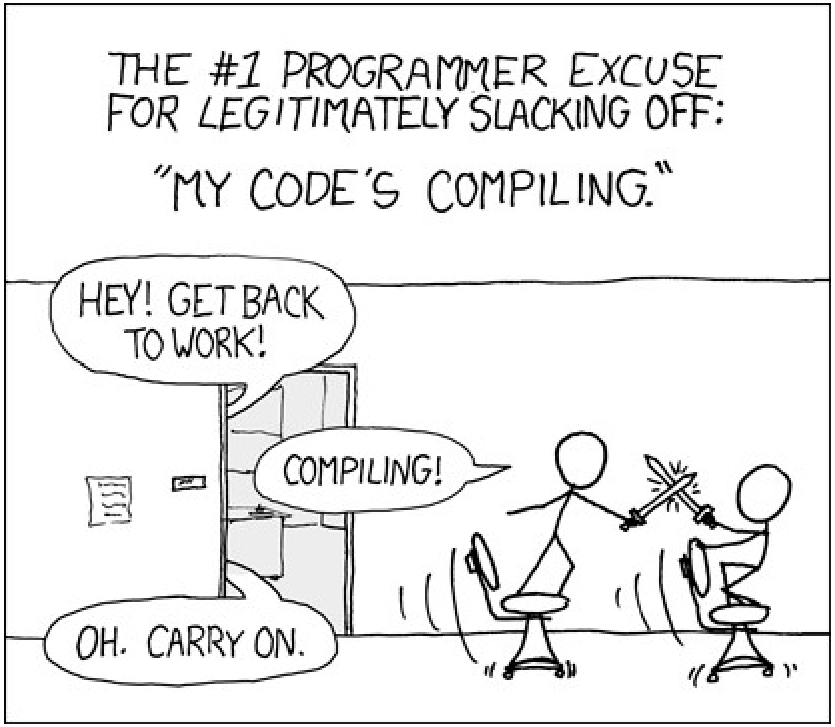
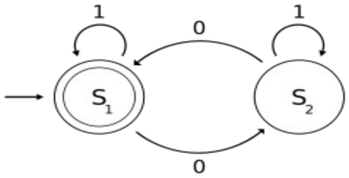
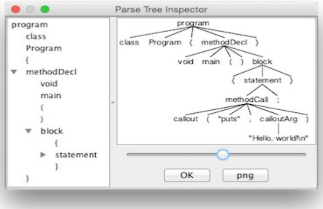
CS 432
Fall 2022

Mike Lam, Professor





Compilers



```
program
   class
   Program
   {
▼  methodDecl
      void
      main
      (
      )
▼     block
         {
▶        statement
         }
   }
```

Advanced Systems Elective

Discussion question

- What is a compiler?

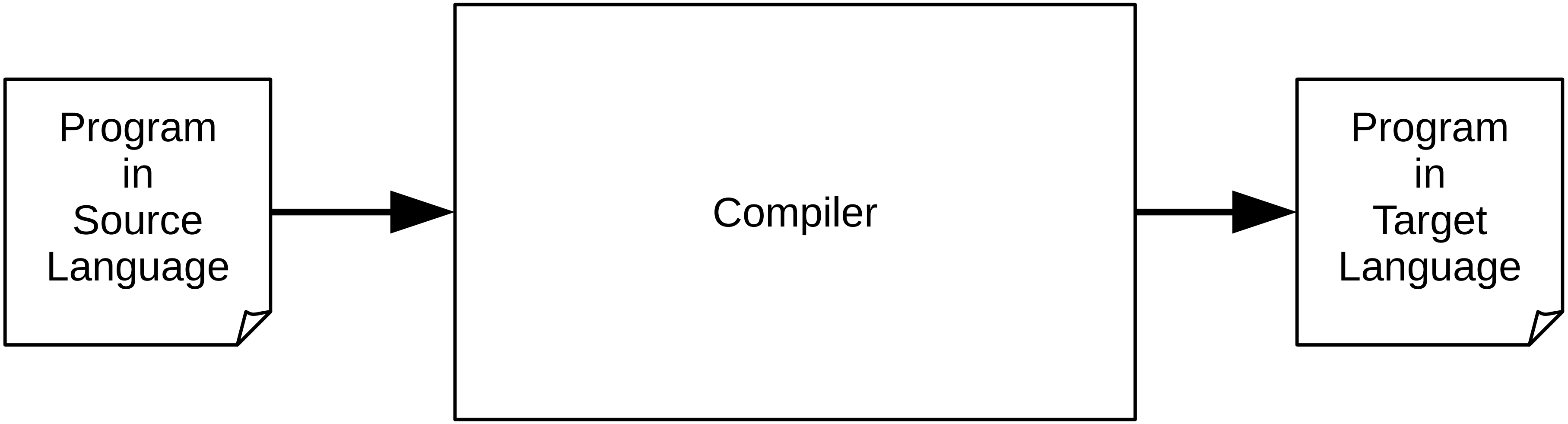
```
Error: obscure syntax mistake [main.cpp:375] !!!
```

“An angry translator.”

