# Linking, Loading, Libraries

# One-Slide Summary

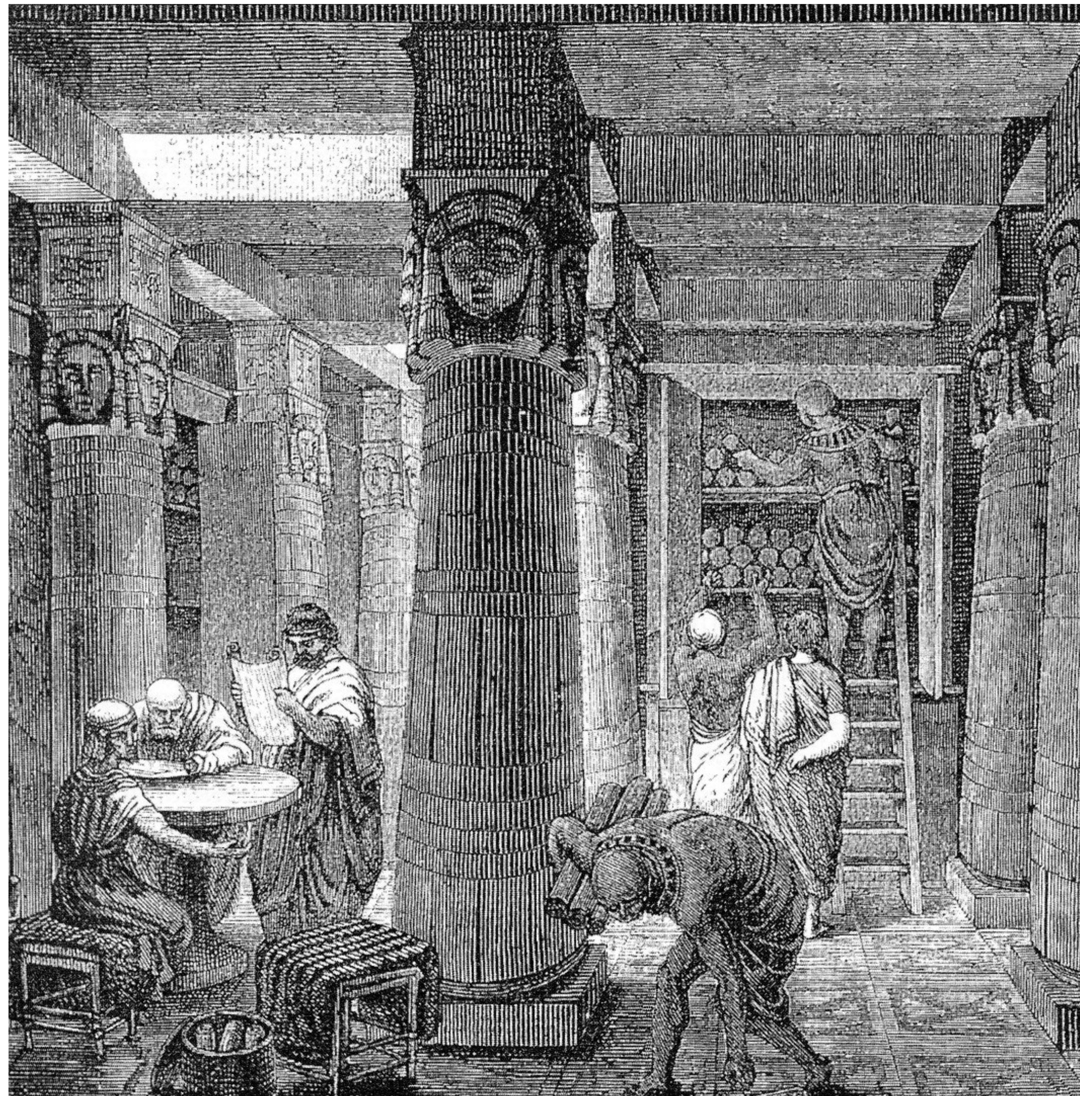
- We want **separate compilation** for program pieces. So we must **link** those compiled pieces together later. We must **resolve** references from one **object** to another.
- We also want to **share** libraries between programs.
- We also want to **typecheck** separately-compiled modules.

