CSE 390B, 2024 Winter

Building Academic Success Through Bottom-Up Computing

Debugging Strategies & Code Generation

Strategies for Debugging Software, Compilers: Code Generation, Two-Tier Compilation

UNIVERSITY of WASHINGTON

Lecture Outline

- **Strategies for Debugging Software**
  - **Debugging Process and The Scientific Method**
- Compilers: Code Generation
  - Generating Target Code from an AST
- Two-Tier Compilation
  - Intermediate Programs and The Java Virtual Machine (JVM)

Sources and Acknowledgements

- This is a subset and an adaptation of a CSE 331 lecture
- If you have taken CSE 331, you have seen this before
  - Part of your task for Project 8
  - This subject is closely connected to metacognition
- If you haven’t taken CSE 331, this is a helpful sneak peek
  - Debugging is an important topic in many CSE courses
- Acknowledgements: CSE 331 instructors, notably Michael D. Ernst, Hal Perkins, and more

Debugging Pre-discussion

- How often do you run into bugs when writing programs?

- What is your debugging process?
  - In other words, when you run into a bug, do you have strategies that you consistently use to find it?
  - For those who have taken 331, maybe think back to before you had the debugging lecture

- What debugging strategies have you come across?

A Bug's Life

- Software bug definitions:
  - Defect – mistake committed by a human
  - Error – incorrect computation
  - Failure – visible error: program violates its specification
- Debugging starts when a failure is observed
  - During testing
  - In the field
- Goal is to go from failure back to defect

Testing Versus Debugging

- Testing ≠ debugging
  - Test: reveals existence of problem (failure)
  - Debug: pinpoint location + cause of problem (defect)

- See CSE 331 for:
  - How to write code that has fewer bugs (so less debugging)
  - How to write code that is easier to test (so easier to reveal bugs)
  - How to make testing easier (so you do it more often)
  - How to write code that is easier to debug (so less time spent debugging)

- These are all incredibly valuable engineering skills

Last (Inevitable) Resort: Debugging

- Defects happen, people are imperfect
  - Industry average: 10 defects per 1000 lines of code(?)
- Defects happen that are not immediately localizable
  - Found during integration testing
  - Or reported by user
- Cost of an error increases by orders of magnitude during program lifecycle

Debugging Lifecycle

- Step 1: Clarify symptom (simplify input), create “minimal” test
- Step 2: Find and understand cause
- Step 3: Fix and understand why it works
- Step 4: Rerun all tests, old and new

The Debugging Process

- Step 1: Find small, repeatable test case that produces the failure
  - May take effort, but helps identify the defect and gives you a regression test
  - Do not start Step 2 until you have a simple repeatable test
- Step 2: Narrow down location and proximate cause
  - Loop: (a) Study the data (b) hypothesize (c) experiment
  - Experiments often involve changing the code
  - Do not start Step 3 until you understand the cause

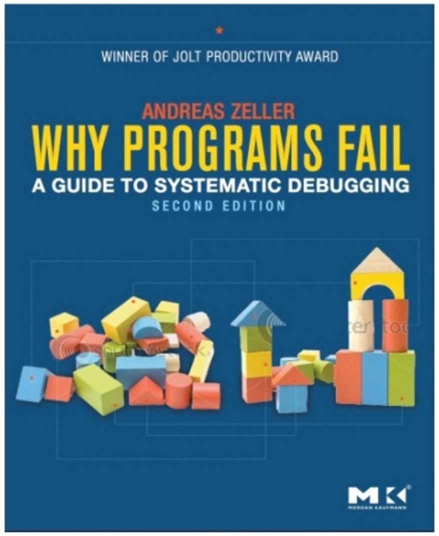
The Debugging Process

- Step 3: Fix the defect
  - Is it a simple typo, or a design flaw?
  - Does it occur elsewhere?

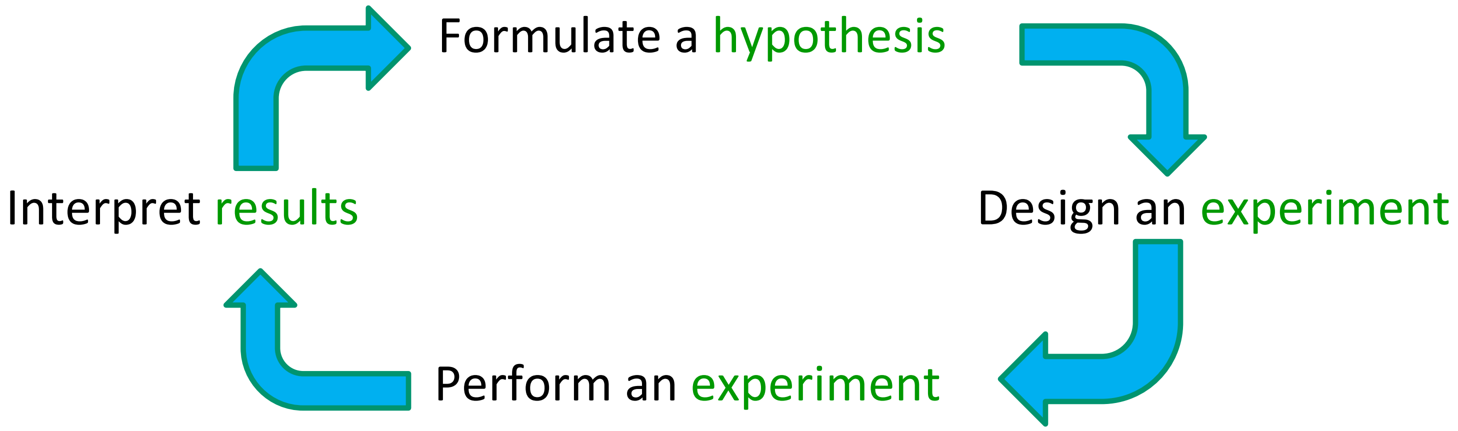
- Step 4: Add test case to regression suite
  - Is this failure fixed? Are any other new failures introduced?

Debugging and The Scientific Method

- Debugging should be systematic
  - Carefully decide what to do instead of flail
  - Keep a record of everything that you do
  - Don't get sucked into fruitless avenues


WINNER OF JOLT PRODUCTIVITY AWARD
ANDREAS ZELLER
WHY PROGRAMS FAIL
A GUIDE TO SYSTEMATIC DEBUGGING
SECOND EDITION
MK

- Use an iterative scientific process:



Debugging Example

```
// returns true iff sub is a substring of full
// (i.e., iff there exists A,B such that full=A+sub+B)
boolean contains(String full, String sub);
```

- User bug report: Cannot find string "**`very happy`**" in:

  `"Fáilte, you are very welcome! Hi Seán! I am very very happy to see you all."`

- Poor responses:
  - Notice accented characters, panic about not knowing about Unicode, begin unorganized web searches and inserting poorly understood library calls, etc.
  - Start tracing the execution of this example
- Better response: simplify or clarify the symptom

Reducing Absolute Input Size

- Find a simple test case by divide-and-conquer

- Pare test down:

```
Cannot find "very happy" within
   "Fáilte, you are very welcome! Hi Seán! I am
   very very     happy to see you all.”
    "I am very very happy to see you all.”
    "very very happy"
Can find "very happy" within
      "very happy"
Cannot find "ab" within "aab"
```

Reducing Relative Input Size

- Can you find two almost identical test cases where one gives the correct answer and the other does not?

```
Cannot find "very happy" within
      "I am very very happy to see you all."

Can find "very happy" within
      "I am very happy to see you all.”
```

