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Friday 2 PM Recitation
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Slides adapted from
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Recitation 6: Assembly

- Agenda
- Course News
- Assembly
- Quiz
- Malloc or Quiz 4, your call!

Agenda

Course News!

Assembly Overview

Quiz

Let's take a poll…

- Lab 4 or Malloc?

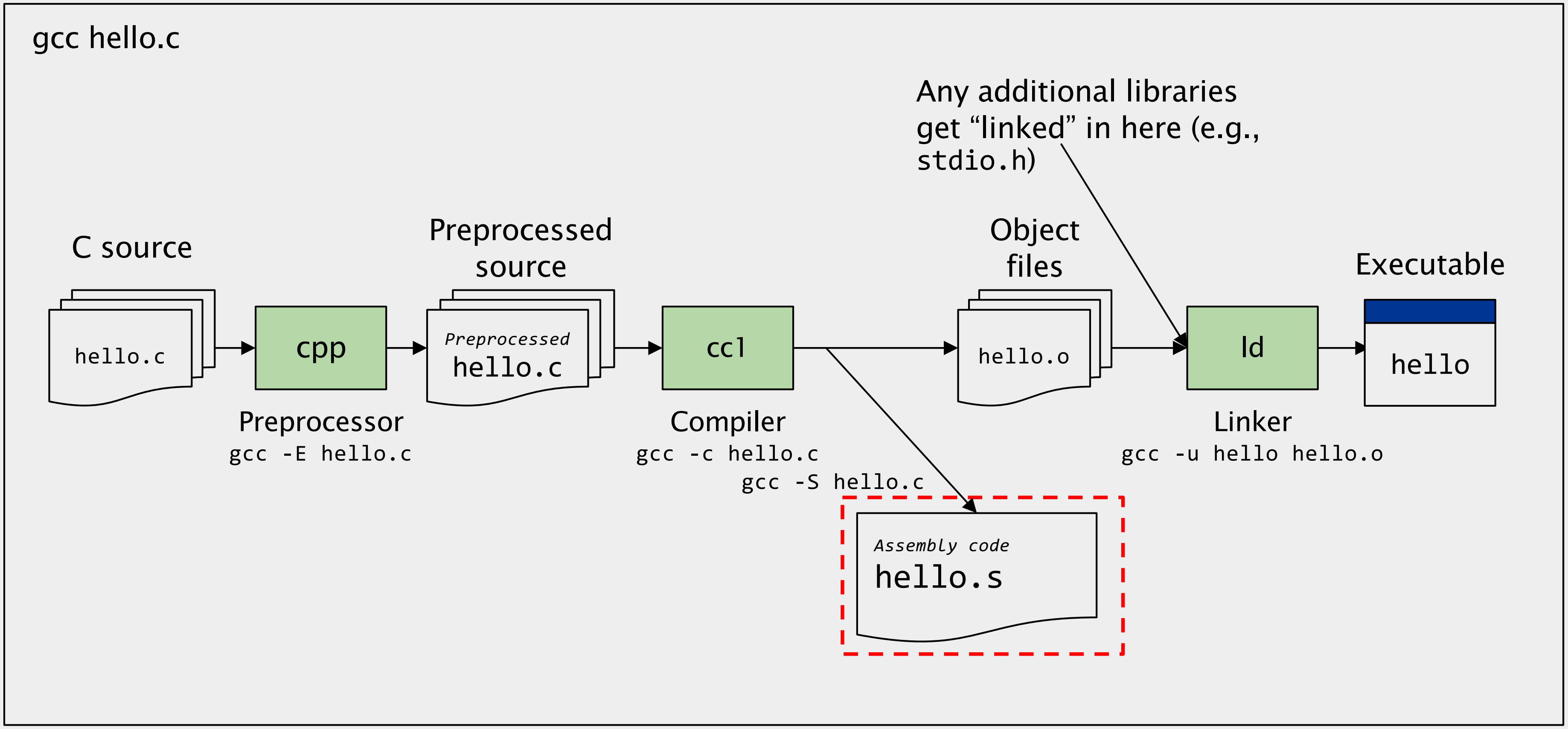
Course News

- Lab 4 (Assembly Lab) is out, due February 29th at 5:59PM
  - Consider coming to my Monday or Tuesday office hours (The line gets long on Thursdays)
- Malloc Project due Monday March 4th at 5:59PM
  - It's a doozy, start early please!

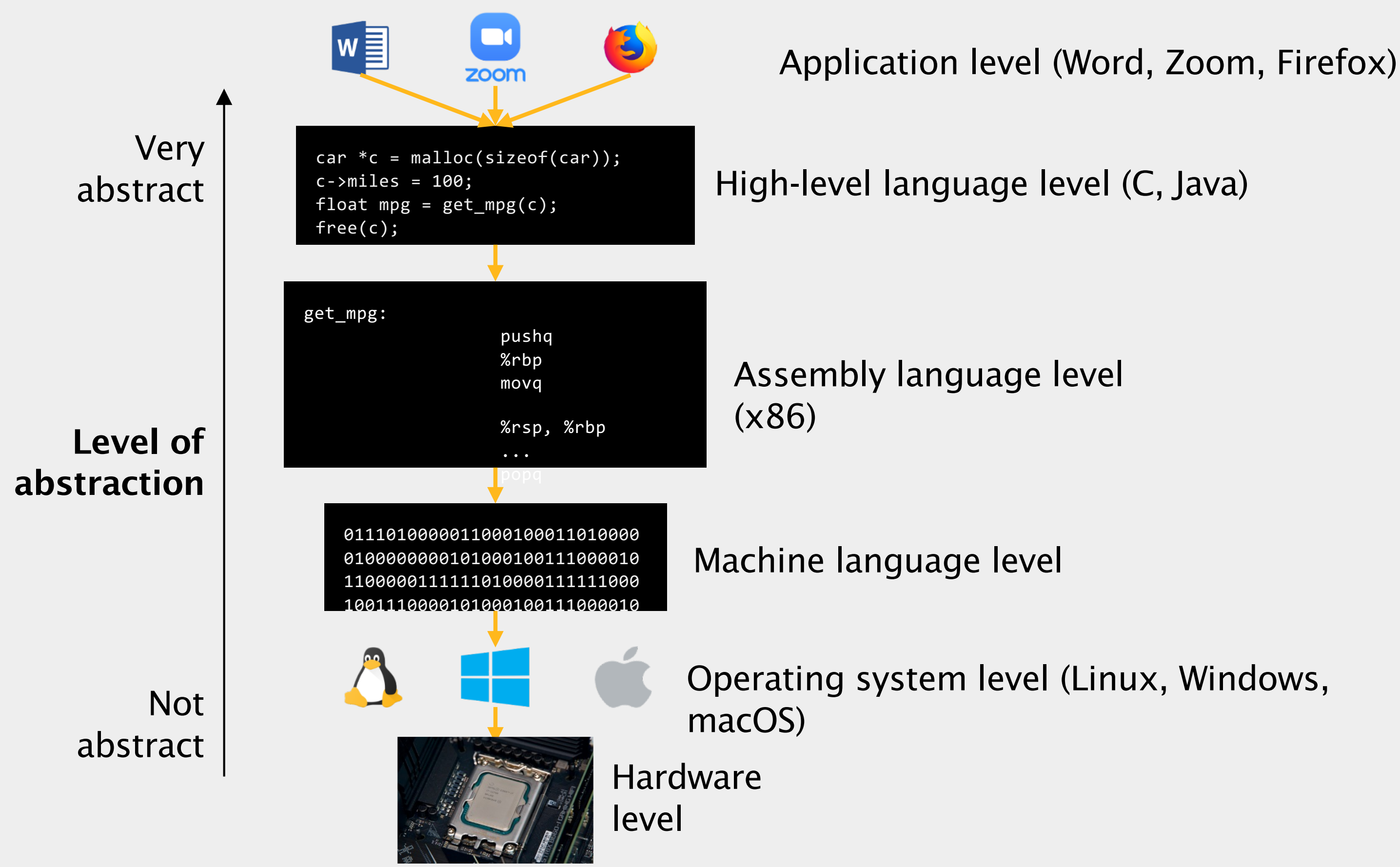
Assembly Language

Because decoding 1s and 0s is hard

What we are building towards...



Moving down the ladder of abstractions



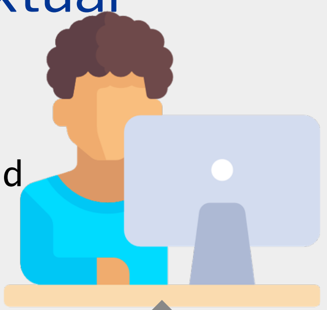
What is assembly?