# Course Goals

- At the end of this course, you will be acquainted with the fundamental concepts in the **design** and **implementation** of high-level programming **languages**. In particular, you will understand the **theory** and **practice** of **lexing**, **parsing**, **semantic** analysis, and **code** interpretation. You will also have gained practical experience programming in multiple **different** languages.

# Lecture Outline

- Object Files
- Linking
- Relocations
- Shared Libraries
- Type Checking



# Separate Compilation

- Compile different parts of your program at different times
- And then **link** them together later
- This is a big win
  - Faster compile times on small changes
  - Software Engineering (modularity)
  - Independently develop different parts (libraries)
- All major languages and big projects use this
  - (“Largest” single file? 528KB single C file Delaunay triangulator http://www.cs.cmu.edu/~quake/triangle.html )

# Pieces

- A compiled program fragment is called an **object file**
- An object file contains
  - Code (for methods, etc.)
  - Variables (e.g., values for global variables)
  - Debugging information
  - References to code and data that appear elsewhere (e.g., printf)
  - Tables for organizing the above
- Object files are implicit for interpreters

# Two Big Tasks

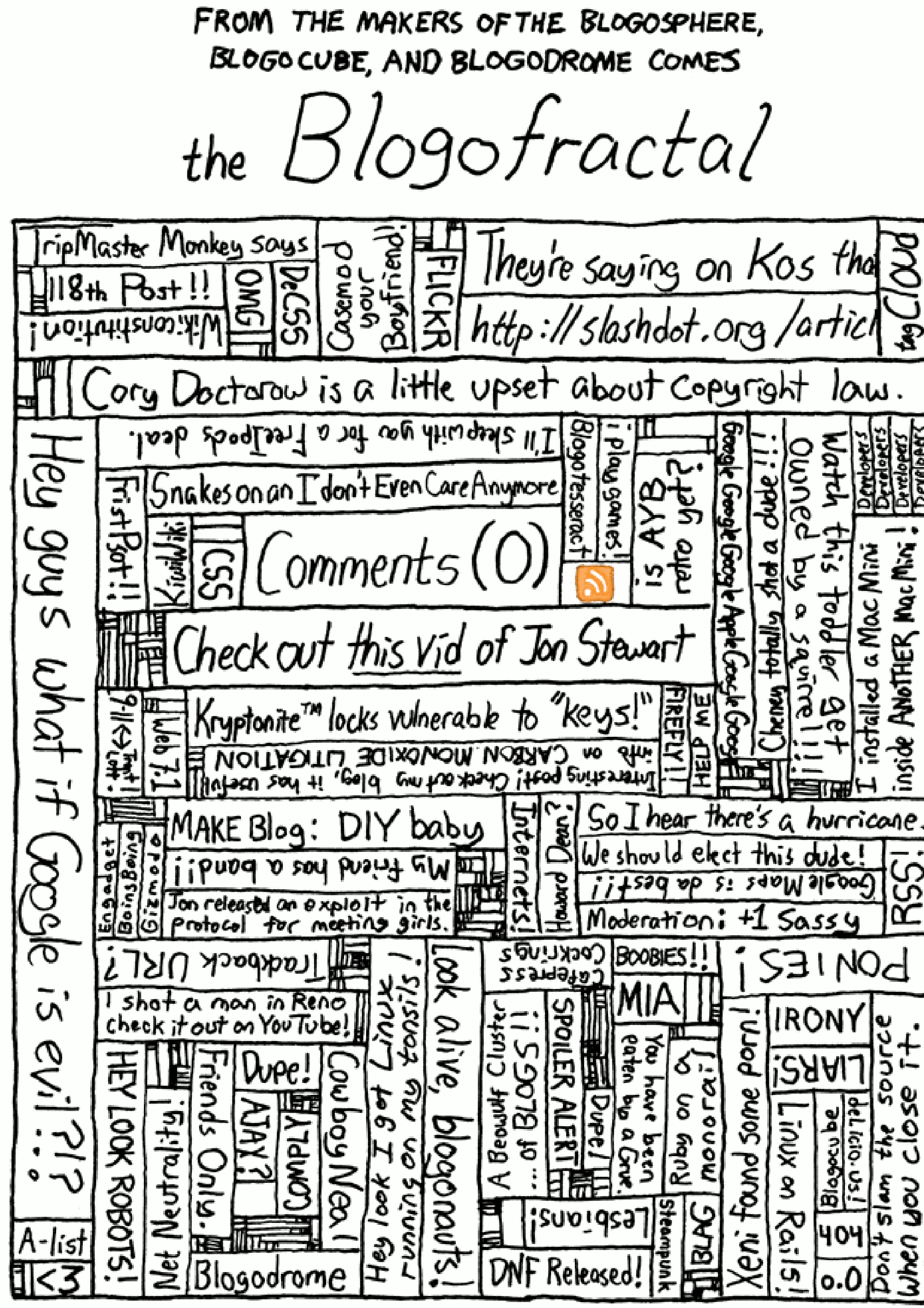
- The operating system uses **virtual memory** so every program starts at a standard [virtual] address (e.g., address 0)
- **Linking** involves two tasks
  - **Relocating** the code and data from each object file to a particular fixed virtual address
  - **Resolving references** (e.g., to variable locations or jump-target labels) so that they point to concrete and correct virtual addresses in the New World Order

