CS 33:
Introduction to Computer Organization

Week 4

Agenda

- Midterm 1 Review
- Homework 3
  - struct practice problem
- Lab 2
  - gdb demonstration

Admin

- Homework 3 “due” Monday, October 26th
- Lab 2 “due” Wednesday, October 28th
  - What? Is that right?

Midterm 1 Stats

- Out of 99 points:
- Median: 50
- Mean: 50.9
- Std Dev: 13
- If you're not feeling optimistic, recall that the midterm is only worth 12.5% of your grade. Compare that against 10%, which is how much the labs are worth.

Midterm 1: Question 1

- 1. You want to create a repeated bit pattern in a 64-bit unsigned word. The pattern repeats every 8 bits. For example, repeating the bit-pattern 10011011 would yield the world 0x9b9b9b9b9b9b9b9b. In one of the more confusing naming scheme's we'll tell you to follow (and that's saying something), write a C function rbp(p) that returns such a word, given an 8-bit pattern p. Have your function execute as few instructions as possible.

Midterm 1: Question 2

- The PDP-11 architecture is “mixed-endian”: within a 16-bit short word, the least significant byte comes first, whereas within a 32-bit long word, the *most* significant short word comes first. Diagram how the signed 32-bit number -25306982 (-0x1822766) is represented as a series of unsigned 8-bit bytes (a) on a PDP-11, (b) on an x86-64 machine, and (c) on a big endian machine like the SPARC. Your diagram should list the offset of each byte.

Midterm 1: Question 3

- Consider these two functions:

```
#include <stdbool.h>
bool pushme(unsigned long v)
{
  return 255 <= (v >> 3);
}
bool pullyou (long v)
{
  return ! (0 <= (v >> 3) && (v >> 3) < 255);
}
```

Midterm 1: Question 3

- ...and this assembly-language implementation:

```
pushme: cmpq $2039, %rdi
        setq %al
        ret
pullyou:cmpq $2039, %rdi
        setq %al
        ret
```

- a. Explain why those “2039”s are correct, even though the source code does not mention 2039.
- b. How can pushme and pullyou have identical machine code, even though the functions have different types and implementations? Explain?

Midterm 1: Question 4

- Would the following be a valid implementation of (3)'s pushme and pullyou functions? If now, explain why not. If so, give another implementation of pushme and pullyou that would be even shorter (i.e., would take fewer bytes of machine code).

```
pushme: cmpq $2039, %rdi
        seta %al
        ret
pullyou:jmp  pushme
```

Midterm 1: Question 5

- The following is a buggy implementation of (3)'s pushme function. Three of its instructions are incorrect. Fix the bugs with as few changes as you can and briefly explain why your fixes are needed. (on board)

```
pushme: pushq %rbx
        movq  %rsp, %rbp
        movq  %rdi, -8(%rbp)
        movq  -8(%rbp), %rax
        shrq  $3, %rax
        cmpq  $255, %rax
        seta  %al
        popq  %rbx
        ret
```

Midterm 1: Question 6

- Explain what the following assembly-language function does, at a high level. Give C source code that corresponds to its behavior as closely as possible.

```
mystery: movzbl %dil, %eax
         movabs $0x1010101010101, %rdx
         imul   %rdx, %rax
```

- What ever could this be?

Midterm 1: Question 7

- What does the following assembly-language code do? Briefly explain how to use it from C source code, how it executes, and what its behavior is from the C point of view.

```
callme: leaq  (%rdi, %rsi), %rax
        callq .L1
.L1     ret
```

Midterm 1: Question 8

```
1  #include <stdio.h>
2  #include <string.h>
3
4  long n = 3;
5  extern int (*p) (void);
6
7  void
8  output(int n)
9  {
10  printf("0x%x\n", n);
11 }
```

```
13 int
14 badfun (void)
15 {
16  int i;
17  memcpy(&i + 3, &p, sizeof p);
18  output(*(&i + n));
19  return i;
20 }
21
22 int
23 main (void)
24 {
25   return ! badfun();
26 }
27
28 int (*p) (void) = main;
```