→ **Assembly language** is a human-readable textual representation of machine language

High-level language (C, Java)

```
car *c = malloc(sizeof(car));
c->miles = 100;
c->gals = 17;
float mpg = get_mpg(c);
free(c);
```

Relatively Easy for us to understand



```
get_mpg:
        pushq       %rbp
        movq
        %rsp, %rbp
        ...
        popq
        %rbp
        ret
```

Assembly acts as a translator between high-level code and machine code

Machine language

```
0111010000011000100011010000
0010000000010100010011100000
1011000001111110100001111111
1000001111110100001111111100
```

Easy for computer to understand

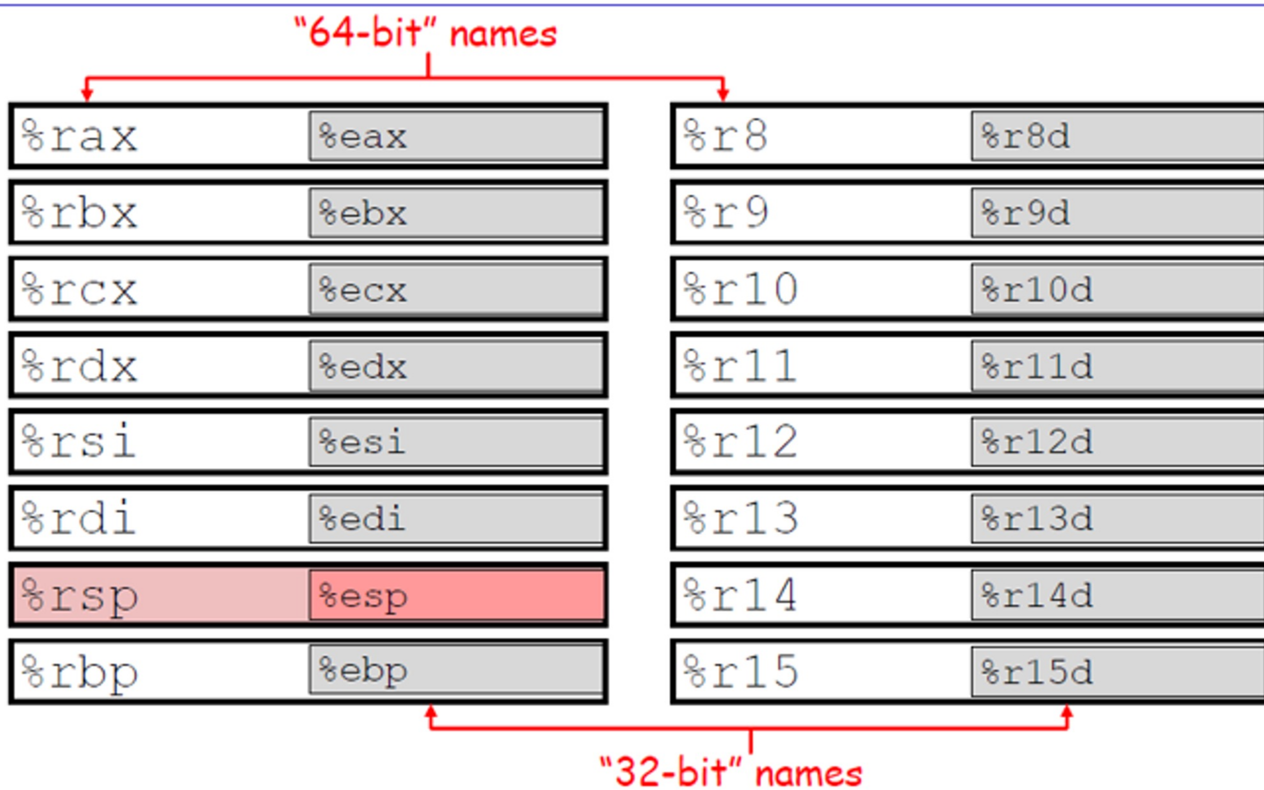
Keeping track of the registers

- Like in MIPS, x86 has calling conventions
  - The **C Application Binary Interface (ABI)**
  - Like MIPS, certain registers are typically used for returns values, args, etc
- The ABI is not defined by the language, but rather the OS
  - Windows and Linux (UNIX/System V) have a different C ABI
- In our x86-64 Linux C ABI,
  - `%rdi, %rsi, %rdx, %rcx, %r8, %r9` are used to pass arguments (like the `a` registers in MIPS)
    - Remaining arguments go on the stack
  - A function callee must preserve `%rbp, %rbx, %r12, %r13, %r14, %r15` (like the `s` registers in MIPS)
  - `%rax` (overflows into `%rdx` for 128-bits) stores the return value (like `v0, v1` in MIPS)
- Reference manual provides extra information

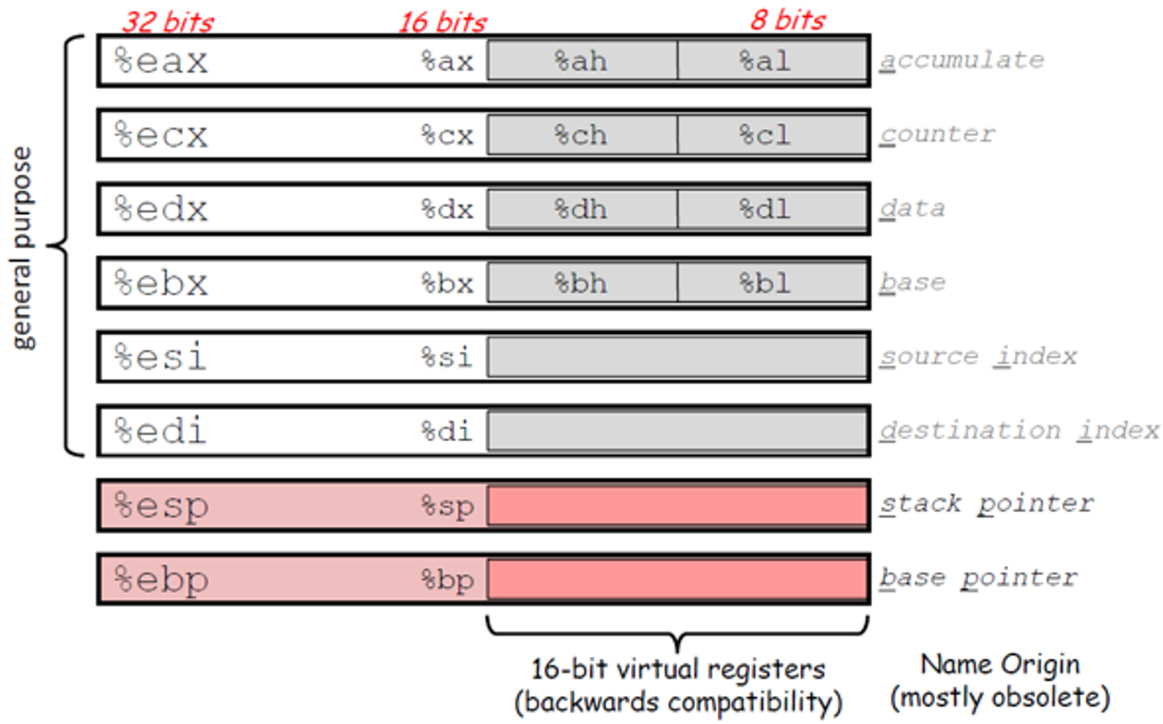
Registers

- A register is a location within the processor that is able to store data
  - Names, not addresses
  - Much faster than DRAM
  - Can hold any value: addresses, values from operations, characters etc.
  - Usually, register
    - `%rip` stores the address of the next instruction
    - `%rsp` is used as a stack pointer
    - `%rax` holds the return value from a function
  - A register in x86-64 is 64 bits wide
    - 'The lower 32-, 16- and 8-bit portions are selectable by a pseudo-register name'.

https://ctf101.org/binary-exploitation/what-are-registers/
https://web.stanford.edu/class/archive/cs/cs107/cs107.1212/guide/x86-64.html



Dr Petrucci's slides - "Intro to x86-64"



Dr Petrucci's slides - "Intro to x86-64"

mov

General form: `mov_ source, destination`

- `movb src, dst`
  Move 1-byte "byte"
- `movw src, dst`
  Move 2-byte "word"
- `movl src, dst`
  Move 4-byte "long word"
- `movq src, dst`
  Move 8-byte "quad word"

- movq src, dst # general form of instruction dst = src
- movl $0, %eax # %eax = 0
- movq %rax, $100 #Invalid!! destination cannot be an immediate value
- movsbl %al, %edx # copy 1-byte %al, sign-extend into 4-byte %edx
- movzbl %al, %edx # copy 1-byte %al, zero-extend into 4-byte %edx

https://web.stanford.edu/class/archive/cs/cs107/cs107.1212/guide/x86-64.html
Dr Petrucci's slides - "Intro to x86-64"

Operand Combinations

	Source	Dest	Src, Dest	C Analog
movq	Imm	Reg	`movq $0x4, %rax`	`var_a = 0x4;`
		Mem	`movq $-147, (%rax)`	`*p_a = -147;`
	Reg	Reg	`movq %rax, %rdx`	`var_d = var_a;`
		Mem	`movq %rax, (%rdx)`	`*p_d = var_a;`
	Mem	Reg	`movq (%rax), %rdx`	`var_d = *p_a;`

Addressing Modes - Example

- `movq %rdi, 0x568892` # direct (address is constant value)
- `movq %rdi, (%rax)` # indirect (address is in register %rax)
- mov (%rsi), %rdi #%rdi = Mem[%rsi]
- `movq %rdi,-24(%rbp)` # indirect with displacement (address = %rbp -24)
- `movq %rsi, 8(%rsp, %rdi, 4)`

indirect with displacement and scaled-index (address = 8 + %rsp + %rdi*4)

- `movq %rsi, 0x4(%rax, %rcx)` #Mem[0x4 + %rax +%rcx*1] = %rsi
- `movq %rsi, 0x8(, %rdx, 4)` #Mem(0x8 + %rdx*4) = %rsi

https://web.stanford.edu/class/archive/cs/cs107/cs107.1212/guide/x86-64.html

lea

- `leaq src, dst`
  - "`lea`" stands for *load effective address*
  - `src` is address expression (any of the formats we've seen)
  - `dst` is a register
  - Sets `dst` to the *address* computed by the `src` expression (does not go to memory! – it just does math)
  - Example: `leaq (%rdx,%rcx,4), %rax`

lea

- lea or Load effective address
  - Does not dereference the source address, it simply calculates its location.
  - leaq 0x20(%rsp), %rdi   # %rdi = %rsp + 0x20 (no dereference!)
  - leaq (%rdi,%rdx,1), %rax   # %rax = %rdi + %rdx * 1

https://web.stanford.edu/class/archive/cs/cs107/cs107.1212/guide/x86-64.html

Will I have to write assembly code for this course?