General Strategy: Simplify

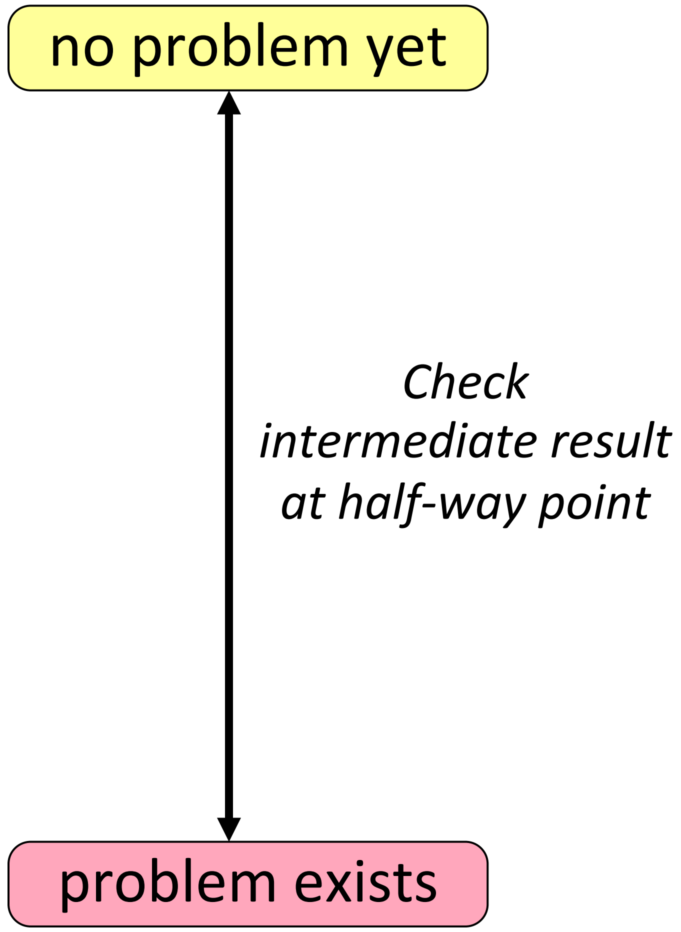
- In general: Find simplest input that will provoke failure
  - Usually not the input that revealed existence of the defect
- Start with data that revealed the defect
  - Keep paring it down ("binary search" can help)
  - Often leads directly to an understanding of the cause
- When not dealing with simple method calls:
  - The "test input" is the set of steps that reliably trigger the failure
  - Same basic idea

Localizing a Defect

- Take advantage of modularity
  - Start with everything, take away pieces until failure goes away
  - Start with nothing, add pieces back in until failure appears
- Take advantage of modular reasoning
  - Trace through program, viewing intermediate results
- Binary search speeds up the process
  - Error happens somewhere between first and last statement
  - Do binary search on that ordered set of statements

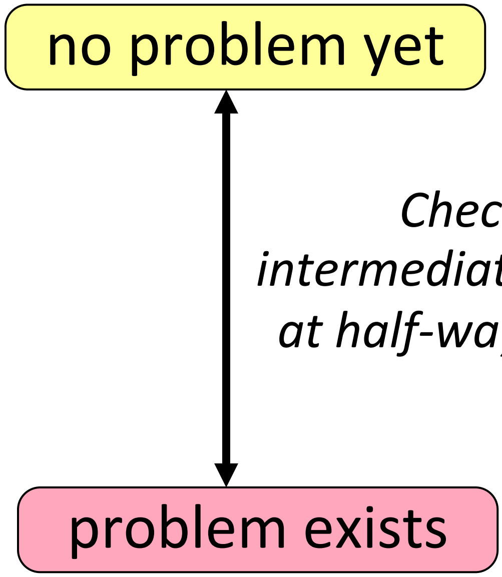
Binary Search on Buggy Code

```
public class MotionDetector {
    private boolean first = true;
    private Matrix prev = new Matrix();

    public Point apply(Matrix current) {
        if (first) {
            prev = current;
        }
        Matrix motion = new Matrix();
        getDifference(prev,current,motion);
        applyThreshold(motion,motion,10);
        labelImage(motion,motion);
        Hist hist = getHistogram(motion);
        int top = hist.getMostFrequent();
        applyThreshold(motion,motion,top,top);
        Point result = getCentroid(motion);
        prev.copy(current);
        return result;
    }
}
```



Binary Search on Buggy Code

```
public class MotionDetector {
    private boolean first = true;
    private Matrix prev = new Matrix();

    public Point apply(Matrix current) {
        if (first) {
            prev = current;
        }
        Matrix motion = new Matrix();
        getDifference(prev,current,motion);
        applyThreshold(motion,motion,10);
        labelImage(motion,motion);
        Hist hist = getHistogram(motion);
        int top = hist.getMostFrequent();
        applyThreshold(motion,motion,top,top);
        Point result = getCentroid(motion);
        prev.copy(current);
        return result;
    }
}
```



Check intermediate result at half-way point

Detecting Bugs in the Real World

- Real Systems
  - Large and complex
  - Collection of modules, written by multiple people
  - Complex input
  - Many external interactions
  - Nondeterministic
- Replication can be an issue
  - Infrequent failure
  - Instrumentation eliminates the failure
  - No printf or debugger
- Errors cross abstraction barriers
- Large time lag from corruption (error) to detection (failure)

Heisenbugs

- In a sequential, deterministic program, failure is repeatable
- But the real world is not that nice…
  - Continuous input/environment changes
  - Timing dependencies
  - Concurrency and parallelism
- Failure occurs randomly
  - Depends on results of random-number generation
  - Hash tables behave differently when program is rerun
- Bugs hard to reproduce when:
  - Use of debugger or assertions makes failure goes away
    - Due to timing or assertions having side-effects
  - Only happens when under heavy load and once in a while

Logging Events

- Log (record) events during execution as program runs (at full speed)

- Examine logs to help reconstruct the past
  - Particularly on failing runs
  - And/or compare failing and non-failing runs

- But don’t spend too much time manually reading enormous, confusing logs

More Tricks for Hard Bugs

- Rebuild system from scratch, or restart / reboot
  - Find the bug in your build system or persistent data structures
- Explain the problem to a friend (or to a rubber duck)
- Make sure it is a bug
  - Program may be working correctly and you don’t realize it
- Face reality
  - Debug reality (actual evidence), not what you think is true
- And things we already know:
  - Minimize input required to exercise bug (exhibit failure)
  - Add more checks to the program
  - Add more logging

Where is the Defect?

- The defect is not where you think it is
  - Ask yourself where it cannot be; explain why
  - Look forward and expect to be wrong
- Look for simple easy-to-overlook mistakes first, e.g.,
  - Reversed order of arguments
  - Spelling of identifiers
  - Same object vs. equal: a == b versus a.equals(b)
  - Uninitialized data / variables
  - Deep vs. shallow copy
- Make sure that you have correct source code!
  - Check out fresh copy from repository; recompile everything
  - Does a syntax error break the build? (it should!)