-- previous CS 432 student

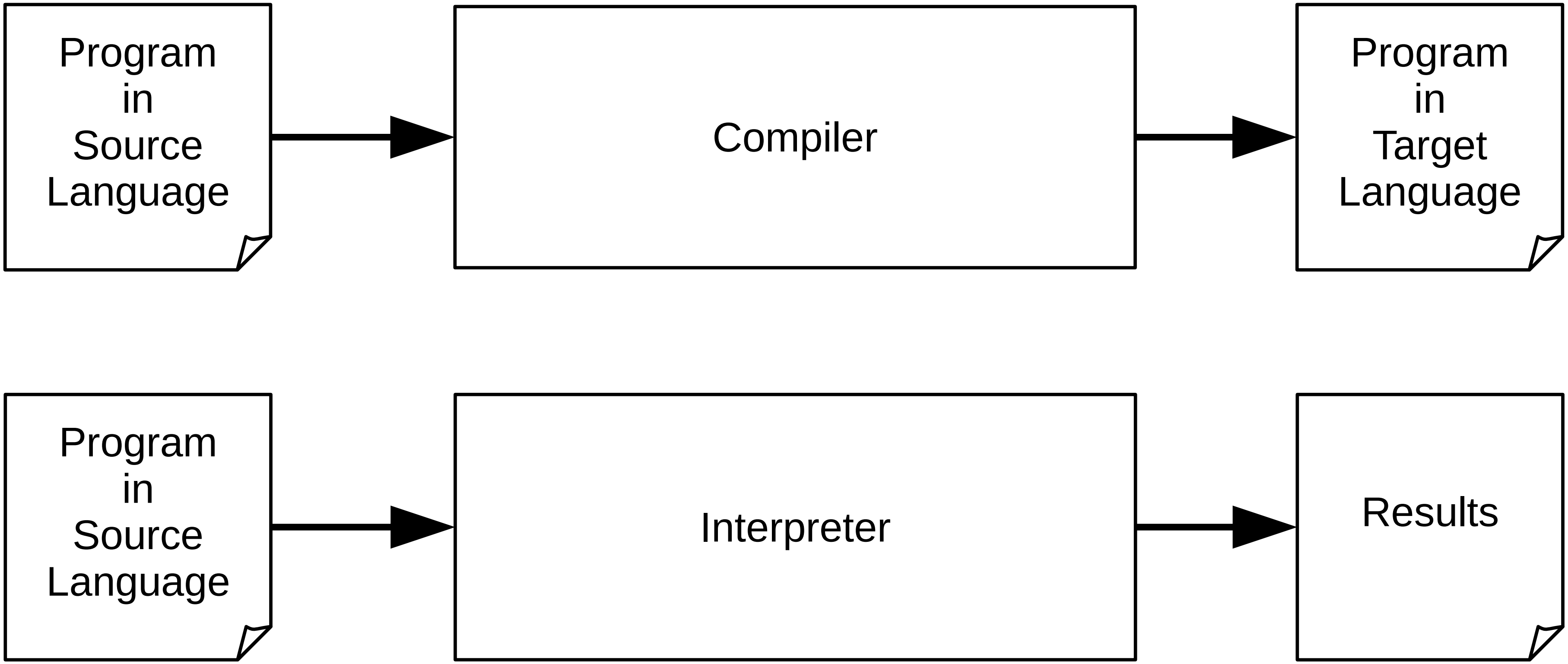
Automated translation

- A compiler is a computer program that **automatically translates** other programs from one language to another
  - (usually from a *human-readable* language to a *machine-executable* language, but not necessarily)