- **No!** No matter how good you are at programming, you are no match for a modern compiler
  - Modern Compilers are just too good at optimization
    - There was a time when humans outperformed compilers
      - Those days are long gone now...
- However, you should be able to ***read*** assembly code
  - To figure out what your machine is doing
  - To *guess* the C code
- By the end of this lab, you should be able to freely translate assembly and C

Quiz time!

Password is __________

Diving into the Code!

See code: https://github.com/shinwookim/asm-demo

Hello World! x86 edition

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

```
text (code) segment:
55 48 89 E5 BF 00 00 00 00 E8 00 00 00
00 B8 00 00 00 00 5D C3

data segment:
48 65 6C 6C 6F 2C 20 57 6F 72 6C

// Symbol table and other info omitted
```

```
.LC0:
    .string "Hello World!"
main:
    pushq   %rbp
    movq    %rsp, %rbp # rsp = stack pointer
    movl    $.LC0, %edi # push func args
    call    puts # call a function
    movl    $0, %eax # eax = return register
    popq    %rbp # prepare to return
    ret # return
```

Linker → Executable

Debugging Assembly

- Recall that **GDB** worked on *executables*
  - You ran `gdb mdriver` and not ~~`gdb mdriver.c`~~
- Having the source was nice
  - We used the `-g` flag when compiling
  - which allowed us to use `layout src` to view the code during execution
- ...but not necessary
- What if we don't have a source file ? (or the program was compiled without `-g` flag)
  - We can still run GDB!
  - Won't be able to see the source code ⇒ We need to inspect assembly code

```
Reading symbols from a.out...
(No debugging symbols found in a.out)
```

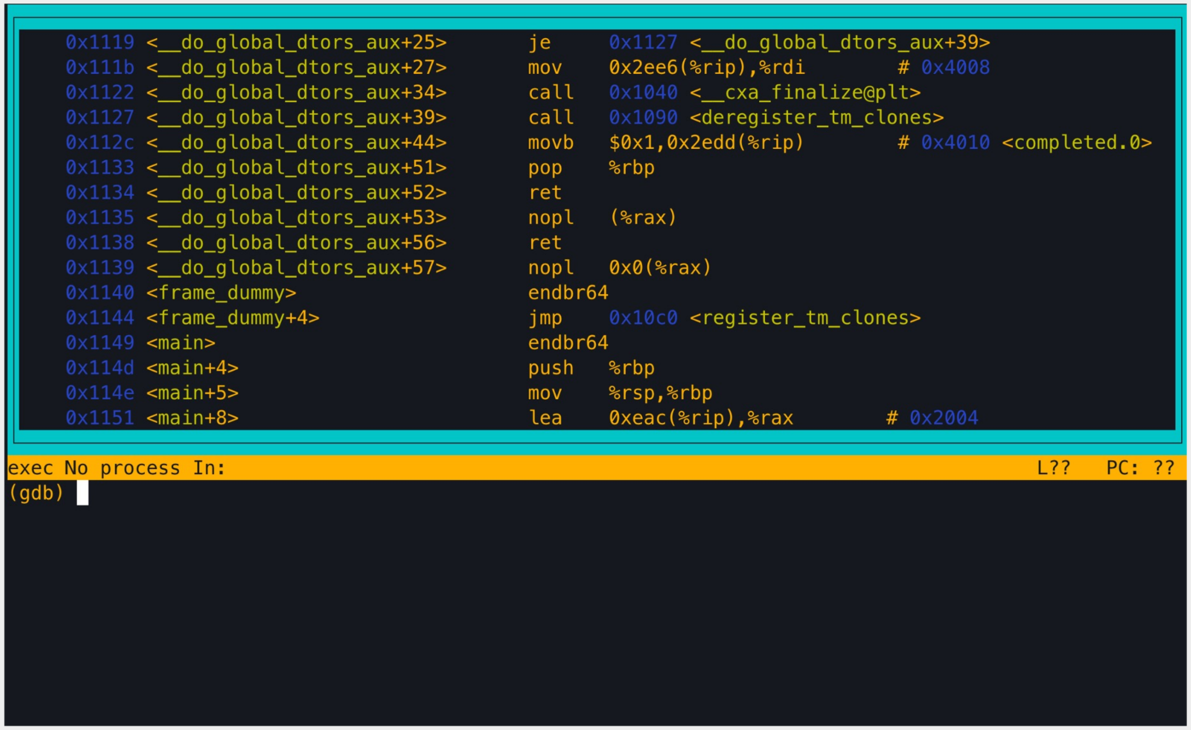
Displaying the assembly with `disas`

- Suppose we are in paused in a breakpoint
- We can view the assembly code around our current memory address using `disas`
  - Memory address that is held by the program counter
- But how do we set a breakpoint
  - if we don't have the code?
- Surely, we need a way to view ASM
  - Without first setting a breakpoint right?

```
Dump of assembler code for function __GI__IO_puts:
Address range 0x7ffff7e09ed0 to 0x7ffff7e0a069:
=> 0x00007ffff7e09ed0 <+0>:     endbr64
   0x00007ffff7e09ed4 <+4>:     push   %r14
   0x00007ffff7e09ed6 <+6>:     push   %r13
   0x00007ffff7e09ed8 <+8>:     push   %r12
   0x00007ffff7e09eda <+10>:    mov    %rdi,%r12
   0x00007ffff7e09edd <+13>:    push   %rbp
   0x00007ffff7e09ede <+14>:    push   %rbx
   0x00007ffff7e09edf <+15>:    sub    $0x10,%rsp
   0x00007ffff7e09ee3 <+19>:    call   0x7ffff7db1490 <*ABS*+0xa8720@plt>
   0x00007ffff7e09ee8 <+24>:    mov    0x197f49(%rip),%r13        # 0x7ffff7fa1e38
   0x00007ffff7e09eef <+31>:    mov    %rax,%rbx
   0x00007ffff7e09ef2 <+34>:    mov    0x0(%r13),%rbp
   0x00007ffff7e09ef6 <+38>:    mov    0x0(%rbp),%eax
   0x00007ffff7e09ef9 <+41>:    and    $0x8000,%eax
   0x00007ffff7e09efe <+46>:    jne    0x7ffff7e09f58 <__GI__IO_puts+136>
   0x00007ffff7e09f00 <+48>:    mov    %fs:0x10,%r14
   0x00007ffff7e09f09 <+57>:    mov    0x88(%rbp),%r8
   0x00007ffff7e09f10 <+64>:    cmp    %r14,0x8(%r8)
   0x00007ffff7e09f14 <+68>:    je     0x7ffff7e0a008 <__GI__IO_puts+312>
   0x00007ffff7e09f1a <+74>:    mov    $0x1,%edx
   0x00007ffff7e09f1f <+79>:    lock cmpxchg %edx,(%r8)
   0x00007ffff7e09f24 <+84>:    jne    0x7ffff7e0a050 <__GI__IO_puts+384>
   0x00007ffff7e09f2a <+90>:    mov    0x88(%rbp),%r8
   0x00007ffff7e09f31 <+97>:    mov    0x0(%r13),%rdi
   0x00007ffff7e09f35 <+101>:   mov    %r14,0x8(%r8)
   0x00007ffff7e09f39 <+105>:   mov    0xc0(%rdi),%eax
--Type <RET> for more, q to quit, c to continue without paging--
```

Displaying the assembly with `layout asm`

- The `layout asm` command displays the assembly of the entire program
  - You can scroll through the code and identify the memory addresses to set breakpoints
- But what if your program is *Huuuuge?*
  - That's gonna be a lot of scrolling



Let’s put the asm in a file ⇒ Now we can `ctrl+f`

`objdump -d program > program.s`

- GNU provides a tool called object dump for unix-like systems
  - Let’s you inspect information from object files
  - The `-d` flag disassembles the program and displays the `.code` section
  - The `>` flag redirects your standard I/O output to a file

```
USER@thoth:$ objdump -d a.out
a.out:     file format elf64-x86-64
Disassembly of section .init:
0000000000001000 <_init>:
    1000:    f3 0f 1e fa              endbr64
    1004:    48 83 ec 08              sub    $0x8,%rsp
    1008:    48 8b 05 d9 2f 00 00     mov    0x2fd9(%rip),%rax        # 3fe8
    100f:    48 85 c0                 test   %rax,%rax
    1012:    74 02                    je     1016 <_init+0x16>
    1014:    ff d0                    call   *%rax
    1016:    48 83 c4 08              add    $0x8,%rsp
    101a:    c3                       ret
…
```

GDB Assembly Edition

- Back to GDB...
- You can still set **breakpoints**
  - Not at specific lines of code...but at specific instructions (which are stored in memory)
  - `break *0x000055555555515b`
  - Why the `*`?
  - `*main+24`
    - You can set breakpoints at function offsets
    - Get this from GDB's `layout asm`
- You can still step through your code
  - Again, not stepping through lines of code, but through CPU instructions
  - Using `stepi` instead of `step`
    - `nexti` instead of `next`
    - `Continue`

GDB Assembly Edition

- Examining Memory
  - We can print values stored at memory address or at registers
  - `print/format expr`
    - Indicate registers with `$` (NOT `%`)
    - To print a value stor`ed in a memory address use `*`
    - `format` tells us how to interpret values at that memory location
      - `d`: decimal
      - `x`:hex
      - `t`: binary
      - `f`: floating point
      - `i`: instruction
      - `c`: character
    - `p $rdi` displays the content at `%rdi` in a decimal format
  - `x MEM_ADDR` prints memory content
    - Just because you print it as decimal does not mean that the value is a decimal
    - Interpretation of values depends on the context (which you need to provide)
  - `info registers` lets you see all registers at once

Need help with GDB?

Come to office hours!

