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 all big projects use this
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 referenced
    • 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:

```c
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);
}
```
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

```c
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);
}
```

<table>
<thead>
<tr>
<th>Address</th>
<th>Instruction</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x0200</td>
<td>r1 = b</td>
</tr>
<tr>
<td>0x0204</td>
<td>r1 = r1 * r1</td>
</tr>
<tr>
<td>0x0208</td>
<td>r2 = 4.0</td>
</tr>
<tr>
<td>0x020c</td>
<td>r2 = r2 * a</td>
</tr>
</tbody>
</table>

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.
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);
}
Big Linking Example
get out some 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 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)
Q: Theatre (002 / 842)

What is Jean Valjean's prisoner number in *Les Miserables*?
Q: TV (051 / 842)

• This 1993 television series typically begins with the phrase "The Truth Is Out There".
Q: TV (089 / 842)

• Name any two of the five "Satellite Of Love" characters mentioned by name in the first-season opening theme song to Mystery Science Theatre: 3000.
This phrase is Swahilian for "there are no concerns here" and was popularized by a 1994 Hamlet-like, mammal-centric Disney film.
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) 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

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 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: 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

main:
  *(sp+N) := gp
  ...

-- call foo:
  t9 := *(gp+A)
  jalr t9
  gp := *(sp+N)
  ...

--load X:
  t0 := *(gp+C)
  t0 := *t0
  ...

--load Y:
  t0 := *(gp+B)
  t0 := *t0

--- Shared code (PIC) ---

foo:
  gp := t9+(E-D)
  ...

--load X:
  t0 := *(gp+F)
  t0 := *t0
  ...

--load Y:
  t0 := *(gp+G)
  t0 := *t0

--- Linkage table (one copy per process) ---

--- Private data (one copy per process) ---

--- Shared library ---

--- Dynamically linked shared library ---

--- gp (main) ---

--- gp (foo) ---
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 - Wednesday April 18th
- WA7 Due Monday April 16
- PA5c Due Monday April 16