15-411/611 Compiler Design

Jan Hoffmann — Spring 2024

http://www.cs.cmu.edu/~janh/courses/411/24

Course Staff

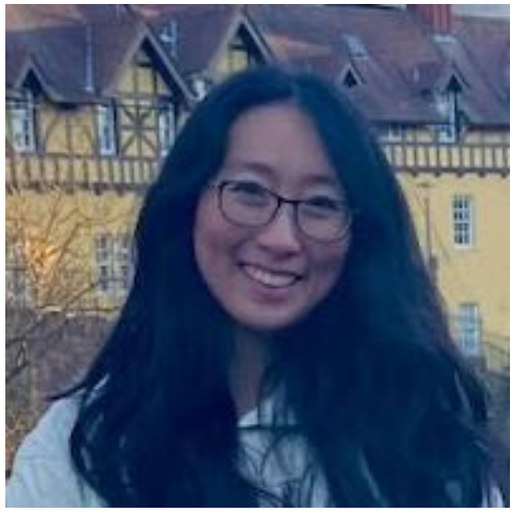
- **Instructor:** Jan Hoffmann

  Office hours: Tue 11:00 am - noon

- **Research**
  - Programming languages
  - Verification (quantitative properties like resource usage)

- **Teaching**
  - 15-411/611 Compiler Design
  - 15-312 Principles of Programming Languages
  - 15-814 Types and Programming Languages

Teaching Assistants



Aimee Feng
CS Senior

(OCaml)

Kyle Booker
CS Junior

(OCaml)

Miles Conn
CS Junior

(Rust)

Runming Li
CS Senior

(OCaml / Rust)

Winston Zha
CS Senior

(OCaml)

Communication and Resources

- **Lecture:** Tue/Thu 9:30-10:50 am, BH A51

  - **Recitation** A: Fri 01:00 - 01:50pm, GHC 4211
    B: Fri 02:00 - 02:50pm, BH 235A
    C: Fri 04:00 - 04:50pm, WEH 2302
    D: Fri 01:00 - 01:50pm, GHC 4301

- **Website:** http://www.cs.cmu.edu/~janh/courses/411/24

- **Piazza and Gradescope:** Enroll from website

- **Lecture notes:** Will be available after the lecture

- **Textbook:** Andrew Appel - Modern Compiler Implementation in ML

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- **Quality measures for a compiler**
  - Correctness (Does the compiled code work as intended?)
  - Code quality (Does the compiled code run fast?)
  - Efficiency of compilation (Is compilation fast?)
  - Usability (Does the compiler produce useful errors and warnings?)

Compilers

- **Compiler History**
  - 1943: Plankalkül, first high-level language (Konrad Zuse)
  - 1951: Formules, first self-hosting compiler (Corrado Böhm)
  - 1952: A-0, term ‘compiler’ (Grace Hopper)
  - 1952: Autocode, first implemented compiler (Alick Glennie)
  - 1957: FORTRAN, first commercial compiler (John Backus; 18 PY)
  - 1958: ALGOL58, first compiler for ALGOL (Friedrich Bauer)
  - 1962: Lisp, garbage collection (Tim Hart and Mike Levin)

- **Compilers today**
  - Modern compilers are complex (gcc has 7.5M LOC)
  - There is still a lot of compiler research (LLVM, verified compilation, …)
  - There is still a lot of compiler development in industry (guest lecture?)

What will you learn?

Compiler Design

- **How to structure compilers**
- **Applied algorithms and data structures**
  - Context-free grammars and parsing
  - Static single assignment form
  - Data flow analysis and type checking
  - Chordal graph coloring and register allocation
- **Focus on sequential imperative programming language**
  Not functional, parallel, distributed, object-oriented, ...
- **Focus on code generation and optimization**
  Not error messages, type inference, runtime system, ...

Focus of the Course

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Software Engineering

- **Implementing a compiler is a substantial software project**
  - Building, organizing, testing, debugging, specifying, …
- **Understanding and implementing high-level specifications**
- **Satisfying performance constraints**
- **Make (and reevaluate) design decision**
  - Implementation language and libraries
  - Data structures and algorithms
  - Modules and interfaces
- **Revise and modify your code**

Software Engineering

We won't discuss this much in lecture.

