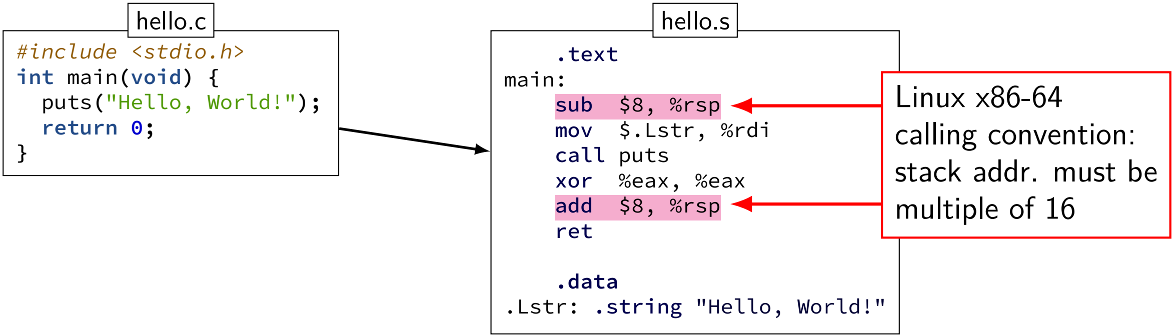
    .data
.Lstr: .string "Hello, World!"
```

hello.s (Intel syntax)

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

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

what’s in those files?



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main:
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```
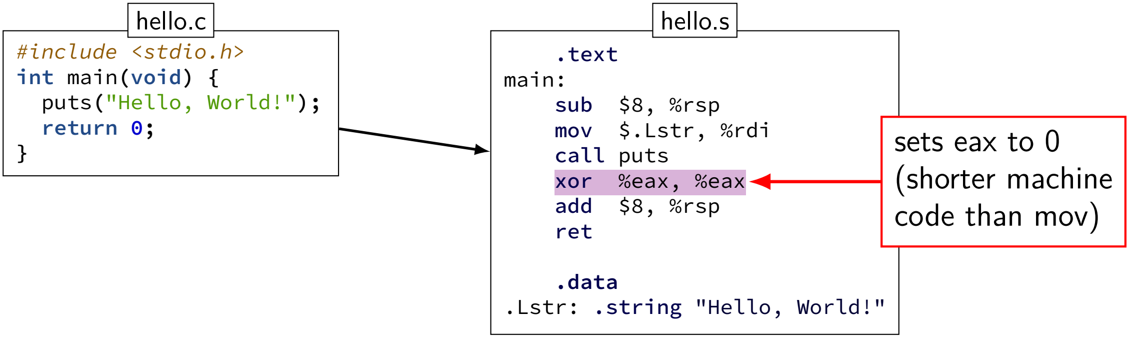

Linux x86-64 calling convention: stack addr. must be multiple of 16

what’s in those files?



hello.c

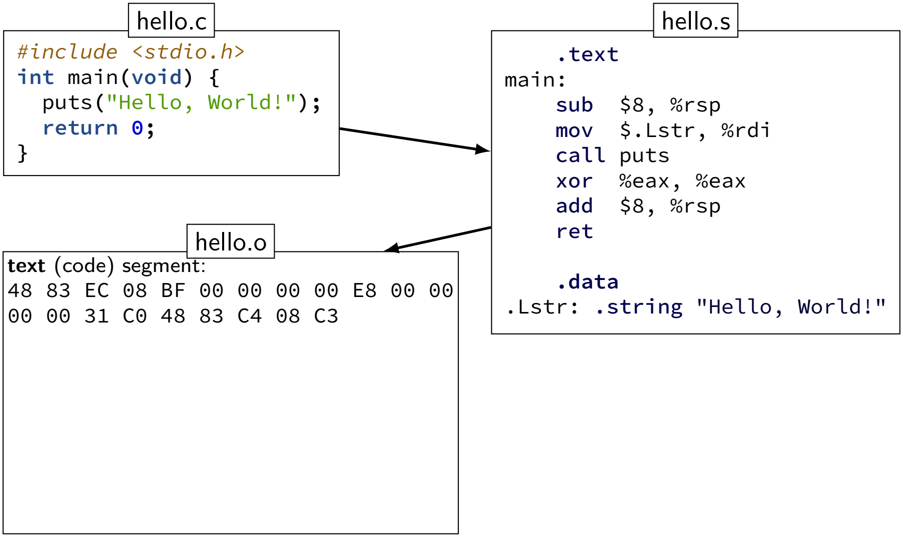
```c
#include <stdio.h>
int main(void) {
  puts("Hello, World!");
  return 0;
}
```

hello.s

