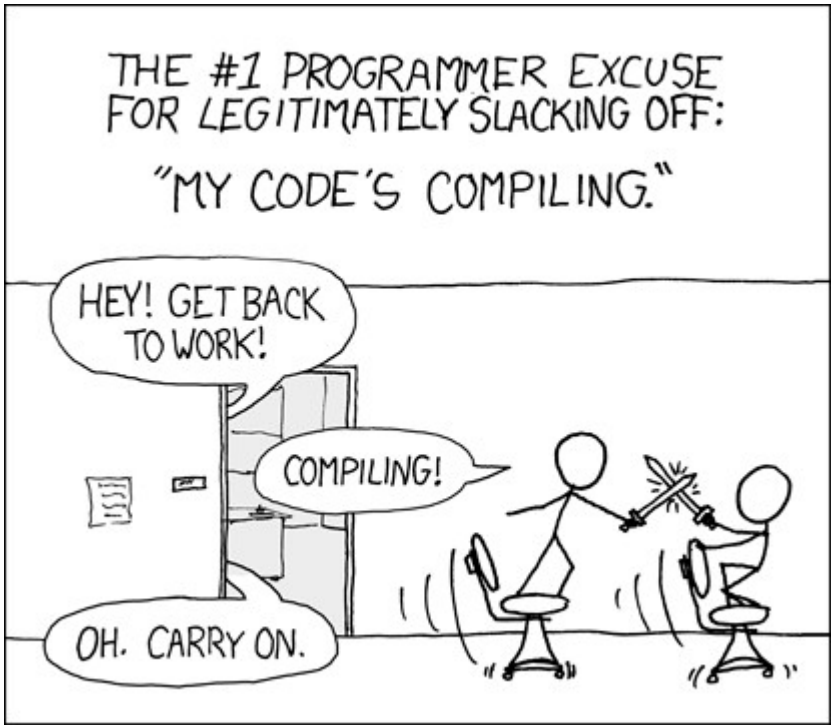
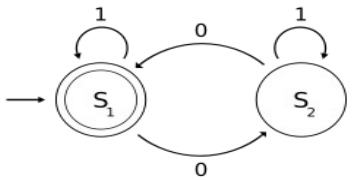
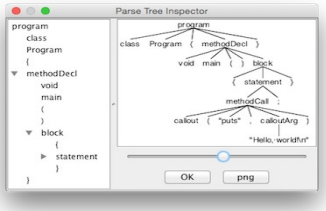
CS 432
Fall 2019

Mike Lam, Professor





Compilers



Advanced Systems Elective

Discussion question

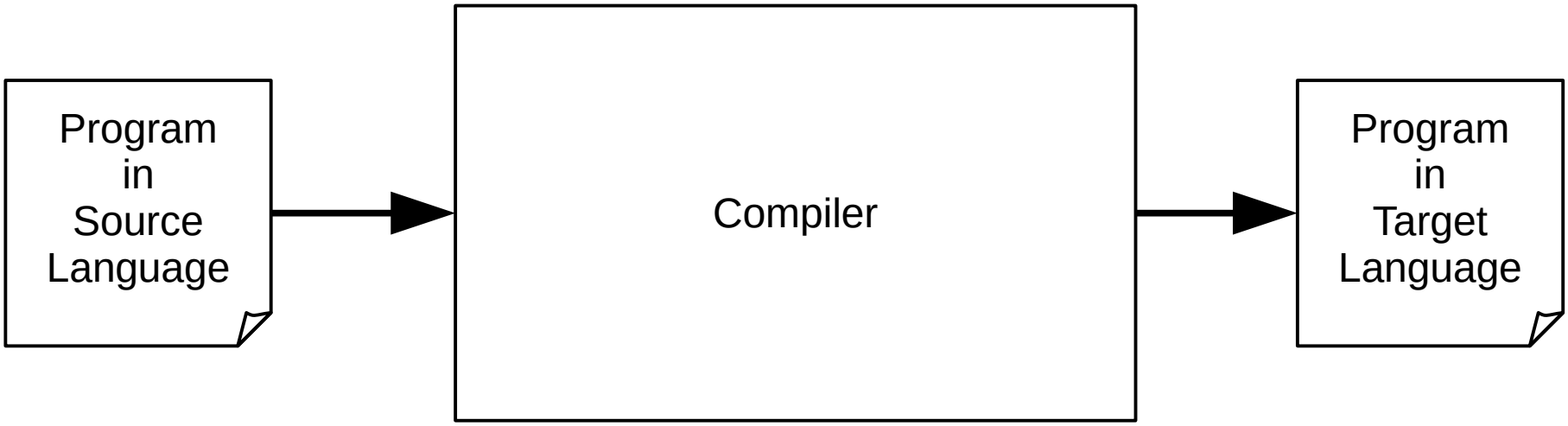
- What is a compiler?