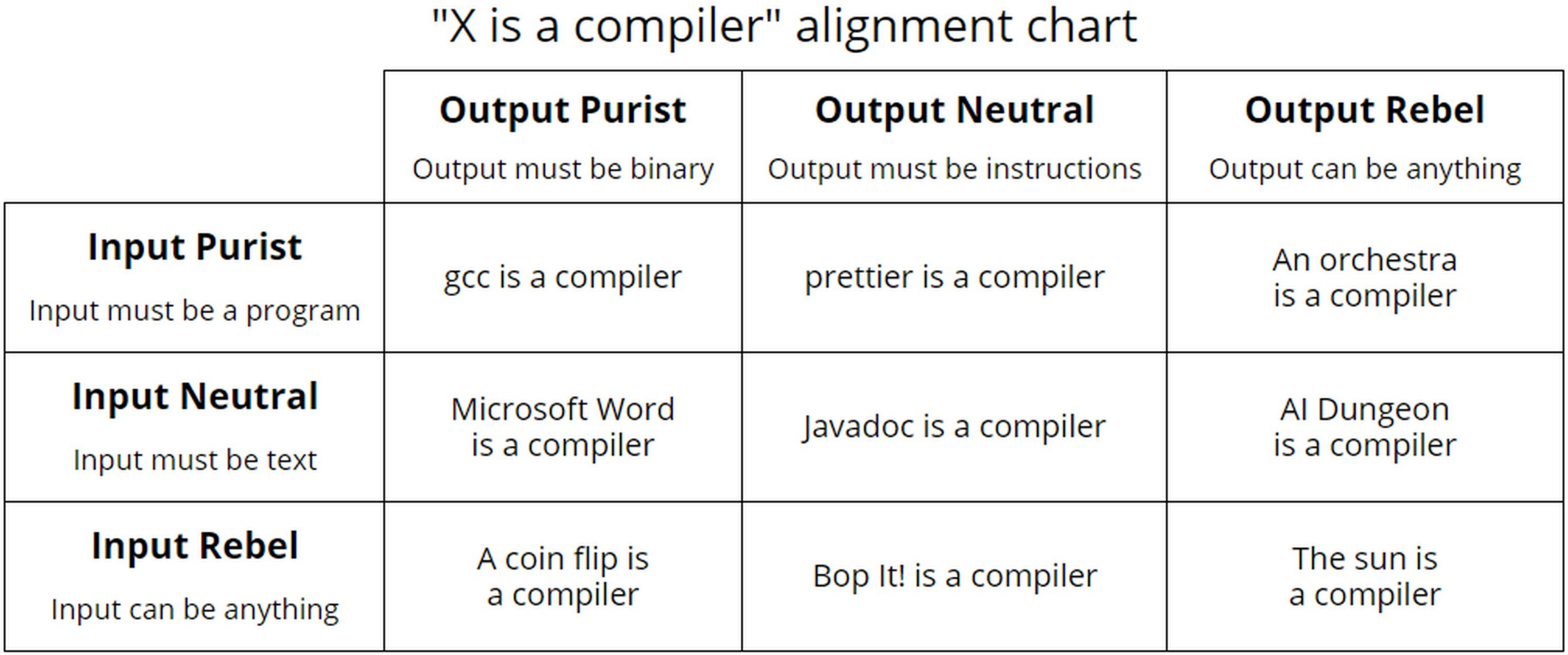
Automated translation

- Compilation vs. interpretation:



Program in Source Language
Compiler
Program in Target Language
Program in Source Language
Interpreter
Results

Aside: Definitions



"X is a compiler" alignment chart

	Output Purist Output must be binary	**Output Neutral** Output must be instructions	**Output Rebel** Output can be anything
Input Purist Input must be a program	gcc is a compiler	prettier is a compiler	An orchestra is a compiler
Input Neutral Input must be text	Microsoft Word is a compiler	Javadoc is a compiler	AI Dungeon is a compiler
Input Rebel Input can be anything	A coin flip is a compiler	Bop It! is a compiler	The sun is a compiler

Rhetorical question

- Why should we study compilers?
  - *(besides getting systems elective credit...)*