When Debugging Gets Tough

- Reconsider assumptions
  - Debug the code, not the comments
    - Ensure that comments and specs describe the code
- Start documenting your system
  - Gives a fresh angle, and highlights area of confusion
- Ask for help
  - We all develop blind spots
  - Explaining the problem often helps (even to rubber duck)
- Walk away
  - Trade latency for efficiency – sleep!
  - One good reason to start early

Key Debugging Concepts

- Testing and debugging are different
  - Testing reveals existence of failures
  - Debugging pinpoints location of defects
- Debugging should be a systematic process
  - Use the scientific method
- Understand the source of defects
  - To find similar ones and prevent them in the future
- Learn from the debugging process
  - It’s inevitable and you have some control over how you approach the frustration

Lecture Outline

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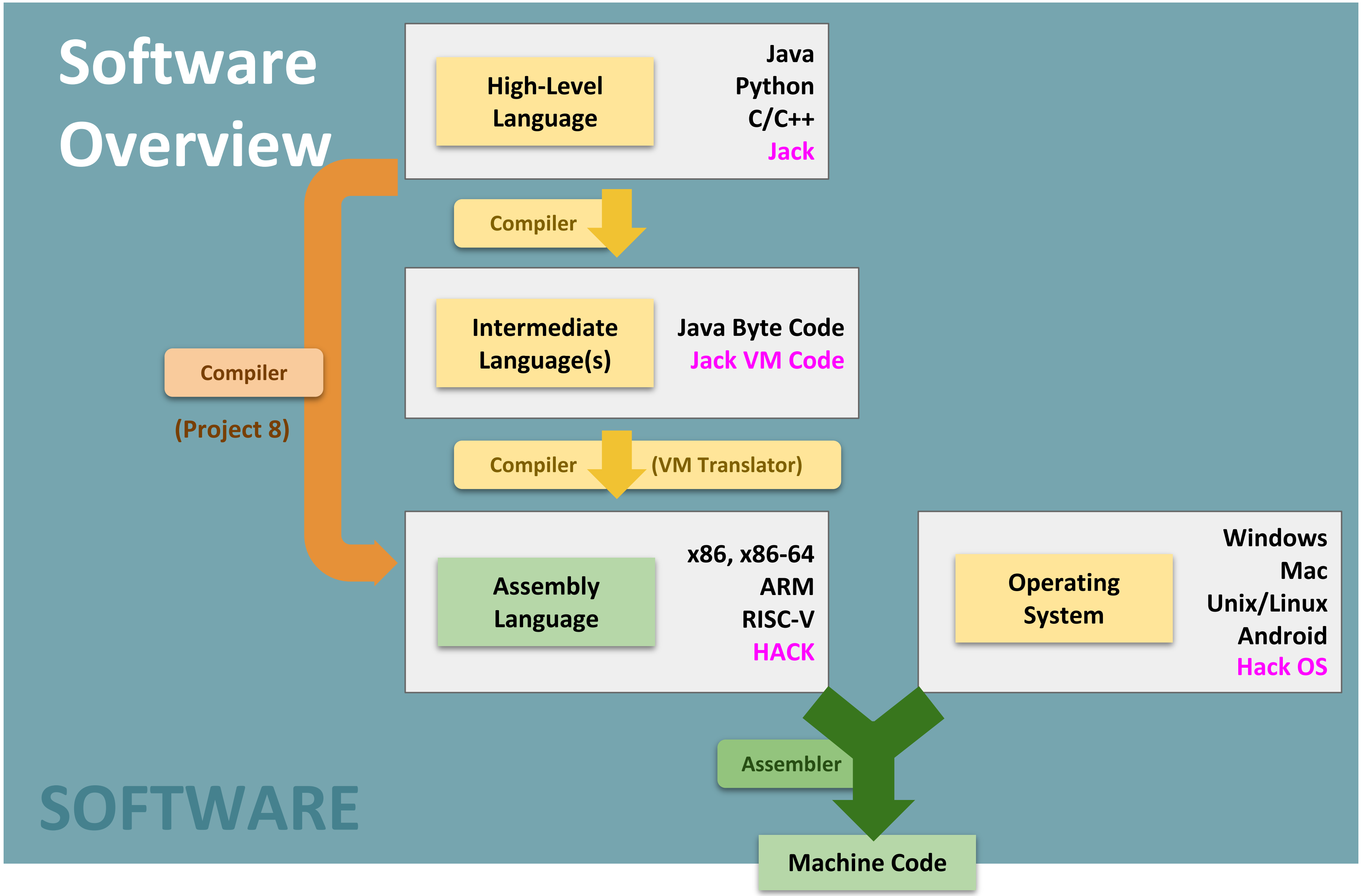
Software Overview



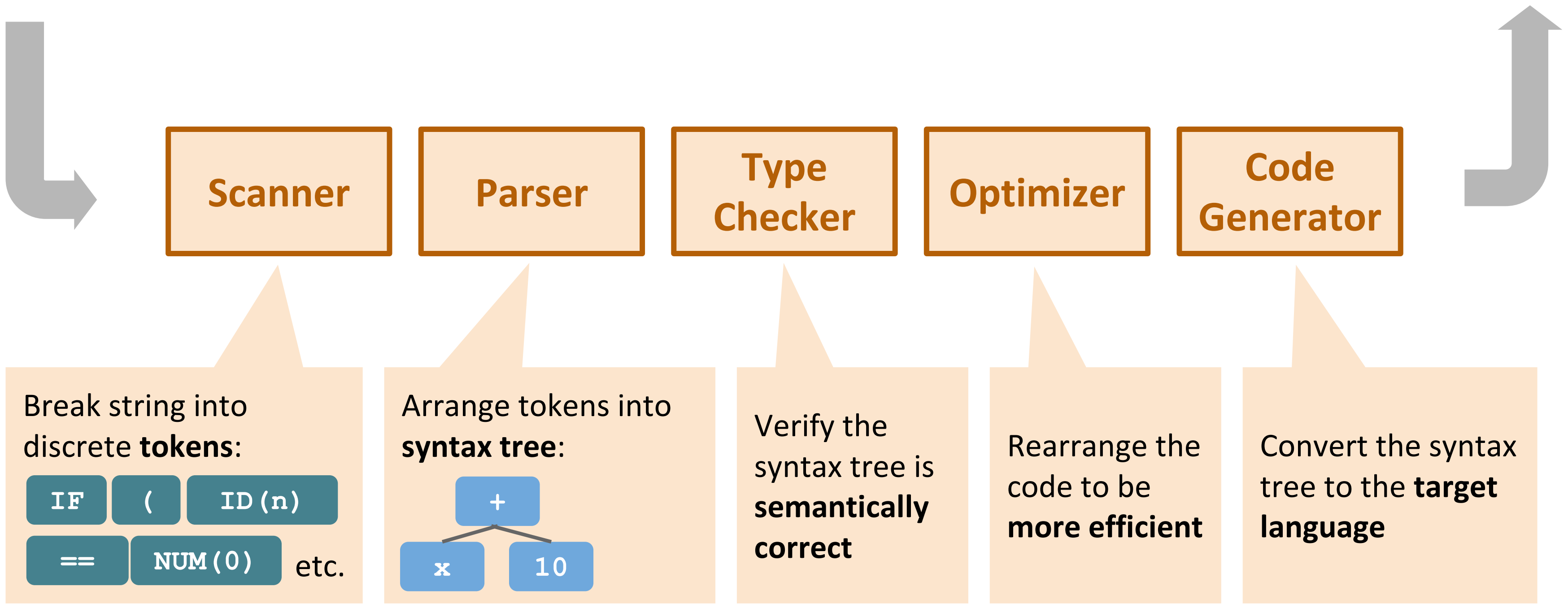
The Compiler: Implementation

```
public int fact(int n) {
  if (n == 0) {
    return 1;
  } else {
    return n * fact(n - 1);
  }
}
```

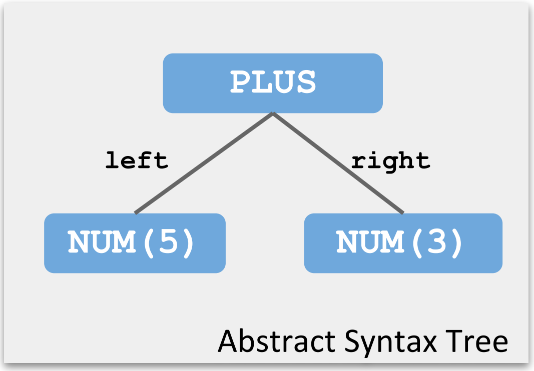
High-Level Language

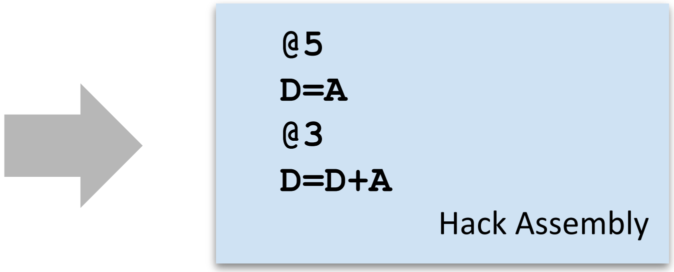
```
(fact)
  @R0
  M=M+1
  @R1
  D=A
  @ifbranch
  D;JEQ
```

