Language Systems

The Classical Sequence

- Integrated development environments are wonderful, but. . .
- Old-fashioned, un-integrated systems make the steps involved in running a program more clear
- We will look the classical sequence of steps involved in running a program
- (The example is generic: details vary from machine to machine)

Creating

- The programmer uses an editor to create a text file containing the program
- A high-level language: machine independent
- This C-like example program calls the function `fred` 100 times, passing each `i` from 1 to 100:

Example

```
int i;
void main() {
  for (i=1; i<=100; i++)
    fred(i);
}
```

Compiling

- Compiler translates to assembly language
- Machine-specific
- Each line represents either a piece of data, or a single machine-level instruction
- Programs used to be written directly in assembly language, before Fortran (1957)
- Now used directly only when the compiler does not do what you want, which is rare

High-level to Assembly

Example (C)

```
int i;
void main() {
  for (i=1; i<=100; i++)
  fred(i);
}
```

Example (compiled assembly)

```
i:      data word 0
main:   move 1 to i
t1:     compare i with 100
        jump to t2 if greater
        push i
        call fred
        add 1 to i
        go to t1
t2:     return
```

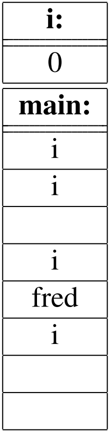
Assembling

- Assembly language is still not directly executable
  - Still text format, readable by people
  - Still has names, not memory addresses
- Assembler converts each assembly-language instruction into the machine's binary format: its *machine language*
- Resulting object file not readable by people

Assembly to Object

Example (assembly)

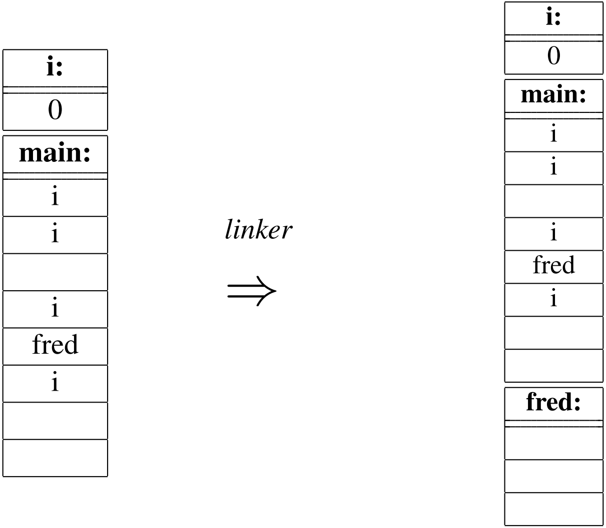
```
i:      data word 0
main:   move 1 to i
t1:     compare i with 100
        jump to t2 if greater
        push i
        call fred
        add 1 to i
        go to t1
t2:     return
```



Linking

- Object file still not directly executable
  - Missing some parts
  - Still has some names
  - Mostly machine language, but not entirely
- Linker collects and combines all the different parts
- In our example, `fred` was compiled separately, and may even have been written in a different high-level language
- Result is the executable file

Linking Object Code into an Executable



Loading

- “Executable” file still not directly executable
  - Still has some names
  - Mostly machine language, but not entirely
- Final step: when the program is run, the loader loads it into memory and replaces names with addresses

A Word About Memory

- For our example, we are assuming a very simple kind of memory architecture
- Memory organized as an array of bytes
- Index of each byte in this array is its address
- Before loading, language system does not know where in this array the program will be placed
- Loader finds an address for every piece and replaces names with addresses

Example

Executable

i:	0
main:	i
	i
	i
	fred
	i
fred:	

loader

$\Rightarrow$

Memory

x0:	
x20 (main):	x80
	x80
	x80
	x60
	x80
x60 (fred):	
x80 (i):	0

Running

- After loading, the program is entirely machine language
    - All names have been replaced with memory addresses
- Processor begins executing its instructions, and the program runs