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

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

sets eax to 0 (shorter machine code than mov)

what’s in those files?



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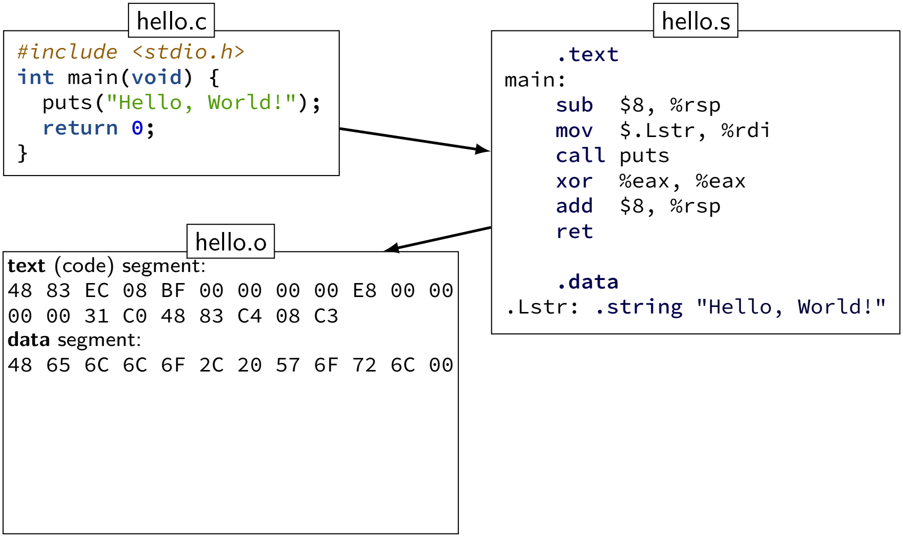
hello.o

text (code) segment:

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

what's in those files?



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}
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hello.s

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48 83 EC 08 BF 00 00 00 00 E8 00 00
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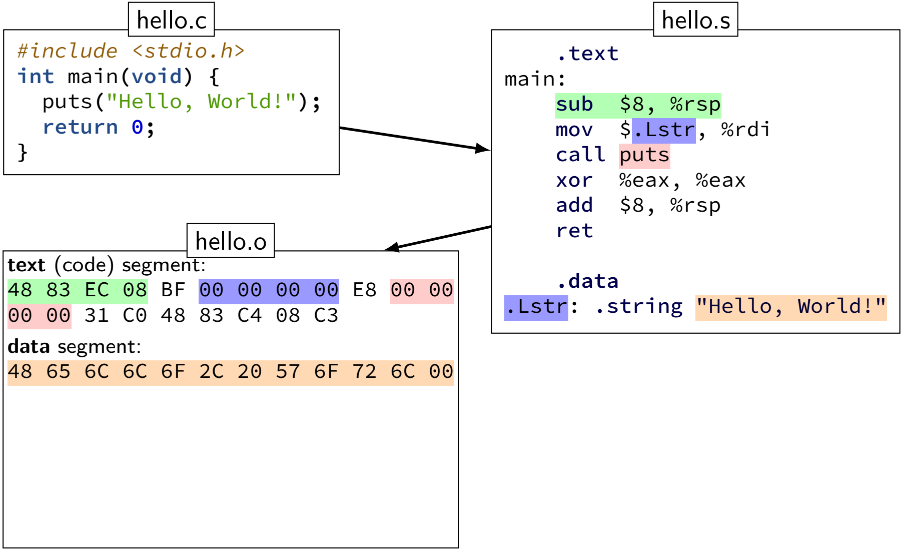
```

