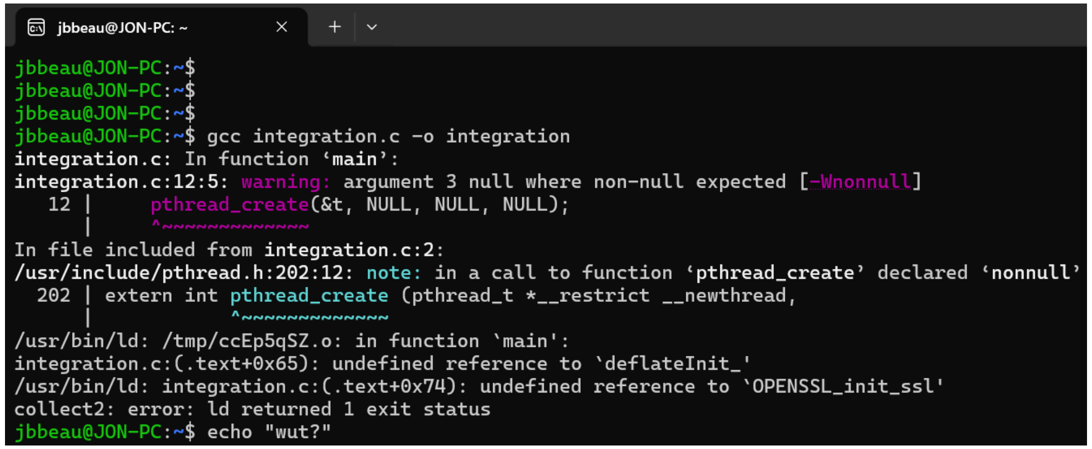
EECS 370 - Lecture 7

Linking



```
jbbeau@JON-PC:~$
jbbeau@JON-PC:~$
jbbeau@JON-PC:~$
jbbeau@JON-PC:~$ gcc integration.c -o integration
integration.c: In function ‘main’:
integration.c:12:5: warning: argument 3 null where non-null expected [-Wnonnull]
   12 |     pthread_create(&t, NULL, NULL, NULL);
      |     ^~~~~~~~~~~~~~
In file included from integration.c:2:
/usr/include/pthread.h:202:12: note: in a call to function ‘pthread_create’ declared ‘nonnull’
  202 | extern int pthread_create (pthread_t *__restrict __newthread,
      |            ^~~~~~~~~~~~~~
/usr/bin/ld: /tmp/ccEp5qSZ.o: in function `main':
integration.c:(.text+0x65): undefined reference to `deflateInit_'
/usr/bin/ld: integration.c:(.text+0x74): undefined reference to `OPENSSL_init_ssl'
collect2: error: ld returned 1 exit status
jbbeau@JON-PC:~$ echo "wut?"
```

