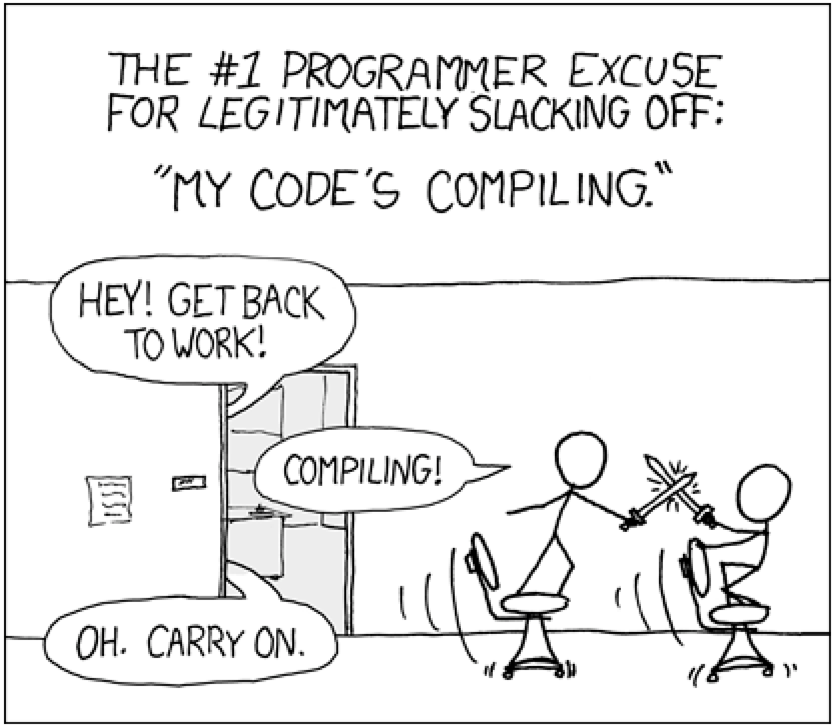
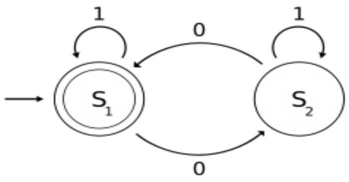
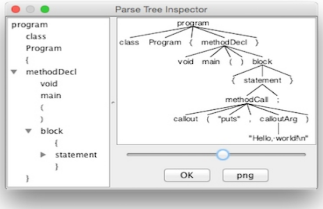
# CS 432
# Fall 2024

Mike Lam, Professor





# Compilers



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

## Advanced Systems Elective

# Discussion question

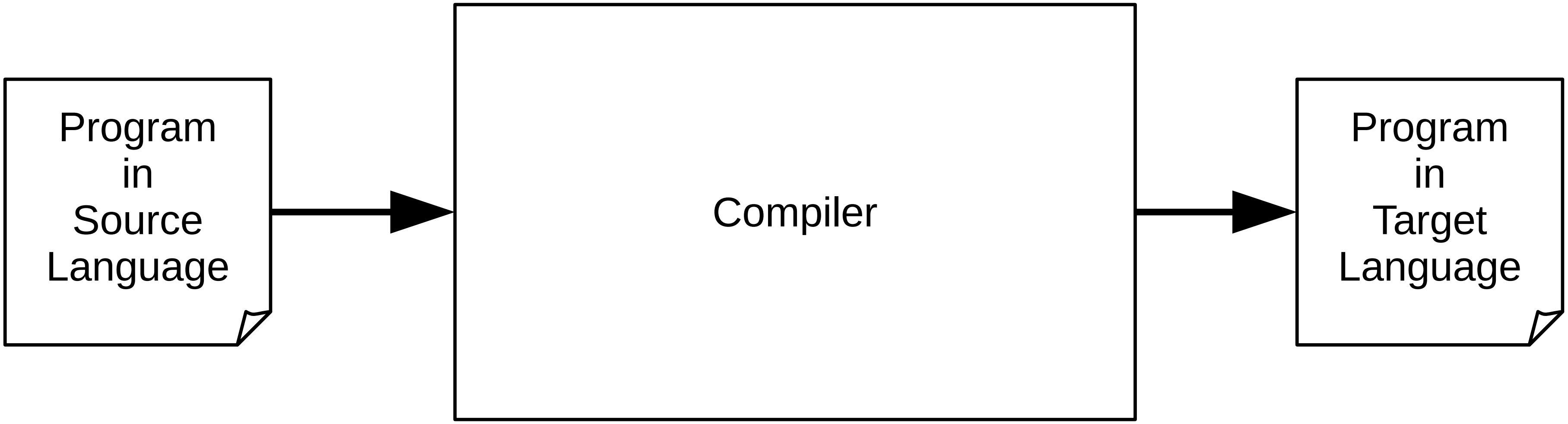
- What is a compiler?