# Relocatable Object Files

- For this to work, a **relocatable object file** comes equipped with three tables
  - **Import Table**: points to places in the code where an external **symbol** (variable or method) is references
    - List of (external_symbol_name, where_in_code) pairs
    - One external_symbol_name may come up many times!
  - **Export Table**: points to symbol definitions in the code that are exported for use by others
    - List of (internal_symbol_name, where_in_code) pairs
  - **Relocation Table**: points to places in the code where local symbols are referenced
    - List of (internal_symbol_name, where_in_code) pairs
    - One internal_symbol may come up many times!

# So Many Tables

- Tables must contain quite a bit of information
- Tables must also be easy to understand
- Let's see some examples ...



# C/Asm Example

- Consider this program:

```
extern double sqrt(double x);

static double temp = 0.0;

double quadratic(double a, b, c) {
  temp = b*b - 4.0*a*c;
  if (temp >= 0.0) { goto has_roots; }
  throw Invalid_Argument;
has_roots:
  return (-b + sqrt(temp)) / (2.0*a);
}
```

# Imports

```
extern double sqrt(double x);

static double temp = 0.0;

double quadratic(double a, b, c) {
  temp = b*b - 4.0*a*c;
  if (temp >= 0.0) { goto has_roots; }
  throw Invalid_Argument;
has_roots:
  return (-b + sqrt(temp)) / (2.0*a);
}
```

| | |
|---|---|
| 0x1000 | ... |
| 0x1004 | push r1 |
| 0x1008 | call $loc_{sqrt}$ |

**Import Table:**
Replace address used at 0x1008 with final location of **sqrt**.

# Exports

```
extern double sqrt(double x);

static double temp = 0.0;

double quadratic(double a, b, c) {
  temp = b*b - 4.0*a*c;
  if (temp >= 0.0) { goto has_roots; }
  throw Invalid_Argument;
has_roots:
  return (-b + sqrt(temp)) / (2.0*a);
}
```

| | |
|---|---|
| 0x0200 | r1 = b |
| 0x0204 | r1 = r1 * r1 |
| 0x0208 | r2 = 4.0 |
| 0x020c | r2 = r2 * a |

**Export Table:**
We provide **quadratic**. If others want it, they can figure out where 0x0200 is finally relocated to. Call that new location R. They then replace all of their references to $loc_{quadratic}$ with R.