Assembly Language


Scanner
Parser
Type Checker
Optimizer
Code Generator
Break string into discrete **tokens**:
IF
(
ID(n)
==
NUM(0)
etc.
Arrange tokens into **syntax tree**:
+
x
10
Verify the syntax tree is **semantically correct**
Rearrange the code to be **more efficient**
Convert the syntax tree to the **target language**

Code Generation: The Task

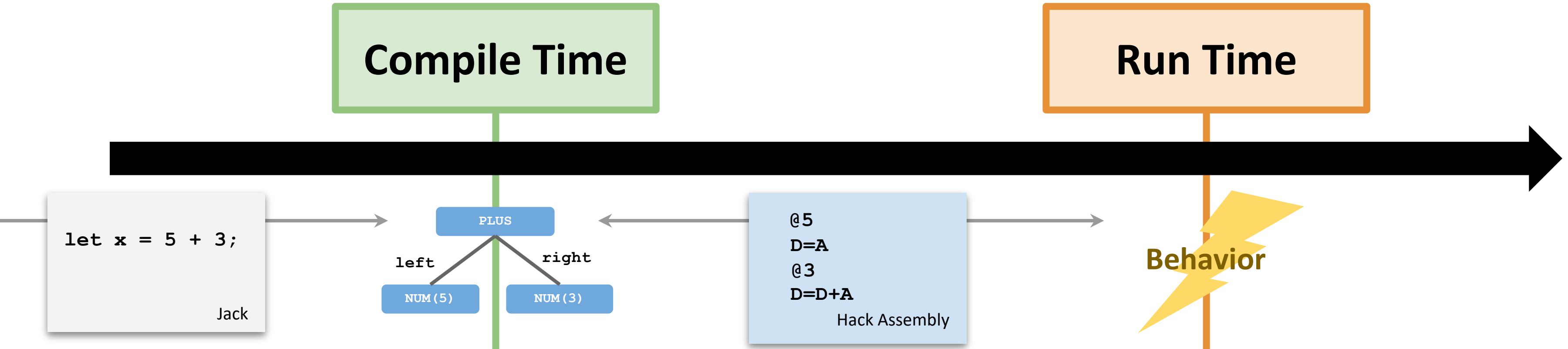




```
@5
D=A
@3
D=D+A
```

- Convert the AST into **target language code** that produces the same result
- Project 8 goal: Produce **reliable**, not efficient, compiler
- The tricky bit: Do it automatically for all possible arrangements of code
  - To stay sane, we'll break the task down: Generate code *for each node type* in the AST

Compile Time vs. Run Time



Compile Time

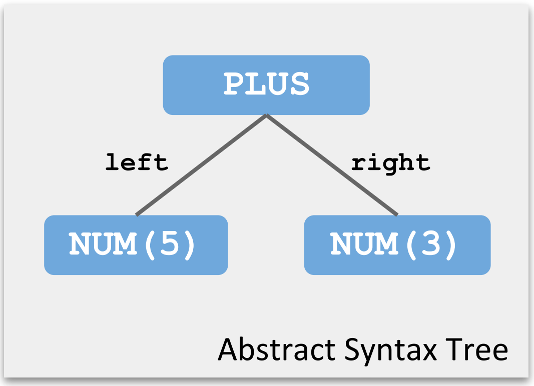
- Compiler (a Java program) is running
- Generates Hack instructions that will be run later
- Know *types* of variables, but NOT the *values* of variables or which *code path* is taken

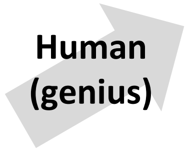
Run Time

- Output (a Hack program) is running on the Hack computer
- Know value of variables, which code path is taken

Code Generation: Example

- Here's how you, a brilliant human, would likely translate this syntax tree into Hack:





```
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@3
D=D+A
```

Hack Assembly

Code Generation: Example

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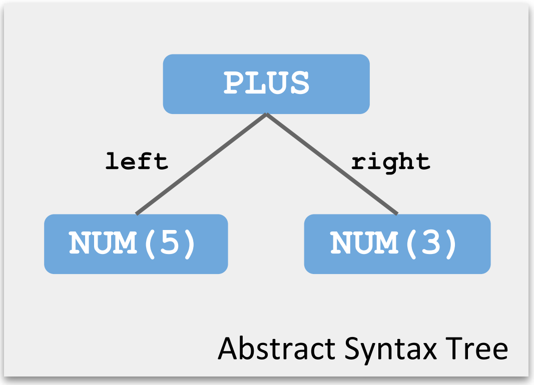


Human (genius)

```
@5
D=A
@3
D=D+A
```

Hack Assembly

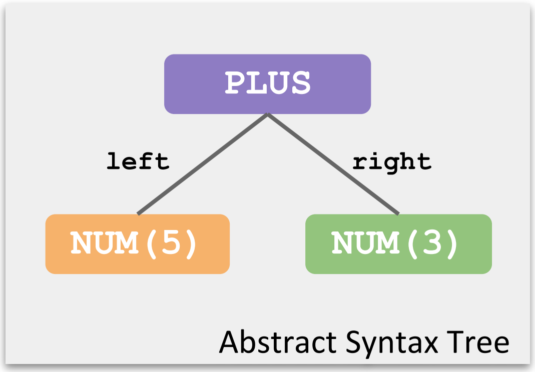
Computer (trying its best)

```
@5
D=A
@R0
M=D
// save R0 somehow

@3
D=A
@R0
M=D

@R0
D=M
// restore R0
@R0
MD=D+M
```

Hack Assembly

Code Generation: Example

- Why? Modularity: We can fit any expression in that slot, as long as **its result ends up in R0!**



Computer (actually, quite clever!)

NUM(2)

```
@5
D=A
@R0
M=D
```

```
// save R0 somehow
```

NUM(3)