data segment:

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

what's in those files?



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}
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hello.s

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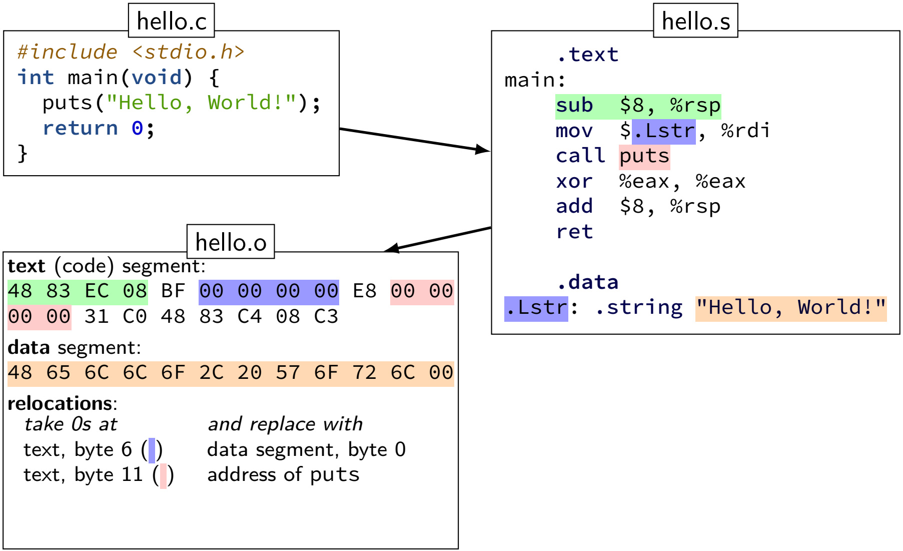

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hello.s

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    ret

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hello.o

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00 00 31 C0 48 83 C4 08 C3
```

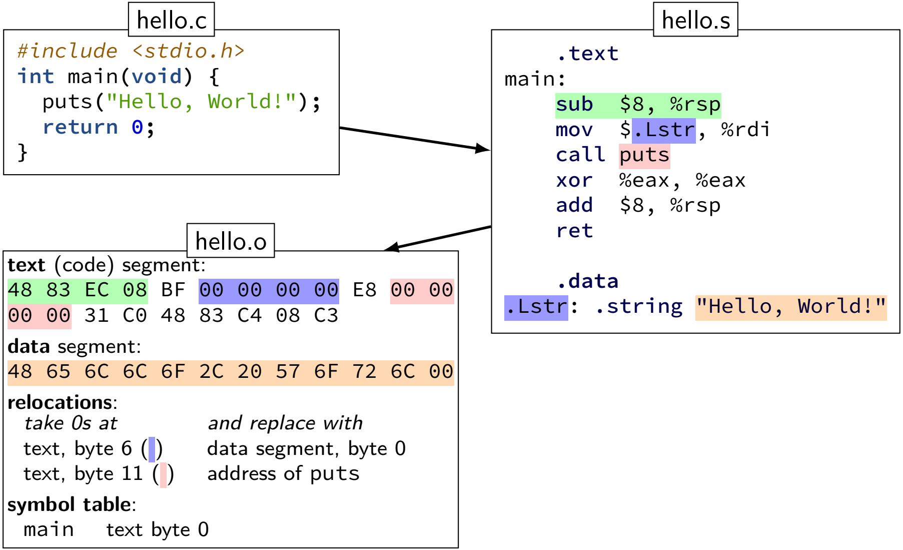
data segment:

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

relocations:

take 0s at	*and replace with*
text, byte 6 (🟦)	data segment, byte 0
text, byte 11 (🟥)	address of puts

what’s in those files?



hello.c

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

hello.s

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

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hello.o

text (code) segment:

```
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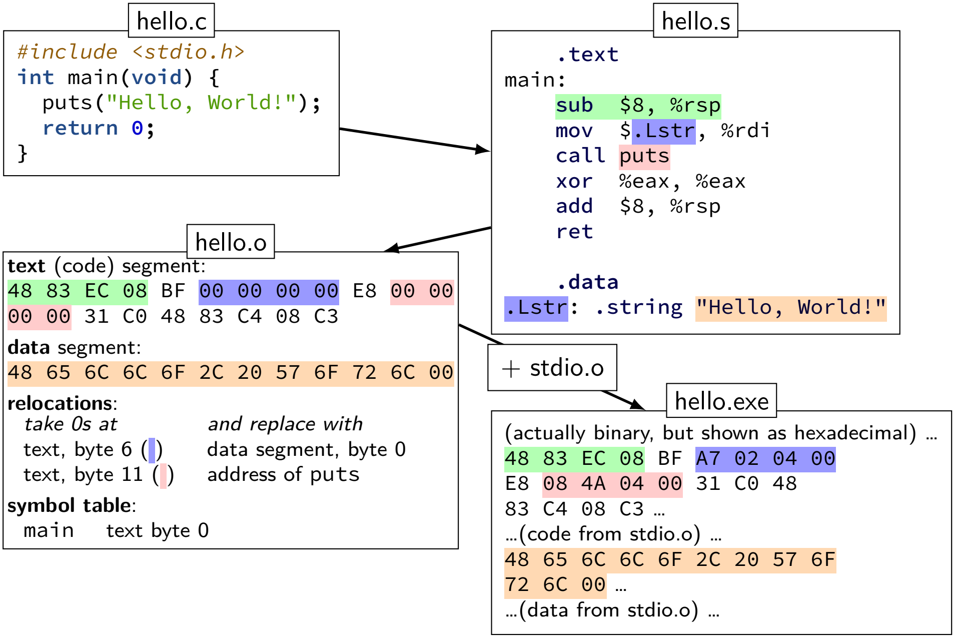
symbol table:

main	text byte 0

what’s in those files?



hello.c

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

hello.s

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

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48 83 EC 08 BF 00 00 00 00 E8 00 00
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```

data segment:

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

relocations:

take 0s at	*and replace with*
text, byte 6 (🟦)	data segment, byte 0
text, byte 11 (🟥)	address of puts

symbol table:

main	text byte 0

+ stdio.o

hello.exe

(actually binary, but shown as hexadecimal) …

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

…(code from stdio.o) …

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

…(data from stdio.o) …

hello.s

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

exercise (1)

main.c:

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

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

A. main.s (assembly)

B. main.o (object)

C. main.exe (executable)

D. B and C

E. A, B and C

F. something else

exercise (2)

main.c:

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

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

A. main.s (assembly)

B. main.o (object)

C. main.exe (executable)

D. B and C

E. A, B and C

F. something else

dynamic linking (very briefly)

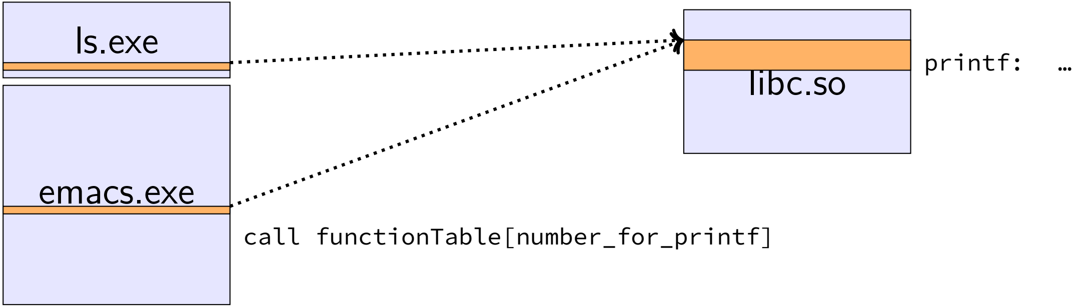
dynamic linking — done when application is loaded

- idea: don't have N copies of `printf` on disk
- other type of linking: *static* (`gcc -static`)

load executable file + its libraries into memory when app starts

often extra indirection:

- `call functionTable[number_for_printf]`
- linker fills in `functionTable` instead of changing `calls`



ldd /bin/ls

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

relocation types

machine code doesn't always use addresses as is

"call function 4303 bytes later"

linker needs to compute "4303"

- extra 'type' field on relocation list

e.g. `call puts` is `0x48` (4-byte *offset* to puts function)

AT&T versus Intel syntax by example

```
movq $42, (%rbx)
               mov QWORD PTR [rbx], 42

subq %rax, %r8
               sub r8, rax

movq $42, 100(%rbx,%rcx,4)
               mov QWORD PTR [rbx+rcx*4+100], 42

jmp *%rax
               jmp rax

jmp *1000(%rax,%rbx,8)
               jmp QWORD PTR [RAX+RBX*8+1000]
```

AT&T versus Intel syntax (1)

AT&T syntax:

```
movq $42, (%rbx)
```

Intel syntax:

```
mov QWORD PTR [rbx], 42
```

effect (pseudo-C):

```
memory[rbx] <- 42
```

AT&T syntax example (1)

```
movq $42, (%rbx)
// memory[rbx] ← 42
```

destination last

( )s represent value in memory

constants start with $

registers start with %

q ('quad') indicates length (8 bytes)

- `l`: 4; w: 2; b: 1
- sometimes can be omitted

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- sometimes can be omitted

AT&T versus Intel syntax (2)

AT&T syntax:

```
movq $42, 100(%rbx,%rcx,4)
```

Intel syntax:

```
mov QWORD PTR [rbx+rcx*4+100], 42
```

effect (pseudo-C):

```
memory[rbx + rcx * 4 + 100] <- 42
```

AT&T versus Intel syntax (2)

AT&T syntax:

```
movq $42, 100(%rbx,%rcx,4)
```

Intel syntax:

```
mov QWORD PTR [rbx+rcx*4+100], 42
```

effect (pseudo-C):

```
memory[rbx + rcx * 4 + 100] <- 42
```

AT&T versus Intel syntax (2)

AT&T syntax:

```
movq $42, 100(%rbx,%rcx,4)
```

Intel syntax:

```
mov QWORD PTR [rbx+rcx*4+100], 42
```

effect (pseudo-C):

```
memory[rbx + rcx * 4 + 100] <- 42
```

AT&T versus Intel syntax (2)

AT&T syntax:

```
movq $42, 100(%rbx,%rcx,4)
```

Intel syntax:

```
mov QWORD PTR [rbx+rcx*4+100], 42
```

effect (pseudo-C):

```
memory[rbx + rcx * 4 + 100] <- 42
```

AT&T syntax: addressing

```
100(%rbx): memory[rbx + 100]

100(%rbx,8): memory[rbx * 8 + 100]

100(,%rbx,8): memory[rbx * 8 + 100]

100(%rcx,%rbx,8):
      memory[rcx + rbx * 8 + 100]

100:
      memory[100]

100(%rbx,%rcx):
      memory[rbx+rcx+100]
```

AT&T versus Intel syntax (3)

`r8` ← `r8 - rax`

AT&T syntax:	`subq %rax, %r8`
Intel syntax:	`sub r8, rax`

same for **`cmpq`**

AT&T syntax: addresses

```
addq 0x1000, %rax
// Intel syntax: add rax, QWORD PTR [0x1000]
// rax ← rax + memory[0x1000]
addq $0x1000, %rax
// Intel syntax: add rax, 0x1000
// rax ← rax + 0x1000
```

no $ — probably memory address

AT&T syntax in one slide

destination last

`()` means value in memory

`disp(base, index, scale)` same as
`memory[disp + base + index * scale]`

- omit disp (defaults to `0`)
- and/or omit base (defaults to `0`)
- and/or scale (defualts to `1`)

`$` means constant

plain number/label means value in memory

extra detail: computed jumps

```
jmpq *%rax
// Intel syntax: jmp RAX
    // goto RAX
jmpq *1000(%rax,%rbx,8)
// Intel syntax: jmp QWORD PTR[RAX+RBX*8+1000]
    // read address from memory at RAX + RBX * 8 + 1
    // go to that address
```