Compilers: a convergent topic

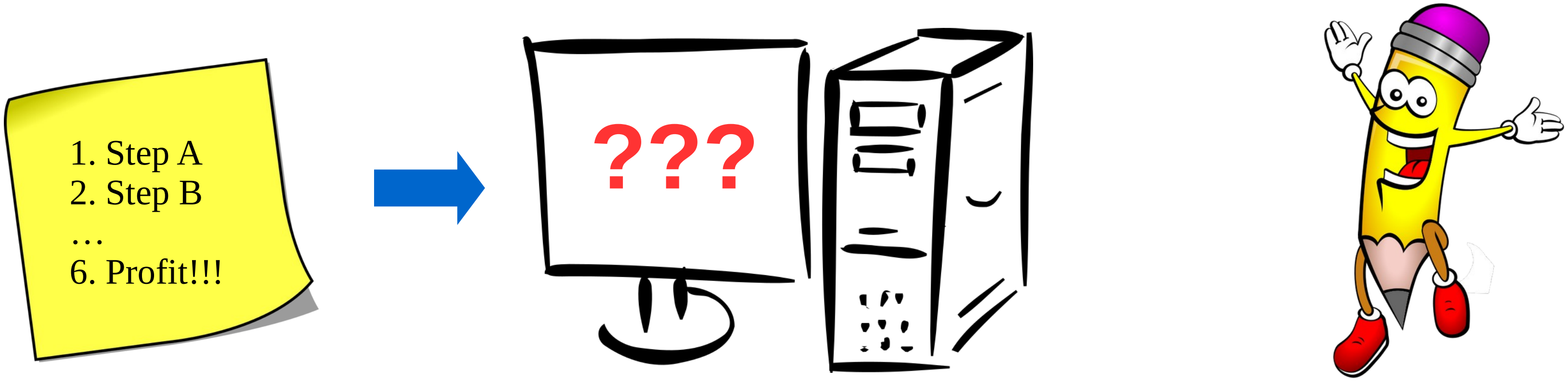
- Data structures
  - CS 240
- Architectures, machine languages, and operating systems
  - CS 261, CS 450
- Automata and language theory
  - CS 327, CS 430
- Graph algorithms
  - CS 327
- Software and systems engineering
  - CS 345, CS 361
- Greedy, heuristic, and fixed-point algorithms
  - CS 452

Reasons to study compilers

- Shows how many areas of CS can be combined to solve a truly "hard" problem (automated language translation)
- Bridges theory vs. implementation gap
  - Theory informs system development
  - We will never lose sight of our primary objective
- Practical experience with large(er) software systems
  - My master copy is over 4K LOC
  - Of this, you will re-write over 1K LOC this semester
  - Need to address software engineering concerns

Course goal

- Fundamental question
  - "How do compilers translate from a human-readable language to a machine-executable language?"
- After this course, your response should be:
  - "It's really cool! Let me tell you..."



1. Step A
2. Step B

…

6. Profit!!!

Course design

- First, a bit of course design theory ...

Course design theory

- Big ideas
  - E.g., "A compiler is a large software system consisting of a sequence of phases"
- Themes (stuff you should remember in five years)
  - E.g, "Large problems can sometimes be solved by composing existing solutions to smaller problems."
- Learning objectives (stuff you should remember at the end of the course)
  - E.g., "Identify the technical challenges of building a large software system such as a compiler."

- Activities and assignments flow from learning objectives
  - E.g., "Draw a diagram illustrating the major phases of a modern compiler."
- Exams reflect activities and assignments
- Goal: “engaged” and *effective* learning

Evolution of CS 432

- Fall 2015 - special topics (CS 480)
  - Adaptation of CS 630 (graduate course) taught in Spring 2015
- Fall 2016 - first time taught as CS 432
  - First time teaching CS 261 as well
- Fall 2017
  - Expanded test suite significantly, added type systems and lambda calculus
- Fall 2018
  - Added Y86 translator to “close the loop” with CS 261, removed lambda calculus
- Fall 2019 (two sections)
  - Removed reflection paper assignments, switched to Dragon book for LR parsing
- Fall 2020
  - Re-wrote entire project in C (w/ re-worked grading scheme), transitioned to take-home exams
- Fall 2021
  - Added hybrid virtual/in-person office hours
- Fall 2022
  - Official support for VS Code + Remote SSH development platform

Course objectives

- Identify and discuss the technical and social challenges of building a large software system such as a compiler.
- Develop and analyze formal descriptions of computer languages.
- Apply finite automata theory to build recognizers (lexers) for regular languages.
- Apply pushdown automata theory to build recognizers (parsers) for context-free languages.
- Evaluate the role of static analysis in automated program translation.
- Apply tree traversals to convert a syntax tree to low-level code.
- Discuss the limitations that an architecture or execution environment places on the generation of machine code.
- Describe common optimizations and evaluate the tradeoffs associated with good optimization.