# (Internal) Relocations

```
extern double sqrt(double x);

static double temp = 0.0;

double quadratic(double a, b, c) {
  temp = b*b - 4.0*a*c;
  if (temp >= 0.0) { goto has_roots; }
  throw Invalid_Argument;
```

.0*a);

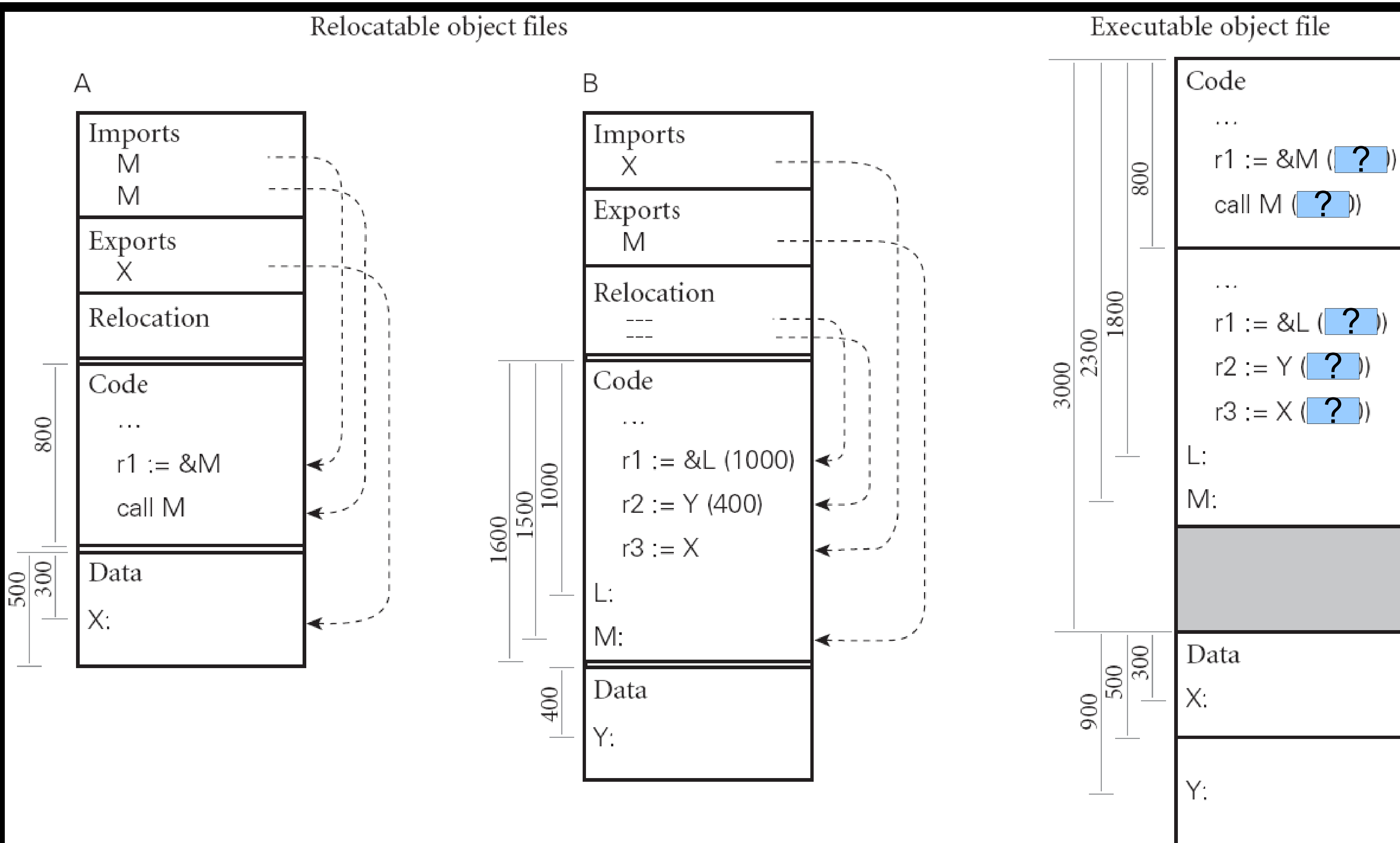
| | |
|---|---|
| 0x0600 | r1 = ld $loc_{temp}$ |
| 0x0604 | jgz r1 $loc_{has\{roots\}}$ |

