Module 1 – CS 4450

Programming Languages, Paradigms, and Systems

Webber: Chapters 1, 4, and 24

Guiding Questions

- Why are there so many programming languages?
- Why are some more popular than others?
- How can we make informed decisions on which languages to use?
  - What features distinguish the different languages?
  - How would you classify programming languages?

Query

- What languages have **you** used?
- Which do you like best?
- Why?

tiobe.com

- http://www.tiobe.com/tiobe-index/
- Programming popularity/demand index
  - Updated monthly

Aug 2021	Aug 2020	Change	Programming Language	Ratings	Change
1	1		C	12.57%	-4.41%
2	3	↑	Python	11.86%	+2.17%
3	2	↓	Java	10.43%	-4.00%
4	4		C++	7.36%	+0.52%
5	5		C#	5.14%	+0.46%
6	6		Visual Basic	4.67%	+0.01%
7	7		JavaScript	2.95%	+0.07%
8	9	↑	PHP	2.19%	-0.05%
9	14	⇈	Assembly language	2.03%	+0.99%
10	10		SQL	1.47%	+0.02%
11	18	⇈	Groovy	1.36%	+0.59%
12	17	⇈	Classic Visual Basic	1.23%	+0.41%
13	42	⇈	Fortran	1.14%	+0.83%
14	8	⇊	R	1.05%	-1.75%
15	15		Ruby	1.01%	-0.03%
16	12	⇊	Swift	0.98%	-0.44%
17	16	↓	MATLAB	0.98%	+0.11%
18	11	⇊	Go	0.90%	-0.52%
19	36	⇈	Prolog	0.80%	+0.41%
20	13	⇊	Perl	0.78%	-0.33%

Position	Programming Language	Ratings
21	SAS	0.67%
22	Delphi/Object Pascal	0.62%
23	Objective-C	0.61%
24	Rust	0.56%
25	Scratch	0.55%
26	Julia	0.51%
27	Ada	0.49%
28	Lisp	0.47%
29	Dart	0.45%
30	PL/SQL	0.43%
31	(Visual) FoxPro	0.42%
32	Scala	0.42%
33	ABAP	0.41%
34	COBOL	0.37%
35	Logo	0.31%
36	F#	0.30%
37	Kotlin	0.30%
38	Transact-SQL	0.27%
39	Lua	0.26%
40	Scheme	0.24%
41	Ladder Logic	0.24%
42	VBScript	0.23%
43	D	0.23%
44	Clojure	0.22%
45	LabVIEW	0.22%
46	Nim	0.22%
47	VHDL	0.21%
48	Apex	0.21%
49	TypeScript	0.21%
50	Bash	0.18%

Programming Paradigms

- Often grouped into 3 major **families**:
  - Imperative
    - Includes object-oriented
    - Statements, loops, variables
  - Functional
  - Logic

- Some are *multi-paradigm*
  - C++, D, Python, Swift, Rust

Imperative Languages

aka "Procedural"

- Example: a factorial function in C

```
int fact(int n) {
  int sofar = 1;
  while (n > 1)
     sofar *= n--;
  return sofar;
}
```

- Hallmarks of imperative languages:
  - **Assignment**
    - Variables are **fixed** to a memory **location**
    - Updated **in place** through assignment
  - **Iteration**

Functional Languages

- Example: a factorial function in ML

```
fun fact x =
  if x <= 0 then 1 else x * fact(x-1);
```

- Hallmarks of functional languages:
  - *All* functions return a **single value** (no **return** keyword)
    - But could return a list, tuple, etc.
  - **Immutable** variables
    - No **side effects**; no explicit state changes!
    - **No** updating memory in place
  - Heavy use of *recursion* (**not** *iteration*)

Factorial in Other Languages

- C
  - int fact(int x)
    { return x <= 0 ? 1 : x * fact(x-1); }
- Python
  - def fact(n):
    return 1 if x <= 0 else n * fact(n-1)
- Rust (most like ML)
  - fn fact(n: i64) -> i64 {
    if n <= 0 {1} else {n * fact(n-1)}
    }

Strengths and Weaknesses

- The different language groups show their "stuff" on different kinds of problems

- For now, one comment: *don't jump to conclusions based on factorial!*
  - Functional languages do well on such functions
  - Imperative languages, a tiny bit less well
  - Object-oriented languages need *larger examples*
    - They were developed for solving complex problems

About Those Families

- There are *many other* language family terms (not exhaustive and sometimes *overlapping*)
  - Applicative, concurrent, constraint, declarative, definitional, procedural, scripting, …
- Some languages *straddle* families
- Others are so *unique* that assigning them to a family is *pointless*
  - FORTH, APL

Example: Forth Factorial

```
: FACTORIAL
  DUP 1 > IF DUP 1- RECURSE * THEN ;
```

- A *stack-oriented* language
  - Like an HP calculator (X,Y,Z,W stacks)
- Postscript is similar
- Could be called *imperative*, but has little in common with most imperative languages

Example: APL Factorial

$\times / \iota X$

$\times/\iota 5 = \times/1\ 2\ 3\ 4\ 5$
$= 1 \times 2 \times 3 \times 4 \times 5$

- An APL expression that computes X's factorial
- *Expands* X into a vector of the integers 1..X, then *multiplies* them all together
  - (You would not really do it that way in APL, since there is a built-in factorial operator: !X)
- Could be called *functional*, but has little in common with most functional languages

Language Standards

- The documents that define language standards are often drafted by *international committees*
- Can be a slow, complicated and rancorous process
- Fortran: 1982 / 90 / 95 / 2003 / 08 / 15
- C++: 1998 / 2011 / 14 / 17 / 20

- Java and C# evolve faster
  - Why?