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Compilers are perfect to practice software engineering.

Learning Goals I

- Distinguish the main phases of a state-of-the-art compiler
- Understand static and dynamic semantics of an imperative language
- Develop parsers and lexers using parser generators and combinators
- Perform semantic analysis
- Translate abstract syntax trees to intermediate representations and static single assignment form
- Analyze the dataflow in an imperative language
- Perform standard compiler optimizations

Learning Goals II

- Allocate registers using a graph-coloring algorithm
- Generate efficient assembly code for a modern architecture
- Allocate registers using a graph-coloring algorithm
- Understand opportunities and limitations of compiler optimizations
- Appreciate design tradeoffs how representation affects optimizations
- Automatically manage memory using garbage collection
- Develop complex software following high-level specifications

How will this work?

Your Responsibilities

- **Attend lectures**
  - Lecture notes are only supplementary material
- **6 Labs: you will impl. compilers for subsets of C0 to x86-64 assembly**
  - Lab1-4: each worth 100 points (total 400 points)
    - Code review after Lab 3: 50 points
    - Project proposal for a Lab 6 project: 50 points
  - Lab 5-6: each 150 points (total 300 points)
- **4 Assignments: you will complete 4 written assignments that help you understand the material presented in the lectures**
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Labs — Overview

- **Labs (700 points)**
  - Lab 1: tests and compiler for L1 (straight-line code)
  - Lab 2: tests and compiler for L2 (conditionals and loops)
  - Lab 3: tests and compiler for L3 (functions)
  - Lab 4: tests and compiler for L4 (memory)
  - Lab 5: compiler and paper (optimizations)
  - Lab 6: code and paper (you choose)

- **Code review (50 points)**
  - You show your code for Lab 3 and get feedback
  - We expect that every team member is familiar with all components
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Support for 411/611 Comes From …

Helps to

- Improve the grading infrastructure
- Refreshments at lectures

Source Language: C0

Subset of C

- Small
- Memory safe
- Fully specified (no undefined behavior)
- Rich enough to be representative and interesting
- Small enough to manage in a semester

Target Language

x86-64 assembly

- Widely used
- Quirky, but you can choose the instructions you use
- Low level enough you can get a taste of the hardware

Runtime system

- C0 uses the ABI (Application Binary Interface) for C
- Need to adhere to ABI internally and for library functions

Finding a teammate for the labs

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I strongly suggest to work in teams of two.

Labs — Finding a Teammate

There are two options

1. **You fill out a questionnaire and we *suggest* a partner (staff selection)**
   - It's expected that you team up when matched
2. **You team up with somebody yourself (self selection)**
   - Like in previous iterations of the course

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Register your team on of before Thursday, Jan 25.

Option 1: Staff Selection

- **You fill out a questionnaire about**
  - Your plans and goals for the class
  - Your strengths and work style
  - And your time constraints
- **We suggest a partner with complem. strength and similar plans/goals**
- **You meet with your partner and (hopefully) decide to team up**
- **Advantages:**
  - You will get a partner who is a good match
  - You will likely meet somebody new
  - Prepares you for working in a software company

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Before Thursday 1/25

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Option 1: Example Questions we Ask

- What programming language would you prefer to use?
- Are you more interested in theory or in building systems?
- Are you familiar with x86 assembly?
- How much time would be so much that you would rather drop?
- How much effort do you plan to invest in Compilers, on average?
- What grade are you aiming for in Compilers?
- Do you prefer to collaborate when writing code?

Option 2: Self Selection

- **Pick your partner carefully!**
- **Have an honest discussion about your goals and expectations**
  - What grades you are willing to accept?
  - How much time will you spend?
  - What times of day you work best?
- **Find somebody who's a good match**
- **Go through the questionnaire and compare your answers**

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Consider switching to Option 1 if there are mismatches.