Midterm 1: Question 8

```
Dump of assembler code for function badfun:
   0x400560 <+0>:     sub    $0x18,%rsp
   0x400564 <+4>:     mov    0x200ad5(%rip),%rax #
0x601040 <p>
   0x40056b <+11>:    mov    %rax,0x18(%rsp)
   0x400570 <+16>:    mov    0x200ad1(%rip),%rax
# 0x601048 <n>
   0x400577 <+23>:    mov    0xc(%rsp,%rax,4),%edi
   0x40057b <+27>:    callq  0x400550 <output>
   0x400580 <+32>:    mov    0xc(%rsp),%eax
   0x400584 <+36>:    add    $0x18,%rsp
   0x400588 <+40>:    retq
End of assembler dump.
```

Midterm 1: Question 8

```
Dump of assembler code for function main:
   0x400430 <+0>:     sub    $0x8,%rsp
   0x400434 <+4>:     callq  0x400560 <badfun>
   0x400439 <+9>:     test   %eax,%eax
   0x40043b <+11>:    sete   %al
   0x40043e <+14>:    add    $0x8,%rsp
   0x400442 <+18>:    movzbl %al,%eax
   0x400445 <+21>:    retq
End of assembler dump.
```

- For each instruction in the machine code, identify the corresponding source-code line number. If an instruction corresponds to two or more source-code line numbers, write them all down and explain.

Midterm 1: Question 9

- When (8)'s program is run it outputs about a million lines of text and then dumps core with a segmentation fault. Explain why this happens, in as much detail as you can. Your explanation should include ***what those text lines look like***, and why.

Homework 3

- At this point, you will probably be well equipped with handling homework 3.
- But here's a practice problem. You know. For “fun”.

Problem 3.69 (3rd ed.)

```
typedef struct {
  int first;
  a_struct a[CNT];
  int last;
} b_struct;

void test(long i, b_struct *bp)
{
  int n = bp->first + bp->last;
  a_struct *ap = &bp->a[i];
  ap->x[ap->idx] = n;
}
```

```
<test>:
mov    0x120(%rsi), %ecx
add    (%rsi), %ecx
lea    (%rdi,%rdi,4), %rax
lea    (%rsi,%rax,8), %rax
mov    0x8(%rax), %rdx
movslq %ecx, %rcx
mov    %rcx, 0x10(%rax,%rdx,8)
ret
```

- What is CNT?
- What is the declaration of a_struct?

Problem 3.69 (3rd ed.)

```
<test>:
[1] mov    0x120(%rsi), %ecx
[2] add    (%rsi), %ecx
[3] lea    (%rdi,%rdi,4), %rax
[4] lea    (%rsi,%rax,8), %rax
[5] mov    0x8(%rax), %rdx
[6] movslq %ecx, %rcx
[7] mov    %rcx, 0x10(%rax,%rdx,8)
[8] ret
```

- %rsi is b_struct *bp.
- We use bp for “int n = bp->first + bp->last;”
- [1+2] perform *(bp+0x120) + *(bp). That looks like a match.
- So bp->last is at bp + 256 + 32 or bp + 288.
- How much does bp->a take up?

Problem 3.69 (3rd ed.)

- How much does bp->a take up?
  - 284 bytes (the 4 bytes of bp->first (int) + the 284 bytes of bp->a make an offset of 284). Right?
- This means sizeof(a_struct) * CNT = 284 right?

Problem 3.69 (3rd ed.)

- How much does bp->a take up?
  - 284 bytes (the 4 bytes of bp->first (int) + the 284 bytes of bp->a make an offset of 284). Right?.
- This means sizeof(a_struct) * CNT = 284 right?
  - Not necessarily. Due to alignment, bp->last must be 4-aligned. We know that bp->a requires 284 bytes but bp->a could actually be anywhere between 281 to 284 bytes and still have bp->last be at offset 288.
  - Heck, maybe there's padding between bp->first and bp->a. If this were true, what would this say about the data types within an instance of a_struct? If you're not sure, stay tuned...

Problem 3.69 (3rd ed.)

```
<test>:
[1] mov    0x120(%rsi), %ecx
[2] add    (%rsi), %ecx
[3] lea    (%rdi,%rdi,4), %rax
[4] lea    (%rsi,%rax,8), %rax
[5] mov    0x8(%rax), %rdx
[6] movslq %ecx, %rcx
[7] mov    %rcx, 0x10(%rax,%rdx,8)
[8] ret
```

- [3] %rax = i + 4*i = 5i
- [4] %rax = bp + 40*i
- [5] %rdx = *(bp + 8 + 40*i)
- What's going on here?