C Control Structures → Assembly

```c
#include <stdio.h>

int main(void)
{
    for (int i = 0; i < 10; i++)
    {
        printf("%d", i);
    }
    return 0;
}
```

```
0x0000000000001155 <+12>:   movl   $0x0,-0x4(%rbp)
0x000000000000115c <+19>:   jmp    0x117b <main+50>
0x000000000000115e <+21>:   mov    -0x4(%rbp),%eax
0x0000000000001161 <+24>:   mov    %eax,%esi
0x0000000000001163 <+26>:   lea    0xe9a(%rip),%rax
0x000000000000116a <+33>:   mov    %rax,%rdi
0x000000000000116d <+36>:   mov    $0x0,%eax
0x0000000000001172 <+41>:   call   0x1050 <printf@plt>
0x0000000000001177 <+46>:   addl   $0x1,-0x4(%rbp)
0x000000000000117b <+50>:   cmpl   $0x9,-0x4(%rbp)
0x000000000000117f <+54>:   jle    0x115e <main+21>
```

C Control Structures → Assembly

```c
#include <stdio.h>

int main(void)
{
    int i = 0;
    while (i < 10)
    {
        printf("%d", i);
        i++;
    }
    return 0;
}
```

```
0x0000000000001155 <+12>:   movl   $0x0,-0x4(%rbp)
0x000000000000115c <+19>:   jmp    0x117b <main+50>
0x000000000000115e <+21>:   mov    -0x4(%rbp),%eax
0x0000000000001161 <+24>:   mov    %eax,%esi
0x0000000000001163 <+26>:   lea    0xe9a(%rip),%rax
0x000000000000116a <+33>:   mov    %rax,%rdi
0x000000000000116d <+36>:   mov    $0x0,%eax
0x0000000000001172 <+41>:   call   0x1050 <printf@plt>
0x0000000000001177 <+46>:   addl   $0x1,-0x4(%rbp)
0x000000000000117b <+50>:   cmpl   $0x9,-0x4(%rbp)
0x000000000000117f <+54>:   jle    0x115e <main+21>
```

C Control Structures → Assembly

```c
#include <stdio.h>

int main(void)
{
    for (int i = 0; i < 10; i++)
    {
        printf("%d", i);
    }
    return 0;
}
```

```
0x0000000000001155 <+12>:   movl   $0x0,-0x4(%rbp)
0x000000000000115c <+19>:   jmp    0x117b <main+50>
0x000000000000115e <+21>:   mov    -0x4(%rbp),%eax
0x0000000000001161 <+24>:   mov    %eax,%esi
0x0000000000001163 <+26>:   lea    0xe9a(%rip),%rax
0x000000000000116a <+33>:   mov    %rax,%rdi
0x000000000000116d <+36>:   mov    $0x0,%eax
0x0000000000001172 <+41>:   call   0x1050 <printf@plt>
0x0000000000001177 <+46>:   addl   $0x1,-0x4(%rbp)
0x000000000000117b <+50>:   cmpl   $0x9,-0x4(%rbp)
0x000000000000117f <+54>:   jle    0x115e <main+21>
```

Wait….why is the assembly code the same?

for loops == while loops!

Your CPU treats them the same way!

* do-while loops also work the same way (Write a short program and inspect the assembly!)

C Control Structures → Assembly

```c
#include <stdio.h>
int main(void)
{
    int input;
    scanf("%d", &input);
    if (input > 10)
printf("Big");
    else printf("Not Big");
    return 0;
}
```

```
11bf:   8b 45 f4               mov    -0xc(%rbp),%eax
11c2:   83 f8 0a               cmp    $0xa,%eax
11c5:   7e 16                  jle    11dd <main+0x54>
11c7:   48 8d 05 39 0e 00 00   lea    0xe39(%rip),%rax
11ce:   48 89 c7               mov    %rax,%rdi
11d1:   b8 00 00 00 00         mov    $0x0,%eax
11d6:   e8 a5 fe ff ff         call   1080
<printf@plt>
11db:   eb 14                  jmp    11f1 <main+0x68>
11dd:   48 8d 05 27 0e 00 00   lea    0xe27(%rip),%rax
11e4:   48 89 c7               mov    %rax,%rdi
11e7:   b8 00 00 00 00         mov    $0x0,%eax
11ec:   e8 8f fe ff ff         call   1080
<printf@plt>
```

Conditional statements works as expected

Who knew that `if-else` executed different based on *conditions?*

Condition Codes

- `cmpq op2, op1` # computes result = op1 - op2, discards result, sets condition codes
- `testq op2, op1` # computes result = op1 & op2, discards result, sets condition codes

- Condition Codes - ***ZF*** *(zero flag),* ***SF*** *(sign flag),* ***OF*** *(overflow flag, signed), and* ***CF*** *(carry flag, unsigned)*

https://web.stanford.edu/class/archive/cs/cs107/cs107.1212/guide/x86-64.html

Our *real* first assembly code analysis

Looking through a real program!

Special thanks to Jake Kasper for providing slides & code

C Control Structures → Assembly

```c
#include <stdio.h>

int main(int argc, char **argv)
{
    int myNum = increment(5);
    printf("My num is %d\n", myNum);
    return 0;
}

int increment(int num)
{
    return ++num;
}
```

Prefix increment
Increments first, then returns

```
0000000000001149 <main>:
1149:       f3 0f 1e fa                 endbr64
114d:       55                          push   %rbp
114e:       48 89 e5                    mov
%rsp,%rbp
1151:       48 83 ec 20                 sub
$0x20,%rsp
1155:       89 7d ec                    mov    %edi,-
0x14(%rbp)
1158:       48 89 75 e0                 mov    %rsi,-
0x20(%rbp)
115c:       bf 05 00 00 00              mov
```

C Control Structures → Assembly

```c
#include <stdio.h>

int main(int argc, char **argv)
{
    int myNum = increment(5);
    printf("My num is %d\n", myNum);
    return 0;
}

int increment(int num)
{
    return ++num;
}
```

```
0000000000001189 <increment>:
1189:      f3 0f 1e fa                  endbr64
118d:      55                           push %rbp
118e:      48 89 e5                     mov
%rsp,%rbp
1191:      89 7d fc                     mov
%edi,-0x4(%rbp)
1194:      83 45 fc 01                  addl
$0x1,-0x4(%rbp)
1198:      8b 45 fc                     mov  -
0x4(%rbp),%eax
119b:      5d                           pop  %rbp
```

C Control Structures → Assembly

%rbp needs maintains the current stack frame
- To preserve the previous stack frame
- it gets pushed onto the stack

```c
#include <stdio.h>

int main(int argc, char **argv)
{
    int myNum = increment(5);
    printf("My num is %d\n", myNum);
    return 0;
}

int increment(int num)
{
    return ++num;
}
```

```
0000000000001189 <increment>:
1189:      f3 0f 1e fa              endbr64
118d:      55                       push %rbp
118e:      48 89 e5                 mov
%rsp,%rbp
1191:      89 7d fc                 mov
%edi,-0x4(%rbp)
1194:      83 45 fc 01              addl
$0x1,-0x4(%rbp)
1198:      8b 45 fc                 mov  -
0x4(%rbp),%eax
119b:      5d                       pop  %rbp
```

C Control Structures → Assembly

```c
#include <stdio.h>

int main(int argc, char **argv)
{
    int myNum = increment(5);
    printf("My num is %d\n", myNum);
    return 0;
}

int increment(int num)
{
    return ++num;
}
```

%edi is our first argument register, so we're moving the value of our argument (num) into the current stack frame

Why -0x4?

```
0000000000001189 <increment>:
1189:     f3 0f 1e fa              endbr64
118d:     55                       push %rbp
118e:     48 89 e5                 mov
%rsp,%rbp
1191:     89 7d fc                 mov
%edi,-0x4(%rbp)
1194:     83 45 fc 01              addl
$0x1,-0x4(%rbp)
1198:     8b 45 fc                 mov   -
0x4(%rbp),%eax
119b:     5d                       pop   %rbp
```

C Control Structures → Assembly

Increment the value of the argument we just stored in the stack

```c
#include <stdio.h>

int main(int argc, char **argv)
{
    int myNum = increment(5);
    printf("My num is %d\n", myNum);
    return 0;
}

int increment(int num)
{
    return ++num;
}
```

```
0000000000001189 <increment>:
1189:      f3 0f 1e fa                endbr64
118d:      55                         push %rbp
118e:      48 89 e5                   mov
%rsp,%rbp
1191:      89 7d fc                   mov
%edi,-0x4(%rbp)
1194:      83 45 fc 01                addl
$0x1,-0x4(%rbp)
1198:      8b 45 fc                   mov  -
0x4(%rbp),%eax
119b:      5d                         pop  %rbp
```

C Control Structures → Assembly

```c
#include <stdio.h>

int main(int argc, char **argv)
{
   int myNum = increment(5);
   printf("My num is %d\n", myNum);
   return 0;
}

int increment(int num)
{
   return ++num;
}
```

Move our data we've been editing in the stack, to our return register

```
0000000000001189 <increment>:
1189:      f3 0f 1e fa              endbr64
118d:      55                       push %rbp
118e:      48 89 e5                 mov
%rsp,%rbp
1191:      89 7d fc                 mov
%edi,-0x4(%rbp)
1194:      83 45 fc 01              addl
$0x1,-0x4(%rbp)
1198:      8b 45 fc                 mov   -
0x4(%rbp),%eax
119b:      5d                       pop   %rbp
```

C Control Structures → Assembly

```c
#include <stdio.h>

int main(int argc, char **argv)
{
    int myNum = increment(5);
    printf("My num is %d\n", myNum);
    return 0;
}

int increment(int num)
{
    return ++num;
}
```

Pop the stack frame from the stack, as we're about to return from the current function scope, and this will load the previous stack frame back to `%rbp`

```
0000000000001189 <increment>:
1189:      f3 0f 1e fa                  endbr64
118d:      55                           push %rbp
118e:      48 89 e5                     mov
%rsp,%rbp
1191:      89 7d fc                     mov
%edi,-0x4(%rbp)
1194:      83 45 fc 01                  addl
$0x1,-0x4(%rbp)
1198:      8b 45 fc                     mov  -
0x4(%rbp),%eax
119b:      5d                           pop  %rbp
```