Labs — Picking a Programming Language

- **You can freely choose a programming language to use**
- **I strongly suggest to use a typed functional language**
  - Writing a compiler is a killer app for functional programming
  - Most teams used Rust or OCaml last year
- **We provide starter code for the following languages**
  - SML, OCaml, and Rust
- **We provide outdated starter code for more languages** (C++, Swift, Haskell, Java)
- **When picking a language also consider the availability of parser generators and libraries**

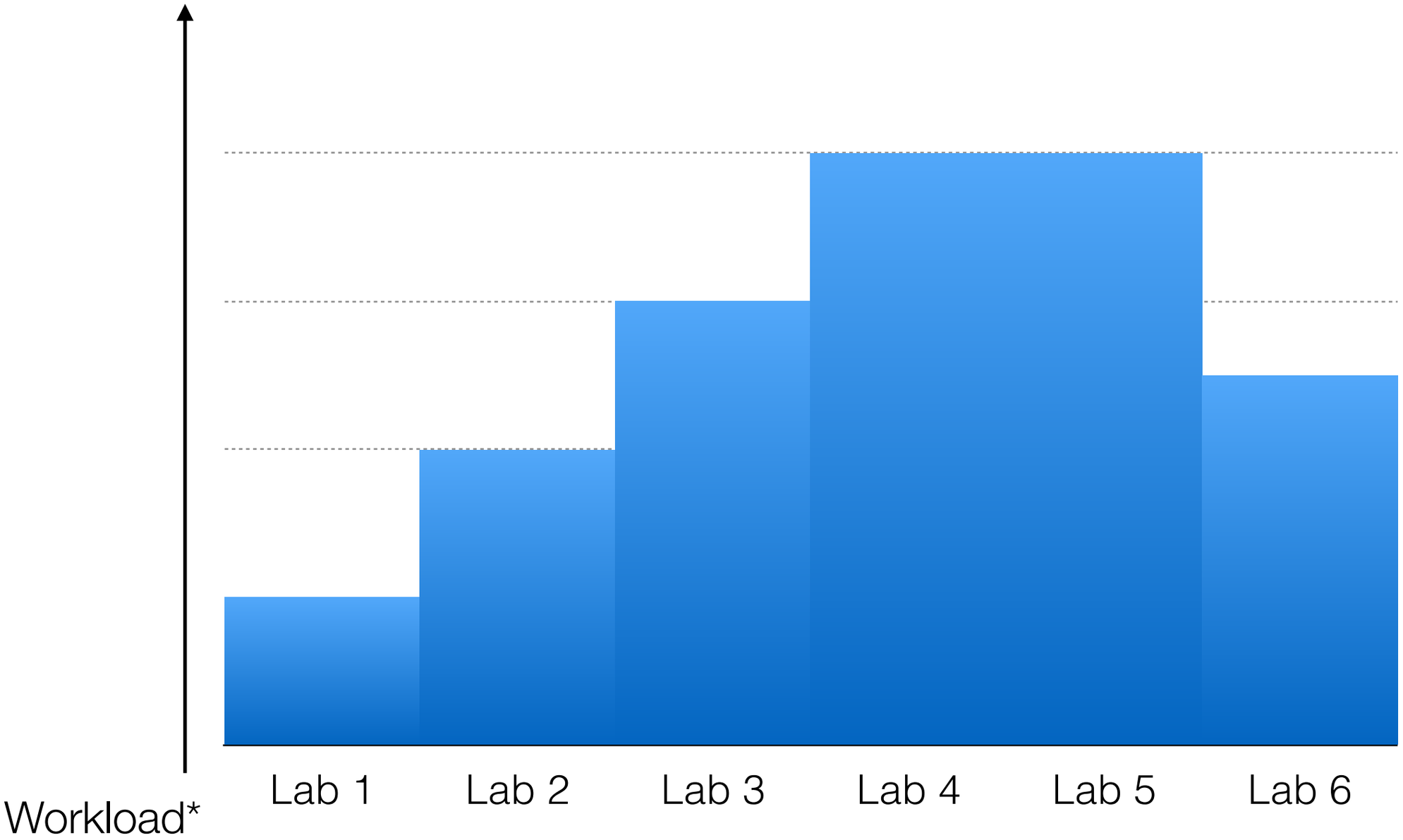
Logistics

- **Assignments and labs submitted via Gradescope**
- **Labs are submitted using GitHub**
  - Get a GitHub account and fill out a google form to register your team
  - Receive your group name
  - Receive an invitation to join your group on GitHub
  - Submit your code by pushing to your repository
- **Auto grading**
  - Your compiler is tested against the test cases of other groups
  - And test cases from previous years
  - You can submit as often as you like
  - Best submission before the deadline counts