The Intriguing Evolution

- Programming languages are evolving rapidly
- New languages are constantly being invented
  - C#, Lua, F#.NET, Scala, Groovy, D, Go, Swift, Rust …
  - F# is ML + objects for .NET
  - Scala is largely an ML front end to the JVM
  - Groovy is a dynamically typed front end to the JVM
  - D and Rust are modern "versions" of C++
  - Go is a modern C
  - Swift is part functional, very cool, but designed for the Mac

Turing Equivalence

- General-purpose languages have different strengths, but fundamentally they all have the *same power*
  - {problems solvable in Java}
    = {problems solvable in Fortran}
    = …
- And all have the same power as various mathematical models of computation
  - = {problems solvable by Turing machine}
    = {problems solvable by lambda calculus}
    = …
- *Church-Turing thesis*: this is what "computability" means

Language Systems

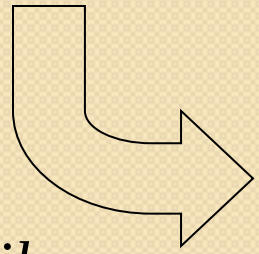
Sequence from source code to executable program

Compiling

- **Compiler** translates to *assembly language*
  - *Machine-specific* instructions
  - C, C++, D, Rust, and Go compile to *native code*
  - Java, C#, Python, Javascript, PHP do **not**

- This is the first step in going from source code to a running program…

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



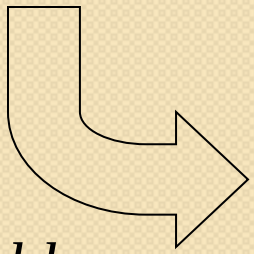
compiler

```
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
```

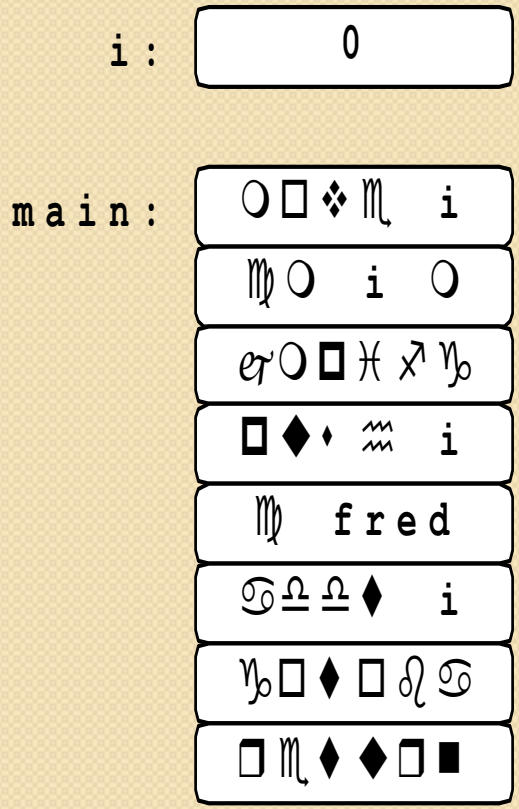
Assembling

- Assembly language is *not* directly executable
  - Still text format, *readable* by (nerdy) people
  - Still has *names*, not memory addresses
- *Assembler* converts each assembly-language instruction into *machine language*
  - Resulting object file not readable by people
- This step is not visible in modern compilers
  - And may even be *skipped*
  - Compilers usually directly yield machine code

```
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
```