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

***"An angry translator."***
-- previous CS 432 student

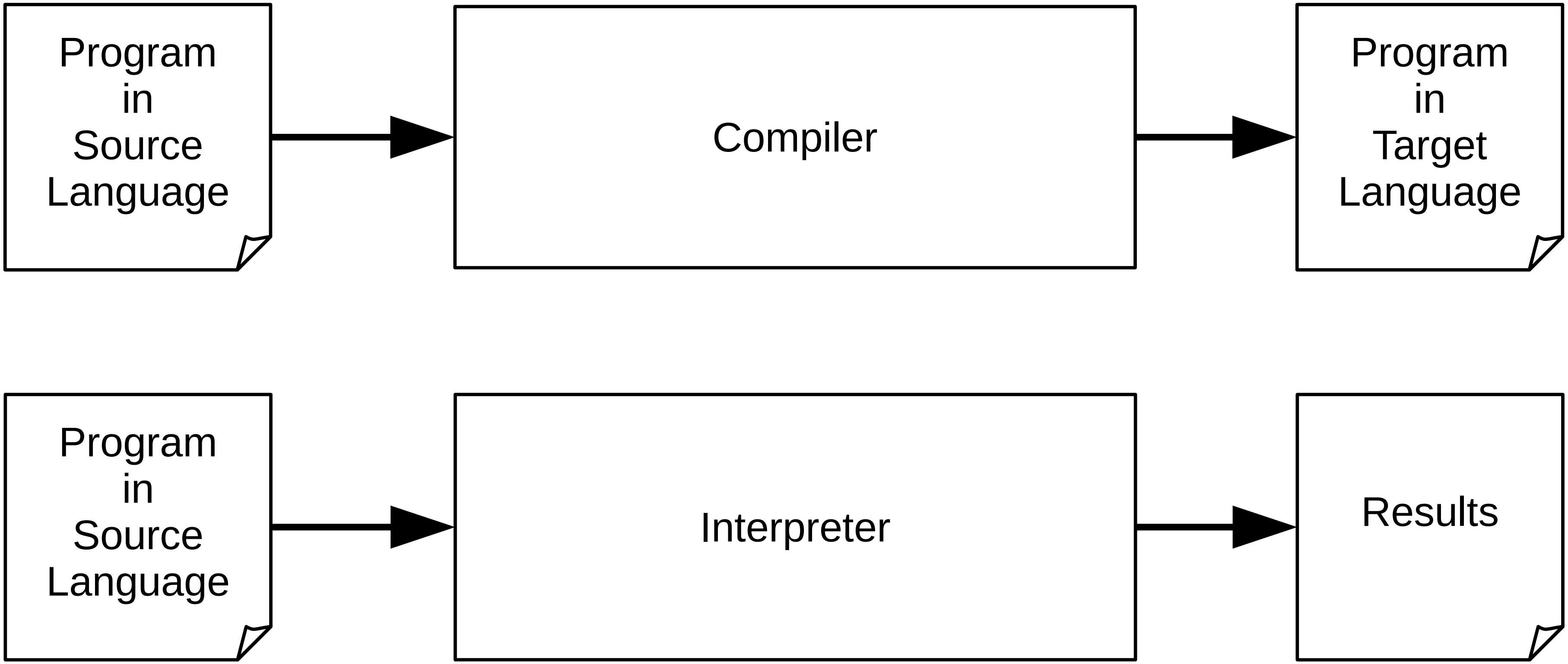
# Automated translation

- 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

# Rhetorical question

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

# Compilers: a convergent topic

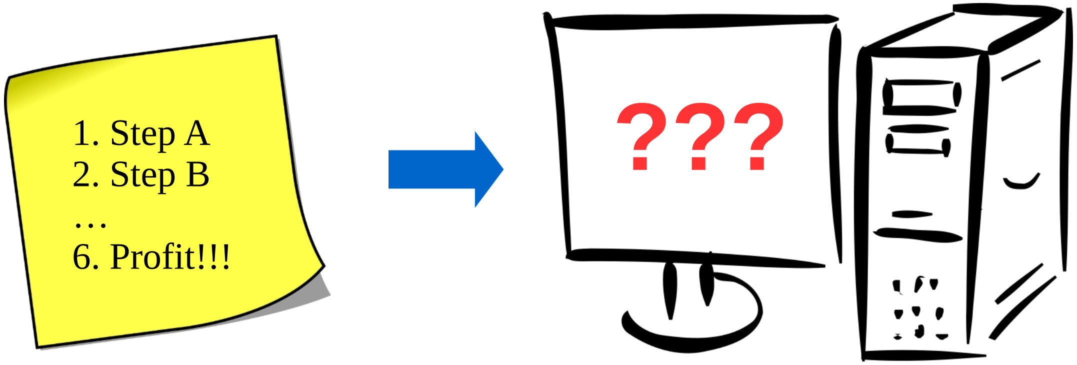
- Data structures
  - CS 240
- Architectures, machine languages, and operating systems
  - CS 261, CS 450
- Automata and language theory
  - CS 327, CS 430
- Graph algorithms
  - CS 327
- Software and systems engineering
  - CS 345, CS 361
- Greedy, heuristic, and fixed-point algorithms
  - CS 452

# 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..."

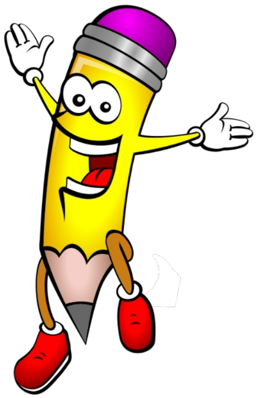


1. Step A
2. Step B

…

6. Profit!!!

???



# Course 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 the 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**

# 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
- Fall 2023
  - First semester allowing AI-assist tools on projects, transitioned back to in-class exams
- Fall 2024
  - Split midterm into two smaller exams

# 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)
    - Unlike 261, most test cases are NOT provided in advance
    - Grade point conversion: A = 100, B = 85, C = 70, D = 50, F = 25

- Submission: code (90%) + review (8%) + response (2%)
  - Code can be written in teams of two
    - Benefits vs. costs of working in a team
    - **Must include an AI-Assist Statement at the top in a comment**
  - Individual graded code reviews due a week later
  - Review responses (how useful was the review?)