Advice

- **Labs are difficult and take time**
  - Plan ahead!
  - Set up meetings with lab partners
  - Talk to us and others about design decisions
- **Don’t start the compiler after the tests**
- **Errors carry over to the next lab**
- **Submit early and often**
- **Compilers are complex**
  - That’s part of the fun

Workload Over the Semester



* scale from the movie Spaceballs.

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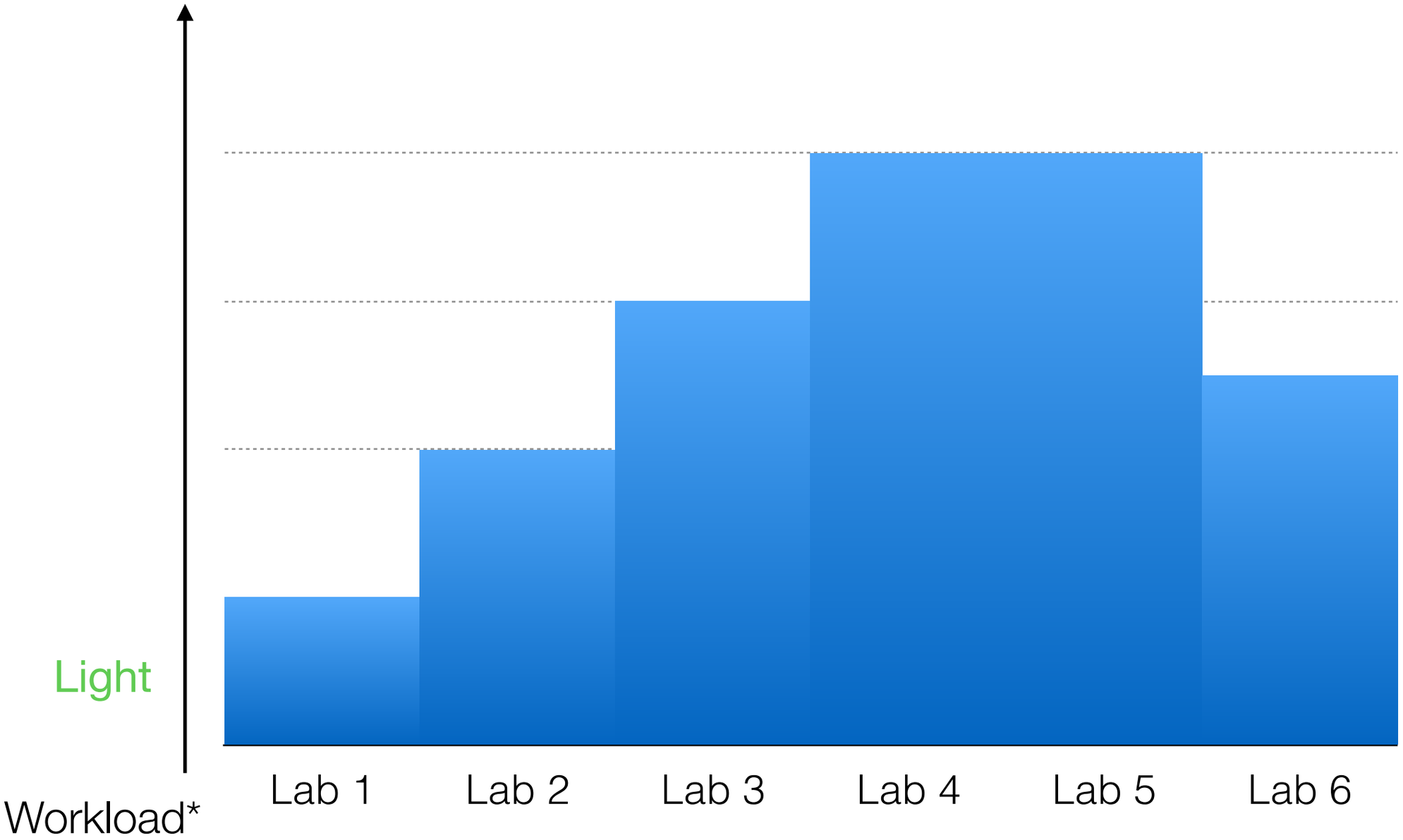