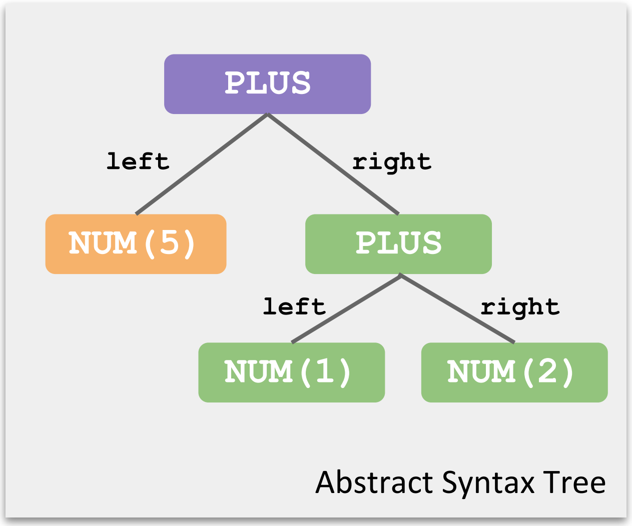
```
@3
D=A
@R0
M=D
```

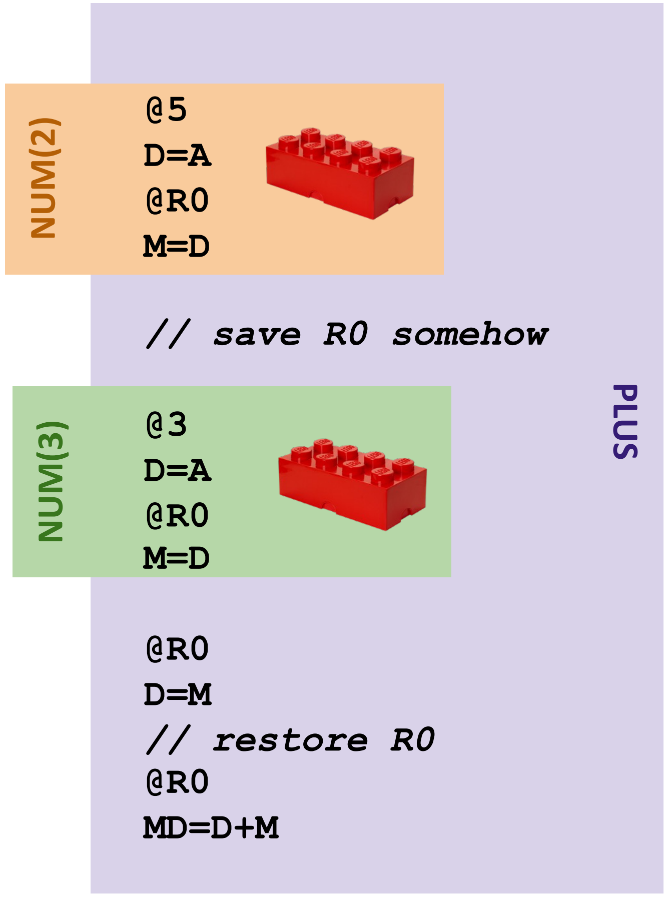
```
@R0
D=M
// restore R0
@R0
MD=D+M
```

PLUS

Code Generation: Example

- Why? Modularity: We can fit any expression in that slot, as long as **its result ends up in R0!**
  - Even another PLUS

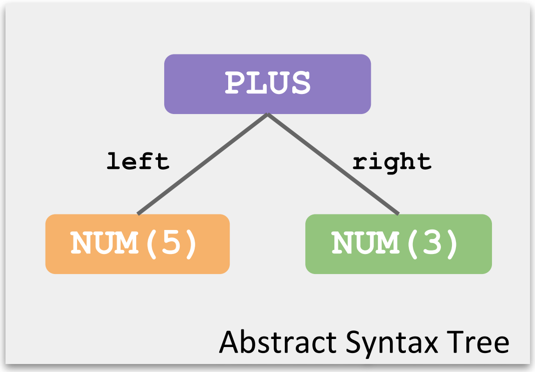


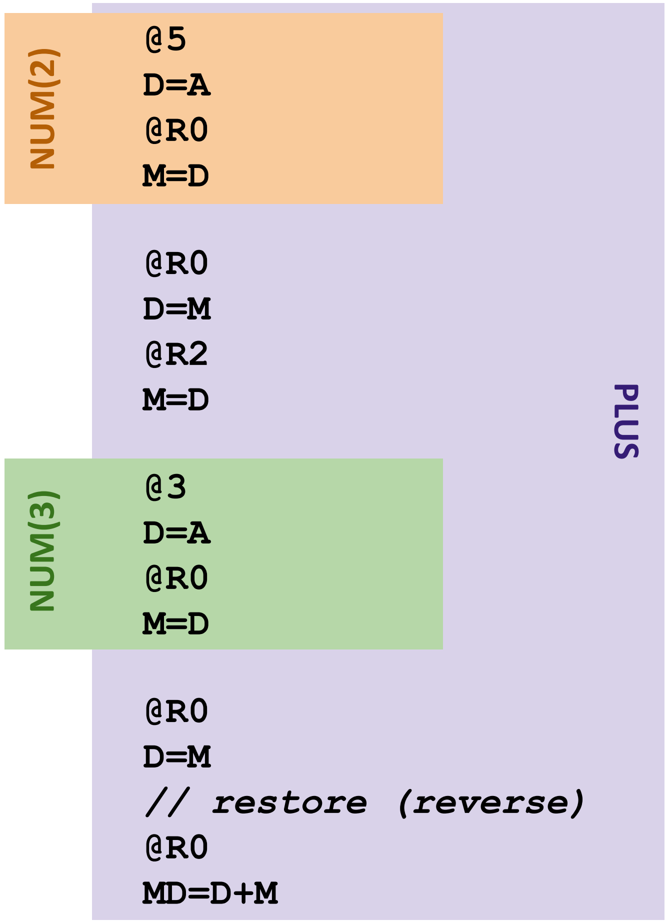


```
@5
D=A
@R0
M=D

// save R0 somehow

@3
D=A
@R0
M=D

@R0
D=M
// restore R0
@R0
MD=D+M
```

Code Generation: Example

- Now, we need to save R0 somehow
  - What if we save it in a temporary register? Let's pick R2

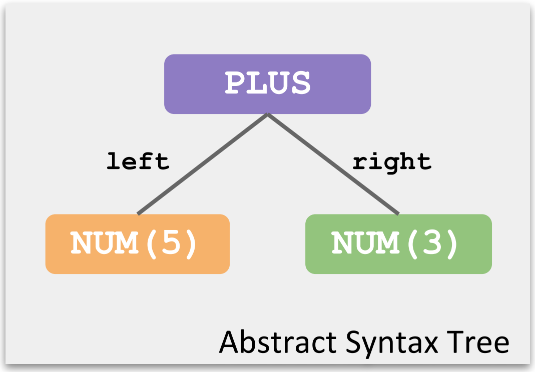




```
@5
D=A
@R0
M=D

@R0
D=M
@R2
M=D

@3
D=A
@R0
M=D

@R0
D=M
// restore (reverse)
@R0
MD=D+M
```

Code Generation: Example

- Now, we need to save R0 somehow
  - What if we save it in a temporary register? Let's pick R2

