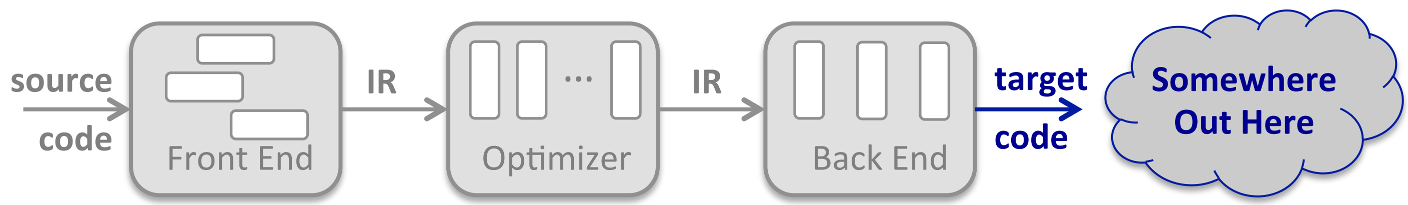
Taken from COMP 506
Rice University
Spring 2017

The Software Stack:

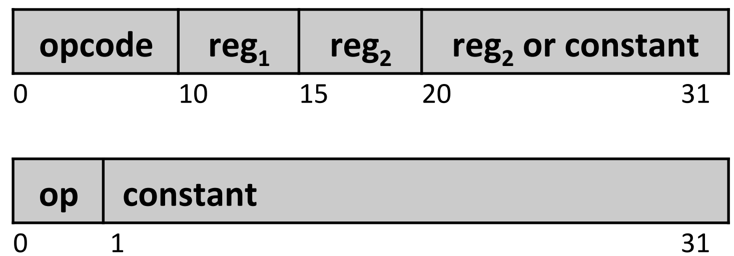
From Assembly Language to Machine Code



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



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
  - $\mathbf{r_1}$, $\mathbf{r_2}$, $\mathbf{r_3}$, …

ILOC Code:

load @b $\Rightarrow r_1$
load @c $\Rightarrow r_2$
mult $r_1, r_2 \Rightarrow r_3$
load @d $\Rightarrow r_4$
add $r_3, r_4 \Rightarrow r_5$
store $r_5 \Rightarrow$ @a
load @f $\Rightarrow r_6$
add $r_5, r_6 \Rightarrow r_7$
store $r_7 \Rightarrow$ @e

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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- Register names specified with integers
  - ♦ r_1, r_2, r_3, …

ILOC Code:

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mult r_1,r_2 ⇒ r_3
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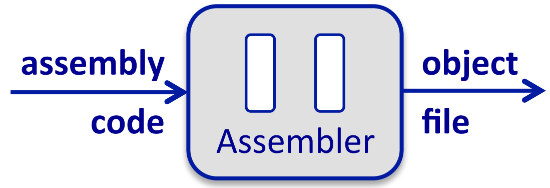
load @f ⇒ r_6
add r_5,r_6 ⇒ r_7
store r_7 ⇒ @e

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 ***regsiter allocator***
- Software stack (***assembler***, ***linker***, ***loader***) converts labels to virtual addresses

Symbolic Assembly Code



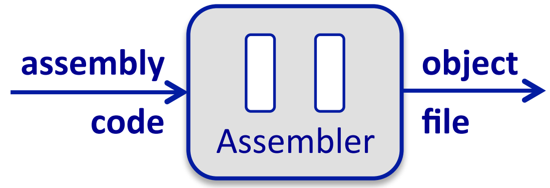
In assembly code, the fields in an operation are alphanumeric symbols

- 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

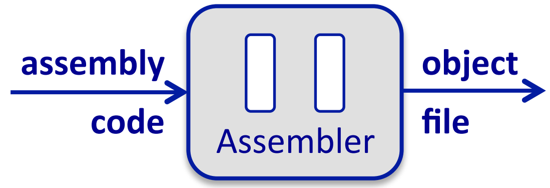


What does an object file contain?

- ***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(|operations|) **time** (*if hash lookup is **O**(*1*)*)

→ Number of symbols is **O**(|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

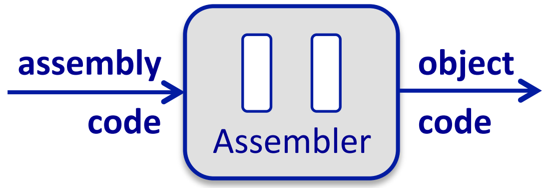
For each operation

- 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(|operations|) (*if hash lookup is* ***O****(*1*)*)

Building an Efficient Assembler



An assembler can do most of its translation in the first pass

- Can translate most operations directly in pass 1
  - ♦ E.g., **add r1, r2 => r3** contains all the information that it needs
  - ♦ **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

Classic "Pass & a Half" Assembler

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

```
_@A:  dss  1024
_@B:  bss   128
```

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 **fee()** might create something like _.fee_
- Static **fee()** in file **foe()** might create something like _.foe.fee_

So, What Happens With All Those Object Modules?