**Relocation Table:**

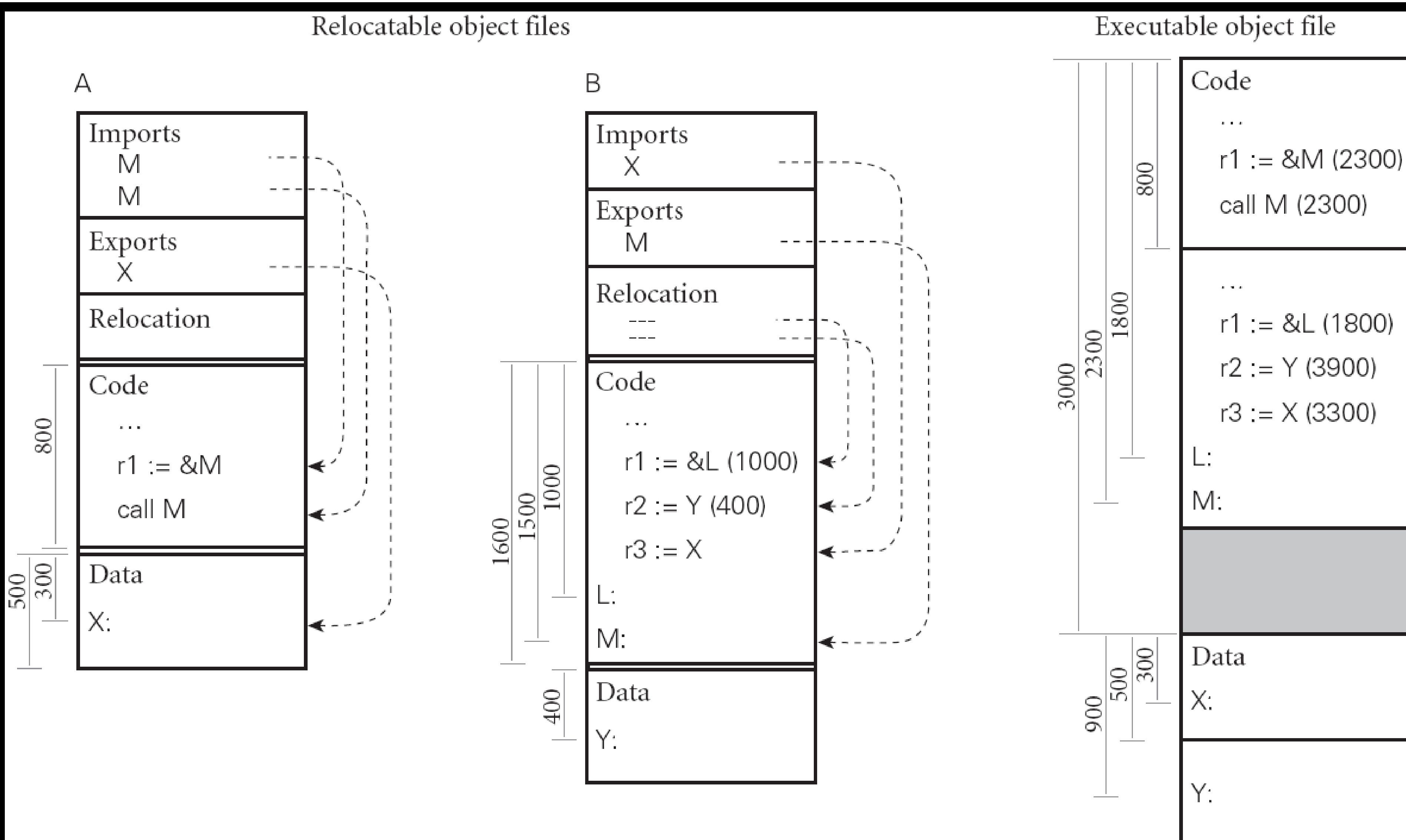
Find final relocated address of **temp**. Call that $R_{temp}$. Find final relocated address of 0x0600. Call that $R_{0x0600}$. Replace address referenced at $R_{0x0600}$ with $R_{temp}$.