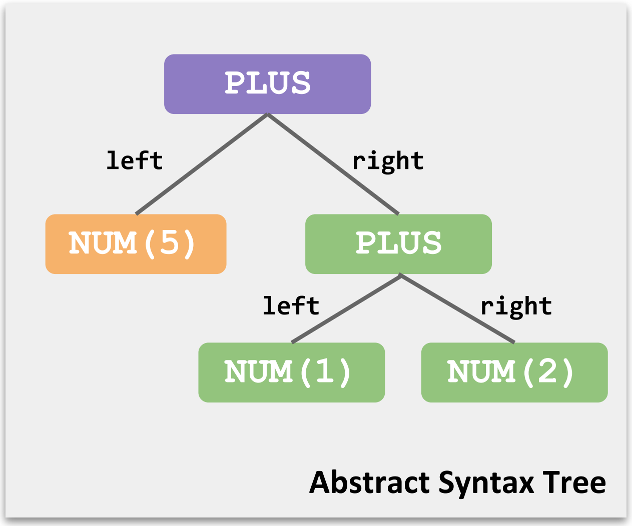


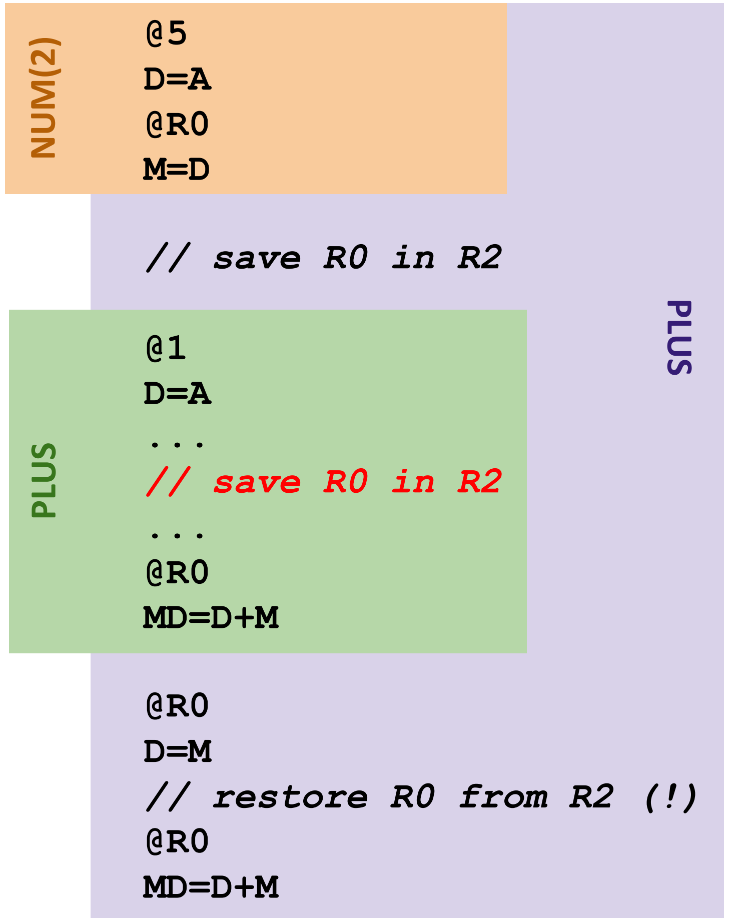
```
@5
D=A
@R0
M=D

@R0
D=M
@R2
M=D

@3
D=A
@R0
M=D

@R0
D=M
// restore (reverse)
@R0
MD=D+M
```

Why won't this always work?

Code Generation: Example

- It's those pesky nested expressions! The outer PLUS saves a value in R2, but the inner PLUS overwrites that value during its computation

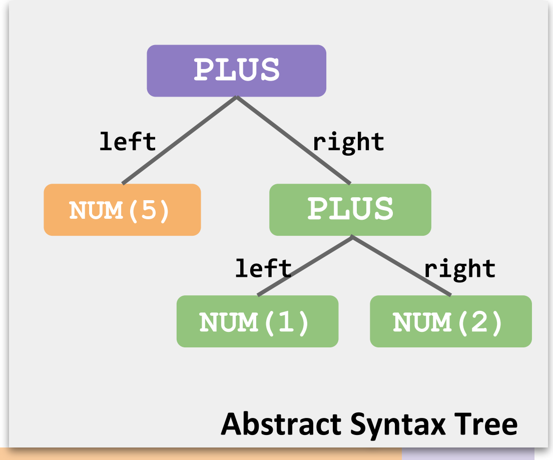




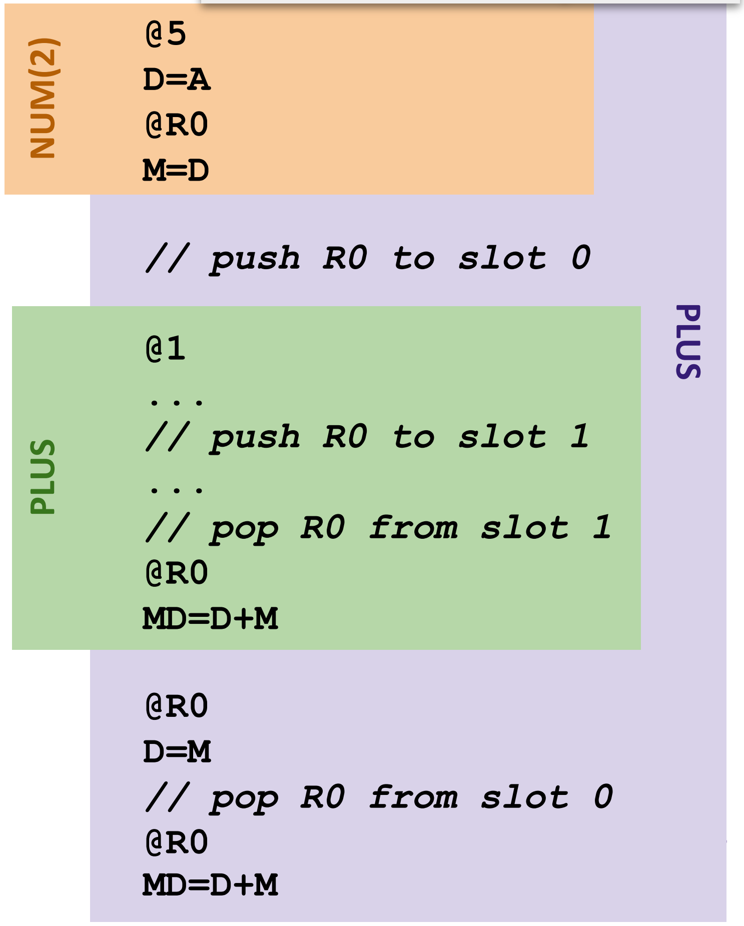
```
@5
D=A
@R0
M=D

// save R0 in R2

@1
D=A
...
// save R0 in R2
...
@R0
MD=D+M

@R0
D=M
// restore R0 from R2 (!)
@R0
MD=D+M
```

Code Generation: Example

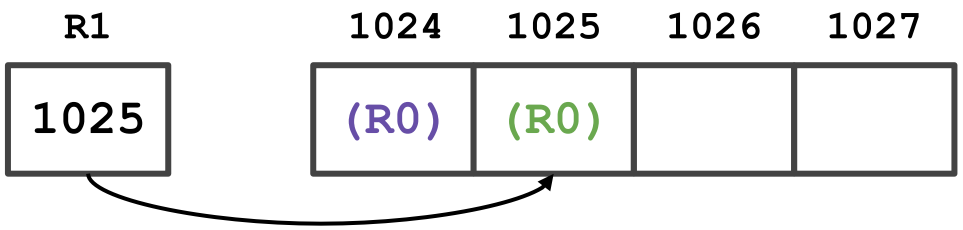
- Solution: Store "saved" values in a stack
  - Not quite the same as "The Stack" or function call stack frames (but used for a similar reason)
- We'll keep a stack starting at memory address 1024
  - R1 is our *stack pointer*: always stores address of last used stack position
  - No built-in Hack push: manually copy to memory and increment R1



Abstract Syntax Tree



```
@5
D=A
@R0
M=D

// push R0 to slot 0

@1
...
// push R0 to slot 1
...
// pop R0 from slot 1
@R0
MD=D+M

@R0
D=M
// pop R0 from slot 0
@R0
MD=D+M
```



Code Generation: Example

- What about variables?

```
var int arr[5];
var int bar, star;

let bar = star;
```

Jack

```
@261
D=M
@262
M=D
```

Hack Assembly

arr	256
bar	261
star	262
screen	16384

- Just like Assembler: Generate symbol table with mapping from variable names to spots in memory
  - Arrays get more (contiguous) spots
  - **`screen`** and **`keyboard`** are built-in array variables, allowing I/O

Code Generation: Takeaways

- Code Generation task: Writing several small snippets of Hack assembly
  - But need to be very generalizable
  - Whenever a PLUS expression is encountered, should generate almost the same code
- Conventions make the task much easier
  - For example, after any expression code runs, result should always be stored in R0
  - Then parent code can depend on it