BUILD

A

COMPILER

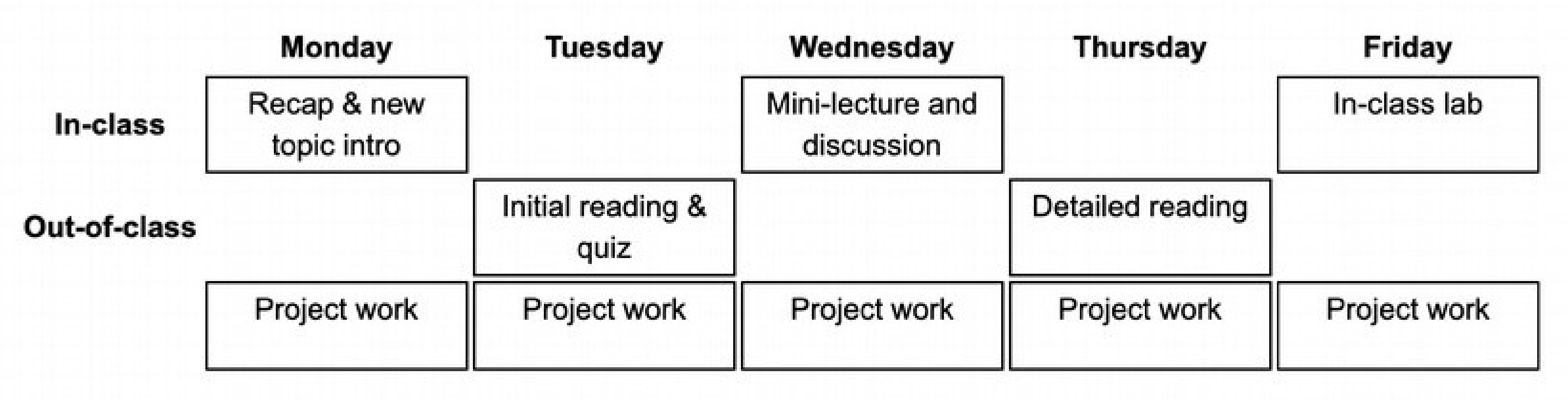
Semester-long project

- Compiler for "Decaf" language
  - Implementation in C11 w/ Makefile and integrated test suite
  - Compiles Decaf programs to ILOC & Y86
  - Five major projects: "pieces" of the full system
  - Primary grade based on functionality tiers (like in 261)

- Submission: code (90%) + review (8%) + response (2%)
  - Code can be written in teams of two
    - Benefits vs. costs of working in a team
  - Individual graded code reviews due a week later
  - Review responses (how did your reviewer do?)

Course format

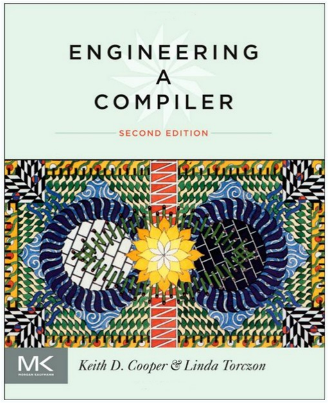
- Website: `https://w3.cs.jmu.edu/lam2mo/cs432/`
  - Make sure you’re using the right year’s website!
- Weekly schedule (roughly)



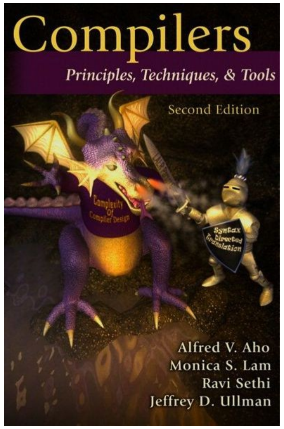
	Monday	Tuesday	Wednesday	Thursday	Friday
In-class	Recap & new topic intro		Mini-lecture and discussion		In-class lab
Out-of-class		Initial reading & quiz		Detailed reading	
	Project work	Project work	Project work	Project work	Project work

- *Formative* vs. *summative* assessment
  - Formative: quizzes and labs (~20% of final grade)
  - Summative: projects and exams (~80% of final grade)

Course text(s)



- **Engineering a Compiler, 2nd Edition**
  - Keith Cooper and Linda Torczon
  - 1st chapter scanned; posted under “Files” on Canvas
  - Reserve copy at Rose library



- **Compilers: Principles, Techniques, & Tools, 2nd Edition**
  - Alfred Aho, Monica Lam, Ravi Sethi, Jeffrey Ullman
  - “The Dragon Book” (premier text on compilers)
  - One section scanned; posted under “Files” on Canvas
- Decaf/ILOC references and type systems reading
  - PDFs on website
- Design patterns reading from GoF book
  - PDF on Canvas

Communication

- Email is always fine (lam2mo)
  - Response likely within a few hours, but no guarantees on weekends or on project deadlines
- Created a Discord server this semester (link in Canvas)
  - Might get a real-time response, maybe not
  - #general, #projects, and #off-topic channels
  - Keep it clean and positive
- Office hours 10-11am M-F (King Hall 227)
  - In person or virtual – link in Canvas
- Schedule appointments outside of office hours
  - Link in Canvas

