EECS 370 - Lecture 7

Linking

Instruction Set Architecture (ISA) Design Lectures

- Lecture 2: ISA - storage types, binary and addressing modes
- Lecture 3 : LC2K
- Lecture 4 : ARM
- Lecture 5 : Converting C to assembly – basic blocks
- Lecture 6 : Converting C to assembly – functions
- **Lecture 7 : Translation software; libraries, memory layout**

Caller/Callee

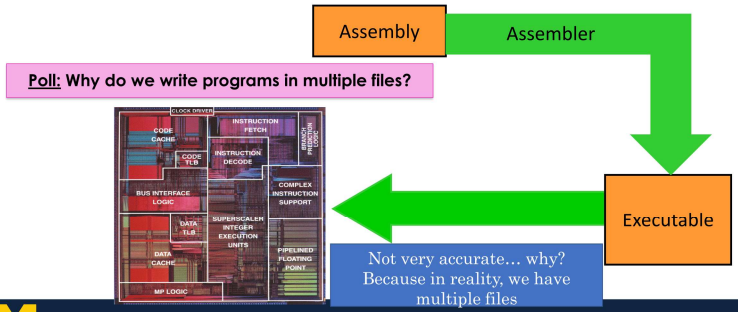
- Still not clicking?
- Don't worry, this is a tricky concept for students to get
- Check out supplemental video
  - https://www.youtube.com/watch?v=SMH5uL3HiiU
- Come to office hours to go over examples

Today we'll finish up software

- Introduce linkers and loaders
  - Basic relationship of complier, assembler, linker and loader.
  - Object files
    - Symbol tables and relocation tables

Source Code to Execution

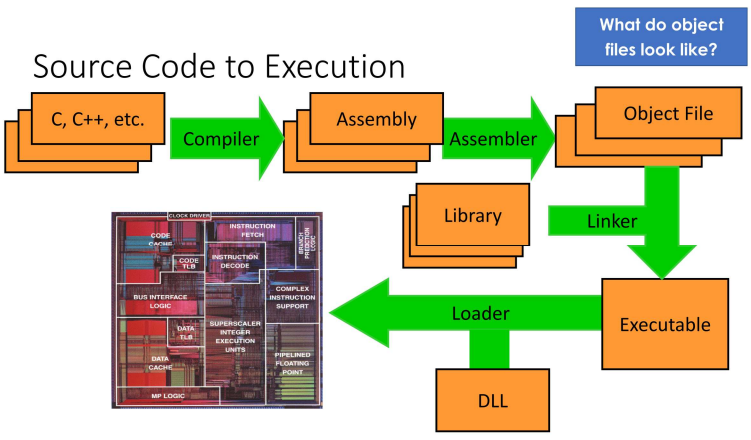
- In project 1a, our view is this:



Multi-file programs

- In practice, programs are made from thousands or millions of lines of code
  - Use pre-existing libraries like stdlib
- If we change one line, do we need to recompile the whole thing?
  - No! If we compile each file into a separate **object file**, then we only need to recompile that one file and **link** it to the other, unchanged object files

Source Code to Execution



What do object files look like?

```
extern int X;
extern void foo();
int Y;

void main() {
  Y = X + 1;
  foo();
}
```

"extern" means defined in another file

```
extern int Y;
int X;

void foo() {
  Y *= 2;
}
```

Compile

```
.main:
LDUR    X1, [XZR, X]
ADDI    X9, X1, #1
STUR    X9, [XZR, Y]
BL      foo
HALT
```

Uh-oh! Don't know address of X, Y, or foo!

Compile

```
.foo:
LDUR    X1, [XZR, Y]
LSL     X9, X1, #1
STUR    X9, [XZR, Y]
BR      X30
```

Linking

```
.main:
LDUR    X1, [XZR, X]
ADDI    X9, X1, #1
STUR    X9, [XZR, Y]
BL      foo
HALT
```

Assemble → ???

```
.foo:
LDUR    X1, [XZR, Y]
LSL     X9, X1, #1
STUR    X9, [XZR, Y]
BR      X30
```

Assemble → ???