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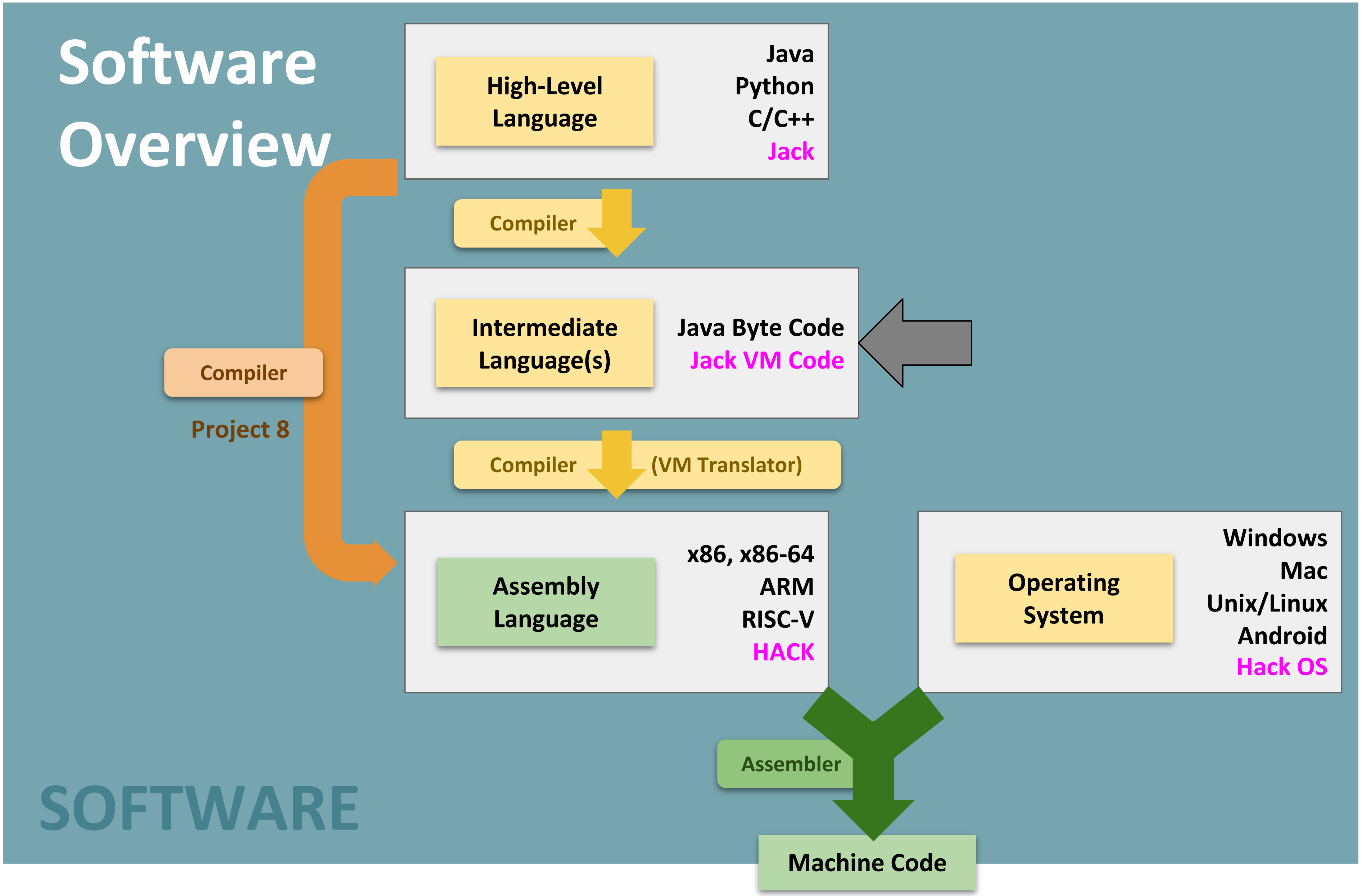
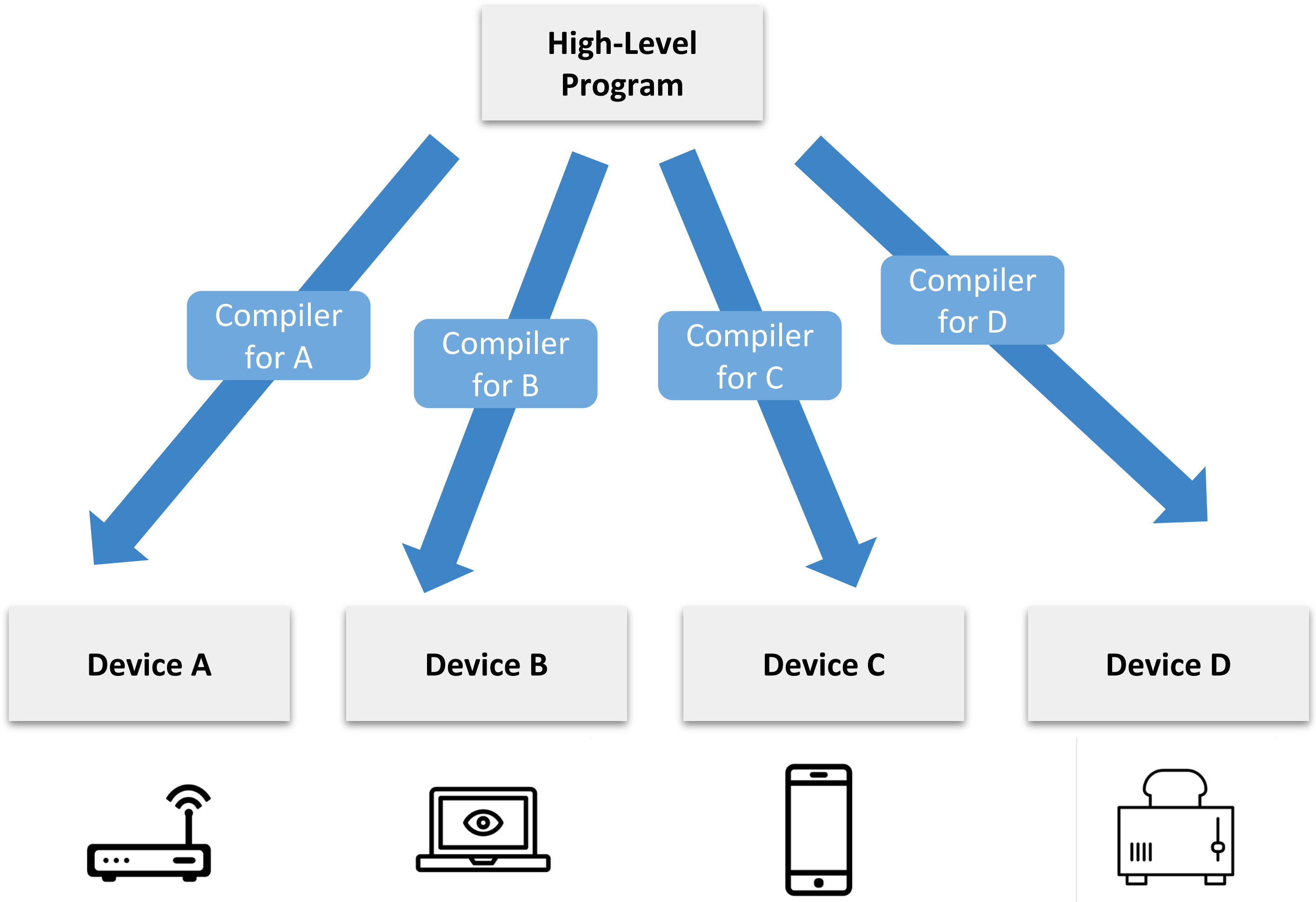
Software Overview