Announcements

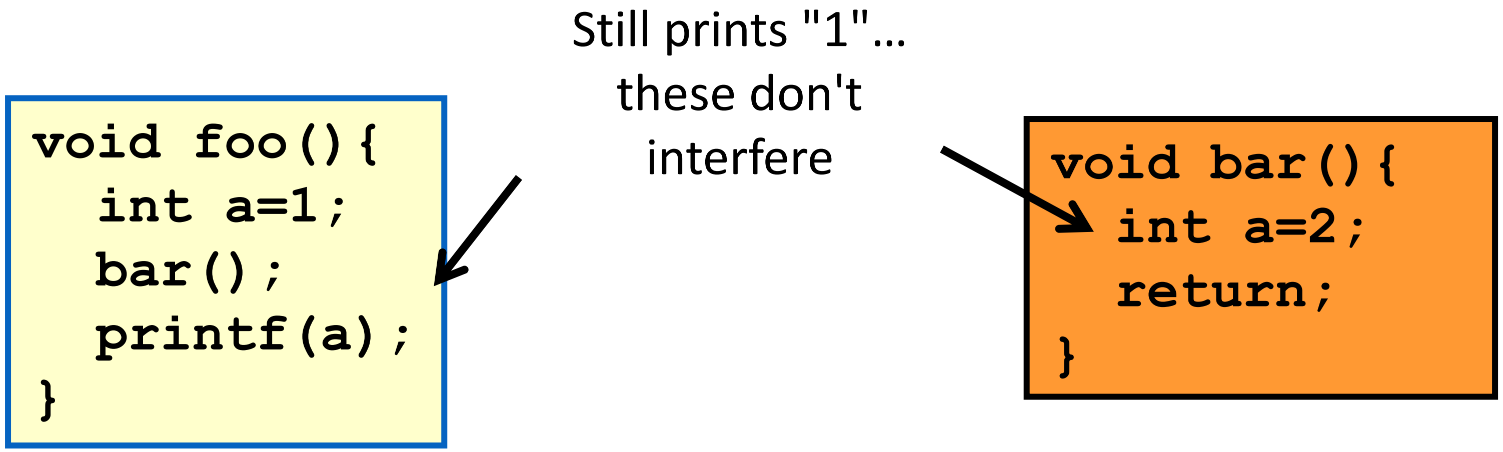
- P1
  - Project 1 s + m due Thu
  - Instructor assembler available on the AG
- HW 1
  - Due Monday (9/22)
- Lab 4 meets Fr/M
  - Pre-Lab 4 quiz due Thursday
- Get exam conflicts sent to us **ASAP**
  - Forms listed on Ed
- My OH adjustments:
  - Today’s OH: in **2733 BBB** (instead of 2901)
  - Thursday OH cancelled for this week
  - I’m adding Monday and Wednesday OH as well (see Google calendar)

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**

Review - Saving / Restoring Registers

- Higher level languages (like C/C++) provide many abstractions that don't exist at the assembly level
- E.g. in C, each function has its own local variables
  - Even if different function have local variables with the same name, they are independent and guaranteed not to interfere with each other!



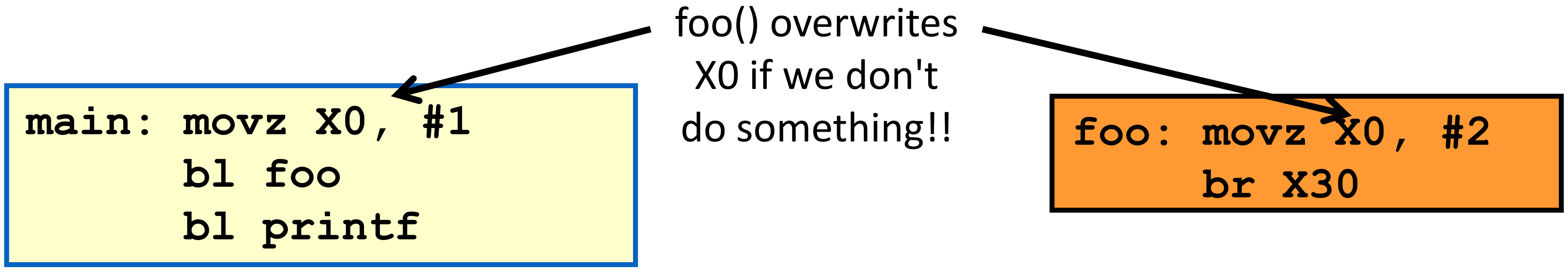
```
void foo(){
  int a=1;
  bar();
  printf(a);
}
```

Still prints "1"…
these don't
interfere

```
void bar(){
  int a=2;
  return;
}
```

What about registers?

- But in assembly, all functions share a small set (e.g. 32) of registers
  - Called functions will overwrite registers needed by calling functions



```
main: movz X0, #1
      bl foo
      bl printf
```

foo() overwrites
X0 if we don't
do something!!

```
foo: movz X0, #2
     br X30
```

- "Someone" needs to save/restore values when a function is called to ensure this doesn't happen

Two Possible Solutions

- Either the **called** function saves register values before it overwrites them and restores them before the function returns (**callee** saved)…

```
main: movz X0, #1
      bl foo
      bl printf
```

```
foo: stur X0, [stack]
     movz X0, #2
     ldur X0, [stack]
     br X30
```

- Or the **calling** function saves register values before the function call and restores them after the function call (**caller** saved)…

```
main: movz X0, #1
      stur X0, [stack]
      bl foo
      ldur X0, [stack]
      bl printf
```

```
foo: movz X0, #2
     br X30
```

a->r1, b->r2, etc.