# F24: AI assist on projects

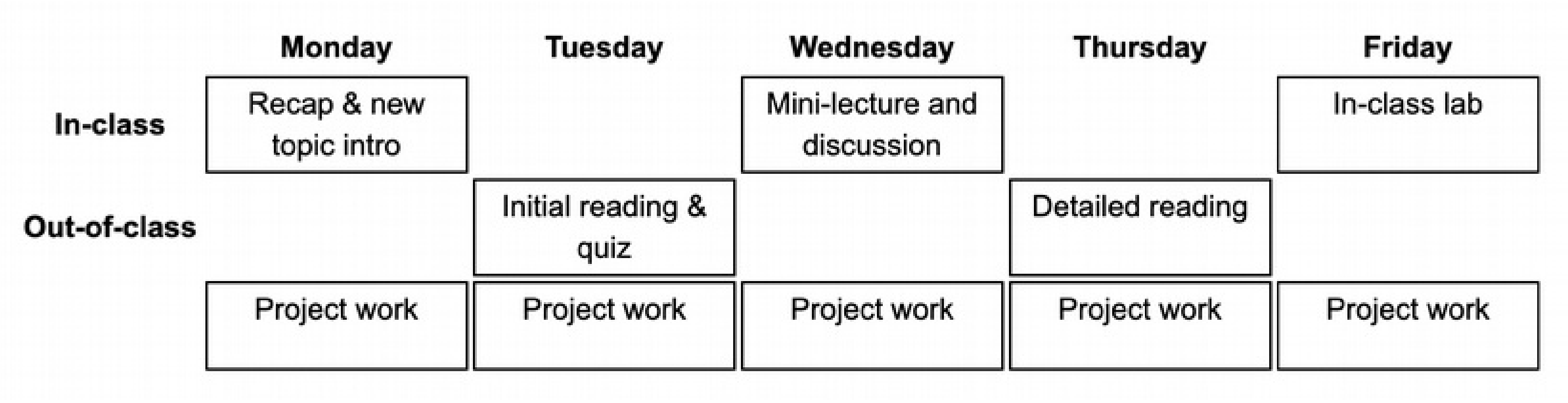
- From the syllabus:
  - The use of AI-assisted code generation tools such as Github Copilot **are allowed** on the labs and projects for this course this semester.
  - In the comments at the top of each project submission, you must include an "AI-Assist Statement" that discloses the extent of your use of AI-assist technologies on the assignment. If you did not use such a technology, you may simply state "I did not use any AI-assist tools while creating this solution."
  - **This policy is experimental and will be re-evaluated throughout the semester, potentially with modifications mid-semester.** Any revisions to the policy will be broadcast via Canvas announcement and discussed in class at least 72 hours prior to the next applicable deadline.
- Last semester, this change did not appear to fundamentally affect the learning outcomes of this course
  - Some students found the tools helpful, some did not
  - There did not appear to be a strong correlation with grades
  - I anticipate this semester will be similar

# Aside: project submissions

- Issue: Canvas is not a great system for code reviews
- Total of five (5) things to submit for most projects:
  1) Submit project on stu (for grading, similar to 261)
  2) Submit .c file on Canvas (for code reviewers)
  3) Submit code reviews on Canvas assignment (for grading)
  4) Send code reviews to reviewees via Canvas message (for their benefit)
  5) Submit code review response quiz
- Due dates:
  - Original project deadline: #1 and #2
    - Note: two projects (P2 and P3) also include “milestone” deadlines a week before
    - Milestone deadlines are optional and intended to help you stay on track to finish
  - One week after project deadline: #3 and #4 (code reviews)
    - Note: no code reviews for last project (P5)
  - Tuesday after code review deadline: #5 (code review responses)

# Course format

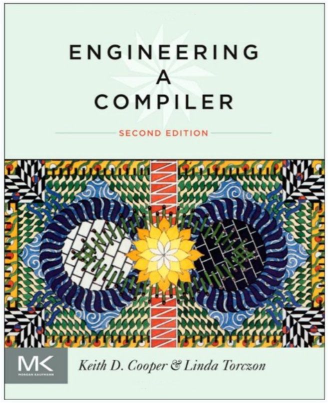
- Website: `https://w3.cs.jmu.edu/lam2mo/cs432/`
  - Make sure you're using the right year's website!
- Weekly schedule (most weeks)



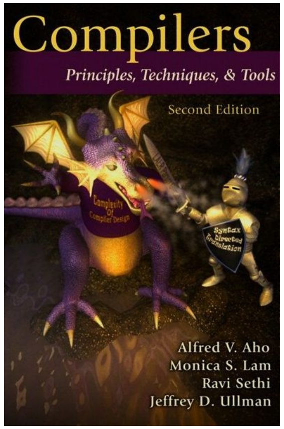
| | Monday | Tuesday | Wednesday | Thursday | Friday |
|---|---|---|---|---|---|
| **In-class** | Recap & new topic intro | | Mini-lecture and discussion | | In-class lab |
| **Out-of-class** | | Initial reading & quiz | | Detailed reading | |
| | Project work | Project work | Project work | Project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