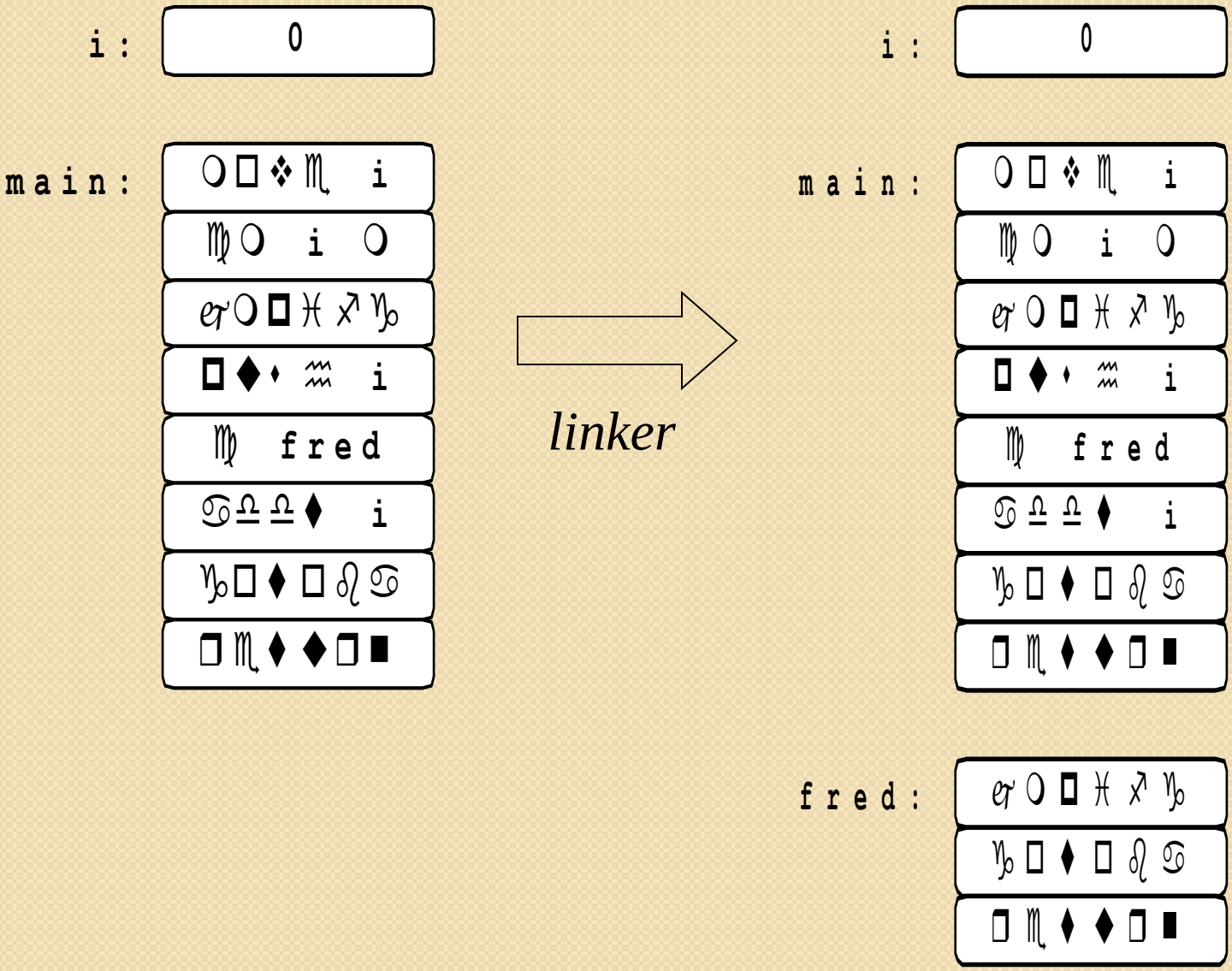


assembler



Linking

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

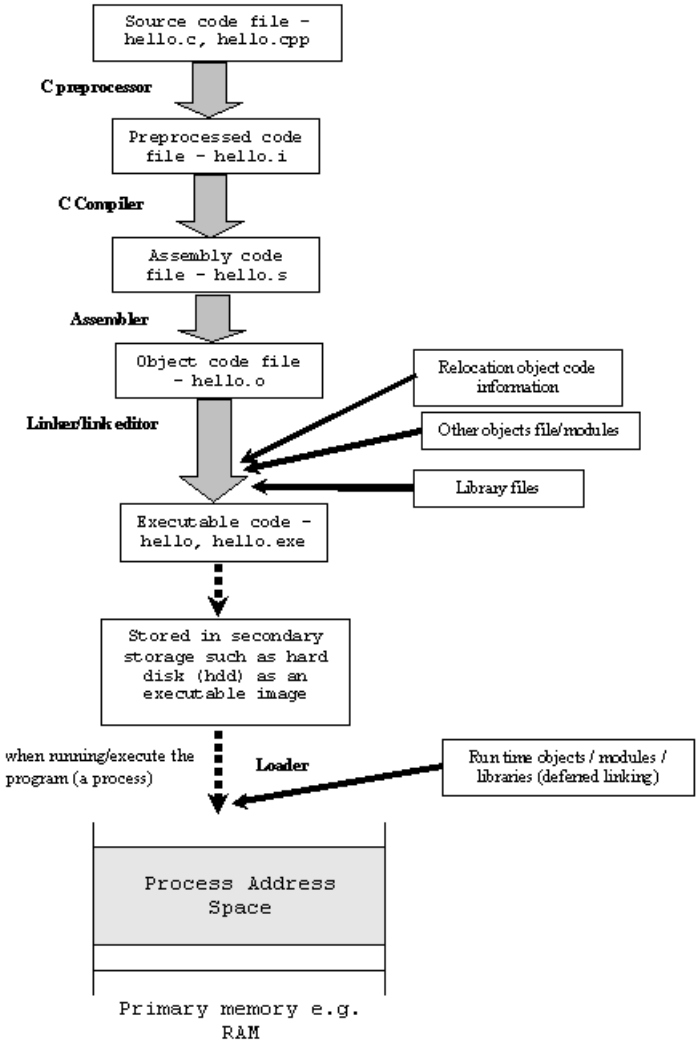

i :
0
main :
fred :
linker

Loading

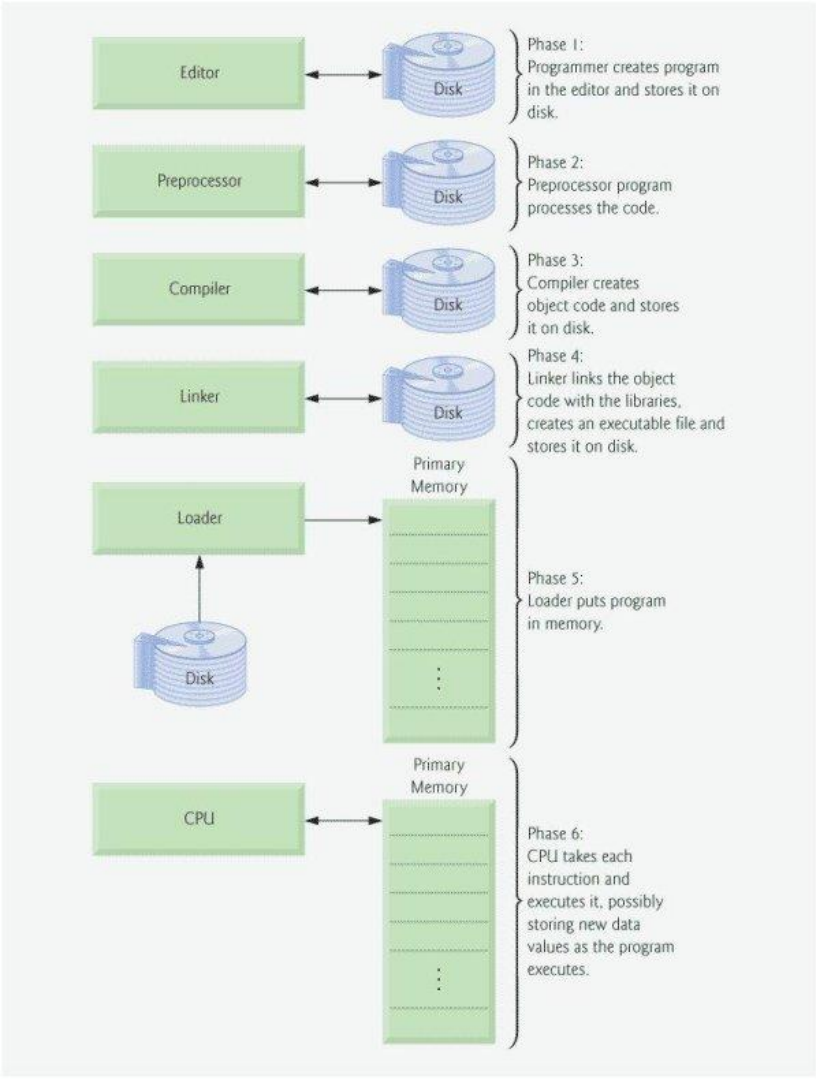
- "Executable" file *still* not directly executable
  - *Still* has some *names*
  - Mostly machine language, but not entirely

- Final step: when the program is run, the *loader* loads it into memory and replaces remaining names with *fixed addresses*