# Big Linking Example

## let's do it on paper!



# Big Linking Example Answers



# Summary

- Your relocatable object file: main.o
  - Exports main(), imports sqrt(), relocations …
- Your math library: math.o
  - Exports sqrt(), relocations
  - Libraries themselves can have imports: example?
  - In Unix, math.o lives in libmath.a and –lmath on the command line will find it
- The linker reads them in, picks a fixed final relocation address for all code and data (1st pass) and then goes through and modifies every instruction with a symbol reference (2nd pass)

# Television

- This 1993-2002 and 2016-2018 scifi drama series typically begins with the phrase *"The Truth Is Out There"*.


# Bowdoin Sports Trivia

(double student "memorial")

- In addition to intercollegiate athletics teams and varsity sports, Bowdoin Athletics also offers a number of "clubs". Which *three* of these are Bowdoin clubs (rather than, say, NESCAC teams):
  - Field Hockey
  - Golf
  - Nordic / Alpine Skiing
  - Rowing
  - Rugby
  - Ultimate Frisbee

# Movies and Languages

- This phrase is Swahilian for "there are no concerns here" and was popularized by a 1994 Hamlet-like, mammal-centric Disney film.

# Spots Trivia

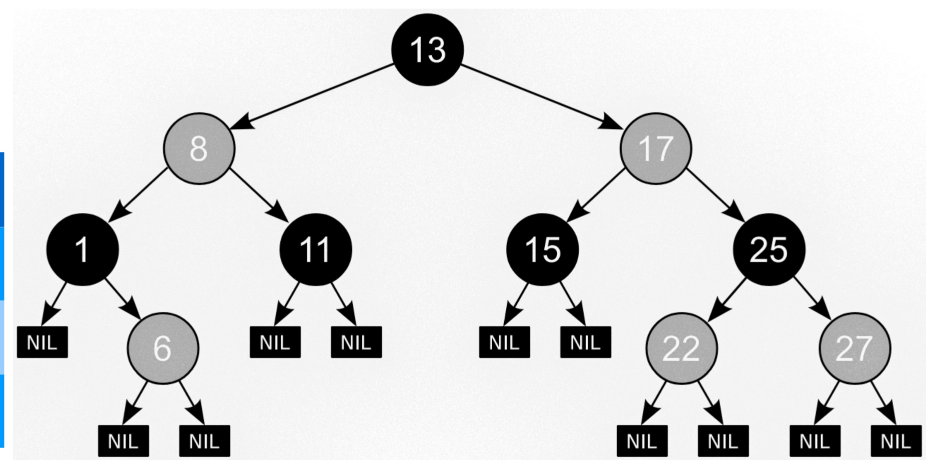

- This full-contact martial art includes punching and kicking. Fights normally include gloves, mouth guards, shorts and bare feet. There are many variations (e.g., K-1/Unified rules allow punches, high and low kicks, and knee strikes, while American rules use punches and high kicks). Muay Thai and Savate are examples.

# Data Structures

(student "memorial")

- This specialized binary search tree is self-balancing. Each node holds an extra bit (called the "color") that is used when reorganizing the tree to ensure approximate balance (e.g., every path from a given node to a leaf goes through the same number of XYZ nodes).

| Operation | Amortized | Worst Case |
|---|---|---|
| Search | O(log n) | O(log n) |
| Insert | O(1) | O(log n) |
| Delete | O(1) | O(log n) |



# Real-World Languages

- This Austroasiatic language borrows vocabulary from Chinese and boasts 75 million native speakers. The modern alphabet (quốc ngữ) is Latin with tone-indicative diacritical marks. It has a large number of vowels (all with an inherent tone), an SVO word order, and no morphological markings of gender, number, case or tense. Its 1820 epic poem The Tale of Kiều (Đoạn Trường Tân Thanh, aka A New Cry From A Broken Heart, aka Truyện Kiều) recounts the trials of a sacrificing young woman.

# Something Missing?

- That was fine, but if two programs both use math.o they will each get a copy of it

# Are We Done?

- That was fine, but if two programs both use math.o they will each get a copy of it
  - You can optimize this a bit by only linking and copying in the parts of a library that you really need (transitive closure of dependencies), but that's just a band-aid
- If we run both programs we will load both copies of math.o into memory – wasting memory (recall: they're identical)!
- How could we go about sharing math.o?