C Control Structures → Assembly

```c
#include <stdio.h>

int main(int argc, char **argv)
{
    int myNum = increment(5);
    printf("My num is %d\n", myNum);
    return 0;
}

int increment(int num)
{
    return ++num;
}
```

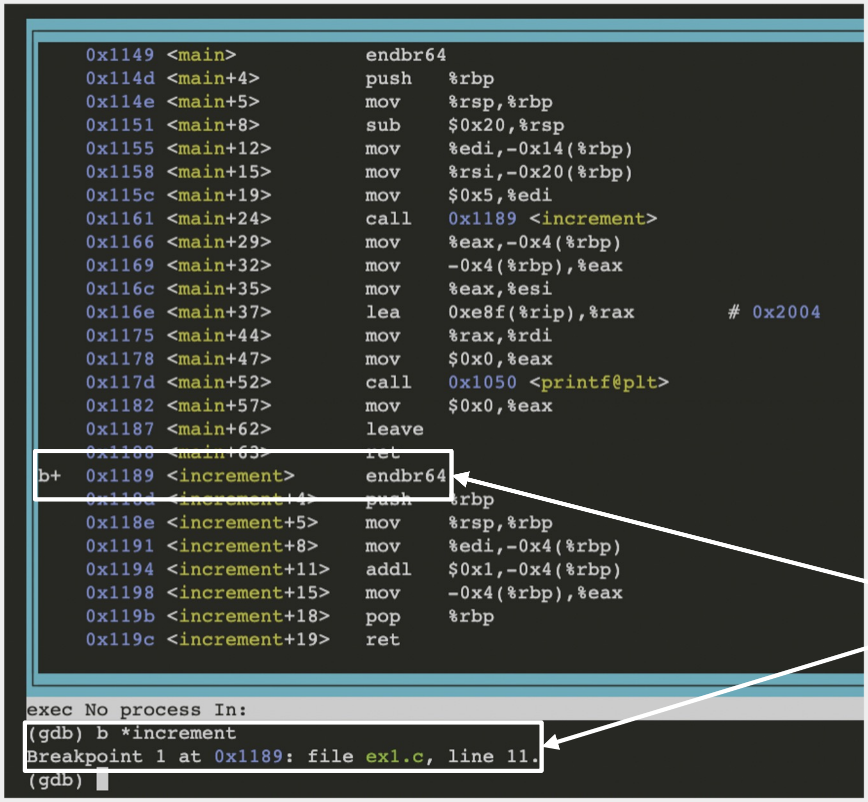
Return to caller

What about the return value?

It's already in the return register(%eax)

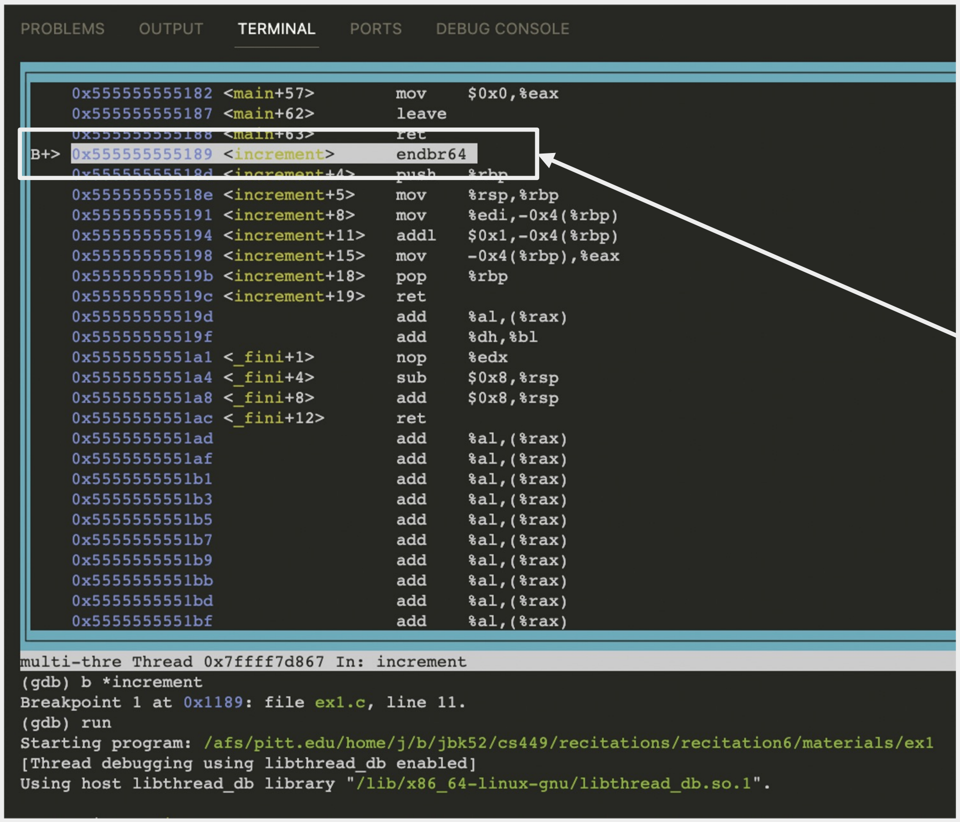
```
0000000000001189 <increment>:
1189:    f3 0f 1e fa         endbr64
118d:    55                  push %rbp
118e:    48 89 e5            mov
%rsp,%rbp
1191:    89 7d fc            mov
%edi,-0x4(%rbp)
1194:    83 45 fc 01         addl
$0x1,-0x4(%rbp)
1198:    8b 45 fc            mov  -
0x4(%rbp),%eax
119b:    5d                  pop  %rbp
```

Let's inspect `increment()` with GDB



Set a breakpoint at the start of the **assembly** for increment using the *

Tracing through the code w/ GDB



After running, we've hit the breakpoint at increment

Let's read the assembly line by line using **`ni`** (`next instruction`), though we can skip ahead a few lines until we get to the more important function details

Tracing through the code w/ GDB

```
    0x555555555182 <main+57>        mov    $0x0,%eax
    0x555555555187 <main+62>        leave
    0x555555555188 <main+63>        ret
B+  0x555555555189 <increment>      endbr64
    0x55555555518d <increment+4>    push   %rbp
  > 0x55555555518e <increment+5>    mov    %rsp,%rbp
    0x555555555191 <increment+8>    mov    %edi,-0x4(%rbp)
    0x555555555194 <increment+11>   addl   $0x1,-0x4(%rbp)
    0x555555555198 <increment+15>   mov    -0x4(%rbp),%eax
    0x55555555519b <increment+18>   pop    %rbp
    0x55555555519c <increment+19>   ret
    0x55555555519d                  add    %al,(%rax)
    0x55555555519f                  add    %dh,%bl
    0x5555555551a1 <_fini+1>        nop    %edx
    0x5555555551a4 <_fini+4>        sub    $0x8,%rsp
    0x5555555551a8 <_fini+8>        add    $0x8,%rsp
    0x5555555551ac <_fini+12>       ret
    0x5555555551ad                  add    %al,(%rax)
    0x5555555551af                  add    %al,(%rax)
    0x5555555551b1                  add    %al,(%rax)
    0x5555555551b3                  add    %al,(%rax)
    0x5555555551b5                  add    %al,(%rax)
    0x5555555551b7                  add    %al,(%rax)
    0x5555555551b9                  add    %al,(%rax)
    0x5555555551bb                  add    %al,(%rax)
    0x5555555551bd                  add    %al,(%rax)
    0x5555555551bf                  add    %al,(%rax)
```

This is the line in which our stack frame pointer, `%rbp`, is being updated to contain the current stack address

Tracing through the code w/ GDB

```
    0x555555555182 <main+57>       mov    $0x0,%eax
    0x555555555187 <main+62>       leave
    0x555555555188 <main+63>       ret
B+  0x555555555189 <increment>     endbr64
    0x55555555518d <increment+4>   push   %rbp
    0x55555555518e <increment+5>   mov    %rsp,%rbp
  > 0x555555555191 <increment+8>   mov    %edi,-0x4(%rbp)
    0x555555555194 <increment+11>  addl   $0x1,-0x4(%rbp)
    0x555555555198 <increment+15>  mov    -0x4(%rbp),%eax
    0x55555555519b <increment+18>  pop    %rbp
    0x55555555519c <increment+19>  ret
    0x55555555519d                 add    %al,(%rax)
    0x55555555519f                 add    %dh,%bl
    0x5555555551a1 <_fini+1>       nop    %edx
    0x5555555551a4 <_fini+4>       sub    $0x8,%rsp
    0x5555555551a8 <_fini+8>       add    $0x8,%rsp
    0x5555555551ac <_fini+12>      ret
    0x5555555551ad                 add    %al,(%rax)
    0x5555555551af                 add    %al,(%rax)
    0x5555555551b1                 add    %al,(%rax)
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    0x5555555551b5                 add    %al,(%rax)
    0x5555555551b7                 add    %al,(%rax)
    0x5555555551b9                 add    %al,(%rax)
    0x5555555551bb                 add    %al,(%rax)
    0x5555555551bd                 add    %al,(%rax)
    0x5555555551bf                 add    %al,(%rax)
```

We've now executed the instruction to add the current stack pointer to %rbp

We are also about to execute the line to put the argument register's contents into the stack frame, so let's check the value of the argument register:

`p $rdi` →

```
(gdb) p $rdi
$1 = 5
```

This makes sense, as we passed 5 into our function in our C code

```
increment(5);
```