- *Formative* vs. *summative* assessment
  - Formative: quizzes and labs (together 20% of final grade)
  - Summative: projects (25%) and in-person exams (55%)

# 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: `lam2mo@jmu.edu`
  - Response likely within a few hours, but no guarantees on weekends or on project deadlines
- Office hours posted on Canvas
  - **NOTE:** I have two offices this semester
    - King 227 is my CS faculty office (MWF)
      - Drop-in office hours and advising meetings
    - King 365 is my assistant dean office (TuTh)
      - Meetings by appointment

# Class Policies

- If you test positive for COVID-19 or the flu, 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

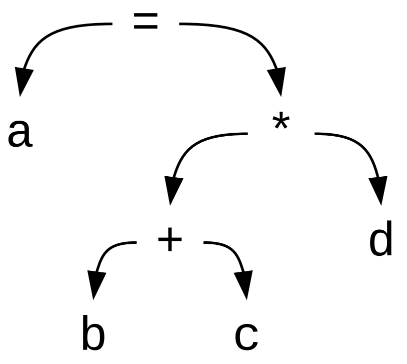
- Questions?

# Compiler rule #1

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

# Intermediate representation

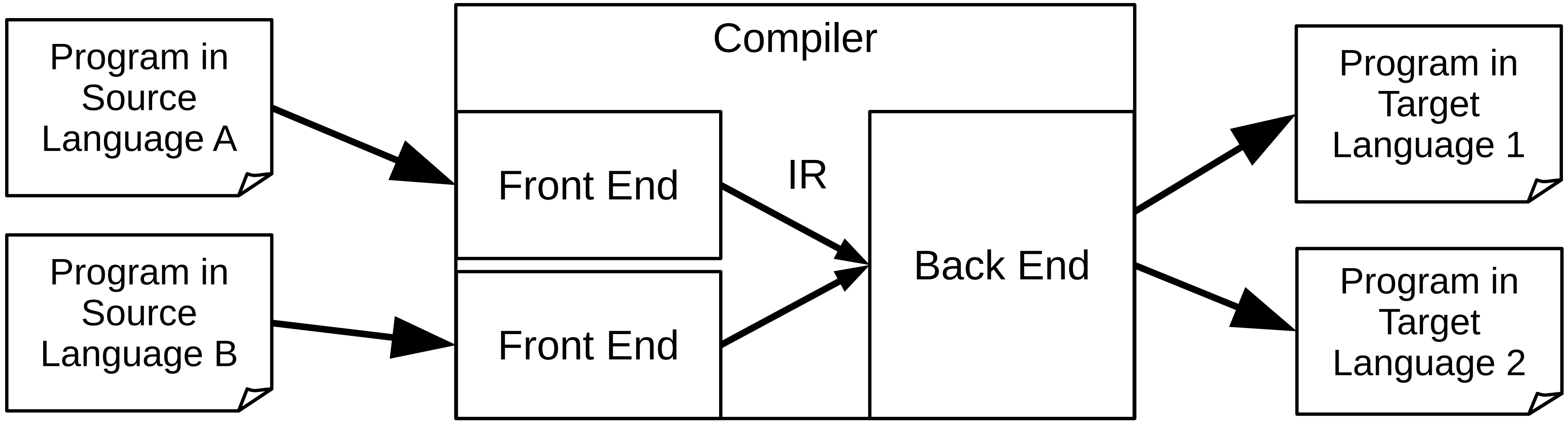
- Compilers encode a program's meaning using an intermediate representation (IR)
  - Tree- or graph-based: abstract syntax tree (AST), control flow graph (CFG)
  - Linear: register transfer language (RTL), Java bytecode, intermediate language for an optimizing compiler (ILOC)