Class Policies

- If you test positive for COVID-19 or are consistently coughing and/or sneezing, **please stay home**
  - Contact me ASAP regarding missed class
  - If you feel a bit ill but well enough to attend class (and are NOT consistently coughing and/or sneezing), please consider wearing a surgical or N95/KN95 mask to protect others
  - Feel free to wear a mask in class or office hours for any reason
- Feel free to bring laptops to class
  - Please do not cause distractions for others
- These policies may change
  - Changes will be announced via Canvas message

Course policies

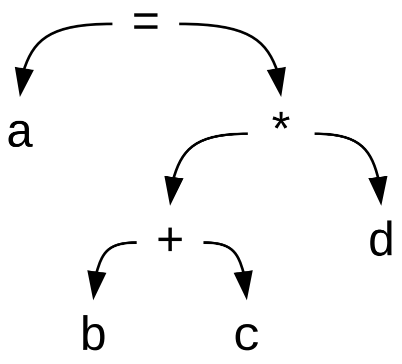
- Questions?

Compiler rule #1

- "The compiler must preserve the *meaning* of the program being compiled."
  - What is a program's *meaning*?

Intermediate representation

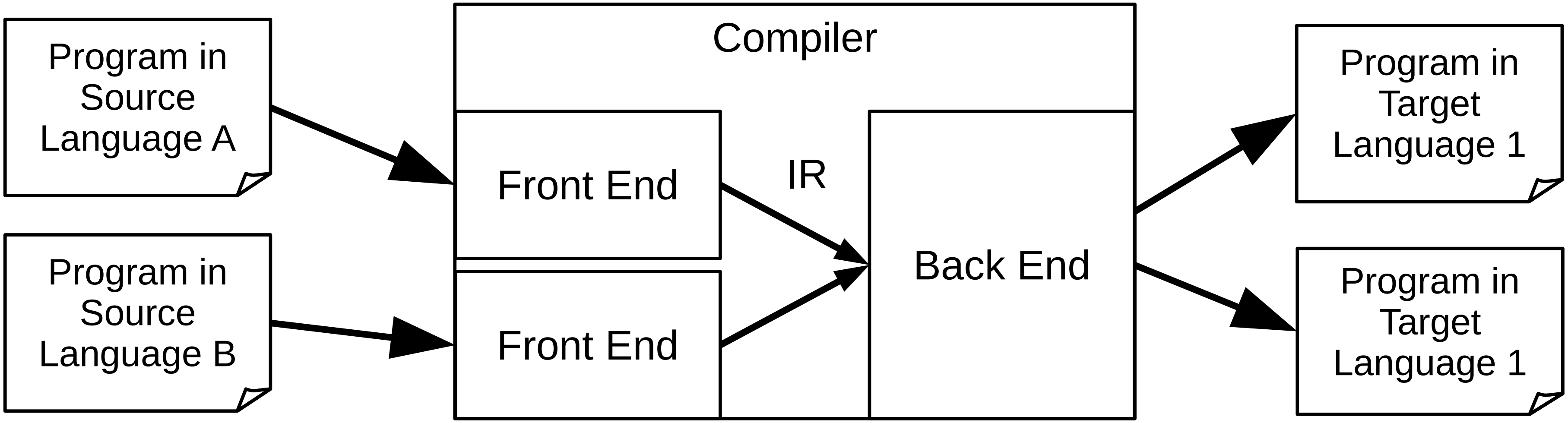
- Compilers encode a program's meaning using an intermediate representation (IR)
  - Tree- or graph-based: abstract syntax tree (AST), control flow graph (CFG)
  - Linear: register transfer language (RTL), Java bytecode, intermediate language for an optimizing compiler (ILOC)



```
load b → r1
load c → r2
add  r1, r2 → r3
load d → r4
mult r3, r4 → r5
store r5 → a
```

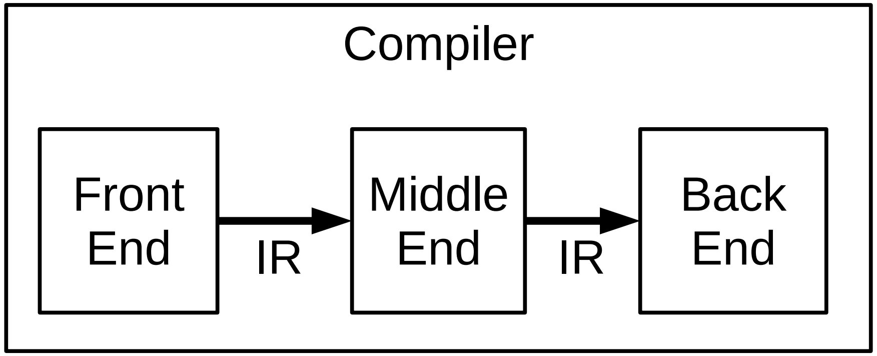
Standard compiler framework

- Front end: understand the program (src → IR)
- Back end: encode in target language (IR → targ)
- Primary benefit: easier *re-targeting* to different languages or architectures