Tracing through the code w/ GDB

```
B+   0x555555555189 <increment>       endbr64
     0x55555555518d <increment+4>     push   %rbp
     0x55555555518e <increment+5>     mov    %rsp,%rbp
     0x555555555191 <increment+8>     mov    %edi,-0x4(%rbp)
  >  0x555555555194 <increment+11>    addl   $0x1,-0x4(%rbp)
     0x555555555198 <increment+15>    mov    -0x4(%rbp),%eax
     0x55555555519b <increment+18>    pop    %rbp
     0x55555555519c <increment+19>    ret
     0x55555555519d                   add    %al,(%rax)
     0x55555555519f                   add    %dh,%bl
     0x5555555551a1 <_fini+1>         nop    %edx
     0x5555555551a4 <_fini+4>         sub    $0x8,%rsp
     0x5555555551a8 <_fini+8>         add    $0x8,%rsp
     0x5555555551ac <_fini+12>        ret
     0x5555555551ad                   add    %al,(%rax)
     0x5555555551af                   add    %al,(%rax)
     0x5555555551b1                   add    %al,(%rax)
     0x5555555551b3                   add    %al,(%rax)
     0x5555555551b5                   add    %al,(%rax)
     0x5555555551b7                   add    %al,(%rax)
     0x5555555551b9                   add    %al,(%rax)
     0x5555555551bb                   add    %al,(%rax)
     0x5555555551bd                   add    %al,(%rax)
     0x5555555551bf                   add    %al,(%rax)
     0x5555555551c1                   add    %al,(%rax)
     0x5555555551c3                   add    %al,(%rax)
     0x5555555551c5                   add    %al,(%rax)
```

Now we stored the argument register value into our stack frame. To check that this update actually changed our stack frame, let's print the integer that lies below the stack pointer:

`x/-4bx $rbp` → Read the previous 4 **bytes**

```
(gdb) x/-4bx $rbp
0x7fffffffe18c: 0x05    0x00    0x00    0x00
```

`x/-1w $rbp` → Read the previous **word** (word is the size of an integer)

```
(gdb) x/-1w $rbp
0x7fffffffe18c: 5
```

We can see both of these led us to the value 5 being stored in the stack frame

Tracing through the code w/ GDB

```
    0x555555555182 <main+57>        mov     $0x0,%eax
    0x555555555187 <main+62>        leave
    0x555555555188 <main+63>        ret
B+  0x555555555189 <increment>      endbr64
    0x55555555518d <increment+4>    push    %rbp
    0x55555555518e <increment+5>    mov     %rsp,%rbp
    0x555555555191 <increment+8>    mov     %edi,-0x4(%rbp)
    0x555555555194 <increment+11>   addl    $0x1,-0x4(%rbp)
  > 0x555555555198 <increment+15>   mov     -0x4(%rbp),%eax
    0x55555555519b <increment+18>   pop     %rbp
    0x55555555519c <increment+19>   ret
    0x55555555519d                  add     %al,(%rax)
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    0x5555555551a1 <_fini+1>        nop     %edx
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    0x5555555551ac <_fini+12>       ret
    0x5555555551ad                  add     %al,(%rax)
    0x5555555551af                  add     %al,(%rax)
    0x5555555551b1                  add     %al,(%rax)
    0x5555555551b3                  add     %al,(%rax)
    0x5555555551b5                  add     %al,(%rax)
    0x5555555551b7                  add     %al,(%rax)
    0x5555555551b9                  add     %al,(%rax)
    0x5555555551bb                  add     %al,(%rax)
    0x5555555551bd                  add     %al,(%rax)
    0x5555555551bf                  add     %al,(%rax)
```

At this point, we've run the line to increment the value in the stack frame, and are waiting to execute this line.

To see if this change was made, let's again print out the values:

`x/-4bx $rbp` → Read the previous 4 **bytes** as **hex**

```
(gdb) x/-4bx $rbp
0x7fffffffe18c: 0x06    0x00    0x00    0x00
```

`x/-1wx $rbp` → Read the previous **word** (word is the size of an integer) as **hex**

```
(gdb) x/-1wx $rbp
0x7fffffffe18c: 0x00000006
```

Since the value changed to 6, the increment was successful, and we can see where that change occurred.

Tracing through the code w/ GDB

```
     0x555555555182 <main+57>          mov    $0x0,%eax
     0x555555555187 <main+62>          leave
     0x555555555188 <main+63>          ret
B+   0x555555555189 <increment>        endbr64
     0x55555555518d <increment+4>      push   %rbp
     0x55555555518e <increment+5>      mov    %rsp,%rbp
     0x555555555191 <increment+8>      mov    %edi,-0x4(%rbp)
     0x555555555194 <increment+11>     addl   $0x1,-0x4(%rbp)
     0x555555555198 <increment+15>     mov    -0x4(%rbp),%eax
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     0x55555555519d                    add    %al,(%rax)
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     0x5555555551a1 <_fini+1>          nop    %edx
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     0x5555555551b5                    add    %al,(%rax)
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     0x5555555551b9                    add    %al,(%rax)
     0x5555555551bb                    add    %al,(%rax)
     0x5555555551bd                    add    %al,(%rax)
     0x5555555551bf                    add    %al,(%rax)
```

%eax, the return register, should contain the value 6 that we want to return to the user. Let's see:

`p $rax` →

```
(gdb) p $rax
$3 = 6
```

`%eax` now contains the accurate return value from our function, so we can return to the previous caller after adjusting the stack.

Lab 4

Assembly Lab: ASM!

Now, it's your turn!

- In lab 4, you will practice:
    - Reading assembly
    - Recognizing common patterns
    - Using **gdb** to *debug assembly code + inspect memory!*
- Part A: Investigating the code!
    - Reading simple functions
        - Similar to what we just did
    - Deep dive into *control flow, raise operations, hidden arguments*
    - **The Test.**
        - Can you read assembly code tell me what it does?
            - **Gradescope submission**
- Part B: Inspecting memory
    - Can you debug an executable by looking at assembly code and using gdb?
        - **Gradescope submission**

Malloc Tutorial

CS 0449: Introduction to System Software

Slides from Shinwoo Kim

University of Pittsburgh | School of Computing and Information

Malloc Implementation

Consider an allocator implementation with the following characteristics:

The first-fit free algorithm is used to allocate data.
All blocks have a header with a size and a pointer to the previous block.
The header is 16B (2*8bytes) in size.
Positive sizes indicate the block is allocated, and negative sizes indicate it is free.
All freed blocks are immediately coalesced if possible.
When a block is split, the lower (first) part of the block becomes the allocated part and the upper (second) part becomes the new free block.
If the heap doesn't have enough space to hold the data, it grows by the minimum amount needed to fit the data. Always successfully.

Malloc Implementation

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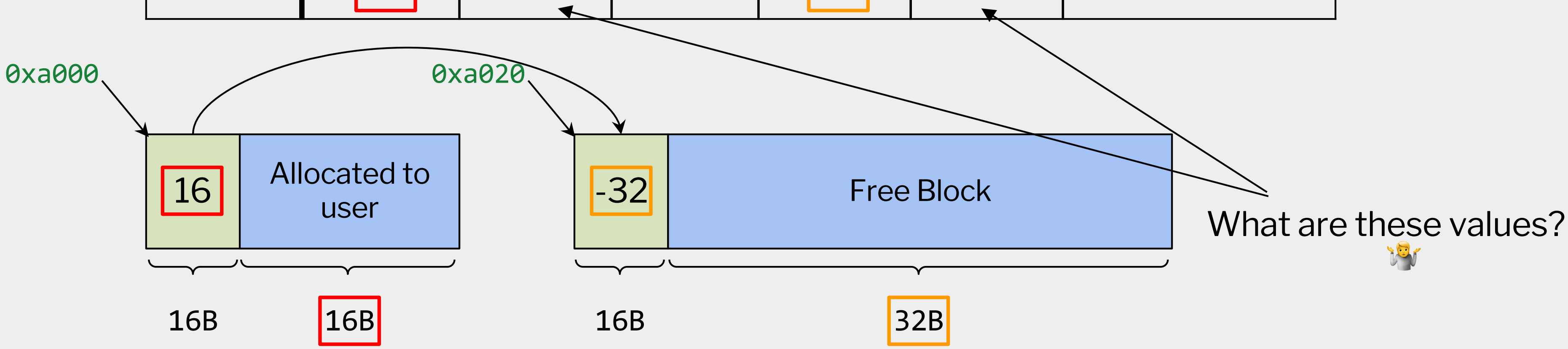
If the heap doesn't have enough space to hold the data, it grows by the minimum amount needed to fit the data. Always successfully.

Memory Diagram

E.g., the following heap contains an allocated block of size 16, followed by a free block of size 32. The top row contains memory addresses, and the bottom row contains the values stored at those memory addresses.

Address	0xa000	0xa008	...	0xa020	0xa028	...
Value	16	0x0000	...	-32	0xa000	...



Assuming an initially empty heap, and given the current state of the heap represented below, which of the malloc sequence was executed?

Address	0xa000	0xa008	…
Value	-64	0x0000	…

1. The only block in the heap is a **free block** of size 64B
   - → For there to be a free block, a block must first have been allocated, then freed
   - → Look for `malloc() and free()` sequence (in that order!)

`p0 = malloc(64);`
`free(p0);`
	`p0 = malloc(64);`
	`p1 = malloc(32);`
	`free(p0);`
	`free(p1);`

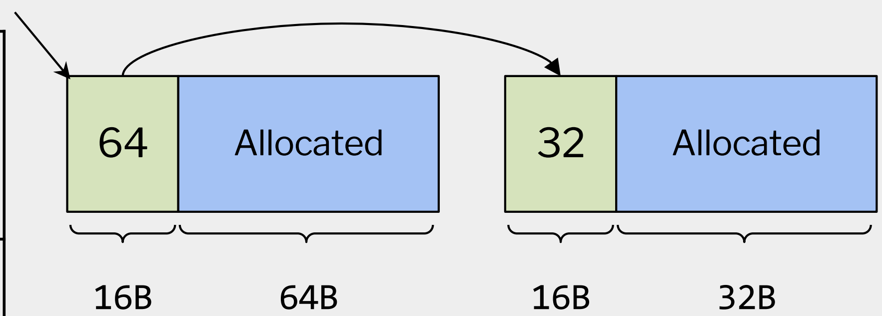
`p0 = malloc(64);`	`p0 = malloc(32);`
	`p1 = malloc(32);`
	`free(p0);`
	`free(p1);`

Assuming an initially empty heap, and given the current state of the heap represented below, which of the malloc sequence was executed?