The Classical Sequence

$\xrightarrow{\text{editor}}$ source file

$\xrightarrow{\text{compiler}}$ assembly-language file

$\xrightarrow{\text{assembler}}$ object file

$\xrightarrow{\text{linker}}$ executable file

$\xrightarrow{\text{loader}}$ running program in memory

About Optimization

- Code generated by a compiler is usually optimized to make it faster, smaller, or both
- Other optimizations may be done by the assembler, linker, and/or loader
- A misnomer: the resulting code is better, but not guaranteed to be optimal

Optimization Example

Example (Original code)

```
int i = 0;
while (i < 100) {
  a[i++] = x*x*x;
}
```

Example (Improved code - loop invariant)

```
int i = 0;
int temp = x*x*x;
while (i < 100) {
  a[i++] = temp;
}
```

Example

- Loop invariant removal is handled by most compilers
- That is, most compilers generate the same efficient code from both of the previous examples
- It is often a waste of the programmer's time to make the code change manually

Other Optimizations

- Some optimizations, like low-level intermediate representation analysis, add variables
- Others remove variables, remove code, add code, move code around, etc.
- All make the connection between source code and object code more complicated
- A simple question, such as “What assembly language code was generated for this statement?” may have a complicated answer

Variations

Variation: Hiding The Steps

- Many language systems make it possible to do the compile-assemble-link part with one command
- Many modern compilers incorporate all the functionality of an assembler
- They generate object code directly

Example (gcc on Unix)

```
#compile/assemble/link
gcc main.c
#-----------#
#compile
gcc main.c -S
#assemble
as main.s -o main.o
#link
ld ...
```

Variation: Integrated Development Environments

- A single interface for editing, running and debugging programs
- Integration can add power at every step:
  - Editor knows language syntax
  - System may keep a database of source code (not individual text files) and object code
  - System may maintain versions, coordinate collaboration
  - Rebuilding after incremental changes can be coordinated, like Unix `make` but language-specific
  - Debuggers can benefit (more on this soon…)

Variation: Interpreters

- To *interpret* a program is to carry out the steps it specifies, without first translating all the code into a lower-level language
- Interpreters are usually much slower
  - Compiling takes more time up front, but program runs at hardware speed
  - Interpreting starts right away, but each step must be processed in software
- Sounds like a simple distinction…

Virtual Machines

- A language system can produce code in a machine language for which there is no hardware: an *intermediate code*
- Virtual machine must be simulated in software – interpreted, in fact
- Language system may do the whole classical sequence, but then interpret the resulting intermediate-code program
- Why?

Why Virtual Machines?

- Cross-platform execution
  - Virtual machine can be implemented in software on many different platforms
  - Simulating physical machines is harder
- Heightened security
  - Running program is never directly in charge
  - Interpreter can intervene if the program tries to do something it shouldn't

The Java Virtual Machine

- Java languages systems usually compile to code for a virtual machine: the JVM
- JVM language is sometimes called bytecode
- Bytecode interpreter is part of almost every web browser
- When you browse a page that contains a Java applet, the browser runs the applet by interpreting its bytecode

Intermediate Language Spectrum

- Pure interpreter
  - Intermediate language = high-level language
- Tokenizing interpreter
  - Intermediate language = token stream
- Intermediate-code compiler
  - Intermediate language = virtual machine language
- Native-code compiler
  - Intermediate language = physical machine language

Delayed Linking

- Delay linking step
- Code for library functions is not included in the executable file of the calling program

Delayed Linking: Windows

- Libraries of functions for delayed linking are stored in **.dll** files: dynamic-link library
- Many language systems share this format
- Two flavors:
  - Load-time dynamic linking
    - Loader finds **.dll** files (which may already be in memory) and links the program to functions it needs, just before running
  - Run-time dynamic linking
    - Running program makes explicit system calls to find **.dll** files and load specific functions

Delayed Linking: Unix

- Libraries of functions for delayed linking are stored in **.so** files: shared object
- Suffix **.so** followed by version number
- Many language systems share this format
- Two flavors:
  - Shared libraries
    - Loader links the program to functions it needs before running
  - Dynamically loaded libraries
    - Running program makes explicit system calls to find library files and load specific functions

Delayed Linking: Java

- JVM automatically loads and links classes when a program uses them
- Class loader does a lot of work:
  - May load across Internet
  - Thoroughly checks loaded code to make sure it complies with JVM requirements