Another Visualization

Original C Code

```
void foo(){
  int a,b,c,d;

  a = 5; b = 6;
  c = a+1; d=c-1;


  bar();


  d = a+d;
  return();
}
```

No need to save r2/r3. Why?

Additions for Caller-save

```
void foo(){
  int a,b,c,d;

  a = 5; b = 6;
  c = a+1; d=c-1;
  save r1 to stack
  save r4 to stack
  bar();
  restore r1
  restore r4
  d = a+d;
  return();
}
```

Assume bar() will overwrite all registers

Additions for Callee-save

```
void foo(){
  int a,b,c,d;
  save r1
  save r2
  save r3
  save r4
  a = 5; b = 6;
  c = a+1; d=c-1;
  bar();
  d = a+d;
  restore r1
  restore r2
  restore r3
  restore r4
  return();
}
```

bar() will save a,b, but now foo() must save main's variables

Saving/Restoring Optimizations

CALLER-CALLEE

- Where can we avoid loads/stores?
- Caller-saved
  - Only needs saving if value is "live" across function call
  - Live = contains a useful value: Assign value before function call, use that value after the function call
  - In a leaf function (a function that calls no other function), caller saves can be used without saving/restoring

a, d are live

b, c are NOT live

```
void foo(){
  int a,b,c,d;

  a = 5; b = 6;
  c = a+1; d=c-1;

  bar();

  d = a+d;
  return();
}
```

Saving/Restoring Optimizations

CALLER-CALLEE

- Where can we avoid loads/stores?
- Callee-saved
  - Only needs saving at beginning of function and restoring at end of function
  - Only save/restore it if function overwrites the register

Only use r1-r4

No need to save other registers

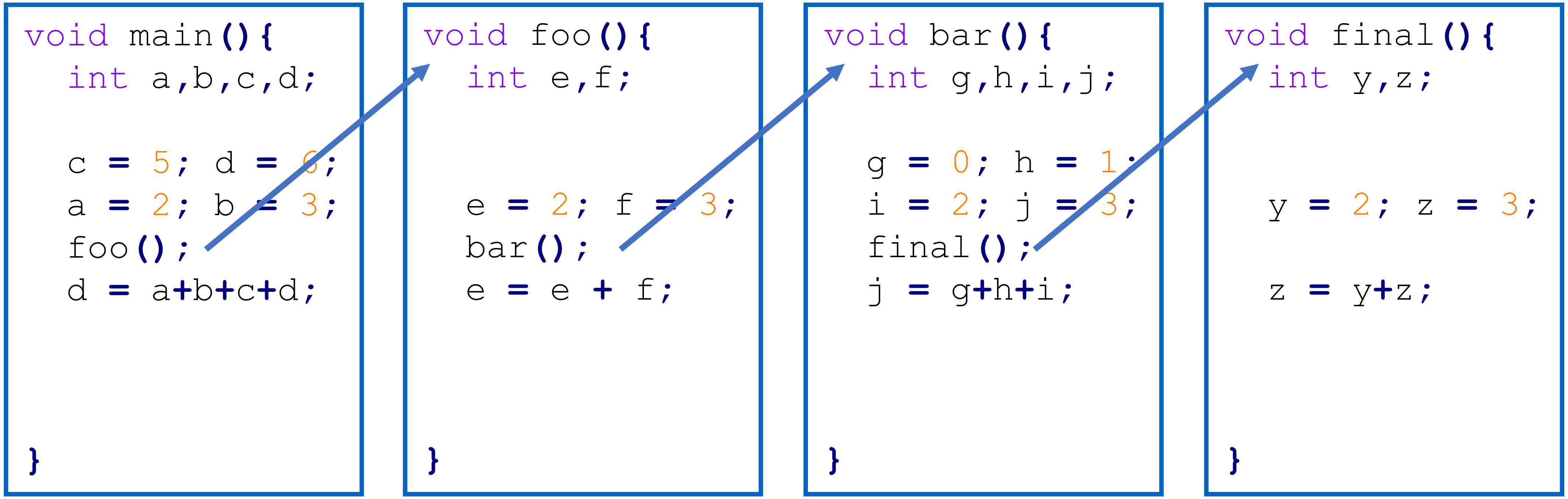
```
void foo(){
  int a,b,c,d;

  a = 5; b = 6;
  c = a+1; d=c-1;

  bar();

  d = a+d;
  return();
}
```