Address	0xa000	0xa008	...
Value	-64	0x0000	...

p0 = malloc(64);
free(p0);
	→ p0 = malloc(64);
	→ p1 = malloc(32);
	free(p0);
	free(p1);

p0 = malloc(64);	p0 = malloc(32);
	p1 = malloc(32);
	free(p0);
	free(p1);



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Address	0xa000	0xa008	...
Value	-64	0x0000	...

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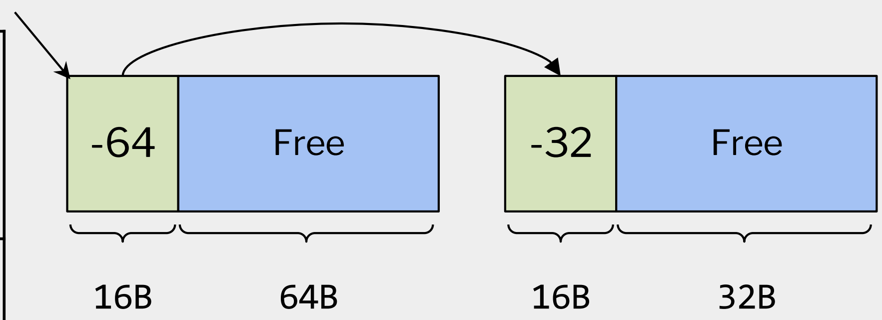
	`p0 = malloc(64);`
	`p1 = malloc(32);`
	`free(p0);`
	`free(p1);`

`p0 = malloc(64);`	`p0 = malloc(32);`
	`p1 = malloc(32);`
	`free(p0);`
	`free(p1);`



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Value	-64	0x0000	...

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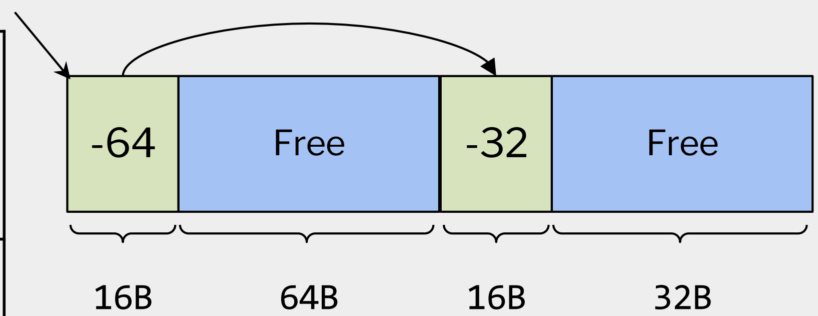
	`p0 = malloc(64);`
	`p1 = malloc(32);`
	`free(p0);`
	`free(p1);`

`p0 = malloc(64);`	`p0 = malloc(32);`
	`p1 = malloc(32);`
	`free(p0);`
	`free(p1);`



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Value	-64	0x0000	...

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`free(p0);`
	`p0 = malloc(64);`
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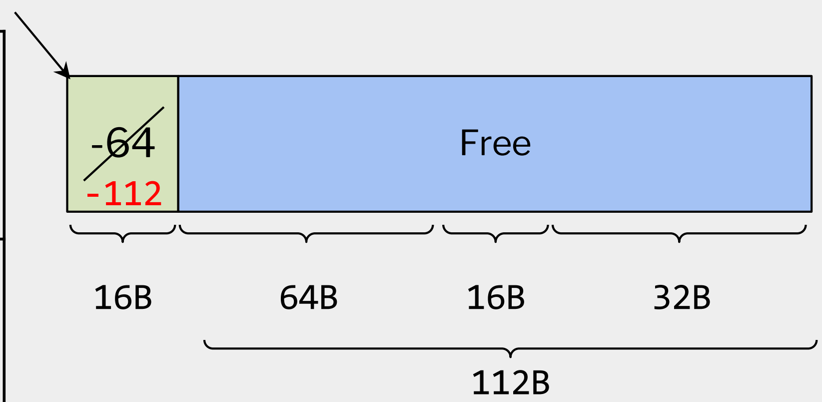
	`free(p0);`
	`free(p1);`

`p0 = malloc(64);`	`p0 = malloc(32);`
	`p1 = malloc(32);`
	`free(p0);`
	`free(p1);`



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Address	0xa000	0xa008	...
Value	-64	0x0000	...

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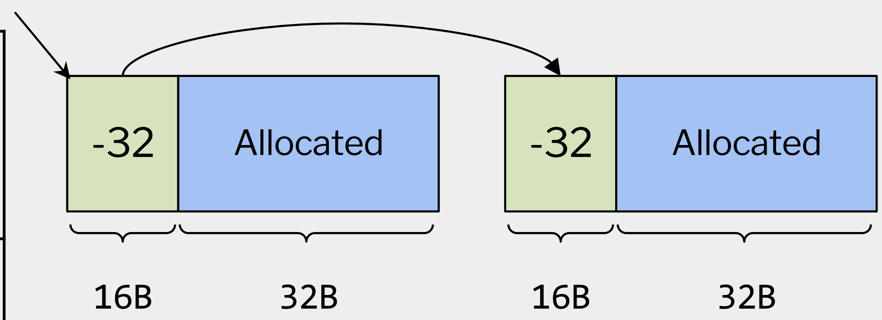
`free(p0);`
	`p0 = malloc(64);`
	`p1 = malloc(32);`
	`free(p0);`
	`free(p1);`

`p0 = malloc(64);`	`p0 = malloc(32);`
	`p1 = malloc(32);`
	`free(p0);`
	`free(p1);`



Assuming an initially empty heap, and given the current state of the heap represented below, which of the malloc sequence was executed?

Address	0xa000	0xa008	…
Value	-64	0x0000	…

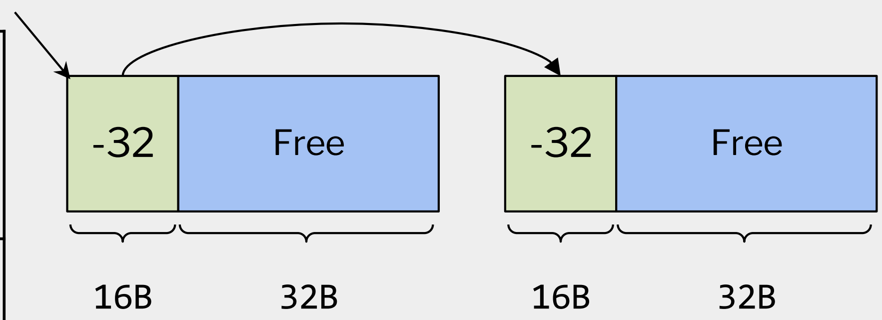
1. All freed blocks are immediately coalesced if possible.

```
p0 = malloc(64);
free(p0);
```

```
p0 = malloc(64);
p1 = malloc(32);
free(p0);
free(p1);
```

```
p0 = malloc(64);
```

```
p0 = malloc(32);
p1 = malloc(32);
free(p0);
free(p1);
```



Assuming an initially empty heap, and given the current state of the heap represented below, which of the malloc sequence was executed?

Address	0xa000	0xa008	…
Value	-64	0x0000	…

1. All freed blocks are immediately coalesced if possible.

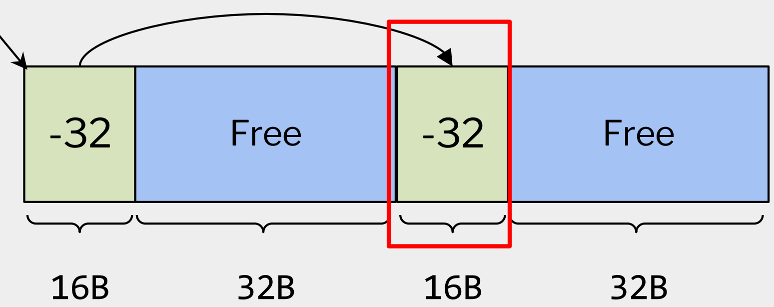
When coalescing, the “header” of the second block is merged into the payload region

```
p0 = malloc(64);
free(p0);
```

```
p0 = malloc(64);
p1 = malloc(32);
free(p0);
free(p1);
```

```
p0 = malloc(64);
```

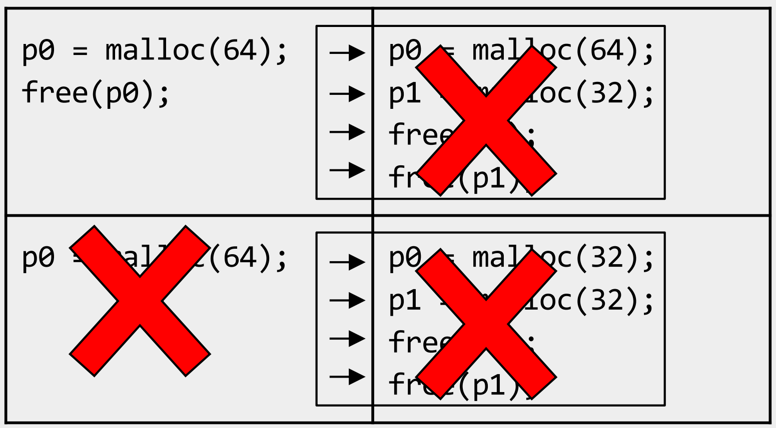
```
p0 = malloc(32);
p1 = malloc(32);
free(p0);
free(p1);
```

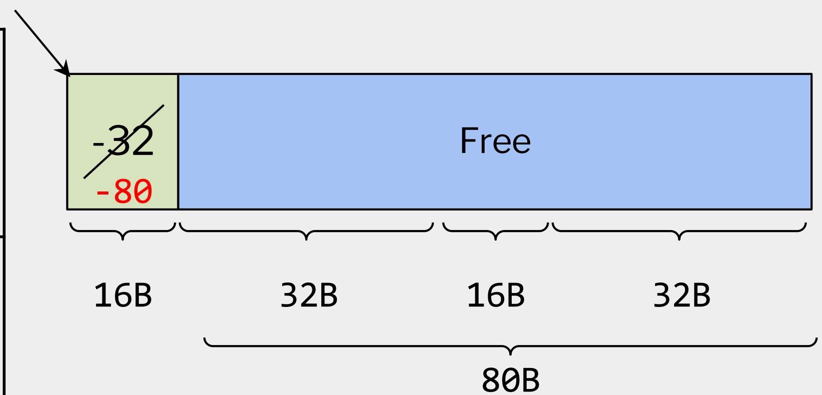


Assuming an initially empty heap, and given the current state of the heap represented below, which of the malloc sequence was executed?