AT&T versus Intel syntax by example

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movq $42, (%rbx)
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subq %rax, %r8
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movq $42, 100(%rbx,%rcx,4)
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jmp *%rax
               jmp rax

jmp *1000(%rax,%rbx,8)
               jmp QWORD PTR [RAX+RBX*8+1000]
```

swap

swap (AT&T syntax)

```
// swap(long *rdi,
//      long *rsi)
swap:
  movq (%rdi), %rax
  movq (%rsi), %rdx
  movq %rdx, (%rdi)
  movq %rax, (%rsi)
  ret
```

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// swap(long *rdi,
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swap:
  movq (%rdi), %rax
  movq (%rsi), %rdx
  movq %rdx, (%rdi)
  movq %rax, (%rsi)
  ret
```

swap (Intel syntax)

```
swap:
  mov RAX, QWORD PTR [RDI]
  mov RDX, QWORD PTR [RSI]
  mov QWORD PTR [RDI], RDX
  mov QWORD PTR [RSI], RAX
  ret
```

swap

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// swap(long *rdi,
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swap:
  movq (%rdi), %rax
  movq (%rsi), %rdx
  movq %rdx, (%rdi)
  movq %rax, (%rsi)
  ret
```

as pseudocode

```
swap:
    RAX ← memory[RDI (arg 1)]
    RDX ← memory[RSI (arg 2)]
    memory[RDI (arg 1)] ← RDX
    memory[RSI (arg 2)] ← RAX
    return
```

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// swap(long *rdi,
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swap:
   movq (%rdi), %rax
   movq (%rsi), %rdx
   movq %rdx, (%rdi)
   movq %rax, (%rsi)
   ret
```

registers

%rax	???
%rdx	???
%rdi	0x04000
%rsi	0x04030
%rsp	0xEFFF8
…	…

memory

address	value
0x00000	0xFFFF3
0x00008	0x32123
…	…
0x04000	0x99999
0x04008	0x00002
…	…
0x04028	0x00090
0x04030	0x77777
0x04038	0x00078
…	…

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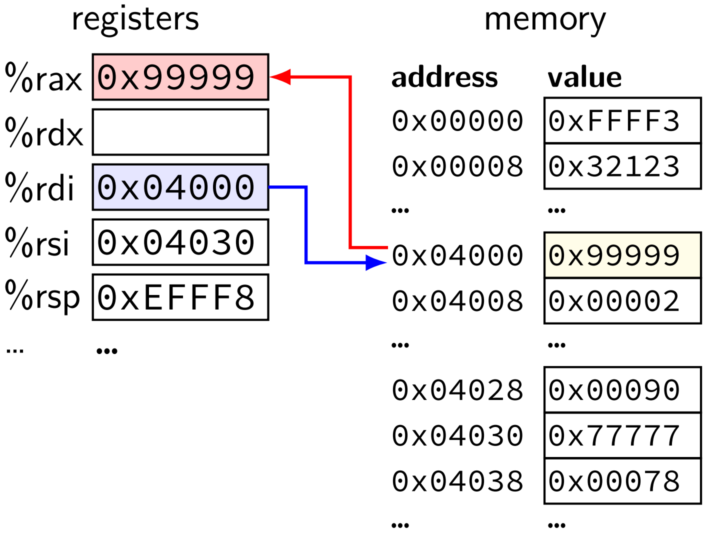

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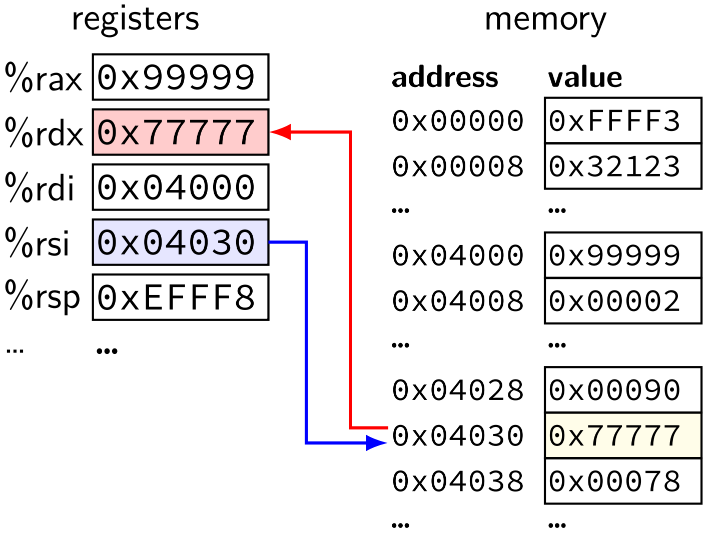