What needs to go in this intermediate "object file"?

LINK

NOTE: this will actually be in machine code, not assembly

```
LDUR    X1, [XZR, #40]
ADDI    X9, X1, #1
STUR    X9, [XZR, #36]
BL      #2
HALT
LDUR    X1, [XZR, #36]
LSL     X9, X1, #1
STUR    X9, [XZR, #36]
BR      X30
// Addr #36 starts here
```


Linking

```
.main:
LDUR    X1, [XZR, X]
ADDI    X9, X1, #1
STUR    X9, [XZR, Y]
BL      foo
HALT
```

Assemble → ???

LINK

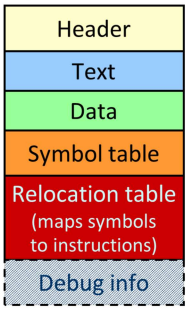
```
LDUR    X1, [XZR, #40]
ADDI    X9, X1, #1
STUR    X9, [XZR, #36]
BL      #2
HALT
LDUR    X1, [XZR, #36]
LSL     X9, X1, #1
STUR    X9, [XZR, #36]
BR      X30
```

We need:
- the assembled machine code:
- list of instructions that need to be updated once addresses are resolved
- list of symbols to cross-ref

What do object files look like?

- Since we can't make executable, we make an object file
- Basically, includes the machine code that will go in the executable
  - Plus extra information on what we need to modify once we stitch all the other object files together
- Looks like this ->

Object code format



We won't discuss "Debug" much. Get's included when you compile with "-g" in gcc

Assembly → Object file - example

```
extern int G;
extern void B();
int X = 3;
main() {
  Y = G + 1;
  B();
}
```

```
LDUR    X1, [XZR, G]
ADDI    X9, X1, #1
BL      B
```

Header	Name	foo	
	Text size	0x0C //probably bigger	
	Data size	0x04 //probably bigger	
Text	Address	Instruction	
	0	LDUR X1, [XZR, G]	
	4	ADDI X9, X1, #1	
	8	BL B	
Data	0	X	3
Symbol table	Label	Address	
	X	0	
	B	-	
	main	0	
	G	-	
Reloc table	Addr	Instruction type	Dependency
	0	LDUR	G
	8	BL	B

Assembly → Object file - example

Header: keeps track of size of each section

```
extern int G;
extern void B();
int X = 3;
main() {
  Y = G + 1;
  B();
}
```

```
LDUR    X1, [XZR, G]
ADDI    X9, X1, #1
BL      B
```

Header	Name	foo	
	Text size	0x0C //probably bigger	
	Data size	0x04 //probably bigger	
Text	Address	Instruction	
	0	LDUR X1, [XZR, G]	
	4	ADDI X9, X1, #1	
	8	BL B	
Data	0	X	3
Symbol table	Label	Address	
	X	0	
	B	-	
	main	0	
	G	-	
Reloc table	Addr	Instruction type	Dependency
	0	LDUR	G
	8	BL	B

Assembly → Object file - example

Text: machine code

```
extern int G;
extern void B();
int X = 3;
main() {
  Y = G + 1;
  B();
}
```

```
LDUR    X1, [XZR, G]
ADDI    X9, X1, #1
BL      B
```

Header	Name	foo	
	Text size	0x0C //probably bigger	
	Data size	0x04 //probably bigger	
Text	Address	Instruction	
	0	LDUR X1, [XZR, G]	
	4	ADDI X9, X1, #1	
	8	BL B	
Data	0	X	3
Symbol table	Label	Address	
	X	0	
	B	-	
	main	0	
	G	-	
Reloc table	Addr	Instruction type	Dependency
	0	LDUR	G
	8	BL	B