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

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

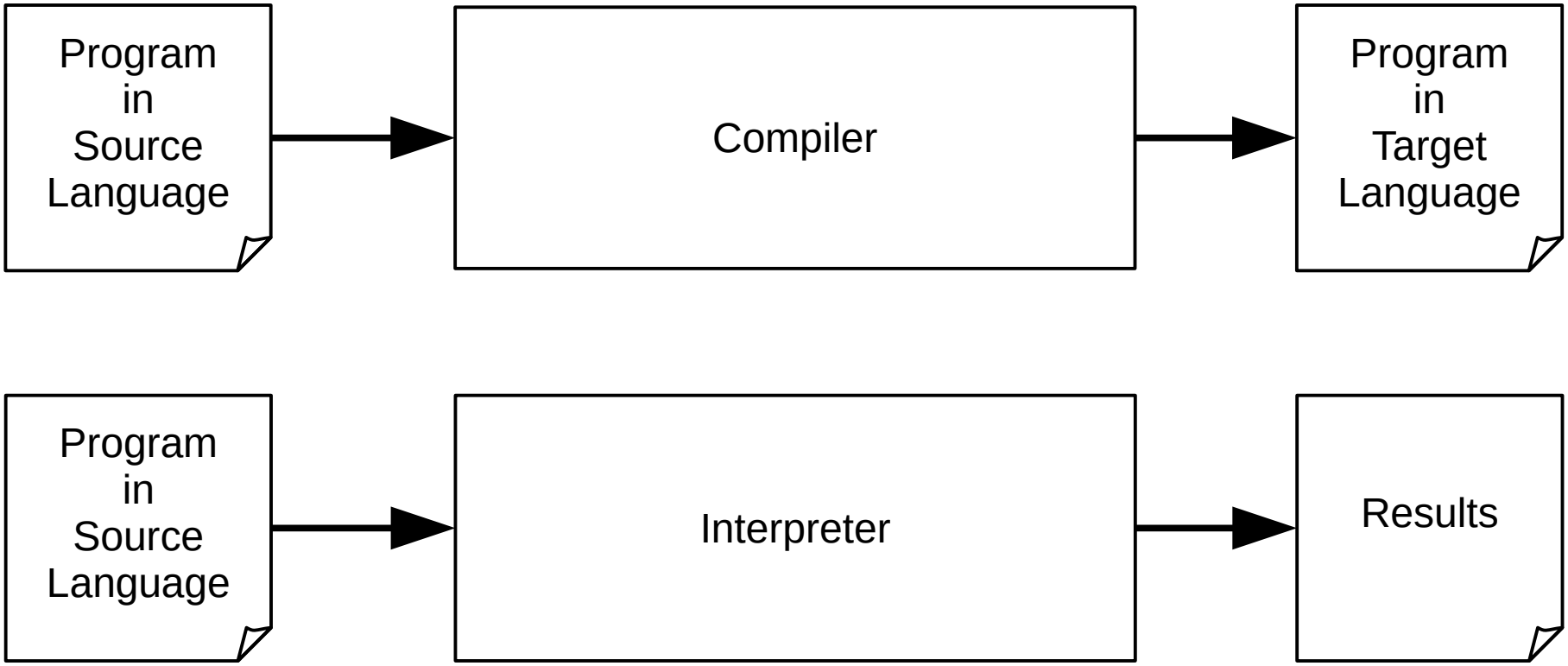
Automated translation

- 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:



Discussion question

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

Compilers: a convergent topic

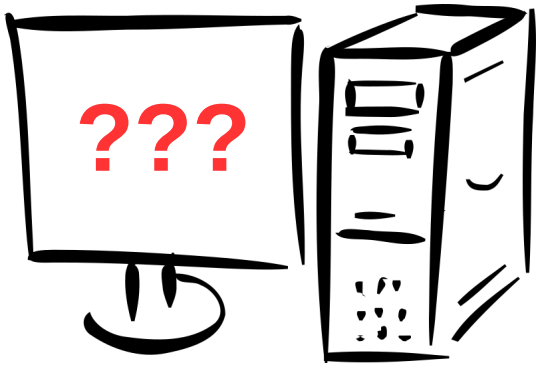
- Data structures
  - CS 240
- Architectures, machine languages, and operating systems
  - CS 261, CS 450
- Automata and language theory
  - CS 327, CS 430
- Graph algorithms
  - CS 327
- Software and systems engineering
  - CS 345, CS 361
- Greedy, heuristic, and fixed-point algorithms
  - CS 452

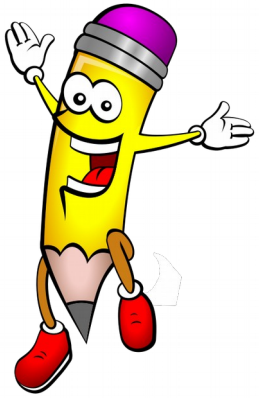
Reasons to study compilers

- 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 implementation
  - Applicable in many other domains
- Practical experience with large(er) software systems
  - My master copy is over 7K LOC
  - Of this, you will re-write over 1K LOC this semester
- Exposure to open problems in CS
  - Many optimization issues are subject to ongoing research

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..."





Course design theory

- First, a bit of background ...

Course design theory

- Big ideas
  - E.g., "A compiler is a large software system consisting of a sequence of phases"
- "Enduring understandings" (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

Learning 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.

Course format

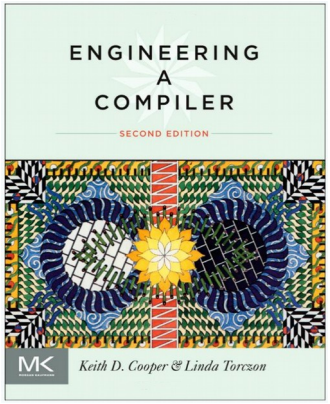
- Website: `https://w3.cs.jmu.edu/lam2mo/cs432/`
  - Make sure you're using the right year's website!
- Weekly schedule (roughly)

	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

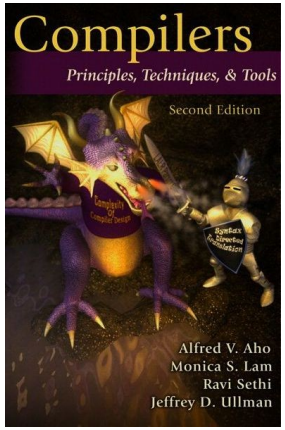
- *Formative* vs. *summative* assessment
  - Formative: quizzes and labs (20% of final grade)
  - Summative: projects and exams (80% of final grade)

Course textbook(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” (definitive text on compilers)
  - Two chapters scanned; posted under “Files” on Canvas



- Decaf/ILOC references
  - PDFs on website

Semester-long project

- Compiler for "Decaf" language
  - Implementation in Java
  - Maven build system w/ fully-integrated test suite
  - Compiles to ILOC (new machine language from textbook)
  - Five major projects: "pieces" of the full system
- Submission: code + review + response
  - 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?)