Address	0xa000	0xa008	...
Value	-64	0x0000	...

1. All freed blocks are immediately coalesced if possible.





Assuming an initially empty heap, and given the current state of the heap represented below, which of the malloc sequence was executed?

Address	0xa000	0xa008	…
Value	-64	0x0000	…

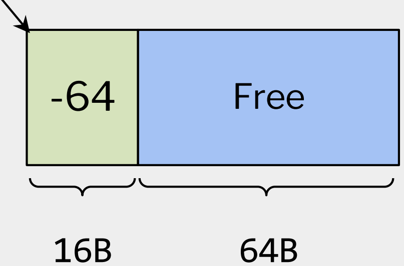
1. The only block in the heap is a **free block** of size 64B
   - → For there to be a free block, a block must first have been allocated, then freed
   - → Look for `malloc() and free()` sequence (in that order!)

```
p0 = malloc(64);
free(p0);
```

```
p0 = malloc(64);
p1 = malloc(32);
free(p0);
free(p1);
```

```
p0 = malloc(64);
```

```
p0 = malloc(32);
p1 = malloc(32);
free(p0);
free(p1);
```

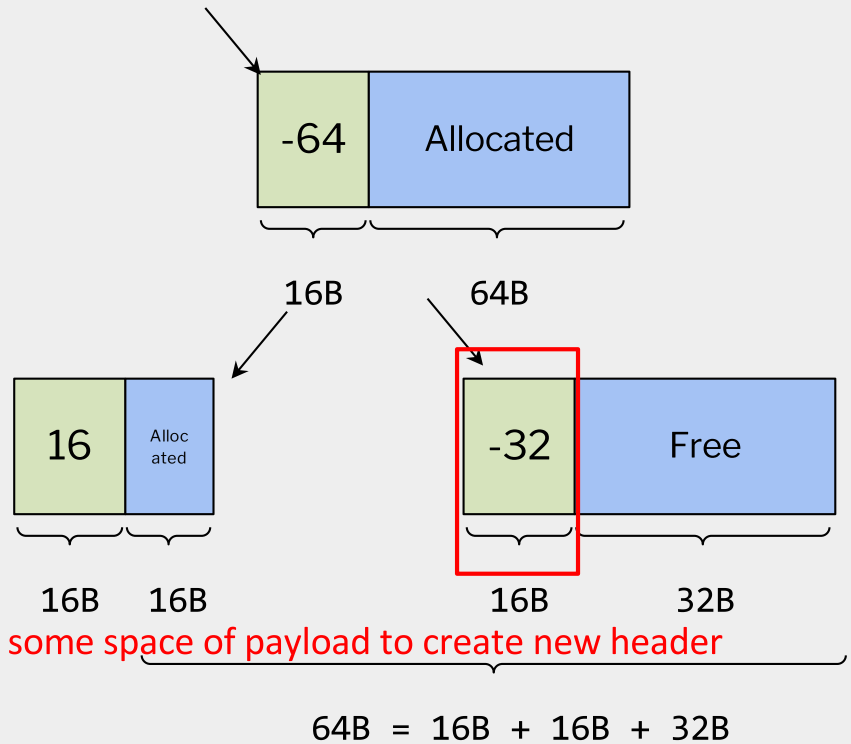


Assuming the heap starts as drawn in the previous question, and given the final state of the heap represented below, which of the malloc sequence was executed?

Address	0xa000	0xa008	...
Value	-64	0x0000	...

⇓

Address	0xa000	0xa008	...	0xa020	...
Value	16	0x0000	...	-32	...



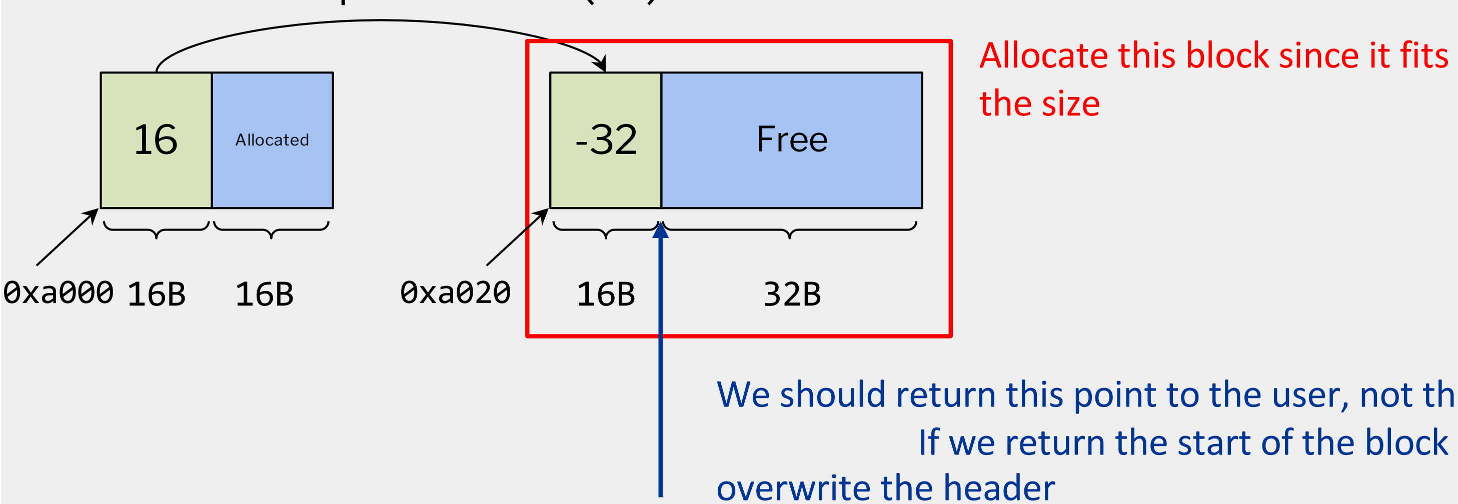
Allocated block of size 16 ⇒ malloc(16) called

When splitting blocks, must use some space of payload to create new header

Assuming the heap starts as drawn above (14 b.), if the following malloc executes, what is the value stored in p1?

Address	0xa000	0xa008	...	0xa020	...
Value	16	0x0000	...	-32	...

```
p1 = malloc(32)
```



We should return this point to the user, not the start of the block.

If we return the start of the block (0xa020), the user might overwrite the header

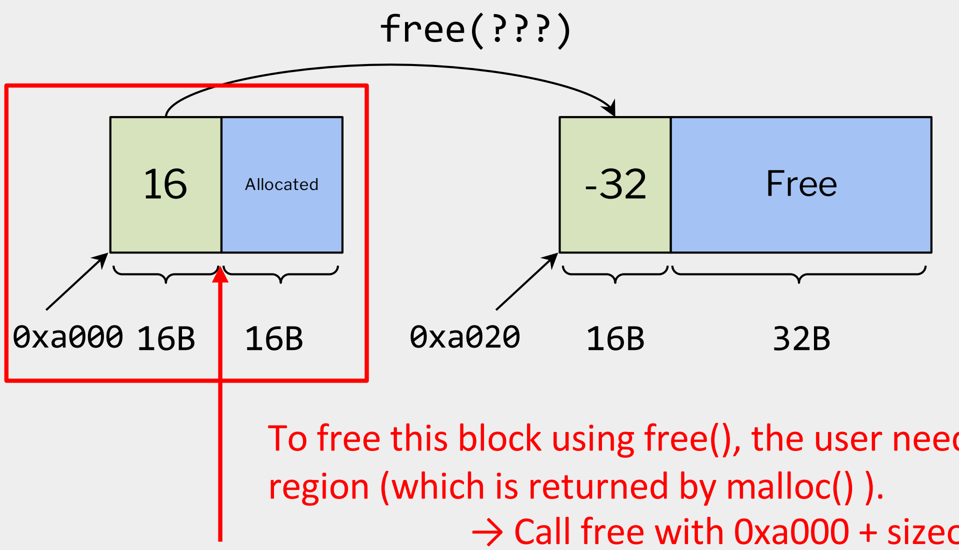
(breaking our pointers to the next block)

To calculate the memory address of this point:

0xa020 + sizeof(Header) = 0xa020 + 16B = 0xa030

Assuming the heap starts as drawn above (14 b.), which value can fill the blank to successfully free the first block?

Address	0xa000	0xa008	…	0xa020	…
Value	16	0x0000	…	-32	…



To free this block using free(), the user needs to pass the pointer (memory address) of the payload region (which is returned by malloc()).

→ Call free with 0xa000 + sizeof(Header)

= free(0xa010)

Why? The user does not know anything about blocks. They simply call free with the same pointer returned by malloc()