Traditional C/C++ Dev. Process



Modern C/C++ Dev. Process

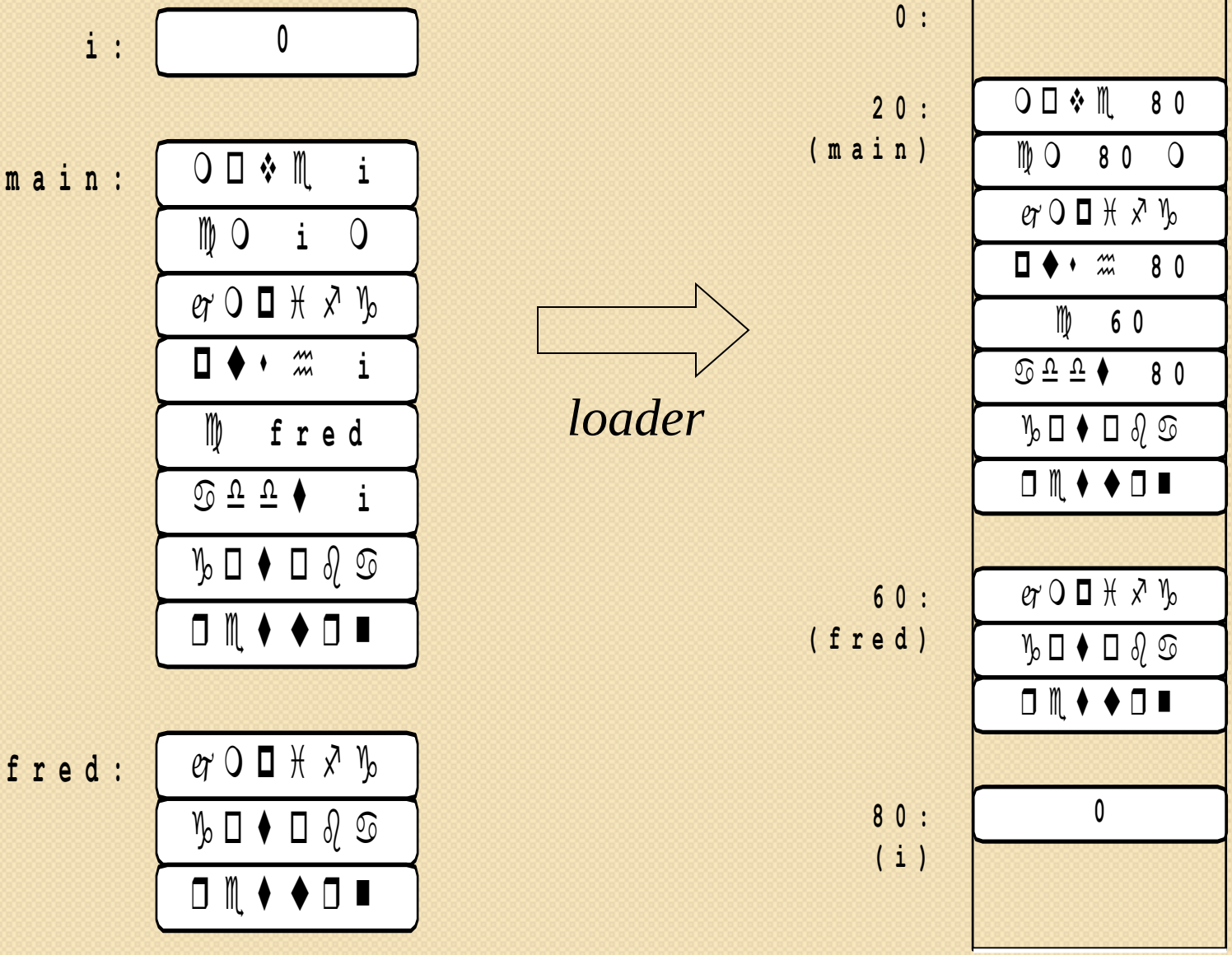


Skips assembler step

A Word About Memory

- Before loading, language system does not know *where* in memory the program will be placed

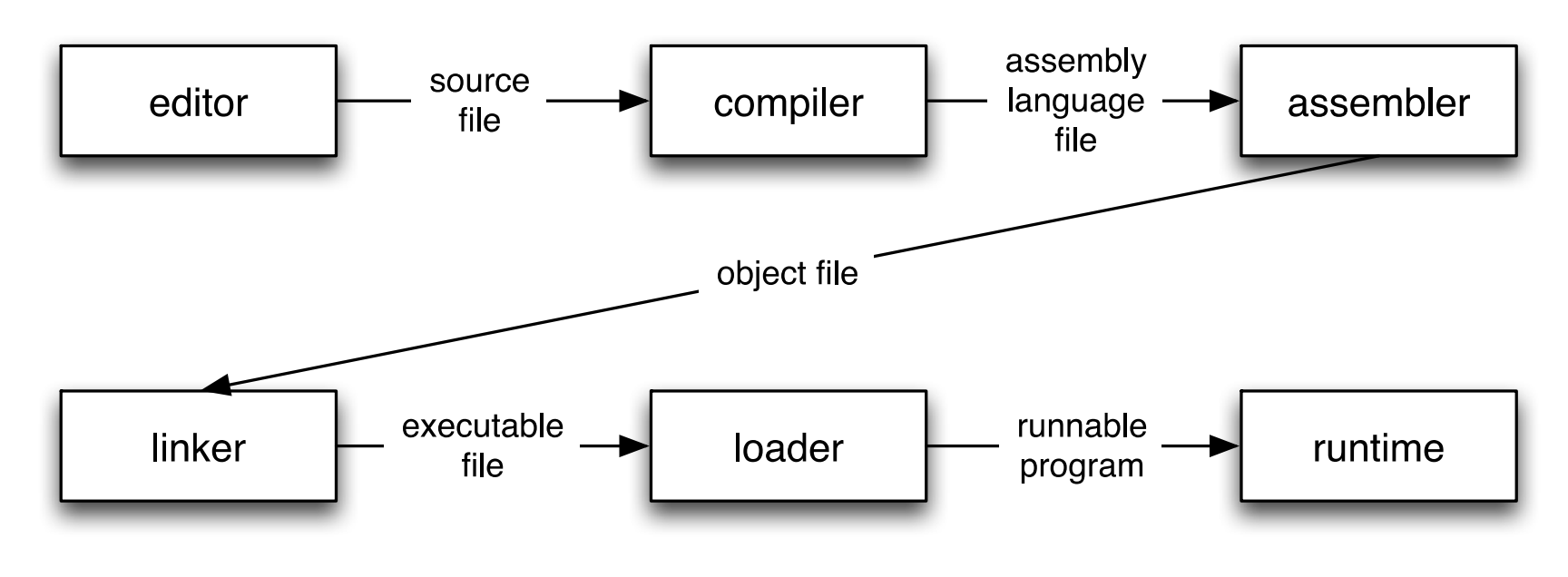
- Loader finds an address for every piece and *replaces names with addresses*
  - like for *static data*
  - There is info in the executable on where the names to be resolved are located
    - By offsets


i :
0
main :
i
i
fred :
0 :
20 :
(main)
80
60 :
(fred)
80 :
(i)
loader

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



Languages like Java, C# and Python compile to *byte code*, which the *virtual machine* loads and *interprets*.

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

Example: Loop Invariants

- Original code:

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

- Improved code, with *loop invariant* moved:

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

The compiler does this (not you!). Unless x is *volatile*.