Problem 3.69 (3rd ed.)

[3] %rax = i + 4*i = 5i

- [4] %rax = bp + 40*i
- [5] %rdx = *(bp + 8 + 40*i)
- What's going on here?
  - The 'i' is the index used to access &bp->a[i]. That's probably what this expression is doing.
- If we use i to access elements of the a_struct, what does this say about the size of a_struct?

Problem 3.69 (3rd ed.)

[3] %rax = i + 4*i = 5i

- [4] %rax = bp + 40*i
- [5] %rdx = *(bp + 8 + 40*i)
- What's going on here?
  - The 'i' is the index used to access &bp->a[i]. That's probably what this expression is doing.
- If we use i to access elements of the a_struct, what does this say about the size of a_struct?
  - sizeof(a_struct) = 40.
- What is the 8 in the expression?

Problem 3.69 (3rd ed.)

[5] %rdx = *(bp + 8 + 40*i)

- What's going on here?
  - The 'i' is the index used to access &bp->a[i]. That's probably what this expression is doing.
- If we use i to access elements of the a_struct, what does this say about the size of a_struct?
  - sizeof(a_struct) = 40.
- What is the 8 in the expression?
  - In order to get to bp->a, we must offset by 8 (even though bp->first is an int). Thus, a_struct has a long in it that forces it to be 8 aligned.
- Thus, bp + 8 + 40*i is &bp->a[i]. Thus, we can rewrite this.

Problem 3.69 (3rd ed.)

[5] %rdx = *(&bp->a[i])

- We're dereferencing a pointer to a struct though. What significance does that have?
  - %rdx is set to the first element in bp->a[i].
- What is the size of the very first element?

Problem 3.69 (3rd ed.)

[5] %rdx = *(&bp->a[i])

- We're dereferencing a pointer to a struct though. What significance does that have?
  - %rdx is set to the first element in bp->a[i].
- What is the size of the very first element?
  - It should be 8 bytes.
- Since &bp->a[i] is assigned to ap:
- [5] %rdx = *(ap);

Problem 3.69 (3rd ed.)

```
<test>:
[1] mov    0x120(%rsi), %ecx
[2] add    (%rsi), %ecx
[3] lea    (%rdi,%rdi,4), %rax
[4] lea    (%rsi,%rax,8), %rax
[5] mov    0x8(%rax), %rdx
[6] movslq %ecx, %rcx
[7] mov    %rcx, 0x10(%rax,%rdx,8)
[8] ret
```

- [5] %rdx = *(ap)
- [6] %rcx = n
- [7] *(16 + bp + 40i + *(ap)*8) = n

Problem 3.69 (3rd ed.)

[7] *(16 + bp + 40i + *(ap)*8) = n
=> *(bp + 8 + 40i + 8 + (*ap) * 8) = n
=> *(ap + 8 + (*ap)*8) = n

- This line matches up with:
  - ap->x[ap->idx] = n;
- Thus, *ap is ap->idx. This implies the first element is the ap->idx.
- If this were true, then in order to access ap->x, we would need to offset ap by an additional 8 bytes to skip over ap->idx.
- Oh look: *(ap ***+ 8*** + (*ap)*8) = n

Problem 3.69 (3rd ed.)

- *(ap **+ *8*** + (*ap)*8) = n

  ```
  struct a_struct {
    long idx;
    <?> x[?];
  }
  ```

- What is the data type of array a_struct->x?

Problem 3.69 (3rd ed.)