Caller versus Callee

- Which is better??
- Let's look at some examples…

- Simplifying assumptions:
  - A function can be invoked by many different call sites in different functions.
  - Assume no inter-procedural analysis (hard problem)
    - A function has no knowledge about which registers are used in either its caller or callee
    - Assume main() is not invoked by another function
  - Implication
    - Any register allocation optimization is done using function local information

Caller-saved vs. callee saved – Multiple function case



```
void main(){
  int a,b,c,d;

  c = 5; d = 6;
  a = 2; b = 3;
  foo();
  d = a+b+c+d;



}
```

```
void foo(){
  int e,f;


  e = 2; f = 3;
  bar();
  e = e + f;



}
```

```
void bar(){
  int g,h,i,j;

  g = 0; h = 1;
  i = 2; j = 3;
  final();
  j = g+h+i;



}
```

```
void final(){
  int y,z;


  y = 2; z = 3;

  z = y+z;



}
```

Note: assume main does not have to save any callee registers

Poll: How many ld/st pairs are needed?

Question 1: Caller-save

```
void main(){
  int a,b,c,d;
  c = 5; d = 6;
  a = 2; b = 3;
  [4 STUR]
  foo();
  [4 LDUR]
  d = a+b+c+d;


}
```

```
void foo(){
  int e,f;

  e = 2; f = 3;
  [2 STUR]
  bar();
  [2 LDUR]
  e = e + f;


}
```

```
void bar(){
  int g,h,i,j;
  g = 0; h = 1;
  i = 2; j = 3;
  [3 STUR]
  final();
  [3 LDUR]
  j = g+h+i;


}
```

```
void final(){
  int y,z;


  y = 2; z = 3;

  z = y+z;



}
```

Total: 9 STUR / 9 LDUR

Question 2: Callee-save

Poll: How many ld/st pairs are needed?

```
void main(){
   int a,b,c,d;

   c = 5; d = 6;
   a = 2; b = 3;
   foo();
   d = a+b+c+d;



}
```

```
void foo(){
   [2 STUR]
   int e,f;

   e = 2; f = 3;
   bar();
   e = e + f;


   [2 LDUR]
}
```

```
void bar(){
   [4 STUR]
   int g,h,i,j;
   g = 0; h = 1;
   i = 2; j = 3;
   final();
   j = g+h+i;


   [4 LDUR]
}
```

```
void final(){
   [2 STUR]
   int y,z;

   y = 2; z = 3;

   z = y+z;


   [2 LDUR]
}
```

Total: 8 STUR / 8 LDUR

Is one better?

- Caller-save works best when we don't have many live values across function call
- Callee-save works best when we don't use many registers overall
- We probably see functions of both kinds across an entire program
- Solution:
  - Use both!
  - E.g. if we have 6 registers, use some (say r0-r2) as caller-save and others (say r3-r5) as callee-save
  - Now each function can optimize for each situation to reduce saving/restoring
  - Not discussed further for this class

LEGv8 ABI- Application Binary Interface

- The ABI is an agreement about how to use the various registers
- Not enforced by hardware, just a convention by programmers / compilers
- If you won't your code to work with other functions / libraries, **follow these**
- Some register conventions in ARMv8
  - X30 is the **link register** – used to hold return address
  - X28 is **stack pointer** – holds address of top of stack
  - X19-X27 are **callee-saved** – function must save these before writing to them
  - X0-15 are **caller-saved** – function must save live values before call
  - X0-X7 used for **arguments** (memory used if more space is needed)
  - X0 used for **return value**