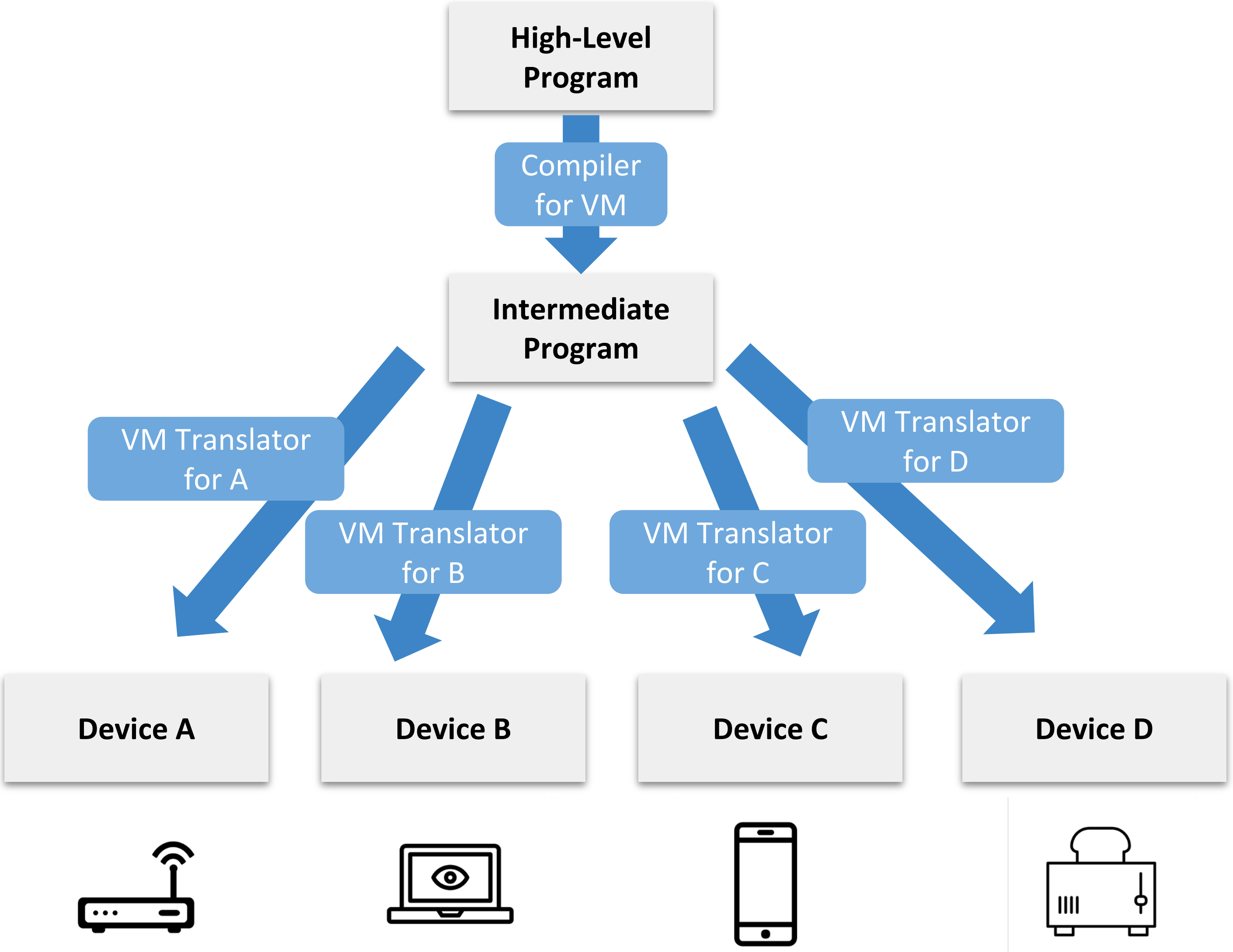


KEY: "Real-World" Examples
Our Computer

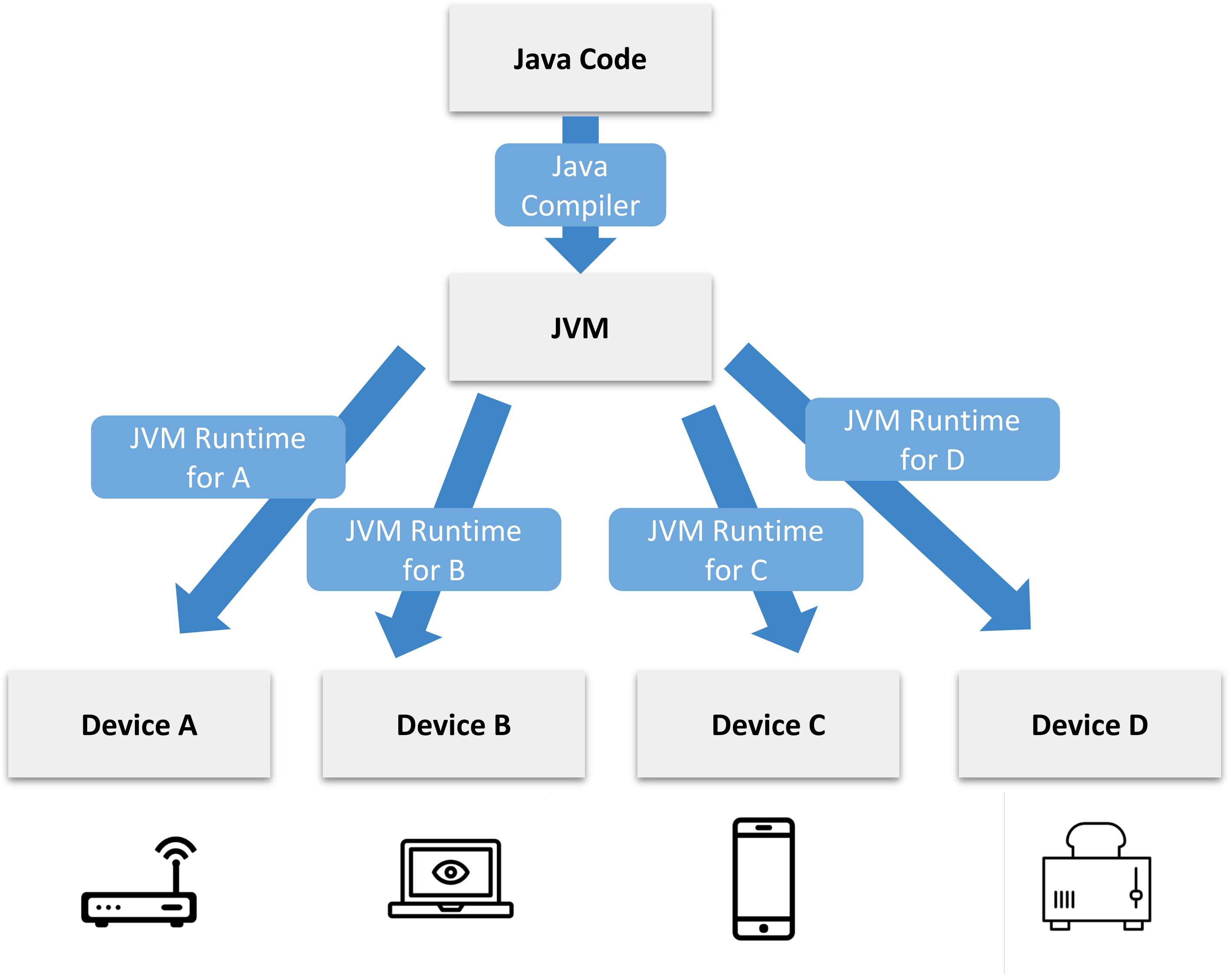
Compiling Code: Single Tier



Compiling Code: Two Tier



The Java Virtual Machine (JVM)



Lecture 15 Reminders

- Project Reminders
  - **Project 7, Part I (Midterm Corrections) due this Friday (2/23) at 11:59pm (no late days may be used)**
  - Project 7, Part II (Professor Meeting Report) due next Friday (3/1) at 11:59pm

- Amy has office hours tomorrow at 1:30pm in **CSE2 153**
  - Feel free to post your questions on the Ed board as well