Example

- *Loop invariant removal* is handled by most compilers
  - That is, most compilers generate the same efficient code as in the previous example
- It is a waste of the programmer's time to make some transformations manually
- "Premature optimization is the root of all evil" (-- Knuth)
  - Premature "pessimization" isn't so great either, though :-)

Other Optimizations

- Some, like LIR, *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!
- Very important issue with *concurrency*
  - Instruction reordering at the machine level can result in *race conditions*

Outline

- The classical sequence
- Variations on the classical sequence
- Binding times
- Runtime support

Variation: Hiding The Steps

- Many language systems make it possible to do the compile-assemble-link part with one command
- Example: `gcc` command on a Unix system:

```
gcc main.c
```

Compile-assemble-link

```
gcc main.c –S
as main.s –o main.o
ld …
```

Compile, then assemble, then link

Variation: Integrated Development Environments

- *A single interface* for editing, running and debugging programs
  - Visual Studio, VSCode, XCode, Eclipse, NetBeans, Thonny…

- Integration can add *power* at every step:
  - Editor knows *language syntax*
    - Syntax highlighting, Intellisense (autofill)
  - System may maintain build *versions* (**git**), coordinate collaboration
  - Rebuilding after incremental changes can be coordinated, like Unix **`make`** but language-specific
  - Debuggers can benefit

Variation: Interpreters

- To *interpret* a program is to carry out the steps it specifies, *without first translating* into a lower-level language

- Interpreters are usually much *slower*
  - Compiling takes *more time up front*, but program runs at *hardware speed*
  - Interpreting starts *sooner*, 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*
  - As opposed to assembly language
  - Not machine-specific (hence "virtual" machine)
- A virtual machine must be simulated in software
  - i.e., *interpreted*

Why Virtual Machines

- Cross-platform execution (*portability*)
  - Virtual machine can be implemented in software on many different platforms
- Heightened security
  - *Your* code is *never directly in charge*
    - The *interpreter* is
  - Interpreter can *intervene* if the program tries to do something it shouldn't
    - It runs in a "sandbox"

The Java Virtual Machine

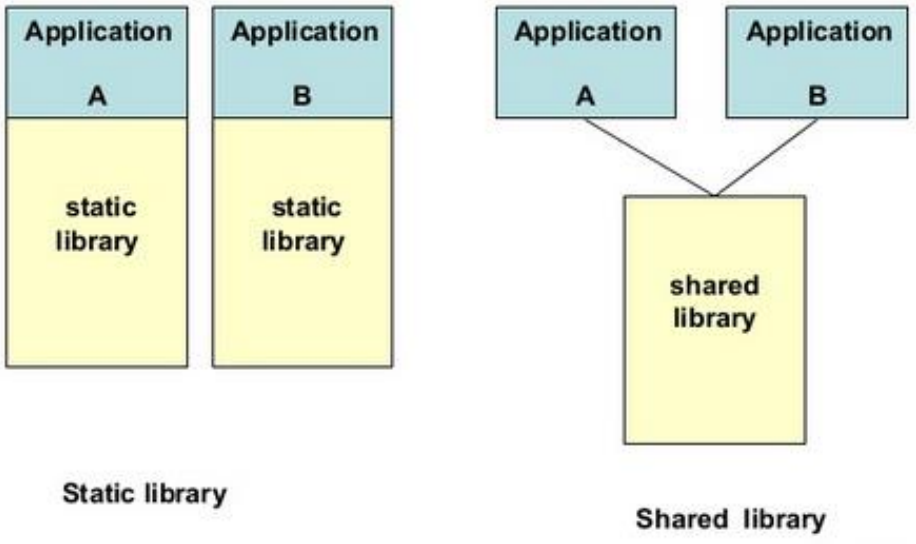
- Java language systems usually compile to code for a virtual machine: the JVM
- JVM language is called *bytecode*
- Bytecode interpreter is part of almost every Web browser
- When you browse a page that contains a Java applet, the browser runs the applet by interpreting its bytecode

Intermediate Language Spectrum

- Pure interpreter (Old BASIC)
  - "Intermediate language" = high-level language
- Tokenizing interpreter (Python)
  - Intermediate language = token stream
- Intermediate-code compiler (Java, C#)
  - Intermediate language = virtual machine language
- Native-code compiler (C++, D)
  - "Intermediate language" = physical machine language

