Linking, Loading, Libraries

Midterm 2, Grades

- Midterm 2 had a nice spread of grades
  - Very Hard: 2(d) – For Loop Opsem
  - Hard: 3(b) – Liveness e := e * e
  - Hard: 4(b) – Array<GlassTable> $\leq$ Array<Table>
  - Hard: 4(f) – lub $\sqcup$ in Exceptions
- Projected Course Grades (emailed to you)
  - Do not include PA5, Final or Extra Credit
  - You will vote for topics on the Final in class (Thu Apr 26 or Tue May 01)

#2

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.

#3

Lecture Outline

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

#4

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 all big projects use this

#5

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

#6

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

#7

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!

#8

C/Asm/Java 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);
}
```

#9

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**.

#10

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 anyone else wants its, 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.

#11

(Internal) Relocations

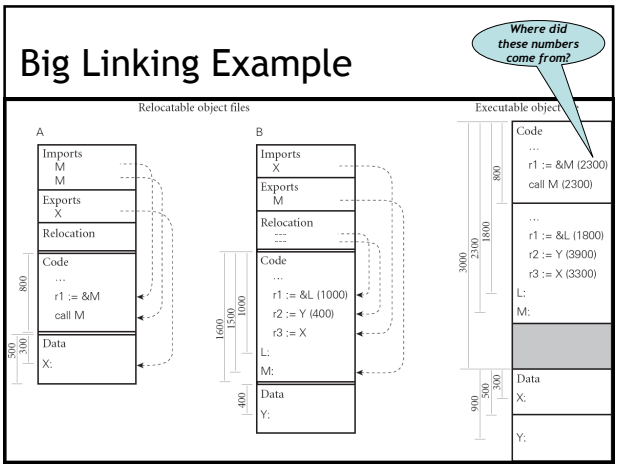
```
extern double sqrt(double x);

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;
has_roots:
  return (-b + sqrt(temp)) / (2.0*
}
```

```
0x0600    r1 = ld loc_temp
0x0604    jgz r1 loc_has{roots}
```

Import 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}.

#12

Big Linking Example



Summary

- Your relocatable object file: main.o
  - Exports main(), imports sqrt(), relocations …
- Your math library: math.o
  - Exports sqrt(), relocations
  - Libraries can have imports: give an 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)

#14

Q: Radio (117 / 842)

- This NPR radio show features Tom and Ray Magliozzi as Click and Clack the Tappet Brothers. It includes Boston accents, a weekly "Puzzler", and is brought to you in part by "Paul Murky of Murky Research" and the law firm of "Dewey, Cheetham and Howe".

#15

Q: Movie Music (430 / 842)

- What reason did Dick Van Dyke's character, in a 1964 Disney film, give for his father giving his "nose a tweak" and telling him he was bad?

#16

Q: Cartoons (671 / 842)

- Name all five main characters and the primary automobile from **Scooby Doo, Where Are You!**

#17

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?

#18

Dynamic Linking

- Idea: **shared libraries** (.so) or **dynamically linked libraries** (.dll) 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?

#19

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!
- 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?*)

#20

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?

#21

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 5 (or GP 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: of the code and data live at fixed offsets, can do e.g. GP = ((PC & 0xFF00)+0x0100)

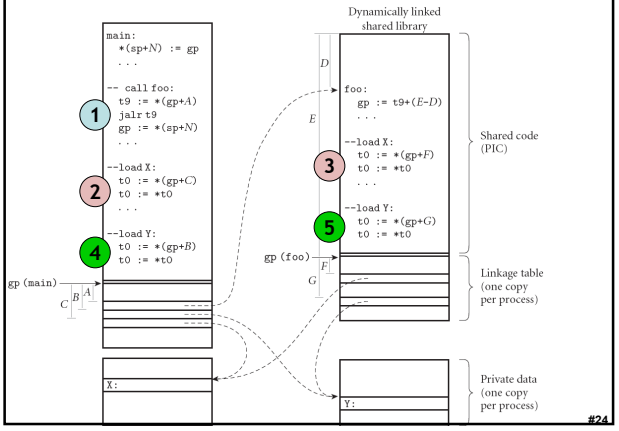
#22

Shared Library = Shared Data?

- Typically each client of a shared library X wants its own copies of X's globals
  - Example: errno in libc
- 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

#23

Not As Bad As It Looks



#24

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)
  - Big deal 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()

#25

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 …;
}
```

#26

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?*

#27

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!

#28

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)

#29

Homework

- WA8 Due Thursday
- PA5 Due Friday April 27 (10 days)

#30