

Create.

↓ editor

text file.

↓ compiler.

assembly language. { data  
instruction.

↓ Assembler

Text, name, (no memory) }  
(machine language) \* } object  
01111111001 } file.

↓ Linker. (e.g. subtring - fixed → collect from  
gather. library)  
link all files

Executable file.

↓ loader. → e.g. fixed, i → are allocated  
load on memory on memory.

Run -

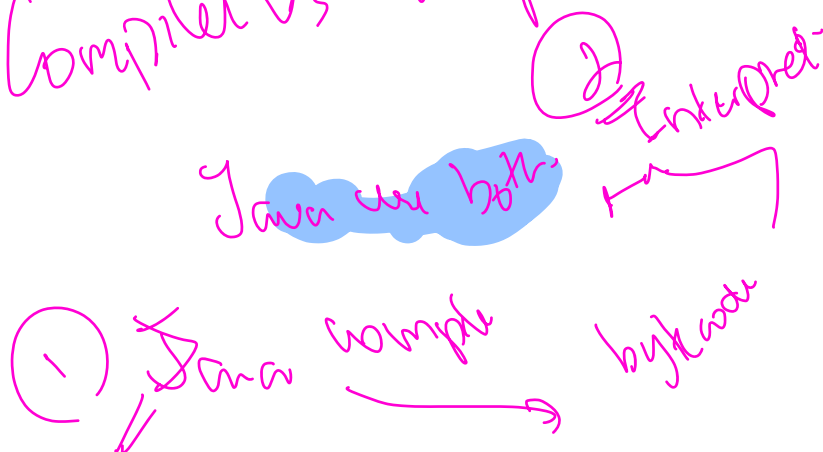
1/10

✓ Optimizer → faster  
→ more space.

loop invariant move!!

✓ In past → run all sequence by human.  
now not necessary → hide the  
sequences.

✓ Compiler vs Interpreter.



VIM

JAVA

write once → use anywhere.

↓  
with JVM.

Virtual machine

More info:

C#

VB

PHP

or Net

→ VM.

Binding

# Language Systems

# Outline

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

# 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 **fred** 100 times, passing each **i** from 1 to 100:

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

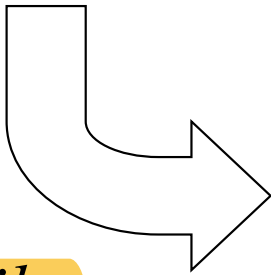


# Compiling

- ❑ 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

```
int i;  
void 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 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

