The Software Stack:

From Assembly Language to Machine Code

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The Hardware Execution Model

Computers execute individual operations, encoded into binary form

• Basic cycle of execution is: \((fetch, decode, execute)\)*
  ♦ **Fetch** brings an operation from memory into the processor’s decode unit
  ♦ **Decode** breaks the operation into its fields, based on the opcode, & sets up the operation’s execution — writes values to appropriate control registers
  ♦ **Execute** clocks the processor’s functional unit to carry out the computation

• Each *operation* has a fixed format
  ♦ A **processor** will support several formats
  ♦ **Opcode** determines format

<table>
<thead>
<tr>
<th>opcode</th>
<th>reg(_1)</th>
<th>reg(_2)</th>
<th>reg(_2) or constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10</td>
<td>15</td>
<td>20</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>op</th>
<th>constant</th>
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<tbody>
<tr>
<td>0</td>
<td>1</td>
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</table>

People are not particularly good at reading & writing binary operations

• Productivity & error rate are better with higher level of abstraction
• People need a tool to translate some symbolic representation to binary
  ⇒ We invented **assemblers** to perform that translation

Bits in the instruction format are a serious architectural limitation
Symbolic Assembly Code

The ILOC that we have seen in examples is a symbolic assembly code for a simplified fictional RISC processor

- Symbolic names for operations
  - load, store, add, mult, jump, ...
- Labels for addresses
  - @a, @b, @c, ...
- Register names specified with integers
  - r₁, r₂, r₃, ...

Of course, the processor would not recognize all these symbolic names. Real processors run from code expressed in binary form.

Symbolic assembly code must be translated before it can execute.
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ILOC has symbolic labels and virtual registers

Machine code needs addresses and physical registers

• Compiler maps virtual registers to physical registers
  ♦ Job of the compiler’s register allocator
• Software stack (assembler, linker, loader) converts labels to virtual addresses
Symbolic Assembly Code

In assembly code, the fields in an operation are alphanumeric symbols

- Opcodes are represented with mnemonics — character strings
  - “add” instead of “0110”
- Registers and constants are written using base 10 or base 16 numbers
  - “r15” instead of “01111”

To prepare an assembly program for execution, it must be translated

- Mnemonics map directly to opcodes – bit patterns
- Symbolic labels map directly to addresses – bit patterns
- Base 10 numbers convert to base 2 numbers – bit patterns
- For the most part, these translations are simple and direct
Building an Assembler

What does an object file contain?

• A list of operations
  ♦ First operation (almost always) has an exported label
  ♦ Complete operations are in final binary form
  ♦ Operations with a symbolic reference have a hole & an index into a symbol table

• A symbol table
  ♦ Each symbol defined in the module has a symbol name, a type, and an offset from the start of the module
  ♦ Each imported symbol has a symbol name, a storage class, and a list of operations in the module that reference this symbol

Storage class might be “static” or “dynamic”, “local” or “global”
Building an Assembler

Assemblers convert assembly code to object code

- Typical assemblers operate in two passes
- Pass 1 builds up a symbol table that maps names to addresses
  - Use a hash table to record the map
  - Linear pass over the input to find symbols & record <name, address> pairs
- Pass 2 rewrites the operations into binary form
  - All symbols should be defined after pass 1
  - Linear pass over the input to rewrite operations into binary form
    → Symbolic references marked with their name and table entry

At the end, the assembler writes out an object file
Building an Assembler

The algorithm for Pass 1 is simple

- Initialize a counter to zero
- Initialize an empty map (a hash table\(^1\))
- At each operation, from the first to the last
  - If the operation is labeled, enter the label in the map with the current counter
  - Enter any undefined labels used as operands in the map, with an invalid counter
  - Compute the length of the current operation
  - Increment the counter by the operation’s length
- Iterate over the map
  - If any symbol has an invalid counter, mark it as an external symbol or signal error
    → Choice of action depends on the rules of the particular assembly language

Pass 1 should operate in \(O(|\text{operations}|)\) time \((\text{if hash lookup is } O(1))\)

→ Number of symbols is \(O(|\text{operations}|)\)

\(^1\) See discussion of hash tables in Chapter 6 and Appendix B in EaC2e
Building an Assembler

Pass 2 iterates over the input again and rewrites it
• Pass 1 resolved all the symbols
• Pass 2 constructs the object code