- *(ap **+ *8*** + (*ap)*8) = n

  struct a_struct {
    long idx;
    <?> x[?];
  }

- What is the data type of array a_struct->x?
  - It's 8 bytes. *ap is idx and in order to use it to index into x, we multiply idx by 8. Thus:
- struct a_struct {

    long idx;
    long x[?];
- }

Problem 3.69 (3rd ed.)

```
struct a_struct {
  long idx;
  long x[?];
}
```

- What is the length of x?
- Recall sizeof(a_struct) is 40 bytes. Thus:

```
struct a_struct {
  long idx;
  long x[4];
}
```

Problem 3.69 (3rd ed.)

```
struct a_struct {
  long idx;
  long x[4];
}
```

- Let's do a final consistency check and determine CNT. Recall that in b_struct:
  - Offset 0: int first
  - Offset ?: a_struct a[CNT];
  - Offset 288: int last
- If this a_struct is correct, the offset would need to be 8. Thus, the array of a would take 280.
- CNT = 280 bytes / 40 bytes per a_struct = 7

Pexex Lab: Getting started

- The objective:
  - Examine the execution of an actual program with a debugger.
  - Learn more about more complicated ways of handling arithmetic.
  - Examine the effect of compiling code with -fwrapv, -fsanitize=undefined, and default.
- Essentially, we're forcing you to learn gdb and using debuggers.

Pexex Lab: Getting started

- You will be examining the execution of Emacs, the text editor.
- Emacs also provides an interpreter for handling “Elisp”, a functional programming language that allows for simple computation.
- Professor Eggert seems to like Emacs so much. It's almost as if Professor Eggert has some hand in making Emacs...
  - For fun, in Linux, type in the command “diff -v”

Pexex Lab: Getting started

- You will concern yourselves with the following files which are located on the SEASnet server.
- Yup, for this one, you've really got no choice but to use SEASnet, preferably lnxsrv09.
- Emacs executable located in:
  - ~eggert/bin64/bin/emacs-24.5
- Emacs source code located in:
  - ~eggert/src/emacs-24.5/

Pexex Lab: Getting started

- In particular, you will examine the execution of the following invocation of Emacs:
  - ~eggert/bin64/bin/emacs-24.5 -batch -eval '(print (* 6997 -4398042316799 179))'
- You will run this command with gdb via the following:
  - gdb --args ~eggert/bin64/bin/emacs-24.5 -batch -eval '(print (* 6997 -4398042316799 179))'
- Or...
  - gdb ~eggert/bin64/bin/emacs-24.5
  - (gdb) r -batch -eval '(print (* 6997 -4398042316799 179))'

Pexex Lab: gdb quick start

- After opening gdb:
- Run the program
  - run (or simply 'r')
- Run the program with arguments
  - r arg1 arg2
- This will run the executable to completion.

Pexex Lab: gdb quick start

- Set break point at function foo:
  - break foo
- Set break point at instruction address 0x100
  - break *0x100
  - Note the asterisk. Without it, it will look for a function called 0x100. Please don't write a function called 0x100.
- When program is run or “continued”, it will run until it hits a break point in which it will stop.
- Resume a program that is stopped
  - continue (or just 'c')

Pexex Lab: gdb quick start

- When a program is break-ed (breaked? broken?) you can step through each instruction either for each assembly instruction or each high level C instruction.
- Execute the next instruction, stepping INTO functions:
  - stepi (or just 'si')
- Execute the next line of source code, stepping INTO functions:
  - step (or just 's')

Pexex Lab: gdb quick start

- Execute the next instruction, stepping OVER functions:
  - nexti (or just 'ni')
- Execute the next line of source code, stepping OVER functions:
  - next (or just 'n')
- Stepping INTO functions means any time you call another function, you will descend into the function. Stepping OVER functions meaning stepping over the function as if it were a single instruction.

Pexex Lab: gdb quick start

- Examining the assembly instructions of function foo:
  - disassemble foo (or just “disas foo”)
- If you are stopped at some instruction in “foo”, the disassembled assembly will also show you where execution is paused at:

```
   0x54352e <arith_driver+46>: 49 89 d7 mov  %rdx,%r15
=> 0x543531 <arith_driver+49>: 49 89 f5 mov  %rsi,%r13
   0x543534 <arith_driver+52>: 41 89 fe mov  %edi,%r14d
```

- This means arith_driver+46 has been executed but arith_driver+49 has not yet been executed.

Pexex Lab: gdb quick start

- disas /m <function name>
  - Display assembly for <function name> prefaced with the corresponding lines of C.
- Using next(i) or step(i), you can also set the debugger to print each instruction as it's executed:
  - set disassemble-next-line on

Pexex Lab: gdb quick start

- Examining registers:
- Print the current state of all registers:
  - info registers
- Print the state of a particular register:
  - info registers $rdi
- Don't you mean “**%**rdi”?
- No. No I don't. And I cry about it every night.