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

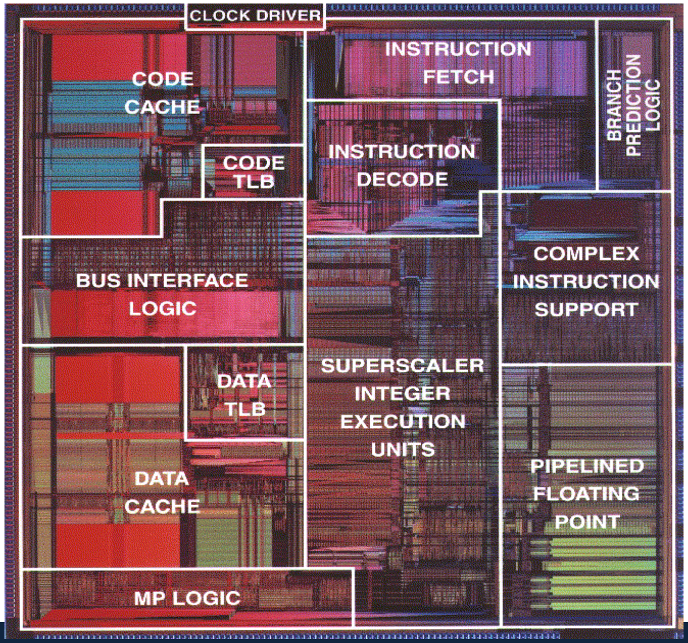
- In project 1a, our view is this:

Assembly

Assembler

Executable

<u>Poll:</u> Why do we write programs in multiple files?



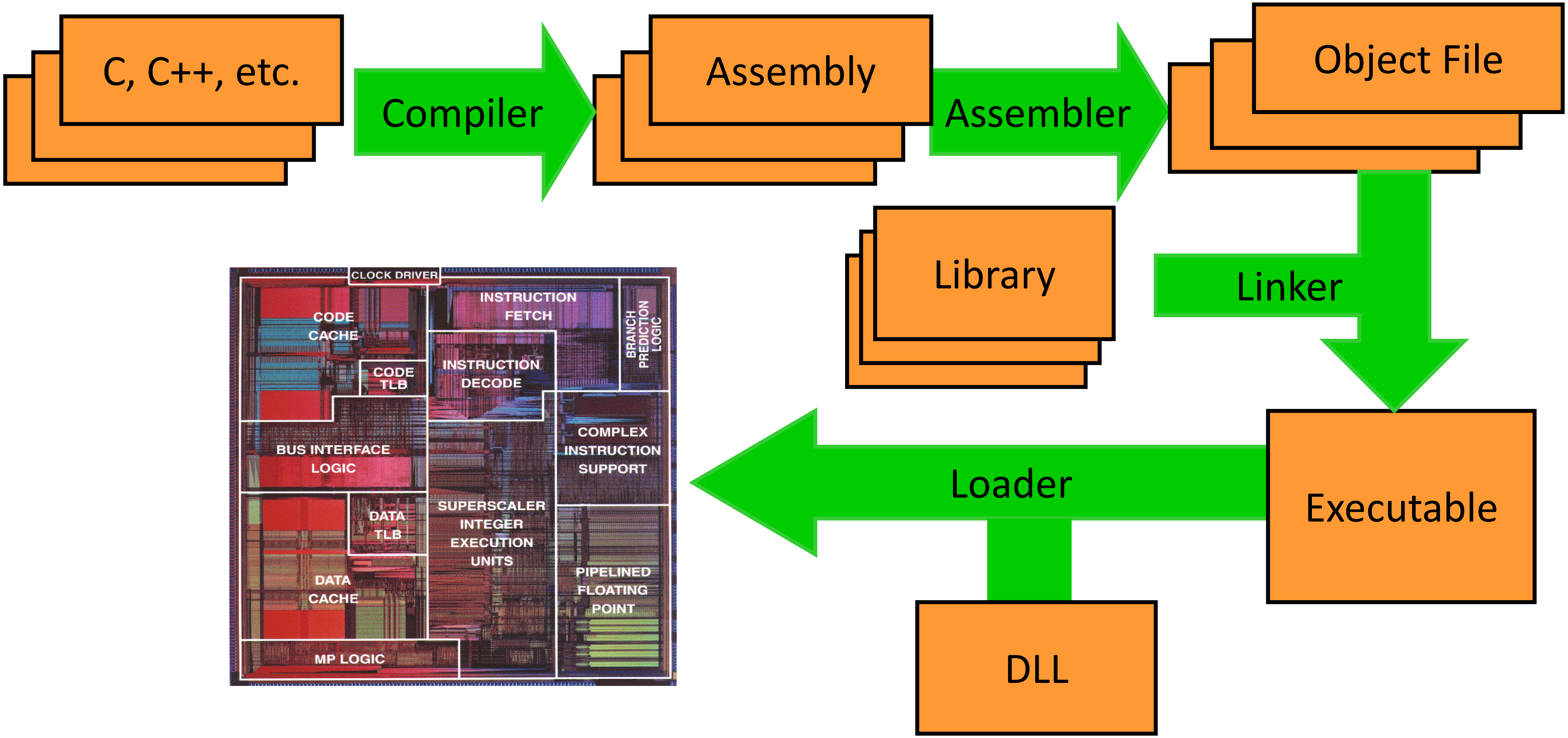
Not very accurate… why?
Because in reality, we have multiple files