For each operation
• Mnemonic becomes a bit pattern for the opcode
• Opcode determines instruction format
• Operands become bit fields
  ♦ The exception is a reference to an externally defined symbol
  ♦ Replace externally defined symbol with a reference into table of such symbols
  ♦ Format for that reference and table is a system-wide convention
• Write out the finished binary operation

At the end, write out the symbol table information

Again, it is all $O(|\text{operations}|)$ \hspace{1cm} (if hash lookup is $O(1)$)
An assembler can do most of its translation in the first pass

• Can translate most operations directly in pass 1
  ♦ E.g., \texttt{add r1, r2} => \texttt{r3} contains all the information that it needs
  ♦ \textbf{Exception} arises from a reference to a symbol that is not yet defined

• When the assembler finds an (as yet) undefined label, it can:
  ♦ Enter that symbol into the symbol table and mark it as undefined
  ♦ Add the current operation to a list of operations containing symbolic references
  ♦ It can process any operation with an (already) defined label

• At the end of pass 1, the assembler can:
  ♦ Traverse the list of unfinished instructions
  ♦ Translate them in place

• After that “half pass”, it can output the object code
Assembler Pseudo-Operations

Almost all assemblers provide pseudo-operations to manipulate layout

- Pseudo-operations define storage, define labels, initialize space, and mark symbols as external
- To create space for a global array \( A \), define storage for it
  - Label that pseudo-operation with a known label, say \( _@A \)
- The pseudo-operations serves two functions
  - It advances the assembler’s internal counter for addresses (by its argument)
  - It provides a place to “hang” the label, at the start of that block of space

If we define \( _@A \) as an external symbol, other code will be able to access it

- The linker will tie the symbols and addresses together
- The linker will match them by name, so only one object file can define \( _@A \)

The process of creating unique labels from names is called “mangling”

- Procedure \( \text{fee}() \) might create something like \( _.fee_ \)
- Static \( \text{fee}() \) in file \( \text{foe}() \) might create something like \( _.foe.fee_ \)
So, What Happens With All Those Object Modules?

The compiler produces a .asm file for each “compilation unit.”

The assembler produces a .o file for each .asm file.

What happens next?

• A collection of .o files can be combined to form an executable file (a.out)
• The program that performs this task is called a linker
• The linker takes a collection of object files and libraries of object files
• It selects out the pieces that it needs to build a complete executable
• It lays out the executable, computes addresses for all external symbols, and rewrites the executable, replacing the external symbols with virtual addresses
A linker composes one or more object modules into an executable program

- Finds all of the entry points and labels in the object code
  - Both exported and imported names
- Finds the main entry point
- Determines the spatial layout of the executable
- Resolves all imported names in an appropriate way
  - Names that are statically linked
    - *Imported names must match an exported name*
    - *Imported names must be rewritten with the exported name’s address*
  - Names that are dynamically linked
    - *Imported names must be rewritten with a stub to load & link the name at runtime*
How does a linker work?

• **Pass 1:** Build a map of all symbols (exported & imported) by the object modules and libraries, and find the the **main** entry point

• **Pass 2:** Add object modules until all static symbols are resolved
  Starting with the module containing **main**:
  ♦ Add the module to the end of the code
  ♦ Assign addresses to its internal labels

• **Pass 3:** Rewrite the code with resolved symbols
  ♦ Static symbols are rewritten with addresses
  ♦ Dynamic symbols are rewritten with a jump to a stub that finds, loads, and links the needed object code

Granularity of inclusion is an object file
Library can be one big file or a collection of smaller modules
Building a Linker

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Does order matter?
— Actually, it does
— See Pettis & Hansen ’90 or Section 8.7.2 in EaC2e
What Happens at Runtime?

How does an a.out execute?

• Some running process\(^1\) (the “parent”) starts the execution
  ◆ In a shell, the user types the name of an executable at an input prompt
• The parent process creates (or “spawns”) a new process
• The new process executes a.out and returns
  ◆ In a shell, the parent process waits for the child to complete
  ◆ In a parallel computation, the parent may spawn many children and wait for them to complete, or it may simply continue without waiting

Obviously, this high-level view obscures some of the detail ...

\(^1\) The first running process is the boot process, created by a hardware signal and the code in the boot sequence.
Creating a New Process  

To create a new process, the parent calls `fork()`

- `fork()` clones the parent process
  - New child has its own copies of all data
    - Includes file descriptors, program counter, ...
    - New child has a distinct process id (PID)
  - `Fork()` returns child’s PID to the parent and 0 to the child

- The parent waits on the child
- The child executes the new command

If the child only executes the new command ...