Program in Source Language A
Program in Source Language B
Compiler
Front End
Front End
IR
Back End
Program in Target Language 1
Program in Target Language 1

Modern compiler framework

- Front-end passes
  - Scanning (lexical analysis
  - Parsing (syntactic analysis)
- Middle-end passes
  - Static/semantic analysis
  - IR code generation
  - IR optimization
- Back-end passes
  - Instruction selection
  - Machine code optimization
  - Register allocation
  - Instruction scheduling
  - Assembling/linking
- Modern approach: nanopasses
  - Dozens or hundreds of passes (`https://llvm.org/docs/Passes.html`)



Compiler

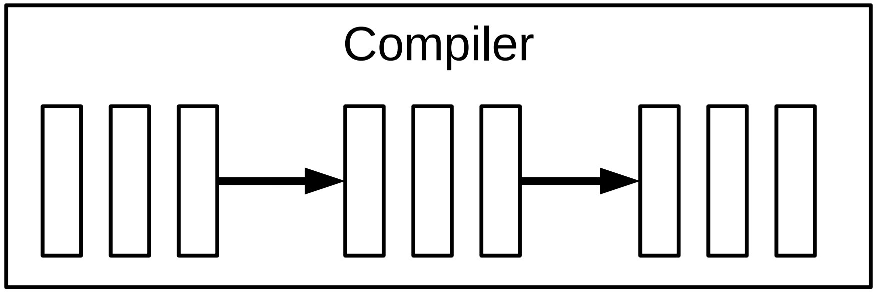
Front End

IR

Middle End

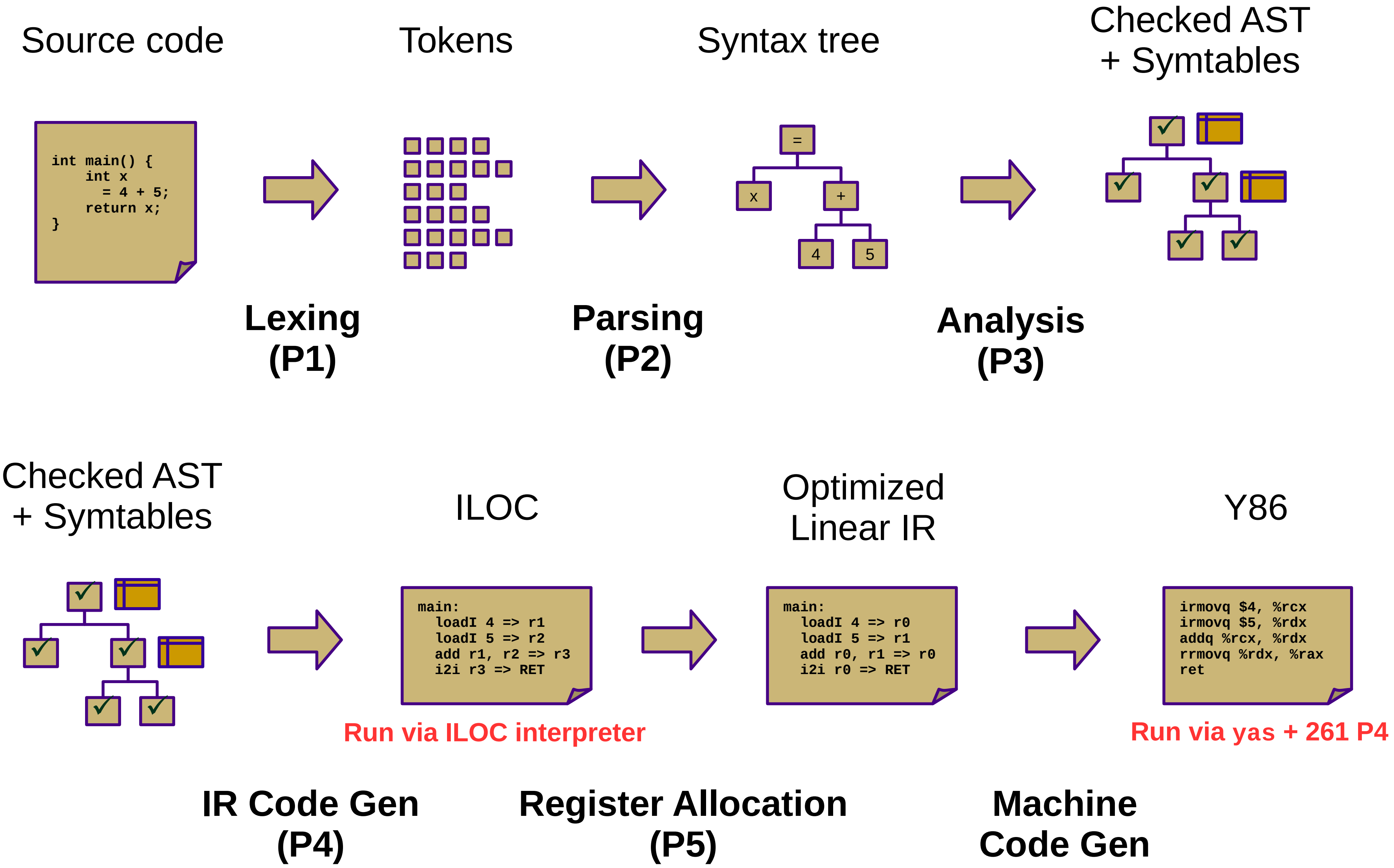
IR

Back End



Compiler

Our Decaf compiler



Source code

```
int main() {
    int x
      = 4 + 5;
    return x;
}
```

Lexing (P1)

Tokens

Parsing (P2)

Syntax tree

Analysis (P3)

Checked AST + Symtables

Checked AST + Symtables

IR Code Gen (P4)

ILOC

```
main:
  loadI 4 => r1
  loadI 5 => r2
  add r1, r2 => r3
  i2i r3 => RET
```

Run via ILOC interpreter

Register Allocation (P5)

Optimized Linear IR

```
main:
  loadI 4 => r0
  loadI 5 => r1
  add r0, r1 => r0
  i2i r0 => RET
```

Machine Code Gen

Y86

```
irmovq $4, %rcx
irmovq $5, %rdx
addq %rcx, %rdx
rrmovq %rdx, %rax
ret
```

Run via yas + 261 P4

Compiler rule #2

- The compiler should *help* the programmer in some way
  - What does *help* mean?

Discussion question

- What would be your design goals for a compiler?
  - E.g., what functionality or properties would you like it to have?
  - (Besides rule #1 – correct translation)

Compiler design goals

- Optimize for fast execution
- Minimize memory/energy use
- Catch software defects early
- Provide helpful error messages
- Run quickly
- Be easily extendable

Differing design goals

- What differences might you expect in compilers designed for the following applications?