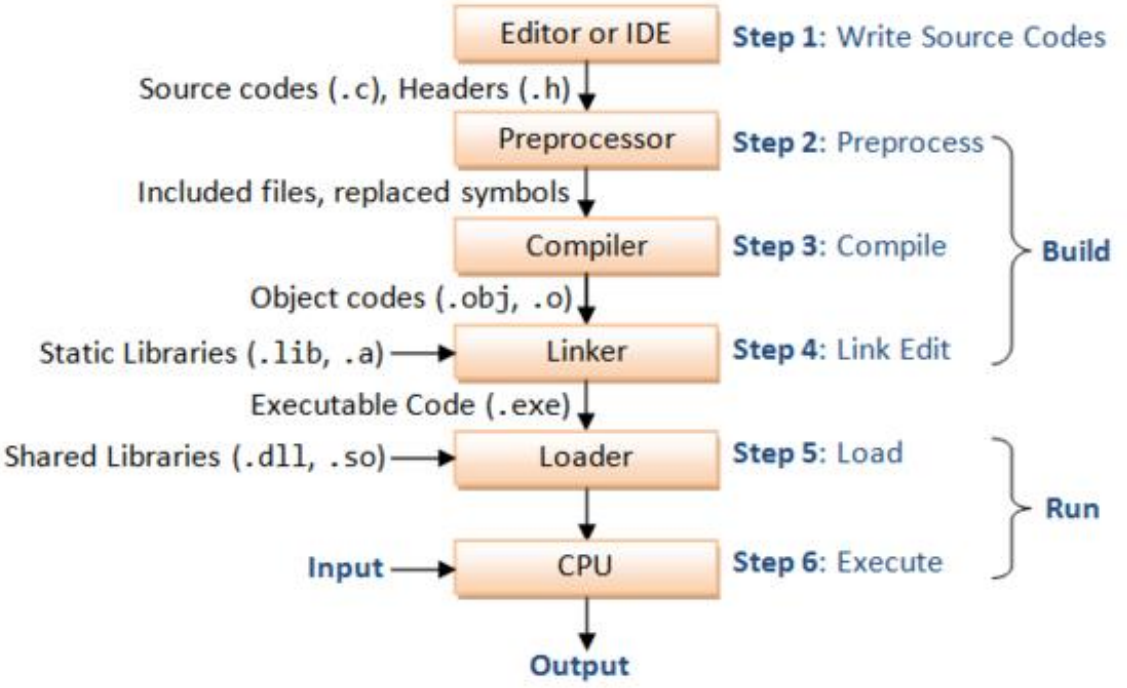
Delayed / Dynamic Linking

- Delays the linking step to *load* or *runtime*
- Code for library functions is *not included* in the executable file for your program



Can you describe 2 advantages of using shared libraries?

Load Time Dynamic Linking



Runtime Dynamic Linking

- You can load shared libraries at **runtime**
- This way you can decide at runtime which version of a library to use
- Each platform provides a system call to load the library on-demand
- Java does this automatically…

Delayed Linking: Java

- JVM automatically loads and links class files from disk when a program uses them
  - $ java myclass
  - At runtime, other classes you reference are automatically loaded

- Java's **class loader** does a *lot* of work:
  - May load across a *network*
  - Thoroughly checks loaded code to make sure it complies with JVM requirements
  - Enforces certain *security* specifications

Delayed Linking Advantages

- Multiple programs can share a copy of library functions: only one copy *on disk*
- Library functions can be *updated* independently of programs: all programs use repaired library code next time they run
- Runtime linking avoids loading code that is never used

Dynamic Compilation

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

Outline

- The classical sequence
- Variations on the classical sequence
- Binding times
- Runtime support

Binding

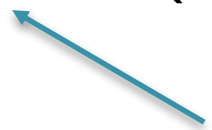
- Binding means *associating* two things—especially, associating some *property* with an *identifier* from the program
- In our example program below:
  - What set of values is associated with **`int`**?
  - What is the type of **`fred`**?
  - What is the address of the object code for **`main`**?
 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

```
int i;
int 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 (*standard specification*)**
  - **Language implementation time (*compiler is developed*)**
  - Compile time
  - Link time
  - Load time
  - Runtime



In some languages, the first two binding times above are the same.

Language Definition Time

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

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

Language Implementation Time

- Some properties are bound when the language system is developed for a *specific platform*:
  - *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

```
int i;
int 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 associated with a given use of a variable, in languages that use *static scoping* (most languages)

```
int i;
int 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:
  - *Pre-compiled machine code* for external functions