Evolution of CS 432

- Fall 2015 - special topics (CS 480)
- 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
  - Finished pure visitor implementation for P5
  - Added Y86 translator
  - Removed lambda calculus
  - Added exam study guides
- Fall 2019
  - Removed reflection paper
  - Switch to Dragon book for LR parsing
  - Streamlined calling conventions

Course policies

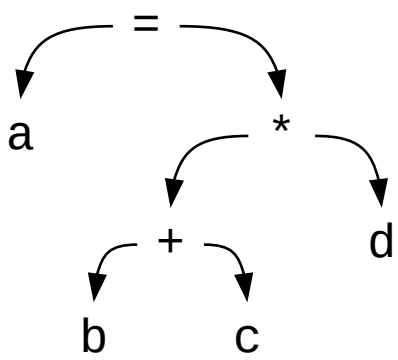
- Questions?

Compiler rule #1

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

Intermediate representation

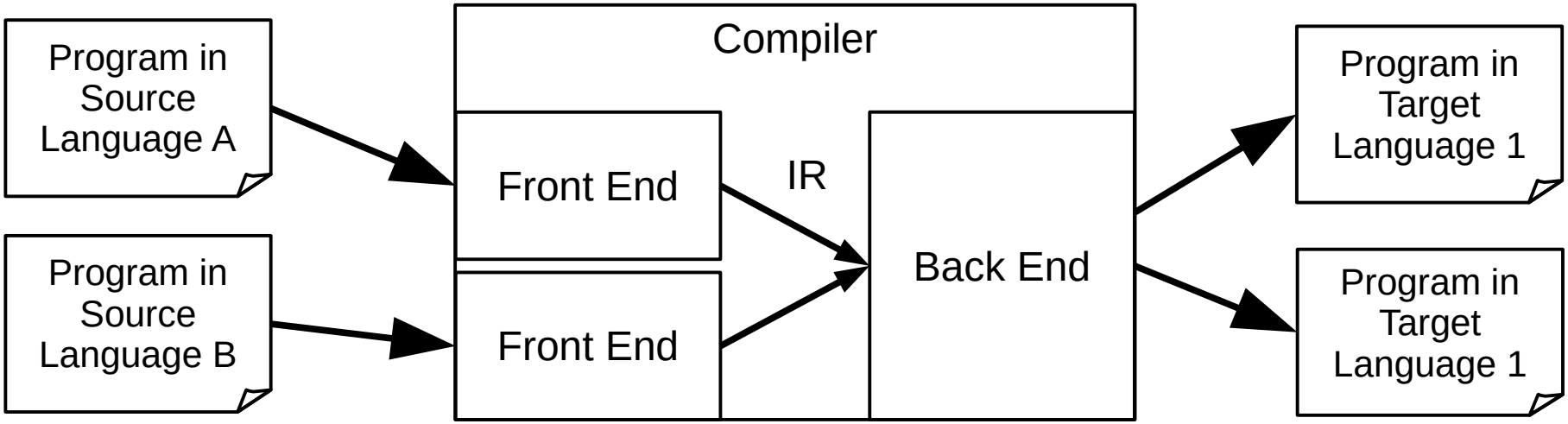
- Compilers encode a program's meaning using an intermediate representation (IR)
  - Tree- or graph-based: abstract syntax tree (AST), control flow graph (CFG)
  - Linear: register transfer language (RTL), Java bytecode, intermediate language for an optimizing compiler (ILOC)