# Dynamic Linking

- Idea: **shared libraries** (.so) or **dynamically linked libraries** (.dll, .dylib) use virtual memory so that multiple programs can share the same libraries in main memory
  - Load the library into physical memory *once*
  - Each program using it has a virtual address *V* that points to it
  - During **dynamic linking**, resolve references to library symbols using that virtual address *V*
- What could go wrong? Code? Security?

# Relocations In The DLL

- Since we are sharing the code to math.dll, we cannot set its relocations separately for each client
- So if math.dll has a jump to $loc_{math\_label}$, that must be resolved to the *same location* (e.g., 0x1234) for *all clients*
  - Because we can only patch the instruction once!
  - And every thread/program shares that patched code!
- So either:
  - Every program using math.dll agrees to put it at virtual address location 0x1000 (*problems? Unix SVR3 …*)
  - math.dll uses *no* relocations in its *code* segment (*how?*)

# Position-Independent Code

- Rather than "0x1000: jump to 0x1060", use "jump to PC+0x60"
  - This code can be relocated to any address
  - This is called **position-independent code** (PIC)
- OK, that works for branches.
- But what about global variables?
  - You tell me:
  - Where should they live?
  - Should they be shared?

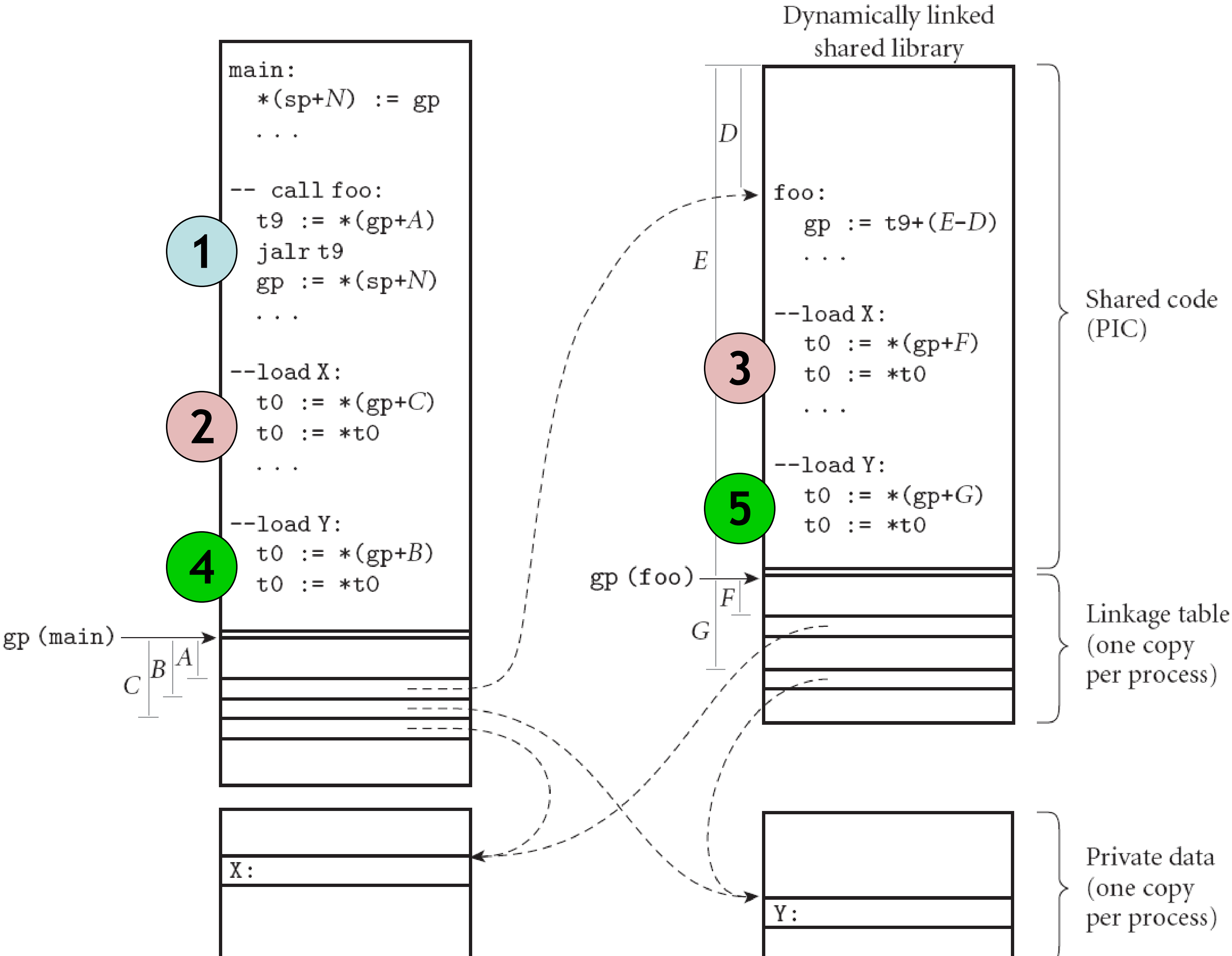
# Data Linkage Table

- Store shared-library global variable addresses starting at some virtual address *B*
  - This table of addresses is the **linkage table**
- Compile the PIC assuming that register **GP** (or R5 or …) will hold the current value of *B*
  - Problems?
- The entry point to a shared library (or the caller) sets register GP to hold *B*
  - Optimization: if the code and data live at fixed offsets, can do e.g. GP = ((PC & 0xFF00)+0x0100)

# Shared Library = Shared Data?

- Typically each client of a shared library X wants its own copies of X's globals
  - Example: **errno** variable in libc (cf. Exceptions lecture)
- When dynamically linking, you share the code segment but get your own copy of the data segment
  - And thus your own base address B to put in GP
  - Optimization: use copy-on-write virtual memory
- Detail: use an extra level of indirection when the PIC shared library code does callbacks to unshared main() or references global variables from unshared main()