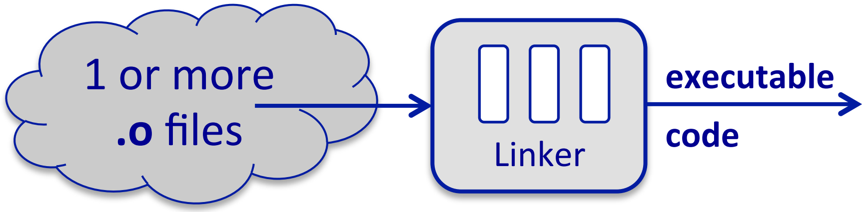
The compiler produces a .asm file for each "compilation unit."

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

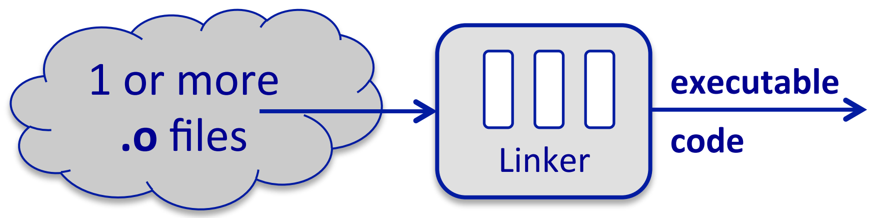
Building a Linker



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 rewritted with a stub to load & link the name at runtime***

Building a Linker



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 — **Operates over the symbol tables**
- **Pass 2:** Add object modules until all static symbols are resolved

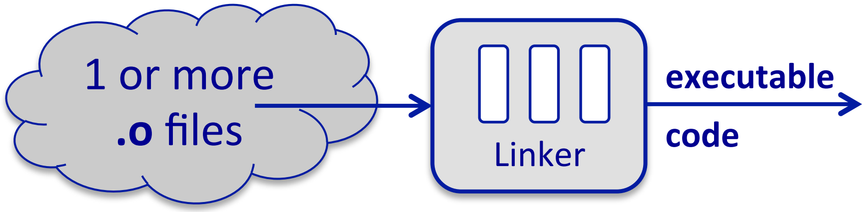
  Starting with the module containing **main:**
  - ♦ Add the module to the end of the code
  - ♦ Assign addresses to its internal labels

  Operates over the object code
- **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

  Operates over the 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

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

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 (Unix/Linux model)

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

```
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()
}
```

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()

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

```
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

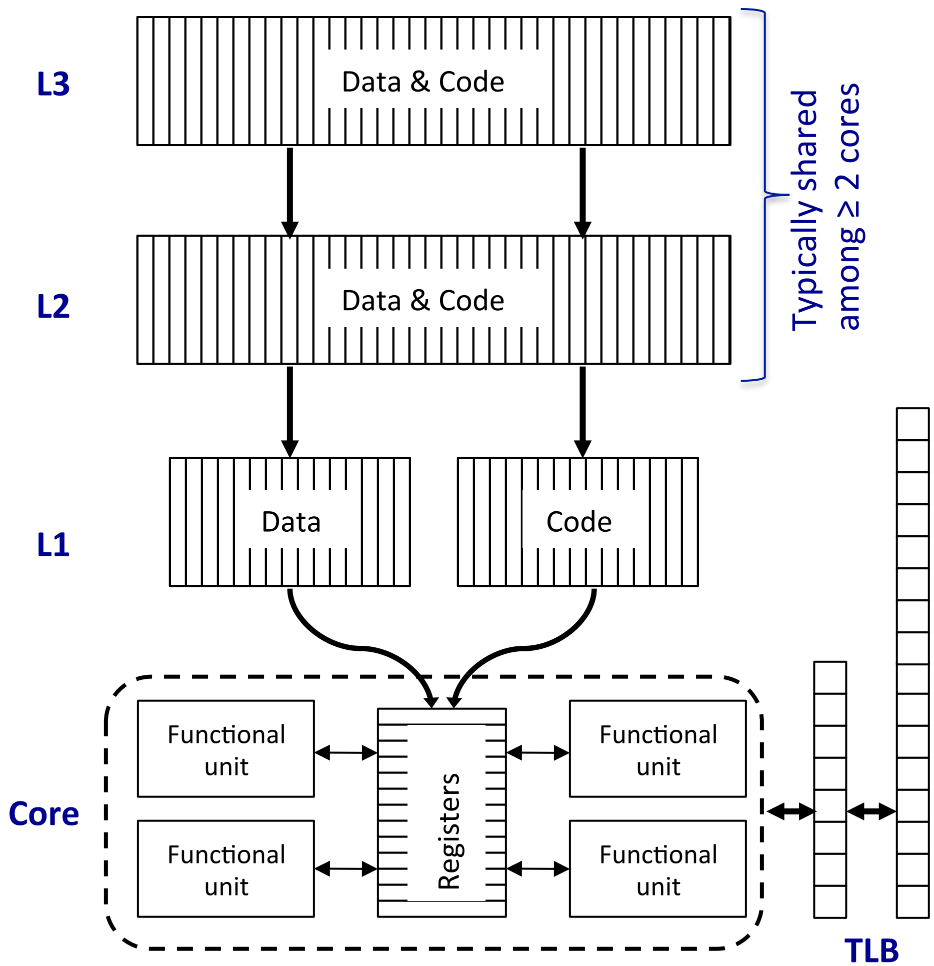
What Happens to the Virtual Address?

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

What Happens to the Virtual Address?

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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