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

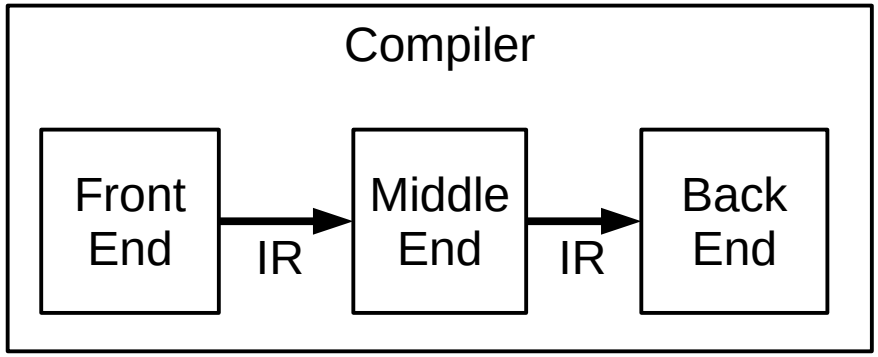
Standard compiler framework

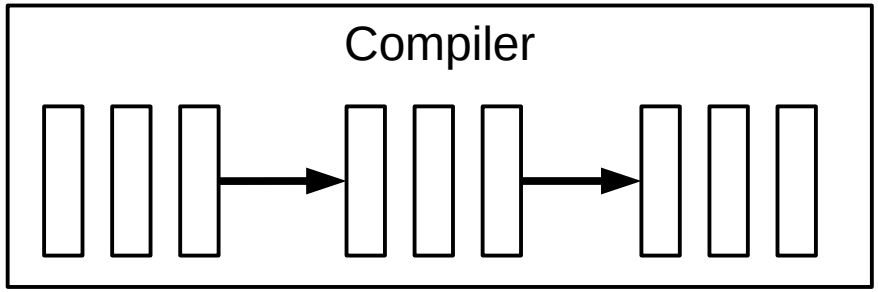
- Front end: understand the program (src → IR)
- Back end: encode in target language (IR → targ)
- Primary benefit: easier *re-targeting* to different languages or architectures



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`)





Our Decaf compiler

Source code

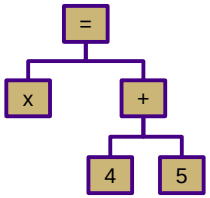
```
int main() {
    int x
      = 4 + 5;
    return x;
}
```

Lexing (P2)

Tokens

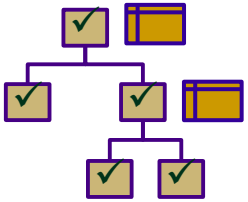
Parsing (P3)

Syntax tree

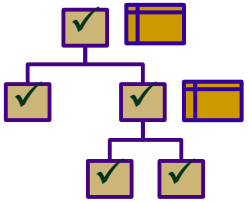


Analysis (P4)

Checked AST + Symtables



Checked AST + Symtables



IR Code Gen (P5)

ILOC

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

Run via ILOC interpreter

Register Allocation (P6)

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

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);
}
```

reference compiler

"interpret" flag and source file

```
$ java -jar decaf-1.0.jar -i add.decaf
5
```

Before Wednesday

- Readings
  - "Engineering a Compiler" (EAC) Ch. 1 (23 pages)
  - Decaf reference ("Resources" page on website)
- Tasks
  - **Complete first reading quiz on Canvas**
  - **Complete course intro survey on Canvas**
  - **Download the reference compiler from Canvas ("Files")**
    - **Bring your laptop on Wednesday!**
  - Write some code in Decaf
  - Install the JDK and Maven on your system

Upcoming events

- CS senior night
  - **Wednesday, Sept. 4 (5-6:30pm ISAT/CS 259)**
  - Graduation info, job fairs, photos, etc.
  - Senior students only
- CISE career fair
  - **Wednesday, Sept. 18 (Festival Ballroom)**
  - Companies looking for technology majors
  - Internships and full-time positions

See you Wednesday

- Have a great semester!