Delayed Linking Advantages

- Multiple programs can share a copy of library functions: one copy on disk and in memory
- Library functions can be updated independently of programs: all programs use repaired library code next time they run
- Can avoid loading code that is never used

Profiling

- The classical sequence runs twice
- First run of the program collects statistics: parts most frequently executed, for example
- Second compilation uses this information to help generate code that optimizes frequently run sections

Dynamic Compilation

- Some compiling takes place after the program starts running
- Many variations:
  - Compile each function only when called
  - Start by interpreting, compile only those pieces that are called frequently
  - Compile roughly at first (for instance, to intermediate code), spend more time on frequently executed pieces (for instance, compile to native code and optimize)
- Just-in-time (JIT) compilation

Binding times

Binding

- Binding means associating two things – specifically, associating some property with an identifier from the program
- In our example program:
  - What set of values is associated with `int`?
  - What is the type of `fred`?
  - What is the address of the object code for `main`?
  - What is the value of `i`?

Example

```
int i;
void main() {
  for (i=1; i<=100; i++)
    fred(i);
}
```

Binding Times

- Different bindings take place at different times
- There is a standard way of describing binding times with reference to the classical sequence:
  - Language definition time
  - Language implementation time
  - Compile time
  - Link time
  - Load time
  - Runtime

Language Definition Time

- Some properties are bound when the language is defined:
  - Meanings of keywords: `void`, `for`, etc.

Example

```
int i;
void main() {
  for (i=1; i<=100; i++)
    fred(i);
}
```

Language Implementation Time

- Some properties are bound when the language system is written:
  - range of values of type `int` in C (but in Java, these are part of the language definition)
  - implementation limitations: max identifier length, max number of array dimensions, etc

Example

```
int i;
void main() {
  for (i=1; i<=100; i++)
    fred(i);
}
```

Compile Time

- Some properties are bound when the program is compiled or prepared for interpretation:
  - Types of variables, in languages like C and ML that use static typing
  - Declaration that goes with a given use of a variable, in languages that use static scoping (most languages)

Example

```
int i;
void main() {
  for (i=1; i<=100; i++)
    fred(i);
}
```

Link Time

- Some properties are bound when separately-compiled program parts are combined into one executable file by the linker:
  - Object code for external function names

Example

```
int i;
void main() {
  for (i=1; i<=100; i++)
    fred(i);
}
```

Load Time

- Some properties are bound when the program is loaded into the computer's memory, but before it runs:
  - Memory locations for code for functions
  - Memory locations for static variables

Example

```
int i;
void main() {
  for (i=1; i<=100; i++)
    fred(i);
}
```

Run Time

- Some properties are bound only when the code in question is executed:
  - Values of variables
  - Types of variables, in languages like Lisp that use dynamic typing
  - Declaration that goes with a given use of a variable (in languages that use dynamic scoping)
- Also called *late* or *dynamic* binding (everything before run time is *early* or *static*)

Late Binding, Early Binding

- The most important question about a binding time: late or early?
  - Late: generally, this is more flexible at runtime (as with types, dynamic loading, etc.)
  - Early: generally, this is faster and more secure at runtime (less to do, less that can go wrong)
- You can tell a lot about a language by looking at the binding times

Debuggers

Debugging Features

- Examine a snapshot, such as a core dump
- Examine a running program on the fly
  - Single stepping, breakpointing, modifying variables
- Modify currently running program
  - Recompile, relink, reload parts while program runs
- Advanced debugging features require an integrated development environment

Debugging Information

- Where is it executing?
- What is the traceback of calls leading there?
- What are the values of variables?
- Source-level information from machine-level code
  - Variables and functions by name
  - Code locations by source position
- Connection between levels can be hard to maintain, for example because of optimization

Runtime support

Runtime Support

- Additional code the linker includes even if the program does not refer to it explicitly
  - Startup processing: initializing the machine state
  - Exception handling: reacting to exceptions
  - Memory management: allocating memory, reusing it when the program is finished with it
  - Operating system interface: communicating between running program and operating system for I/O, etc.
- An important hidden player in language systems