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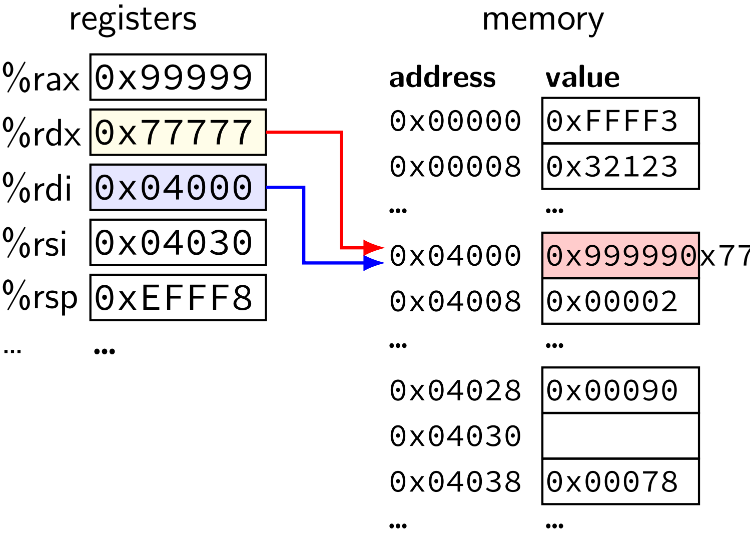
  movq %rdx, (%rdi)
  movq %rax, (%rsi)
  ret
```



registers

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memory

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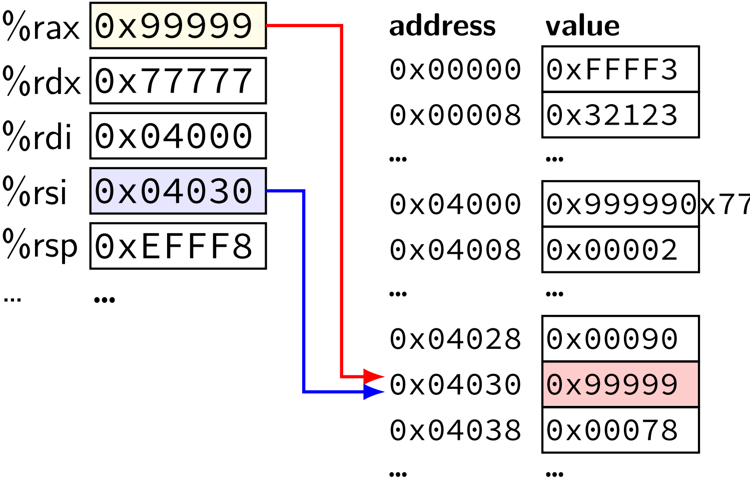
  movq (%rdi), %rax
  movq (%rsi), %rdx
  movq %rdx, (%rdi)
  movq %rax, (%rsi)
  ret
```



registers

%rax	0x99999
%rdx	0x77777
%rdi	0x04000
%rsi	0x04030
%rsp	0xEFFF8
...	...

memory

address	value
0x00000	0xFFFF3
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...	...
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swap

swap (AT&T syntax)

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// swap(long *rdi,
//      long *rsi)
swap:
  movq (%rdi), %rax
  movq (%rsi), %rdx
  movq %rdx, (%rdi)
  movq %rax, (%rsi)
  ret
```

registers

%rax	0x99999
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memory

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0x04028	0x00090
0x04030	0x99999
0x04038	0x00078
…	…

backup slides

objdump -sx test.o (Linux) (1)