  - Allows the unshared non-PIC target address to be kept in the data segment, which is private to each program

# Not As Bad As It Looks



# Fully Dynamic Linking

- So far this is all happening at load time when you start the program
- Could we do it at run-time *on demand*?
  - Decrease load times with many libraries
  - Support dynamically-loaded code (e.g., Java)
  - Important for scripting languages
- Use linkage table as before
  - But instead loading the code for foo(), point to a special **stub** procedure that loads foo() and all variables from the library and then updates the linkage table to point to the newly-loaded foo()

# Type Checking

- So we have separate compilation
- What's wrong with this picture?

**(* Main *)**

```
extern string sqrt();
void main() {
  string str = sqrt();
  printf("%s\n",str);
  return;
}
```

**(* math *)**

```
export double
sqrt(double a) {
  return ...;
}
```

# Header or Interface Files

- When we type-check a piece of code we generate an **interface** file
  - Listing all exported methods *and their types*
  - Listing all exported globals *and their types*
  - The imp map and class map from PA4 suffice perfectly: just throw away the expression information
- When we compile a client of a library we check the interface file for the types of external symbols
  - *Can anything go wrong?*

# Bait And Switch

- Write math.cl where sqrt() returns a string
- Generate interface file
- Give interface file to user
- Write new math.cl: sqrt() returns a double
- Compile source to relocatable objet file
- Give object file to user
- …
- Profit!

# Checksums and Name Mangling

- From the interface file, take all of the exported symbols and all of their types and write them down in a list, then **hash** (or **checksum**) it
- Include hash value in relocatable object
- Each library client also computes the hash value based on the interface it was given
- At link time, *check to make sure* the hash values are the same
  - C++ **name mangling** is the same idea, but done on a per symbol basis (rather than a per-interface basis)

# I'll Form The Head

- We wanted **separate compilation** for program pieces. So we must **link** those compiled pieces together later. We must **resolve** references from one **object** to another.
- We also wanted to **share** libraries between programs.
- We also wanted to **typecheck** separately-compiled modules.

# Homework

- Midterm 2
- Everything Else Due May 8th