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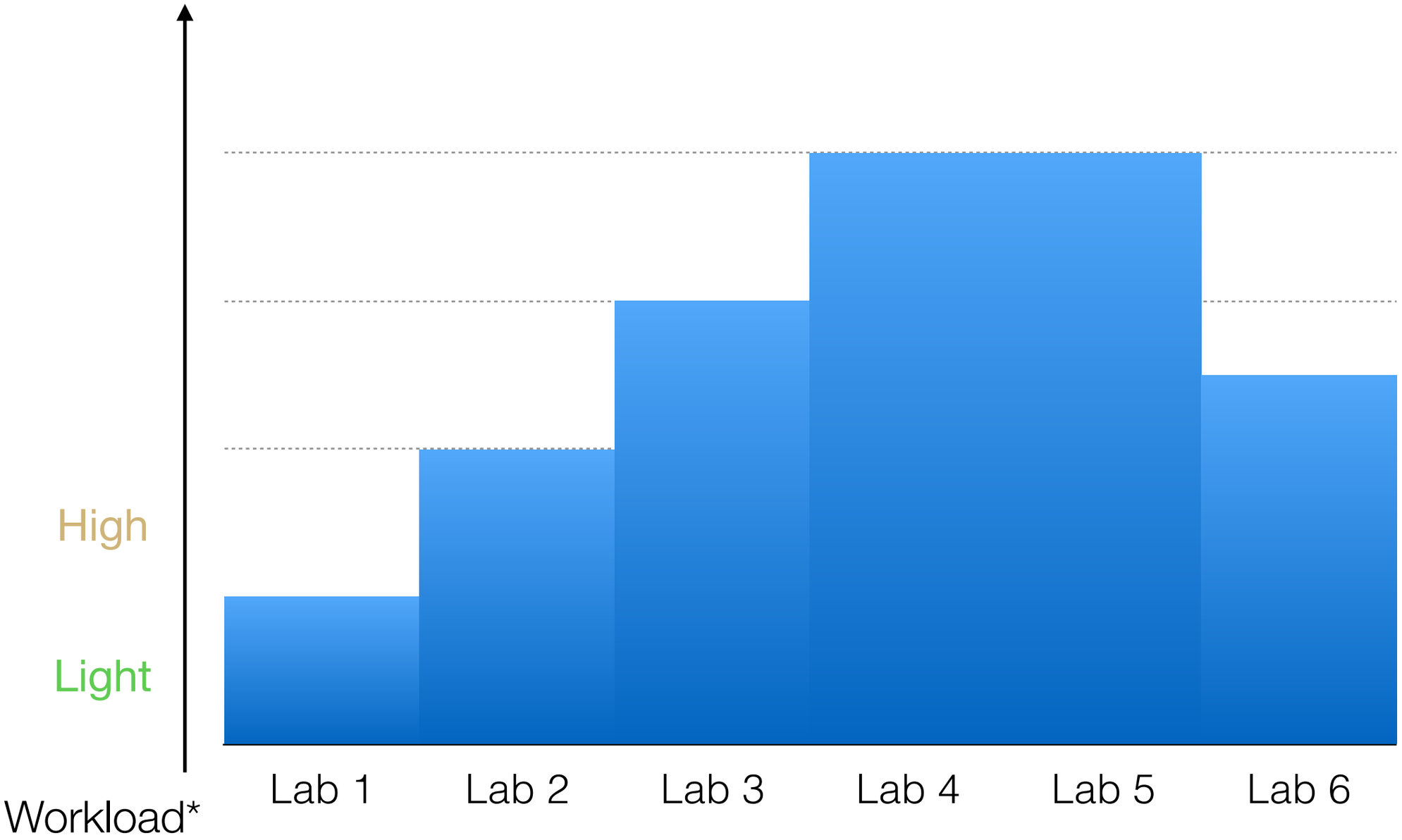