Pexex Lab: gdb quick start

- Print out contents at some memory address with the “x” command.
  - x [addr]
- This was kind of a waste of a whole slide.
- Here is some more text to make it seem like I'm not wasting the slide.
- So, how was your day?
- Please don't print out this slide.

Pexex Lab: gdb quick start

- For more options, use x/nfu [addr] where
  - n specifies how much memory to display (in terms of the unit specified by u), default 1
  - f specifies the format (ie decimal, hexadecimal, etc.), default hex
  - u specifies the unit size for each address (words, bytes, etc.), default word
  - Check out the following link for a more precise listing of the parameters:
  - https://sourceware.org/gdb/onlinedocs/gdb/Memory.html

Pexex Lab: gdb quick start

- Also, print out memory based on an address stored in an register:
- Ex: x/20xw $rsp
  - Print out 20 words(w) in hex(x) starting from the address stored in %rsp.

Pexex Lab: TODO

- Set a break point at Ftimes.
- For each instruction until Ftimes completes, examine what each instruction is doing, checking the status of the registers and memory as necessary.
- Answer the questions.

Pexex Lab: TODO

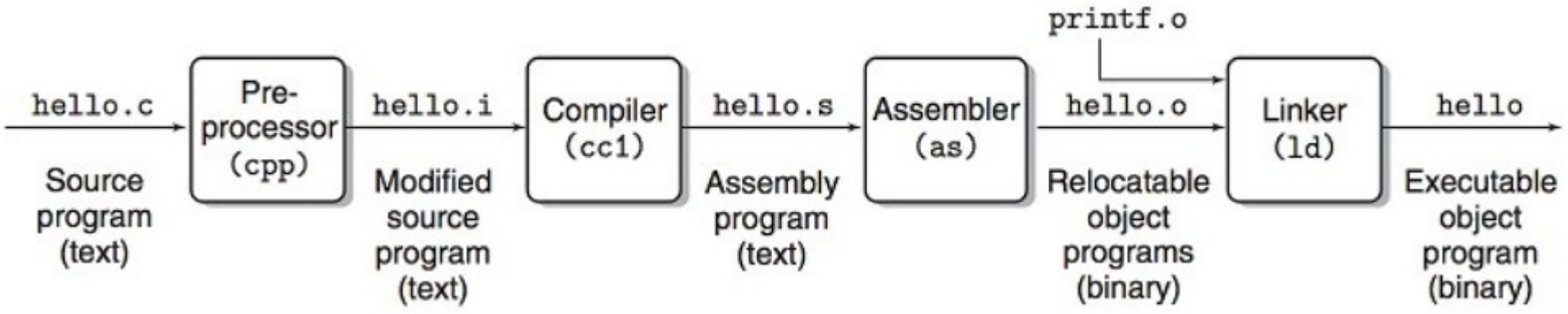
- For part 2, there are three ways:
- gcc -S -fno-asynchronous-unwind-tables <ADDITIONAL FLAGS> testovf.c
  - This produces testovf.s which you can read with any text editor.
- gcc -c <ADDITIONAL FLAGS> testovf.c
  - This produces testovf.o, which you will have to read using “objdump -d testovf.o”. To save the output of object dump, use “objdump -d testovf.o > testovf.txt”

Pexex Lab: TODO

- gcc <ADDITIONAL FLAGS> testovf.c
  - This produces a.out, which you can examine with “gdb a.out”.
- If you use the -S or -c options, you don't need to include a “main” function. However, if you compile to completion (no -S or -c), you will need to include a main function.
- What is all this nonsense?