```

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

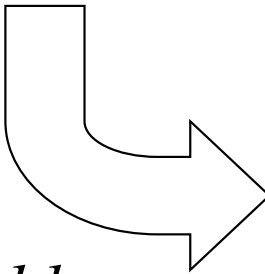
```

i: 

0
---

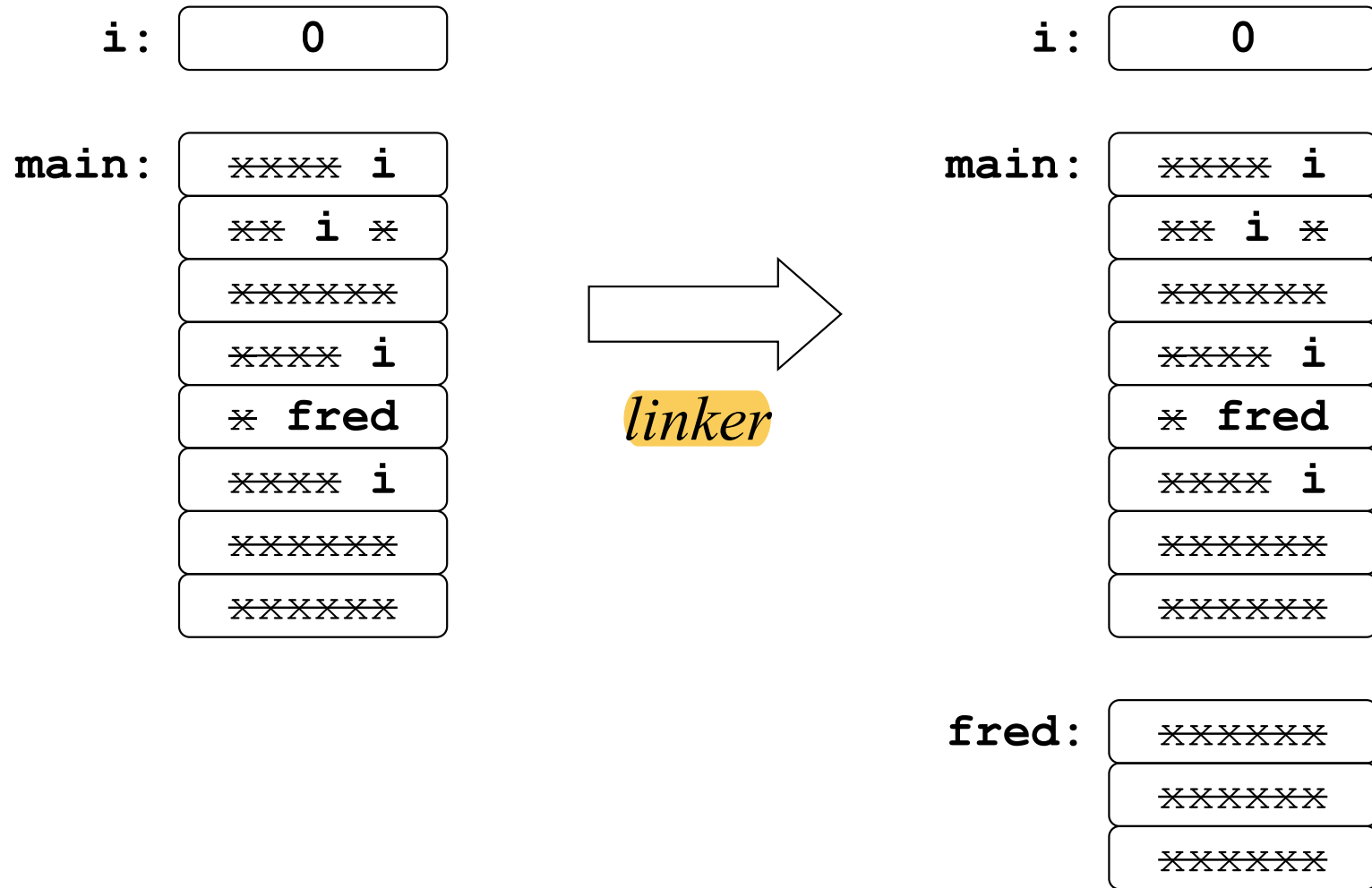
main: 

xxxxx i
xx i x
xxxxxxx
xxxxx i
x fred
xxxxx i
xxxxxxx
xxxxxxx

  
*assembler*

# 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



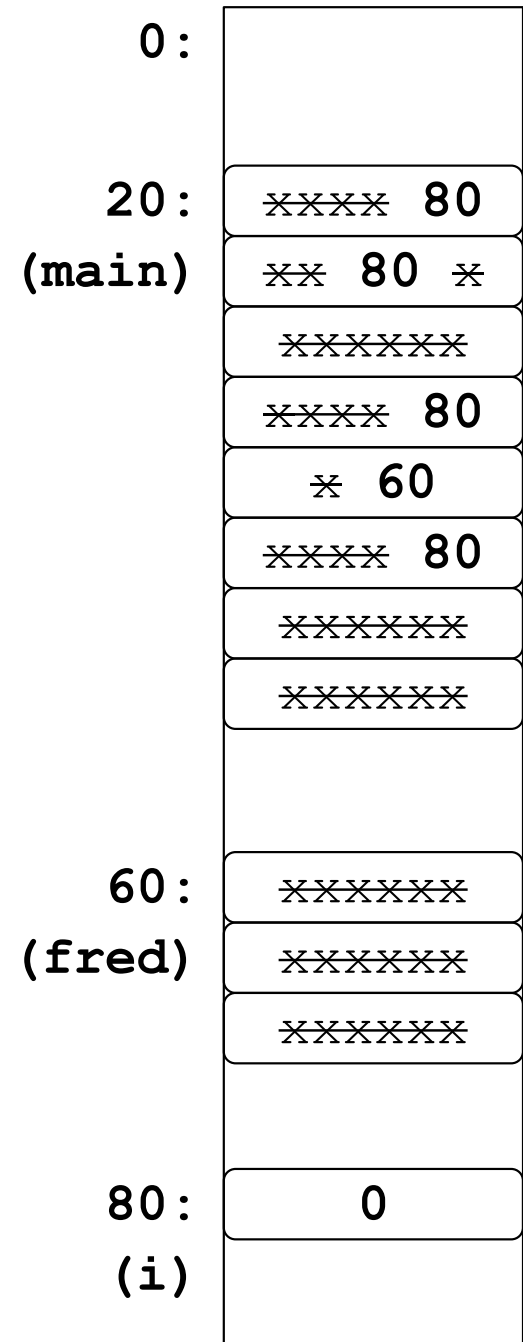
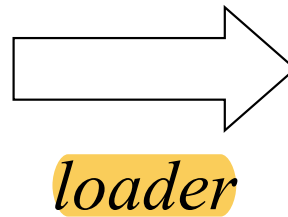
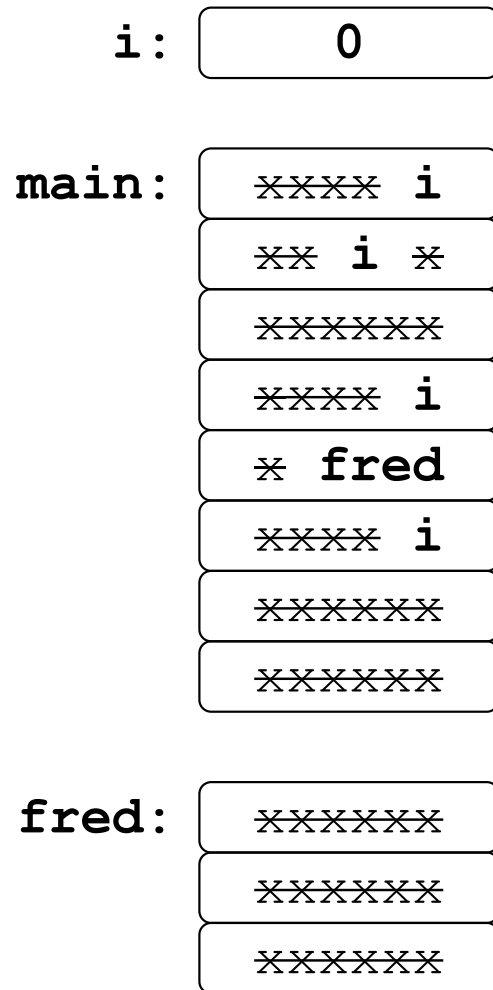
# Loading

- “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**

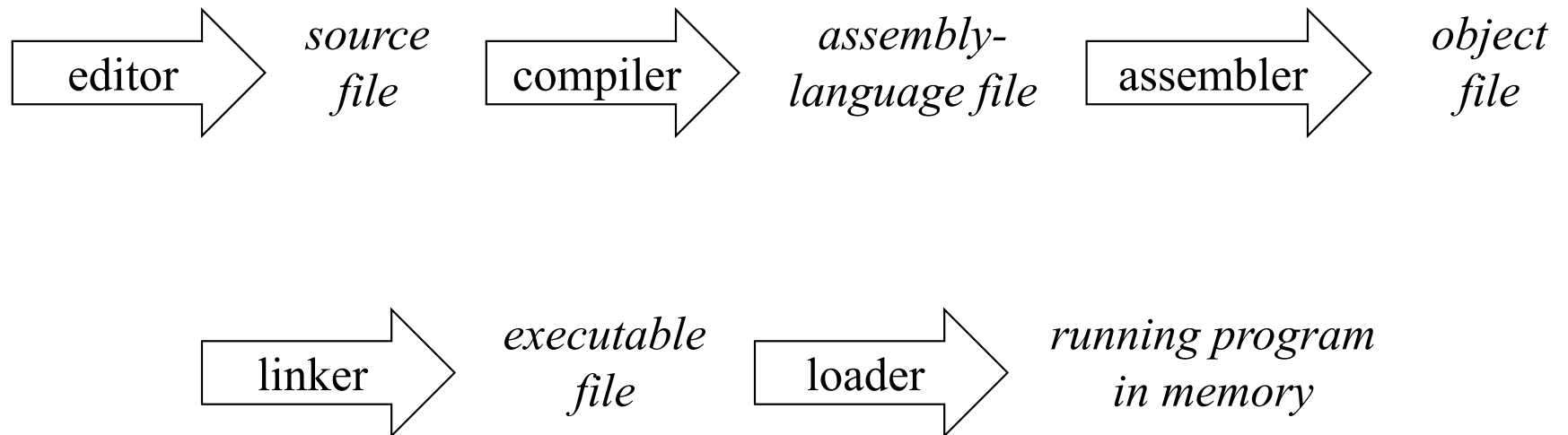




# Running

- 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



# 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

# Example

- 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;
}
```