```
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:
  - Exact *Memory locations* for code for functions, static variables
  - Static => "determined *before* runtime"
    - All the binding times *before runtime* are considered to be statically bound

```
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
  - Location on stack of function parameters and local variables
  - Types of variables, in languages like Lisp and Python that use *dynamic typing*

- Also called *late* or *dynamic* binding
  - Remember: everything before run time is called *early* or *static*
  - Statically bound DLLs on Windows are an anomaly here!

Late Binding, Early Binding

- The most important question about a binding time: late or early?
  - *Late*: generally, this is at runtime; *more flexible* (as with subclass type instances, dynamic loading, etc.)
  - *Early*: generally, this is *faster* and *more secure* than at runtime (less to do at runtime, less that can go wrong)

- You can tell a lot about a language by looking at the binding times

Outline

- The classical sequence
- Variations on the classical sequence
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- Runtime support

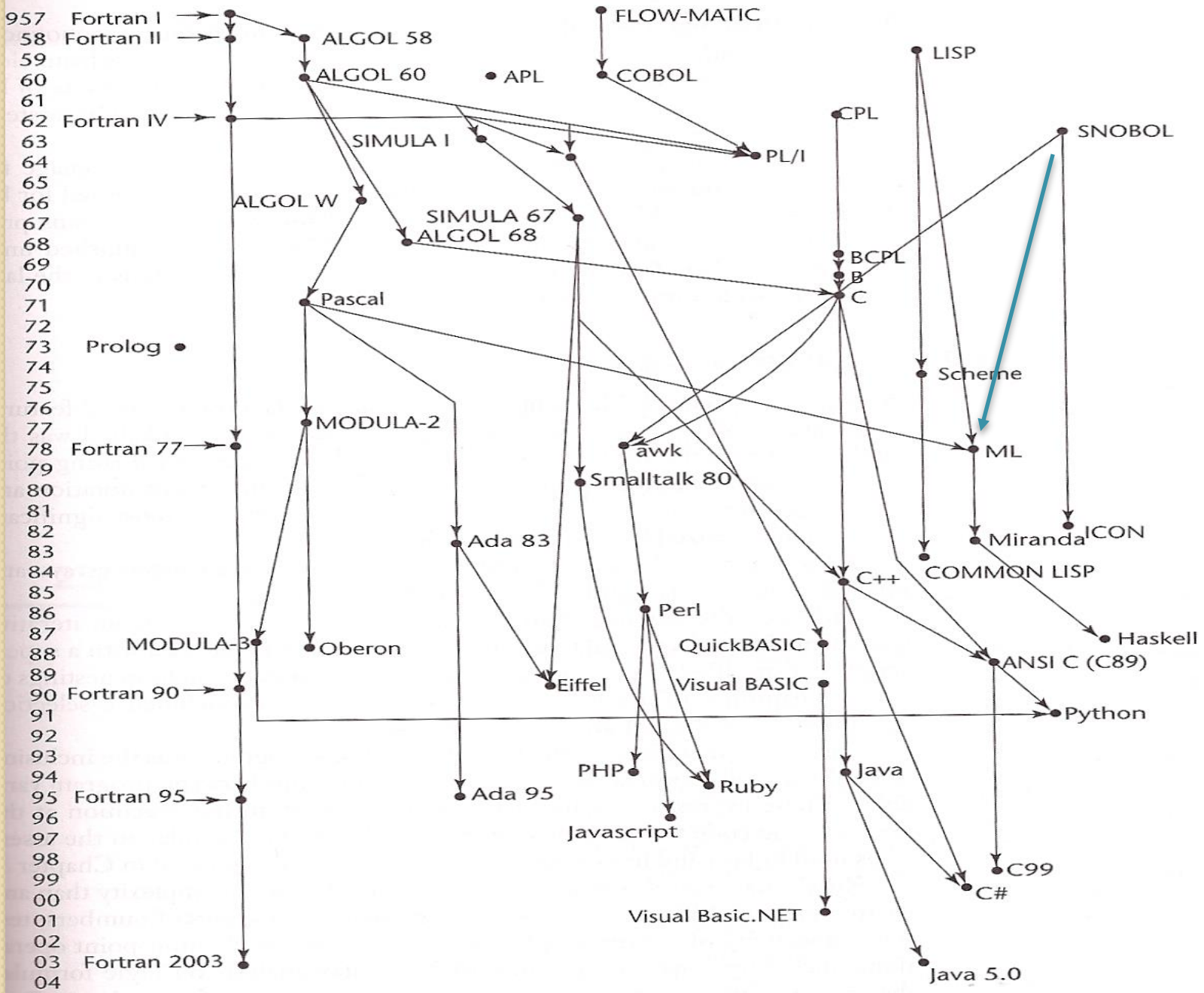
Runtime Support

- Additional code the linker includes even if the program does not refer to it explicitly
  - *Startup processing*: initializing the program state, **argc/argv**
  - *Exception handling*: code that manages exception handlers
  - *Memory management*: allocating and deallocating dynamic memory (stack and heap), garbage collection
  - *Operating system interface*: communicating between running program and operating system for I/O, etc.

- An important *hidden player* in language systems

The History Of Programming Languages

CS 4450 – Chapter 24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Fortran IV
Fortran 77
Fortran 90
Fortran 95
Fortran 2003
ALGOL 58
ALGOL 60
ALGOL W
ALGOL 68
FLOW-MATIC
COBOL
APL
SIMULA I
SIMULA 67
PL/I
LISP
CPL
SNOBOL
BCPL
B
C
Pascal
Prolog
MODULA-2
MODULA-3
Oberon
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awk
Smalltalk 80
Ada 83
Ada 95
Miranda
ICON
COMMON LISP
C++
Haskell
Perl
QuickBASIC
Visual BASIC
Eiffel
ANSI C (C89)
Python
PHP
Ruby
Javascript
Java
C99
C#
Visual Basic.NET
Java 5.0

Fortran

Early 1950s

- The first high-level language
  - The first compiler and linker
- Introduced *scanning*, *parsing*, *register allocation*, *code generation*, and *optimization*
- It is still heavily used in scientific computing
  - Massively parallel processing

Algol
1958–1960

- Introduced:
  - Blocks and static scoping
  - Free format lexical structure
    - Fortran statements started in column 7!
  - Static typing with explicit declarations
  - Nested if-then-else statements
  - Functions are first-class entities (parameters)
  - Operator overloading
- Imperative languages are called "Algol family languages"
  - Most languages are in this family

Lisp
1960

- The first functional programming language
  - Still in use today
- Introduced *conditional expressions*, *recursion*, *dynamic memory* and *garbage collection*
- Influenced modern functional languages like **ML**, **Haskell**, **F#**, **Rust**

ML

1974

- Introduced:
  - Strong static typing
  - Type inference
  - Pattern matching
  - Modules
  - Exceptions
  - Parametric polymorphism (templates/generics)
  - User-defined algebraic types (unions)
- The basis for **Haskell, F#, Scala, Groovy, Rust**

The Rust Language

- From Mozilla
  - Creators of Javascript and Firefox
- A brilliant combination of the best of:
  - C++
  - Python
  - ML
  - Go
  - Lisp
- Faster and safer than C++
  - Only marginally faster, but *much* safer