Simplifying Assumption for EECS370

All globals and static locals (initialized or not) go in the data segment

Assembly → Object file - example

Data: initialized globals and static locals

```
extern int G;
extern void B();
int X = 3;
main() {
  Y = G + 1;
  B();
}
```

```
LDUR    X1, [XZR, G]
ADDI    X9, X1, #1
BL      B
```

Header	Name	foo	
	Text size	0x0C //probably bigger	
	Data size	0x04 //probably bigger	
Text	Address	Instruction	
	0	LDUR X1, [XZR, G]	
	4	ADDI X9, X1, #1	
	8	BL B	
Data	0	X	3
Symbol table	Label	Address	
	X	0	
	B	-	
	main	0	
	G	-	
Reloc table	Addr	Instruction type	Dependency
	0	LDUR	G
	8	BL	B

Assembly → Object file - example

Symbol table: Lists all labels visible outside this file (i.e. function names and global variables)

```
extern int G;
extern void B();
int X = 3;
main() {
  Y = G + 1;
  B();
}
```

```
LDUR
ADDI
BL
```

Header	Name	foo	
	Text size	0x0C //probably bigger	
	Data size	0x04 //probably bigger	
Text	Address	Instruction	
	0	LDUR X1, [XZR, G]	
	4	ADDI X9, X1, #1	
	8	BL B	
Data	0	X	3
Symbol table	Label	Address	
	X	0	
	B	-	
	main	0	
	G	-	
Reloc table	Addr	Instruction type	Dependency
	0	LDUR	G
	8	BL	B

Assembly → Object file - example

```
extern int G;
extern void B();
int X = 3;
main() {
  Y = G + 1;
  B();
}
```

Header	Name	foo
	Text size	0x0C //probably bigger
	Data size	0x04 //probably bigger
Text	Address	Instruction
	0	LDUR X1, [XZR, G]
	4	ADDI X9, X1, #1
	8	BL B
Data	0	X 3
	Label	Address
Symbol table	X	0
	B	-
	main	0
	G	-
Reloc table	Addr	Instruction type Dependency
	0	LDUR G
	8	BL B

Relocation Table: list of instructions and data words that must be updated if things are moved in memory

Class Problem 1

Poll: Which symbols will be put in the symbol table? (i.e. which "things" should be visible to all files?)

file1.c
```
extern void bar(int);
extern char c[];
int a;
int foo (int x) {
  int b;
  a = c[3] + 1;
  bar(x);
  b = 27;
}
```

file 1 – symbol table

sym	loc
a	data
foo	text
c	-
bar	-

file2.c
```
extern int a;
char c[100];
void bar (int y) {
  char e[100];
  a = y;
  c[20] = e[7];
}
```

file 2 – symbol table

sym	loc
c	data
bar	text
a	-

Poll: Which lines / instructions are in the relocation table? (i.e. which "things" need to be updated after linking?)

Class Problem 2

file1.c
```
1 extern void bar(int);
2 extern char c[];
3 int a;
4 int foo (int x) {
5   int b;
6   a = c[3] + 1;
7   bar(x);
8   b = 27;
9 }
```

file 1 - relocation table

line	type	dep
6	ldur	c
6	stur	a
7	bl	bar

file2.c
```
1 extern int a;
2 char c[100];
3 void bar (int y) {
4   char e[100];
5   a = y;
6   c[20] = e[7];
7 }
```

file 2 - relocation table

line	type	dep
5	stur	a
6	stur	c

Note: in a real relocation table, the "line" would really be the address in "text" section of the instruction we need to update.