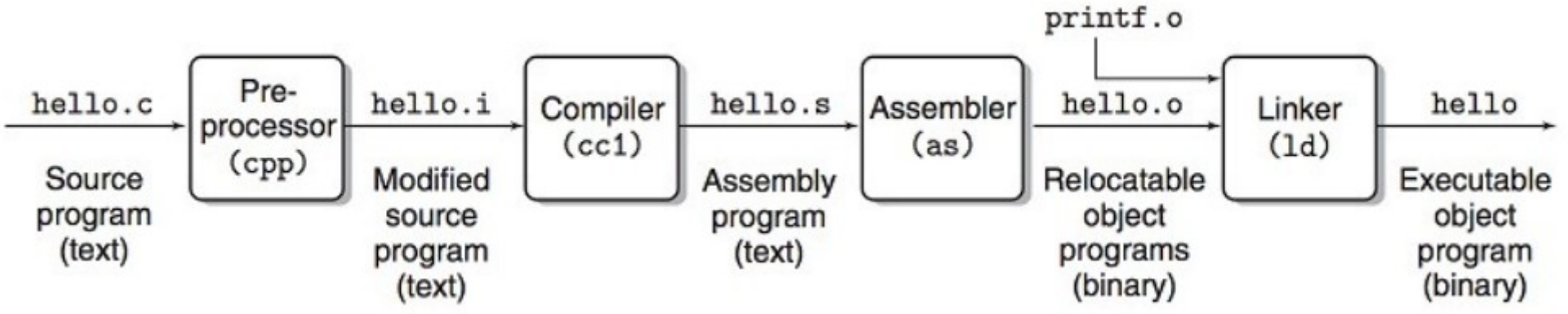
Pexex Lab: TODO

- Recall from Chapter 1 that compilation occurs over several different steps.



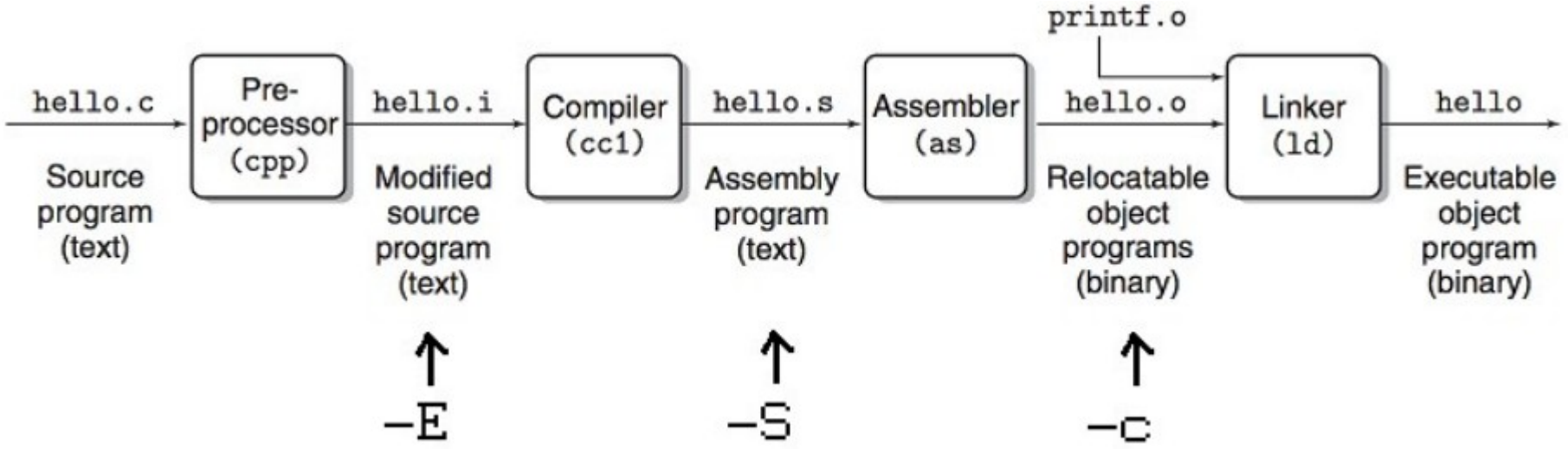
- The result of the Pre-processor step is a modified source with the preprocessor directives(#define, #include) replaced

Pexex Lab: TODO



- The result of the Compiler step is compiled code, which is readable assembly
- The result of the Assembler step is the assembled code which is a binary file.
- Finally, the result of the linker is a fully executable file.
- gcc allows you to compile up to certain steps

Pexex Lab: TODO



- Ex: gcc -E [filename] will get you the modified source file
- Note: Using -E and -S will get you files that you can read with a text editor. To read the output of -c, use objdump.
- To read/disassemble the final executable, use gdb

End of

The Fourth Week

-Six Weeks Remain-