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

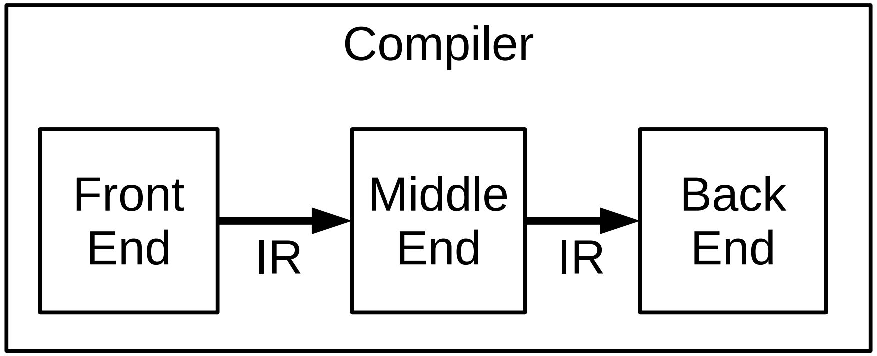
# Standard compiler framework

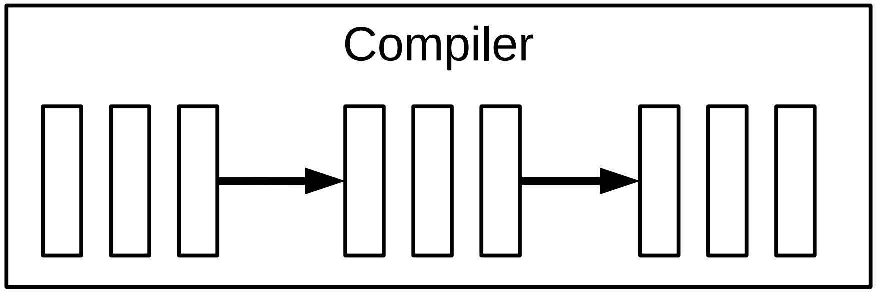
- Front end: understand the program (src → IR)
- Back end: encode in target language (IR → targ)
- Primary benefit: easier *re-targeting* to different languages or architectures