- It does not need the parent’s full address space
- `vfork()` copies just enough of the address space to allow an exec() call
  - It clones file descriptors, process status information, and the code
  - `vfork()` is safe if the process immediately calls `exec()`

```c
pid_t vfork(void);
pid_t process;
...
process = vfork();

if (process < 0)
    fprintf(stderr,"vfork() error.\n");
else if (process == 0) {
    ... execute new command ...
}
else {
    wait()
}
```
Replacing the Address Space  
(Unix/Linux model)

To replace the child process’s address space, it calls exec() ¹

- `execl()` takes a path to the executable file and a list of arguments
- `exec()` constructs the address space of the executable file
  - If the file begins with `#! interpreter`, it runs the interpreter on the rest of the file
  - If the file is an executable, it reads the file’s header information and:
    - Loads the program text, starting at the specified address
    - Loads any initialized data areas, starting at their specified addresses
    - Zeros any pages that are so specified
    - Branches to the **start address of main()**, as specified in the file’s header

- The original address space overwritten, except for parts of its environment
  - File descriptors remain open (unless modified by `fcntl()`)
  - The contents of the global `environ` remain intact
  - Arguments passed through `exec()` are passed to `main` as `argc`, `argv`, and `envp`

```c
int main(int argc, char **argv, char **envp) {
    ...
}
```

¹ `execve()` is the general form; `execl()` is a front end to `execve()`
A Couple More Points

The linker describes the address space

- The executable file is fully resolved, except for dynamically linked labels
  - `exec()`, in effect, inflates the address space based on header info in the `a.out`
  - It creates the code region of the address space, along with static data areas and global data areas

- **main()** must create the stack and the heap
  - `main()` starts the language’s **runtime system**
  - Allocates and initializes space for the stack and the heap
  - Takes care of other critical details
  - The compiler inserts a call to the runtime initialization code at the start of `main()`
    → Special case for the main entry point
    → In **c**, the compiler recognizes `main()` by name.
      → In other languages, the compiler may recognize it by declaration

- On exit, **main()** must shut down the environment
  - Compiler inserts a call to the runtime finalization code at the end of `main()`
What Happened to @A?

We went off on this tale to learn how a compile-time label becomes a physical address. What did happen to @A?

Two cases:

• @A was a label in the code
  ♦ The assembler converted @A to an offset from the start of the object module

• @A was a label on a pseudo-operation
  ♦ The assembler converted @A to an address of a data area (initialized or not)

Then, ...

• The linker computed @A’s virtual address as it laid out memory
• The linker replaced occurrences of @A with its actual virtual address
• exec() built the address space and initialized the memory at @A
• The relevant instructions executed with the @A’s virtual address
  ♦ Load, store, branch, jump, call, etc. see a virtual address rather than @A
What Happens to the Virtual Address?

The hardware uses physical address (*for the most part*)

• At runtime, the operating system and the hardware must translate the virtual address of `_@A` to a physical address
• The process requires cooperation between the processor and the OS
• The process requires both hardware and software support

Remember last lecture?
Cache Memory

Modern hardware features multiple levels of cache & of TLB

- **L1** is typically core-private & tagged with virtual addresses
- **L2** (and beyond) is typically shared between cores & tagged with physical addresses
- Translation from virtual address to physical address is assisted by the **TLB** & requires cooperation between **OS** and the hardware
- Lookup in **L1** and **TLB** proceed in parallel
  - **TLB** can be as fast as **L1** because it is just a cache with very short lines
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Remember last lecture?

- The **L1** caches (code & data) have virtual tags
  - If the code is in the **L1** cache, the virtual address works
- Everything above **L1** uses physical addresses
  - Requires a fast mechanism to translate a virtual address to a physical address
  - Hence, the creation of the **TLB** to speed that translation
    - **TLB** caches page frame address (physical address modulo page size) by virtual address
    - If the virtual address is not in the **TLB**, it requires an expensive lookup in the page tables and, perhaps a page fault (which changes the **TLB** and the virtual to physical mapping)

The virtual address in a load or jump gets translated by the cache/TLB system.
What Happened to @A?

The combination of the software stack and the memory management hardware ensure that @A in the code is a usable address at runtime.

⇒ It is complex, but it works ... billions of times a second