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

What do object files look like?

Source Code to Execution



C, C++, etc.

Compiler

Assembly

Assembler

Object File

Library

Linker

Executable

Loader

DLL

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

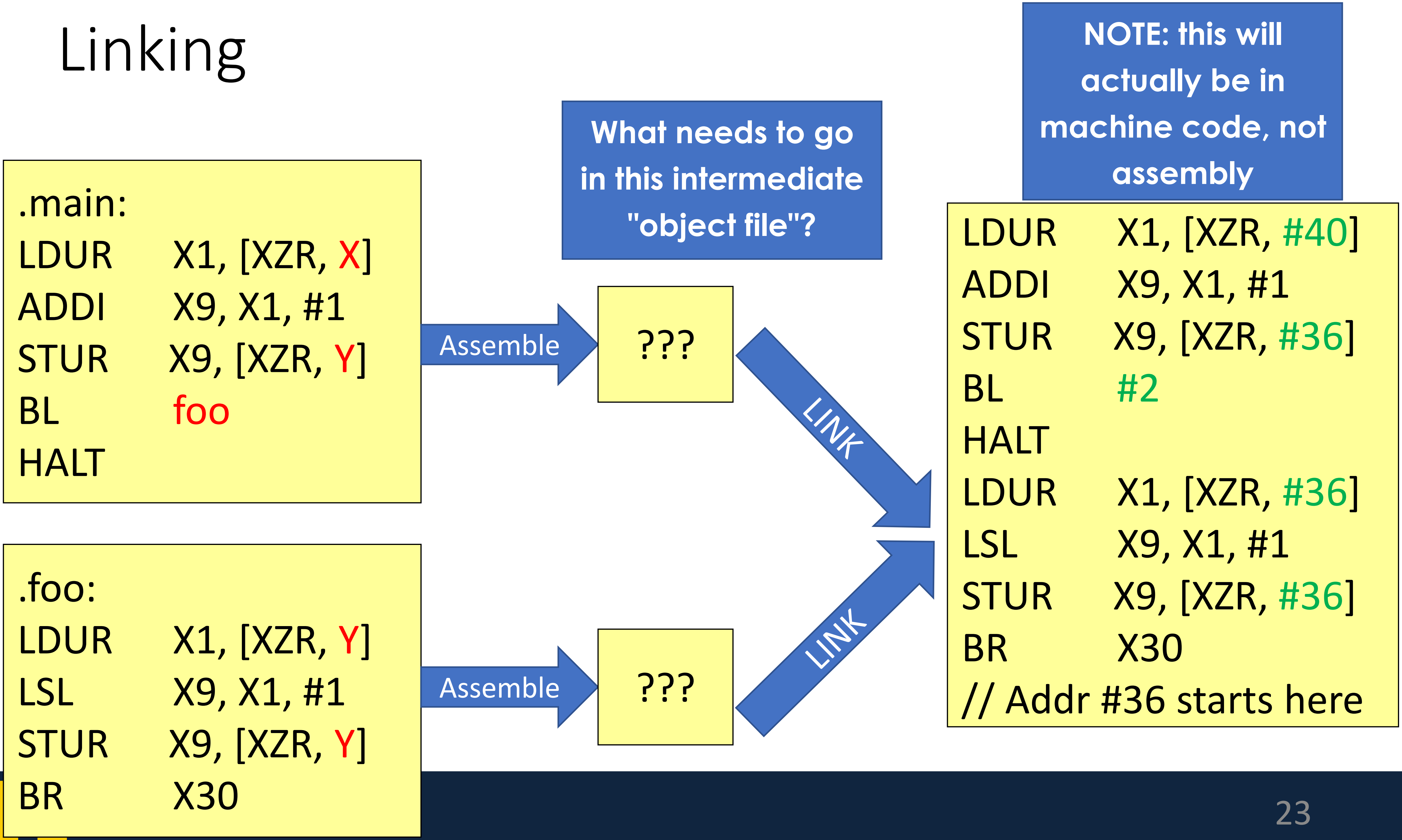
```
.main:
LDUR    X1, [XZR, X]
ADDI    X9, X1, #1
STUR    X9, [XZR, Y]
BL      foo
HALT
```