# Example

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

# 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

# Outline

- The classical sequence
- **Variations on the classical sequence**
- Binding times
- Debuggers
- 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*

# Compiling to Object Code

- Many modern compilers incorporate all the functionality of an **assembler**
- They generate object code directly

# 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 in a minute...)

# 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 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 better code**

# 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**

# Outline

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



# Binding

- Binding means associating two things—especially, 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**?

```
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.

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

Java int → 4 bytes.



# Language Implementation Time

by compiler.

- 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

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

In Fortran  $i$  is always integer.

$i \rightarrow \text{type.}$

# 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)

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

happens at compile time.

↓  
if interpreter

↓  
runtime bind.

link all objects  linker - executable file.

# Link Time

we don't know the memory address yet.

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

✓ know the type: not memory address.

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

# Load Time

*p → Memory address*

- 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

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

# Run Time

int  $i = 10$   $\Rightarrow$  value  
↑  
bind occurs in runtime

- 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*)

static                      dynamic  
(before)                      (late) (runtime)



# 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

# Outline

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

# 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

# Outline

- The classical sequence
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# 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

# Conclusion

- Language systems implement languages
- Today: a quick introduction
- More implementation issues later, especially:
  - Chapter 12: memory locations for variables
  - Chapter 14: memory management
  - Chapter 18: parameters
  - Chapter 21: cost models