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 2

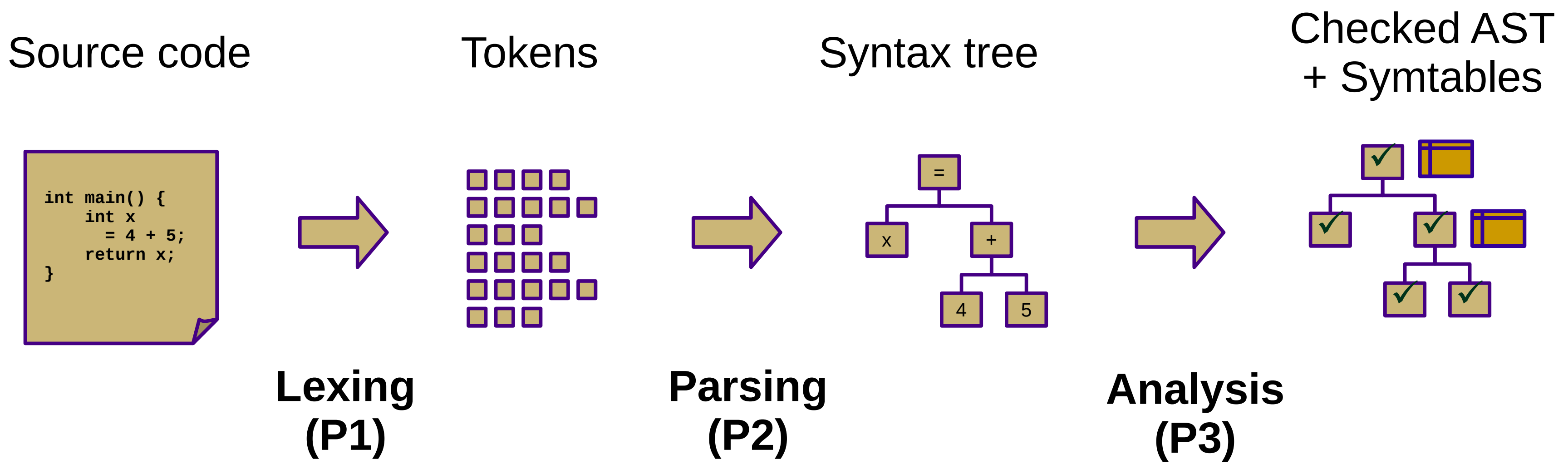
# Modern compiler framework

- 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: pipelined nanopasses
  - Dozens or hundreds of passes (`https://llvm.org/docs/Passes.html`)





# Our Decaf compiler pipeline



Source code

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

Tokens

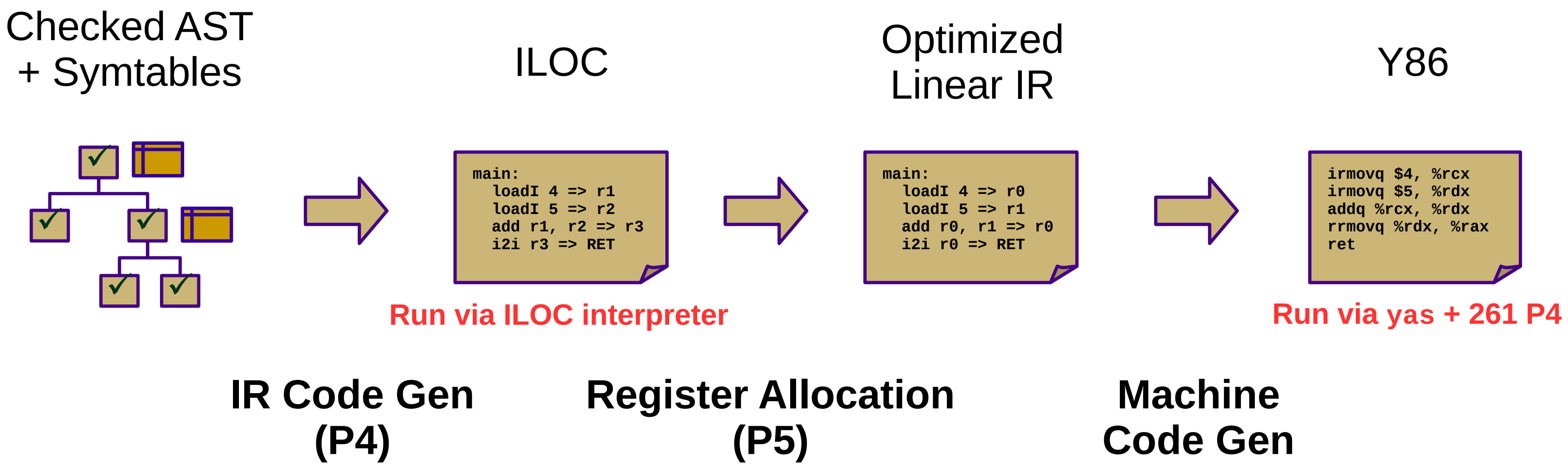
Syntax tree

Checked AST + Symtables

**Lexing (P1)**

**Parsing (P2)**

**Analysis (P3)**



Checked AST + Symtables

ILOC

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

Run via ILOC interpreter

Optimized Linear IR

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

Y86

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

Run via yas + 261 P4

**IR Code Gen (P4)**

**Register Allocation (P5)**

**Machine Code Gen**

# 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/f24/decaf`
  - Bring your laptop on Friday if you are able

# Upcoming college events

- September 9 (Mon), 2-4pm
  - Resume Review with Industry Partners, King 259
- September 9 (Mon), 4-6pm
  - Industry Partner Panel - Pre Fair Preparation, King 259
- September 10 (Tue), 11am-3pm
  - CISE Career and Internship Fair, Festival Ballroom
- More sessions TBD

# 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!