Compile

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

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

Linking



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

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

Assemble

???

Assemble

???

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

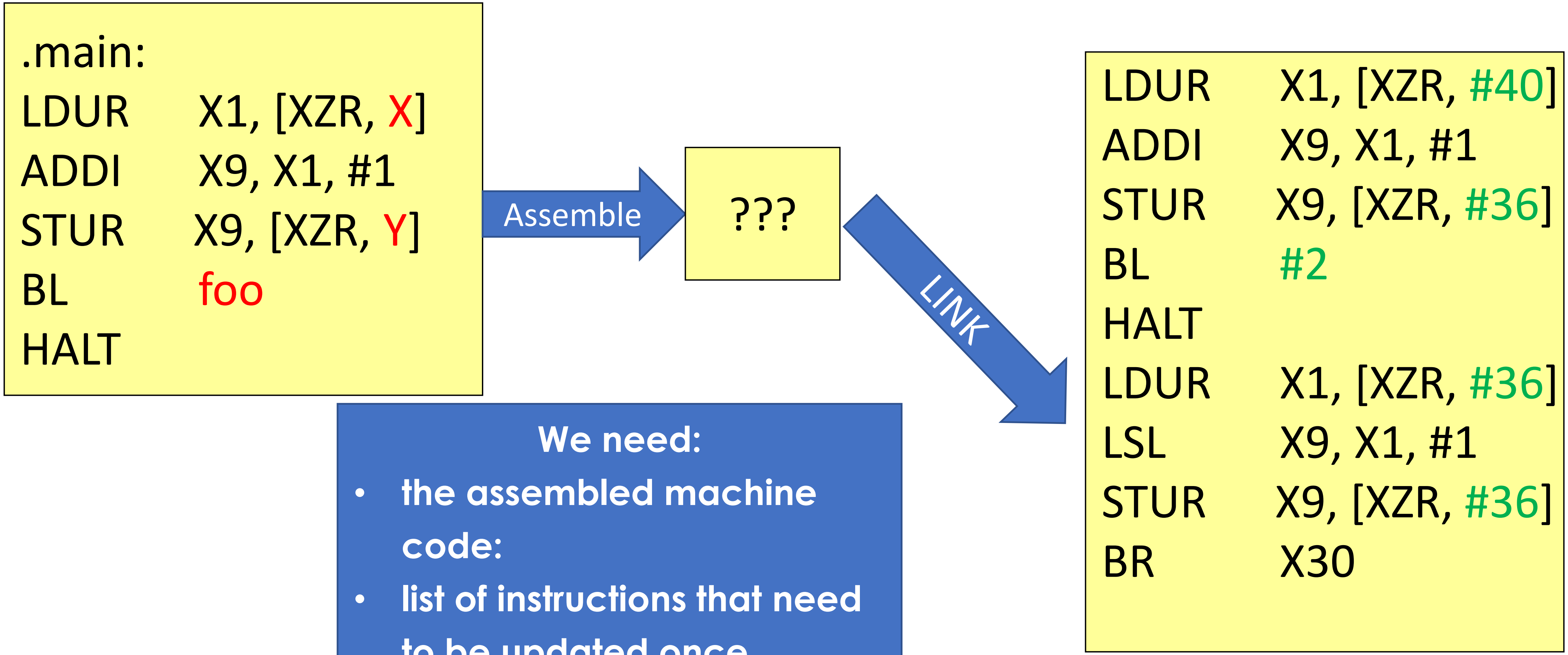
LINK

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
```

```
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
```

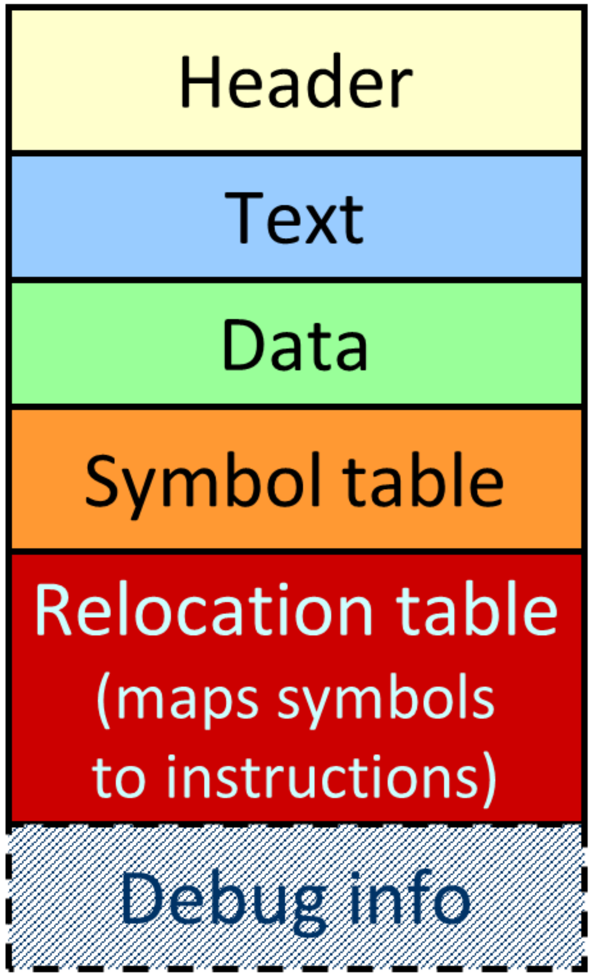
We need:

- **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
	Label	Address	
Symbol table	X	0	
	B	-	
	main	0	
	G	-	
Reloc table	Addr	Instruction type	Dependency
	0	LDUR	G
	8	BL	B

Assembly → Object file - example

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

Header: keeps track of size of each section

```
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
	Label	Address	
Symbol table	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 +
   B();
}
```

Text: machine code

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

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

Simplifying Assumption for EECS370

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

Assembly → Object file - example

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

Data:
initialized globals and static locals

```
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
	Label	Address	
Symbol table	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();
}
```

LDUR
ADDI
BL

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

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

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

LDUR X1, [XZR, G]

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

- What kind of instructions get relocated?
- PC-relative branches? (if/else or loops)
  - No – amount we're branching forwards/backwards doesn't change after sliding instructions around

```
B.EQ          endLoop
```

- Local variable accesses?
  - No – memory addresses are relative to stack pointer (SP) value
    - Relative offsets won't change
    - SP value will – but that's a dynamic value anyway, isn't encoded in instruction

```
sub     sp, sp, #16
mov     x0, #42
stur    x0, [sp, 0]
ldur    x1, [sp, 0]
```

- Global / static local variable access?
  - Yes – these use hardcoded addresses which change after linking

```
ldur    x2, [0, MY_VAR]
```

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

Next Time

- Floating Point Arithmetic
- And… hardware time, baby!