  - A just-in-time compiler for running server-side user scripts
  - A compiler used in an introductory programming course
  - A compiler used to build scientific computing codes to run on a massively-parallel supercomputer
  - A compiler that targets a number of diverse systems
  - A compiler that targets an embedded sensor network platform

- Optimize for fast execution
- Minimize memory/energy use
- Catch software defects early

- Provide helpful error messages
- Run quickly
- Be easily extendable

Decaf language

- Simple imperative language similar to C or Java
- Example:

```
// add.decaf - simple addition example

def int add(int x, int y)
{
    return x + y;
}

def int main()
{
    int a;
    a = 3;
    return add(a, 2);
}
```

```
$ ./decaf add.decaf
RETURN VALUE = 5
```

Before Friday

- Readings
  - "Engineering a Compiler" (EAC) Ch. 1 (23 pages)
  - Decaf reference ("Resources" page on website)
- Tasks
  - **Complete welcome survey on Canvas**
  - **Complete first reading quiz on Canvas**
  - Write some code in Decaf
  - Test the reference compiler
    - `/cs/students/cs432/f22/decaf`
  - Bring your laptop on Friday if you are able

Upcoming college events

- September 7 (Wed), 11am-1pm
  - Career Fair Resume Review, King 259 (pizza served)
- September 12 (Mon), 4:30-5:30pm
  - CISE Career Prep Employer Panel, King 259
- September 13 (Tue), noon-1:30pm
  - Accenture Information Session, King 259 (pizza served)
- September 14 (Wed), 11am-3pm
  - CISE Career and Internship Fair, Festival Ballroom
- September 14 (Wed), 3:30pm
  - MITRE Information Session, King 259

Closing exhortations

- Take care of yourself
  - And if you can, someone else
  - Build (or reconnect with) a support network
  - Protect your boundaries
  - Carve out time to disconnect and rest
  - Talk to someone if things start getting overwhelming
- Have a great semester!