```
test.o:     file format elf64–x86–64
test.o
architecture: i386:x86–64, flags 0x00000011:
HAS_RELOC, HAS_SYMS
start address 0x0000000000000000

Sections:
Idx Name              Size      VMA               LMA               File off  Algn
  0 .text             00000000  0000000000000000  0000000000000000  00000040  2**0
                      CONTENTS, ALLOC, LOAD, READONLY, CODE
  1 .data             00000000  0000000000000000  0000000000000000  00000040  2**0
                      CONTENTS, ALLOC, LOAD, DATA
  2 .bss              00000000  0000000000000000  0000000000000000  00000040  2**0
                      ALLOC
  3 .rodata.str1.1 0000000e  0000000000000000  0000000000000000  00000040  2**0
                      CONTENTS, ALLOC, LOAD, READONLY, DATA
  4 .text.startup 00000014  0000000000000000  0000000000000000  0000004e  2**0
                      CONTENTS, ALLOC, LOAD, RELOC, READONLY, CODE
  5 .comment          0000002b  0000000000000000  0000000000000000  00000062  2**0
                      CONTENTS, READONLY
  6 .note.GNU–stack 00000000  0000000000000000  0000000000000000  0000008d  2**0
                      CONTENTS, READONLY
  7 .eh_frame         00000030  0000000000000000  0000000000000000  00000090  2**3
                      CONTENTS, ALLOC, LOAD, RELOC, READONLY, DATA
```

objdump -sx test.o (Linux) (2)

```
SYMBOL TABLE:
0000000000000000 l    df *ABS*  0000000000000000 test.c
0000000000000000 l    d  .text  0000000000000000 .text
0000000000000000 l    d  .data  0000000000000000 .data
0000000000000000 l    d  .bss   0000000000000000 .bss
0000000000000000 l    d  .rodata.str1.1 0000000000000000 .rodata.str1.1
0000000000000000 l    d  .text.startup  0000000000000000 .text.startup
0000000000000000 l    d  .note.GNU-stack        0000000000000000 .note.GNU-stack
0000000000000000 l    d  .eh_frame      0000000000000000 .eh_frame
0000000000000000 l       .rodata.str1.1 0000000000000000 .LC0
0000000000000000 l    d  .comment       0000000000000000 .comment
0000000000000000 g     F .text.startup  0000000000000014 main
0000000000000000         *UND*  0000000000000000 _GLOBAL_OFFSET_TABLE_
0000000000000000         *UND*  0000000000000000 puts
```

columns:

- memory address (not yet assigned, so 0)
- flags: `l`=local, g=global, F=function, ...
- section (.text, .data, .bss, ...)
- offset in section
- name of symbol

objdump -sx test.o (Linux) (3)

```
RELOCATION RECORDS FOR [.text.startup]:
OFFSET           TYPE              VALUE
0000000000000003 R_X86_64_PC32     .LC0-0x0000000000000004
000000000000000c R_X86_64_PLT32    puts-0x0000000000000004


RELOCATION RECORDS FOR [.eh_frame]:
OFFSET           TYPE              VALUE
0000000000000020 R_X86_64_PC32     .text.startup

Contents of section .rodata.str1.1:
 0000 48656c6c 6f2c2057 6f726c64 2100      Hello, World!.
Contents of section .text.startup:
 0000 488d3d00 00000048 83ec08e8 00000000  H.=....H........
 0010 31c05ac3                             1.Z.
Contents of section .comment:
 0000 00474343 3a202855 62756e74 7520372e  .GCC: (Ubuntu 7.
 0010 332e302d 32377562 756e7475 317e3138  3.0-27ubuntu1~18
 0020 2e303429 20372e33 2e3000             .04) 7.3.0.
Contents of section .eh_frame:
 0000 14000000 00000000 017a5200 01781001  .........zR..x..
 0010 1b0c0708 90010000 14000000 1c000000  ................
 0020 00000000 14000000 004b0e10 480e0800  .........K..H...
```