Linker

- Stitches independently created object files into a single executable file (i.e., a.out)
  - Step 1: Take text segment from each .o file and put them together.
  - Step 2: Take data segment from each .o file, put them together, and concatenate this onto end of text segments.
- What about libraries?
  - Libraries are just special object files.
  - You create new libraries by making lots of object files (for the components of the library) and combining them (see ar and ranlib on Unix machines).
  - Step 3: Resolve cross-file references to labels
    - Make sure there are no undefined labels

Linker - Continued

- Determine the memory locations the code and data of each file will occupy
  - Each function could be assembled on its own
  - Thus, the relative placement of code/data is not known up to this point
  - Must relocate absolute references to reflect placement by the linker
    - PC-Relative Addressing (beq, bne): never relocate
    - Absolute Address (mov 27, #X): always relocate
    - External Reference (usually bl): always relocate
    - Data Reference (often movz/movk): always relocate
- Executable file contains no relocation info or symbol table these just used by assembler/linker

Loader

- Executable file is sitting on the disk
- Puts the executable file code image into memory and asks the operating system to schedule it as a new process
  - Creates new address space for program large enough to hold text and data segments, along with a stack segment
  - Copies instructions and data from executable file into the new address space
  - Initializes registers (PC and SP most important)
- Take operating systems class (EECS 482) to learn more!

Summary

- Compiler converts a single source code file into a single assembly language file
- Assembler handles directives (.fill), converts what it can to machine language, and creates a checklist for the linker (relocation table). This changes each .s file into a .o file
- Assembler does 2 passes to resolve addresses, handling internal forward references
- Linker combines several .o files and resolves absolute addresses
- Linker enables separate compilation: Thus unchanged files, including libraries need not be recompiled.
- Linker resolves remaining addresses.
- Loader loads executable into memory and begins execution

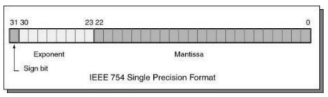
Floating Point Arithmetic

Why floating point

- Have to represent real numbers somehow
- Rational numbers
  - Ok, but can be cumbersome to work with
- Fixed point
  - Do everything in thousandths (or millionths, etc.)
  - Not always easy to pick the right units
  - Different scaling factors for different stages of computation
- **Scientific notation: this is good!**
  - Exponential notation allows HUGE dynamic range
  - Constant (approximately) relative precision across the whole range

IEEE Floating point format (single precision)

- Sign bit: (0 is positive, 1 is negative)
- Significand: (also called the *mantissa*; stores the 23 most significant bits after the decimal point)
- Exponent: used biased base 127 encoding
  - Add 127 to the value of the exponent to encode:
  - -127 → 00000000 1 → 10000000
  - -126 → 00000001 2 → 10000001
  - … …
  - 0 → 01111111 128 → 11111111
- How do you represent zero ? Special convention:
  - Exponent: -127 (all zeroes), Significand 0 (all zeroes), Sign + or -



Floating Point Representation

$$10.625_{10} \Rightarrow 1010.101_{2}$$

- Step 1: convert from decimal to binary
  - 1st bit after "binary" point represents 0.5 (i.e. 2^{-1})
  - 2nd bit represents 0.25 (i.e. 2^{-2})
  - etc.

Floating Point Representation

$$10.625_{10} \Rightarrow 1010.101_{2}$$

$$1.010101 \times 2^{3}$$

- Step 2: normalize number by shifting binary point until you get 1.XXX * 2^{Y}

Floating Point Representation

$$10.625_{10} \Rightarrow 1010.101_{2}$$

$$1.010101 \times 2^{3}$$

This must be a 1! So don't store it.

+/-	Exponent (3)	Significand (1010101)
1 bit	8 bits	23 bits

- Step 3: store relevant numbers in proper location (ignoring initial 1 of significand)

Floating Point Representation

$$10.625_{10} \Rightarrow 1010.101_{2}$$

$$1.010101 \times 2^{3}$$

This must be a 1! So don't store it.

+/-	Exponent (3)	Significand (1010101)
1 bit	8 bits	23 bits

$10.625_{10} = 0 \quad 10000010 \quad 01010100000000000000000$

Next Time

- Wrap up Floating Point
- And… hardware time, baby!