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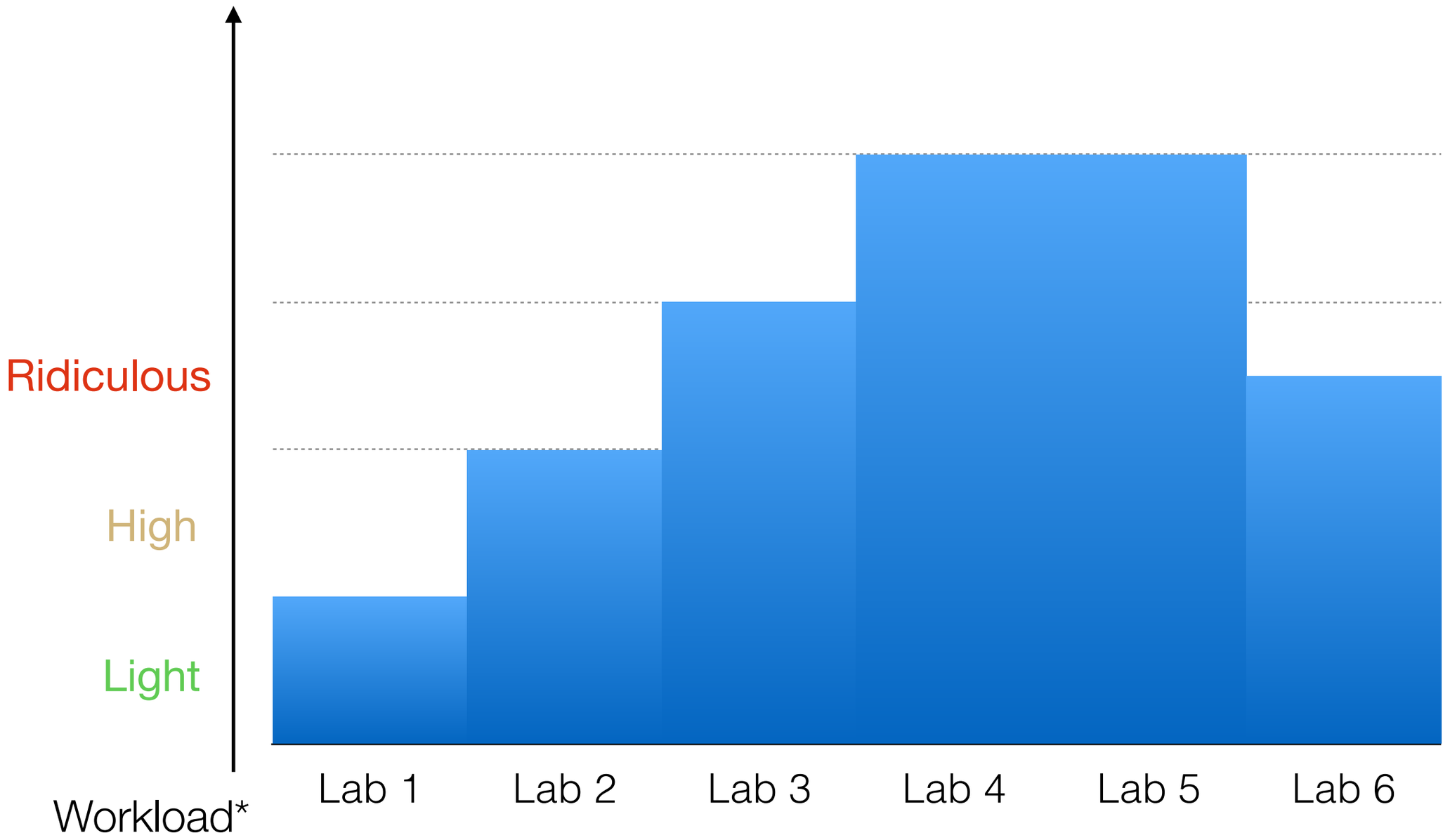

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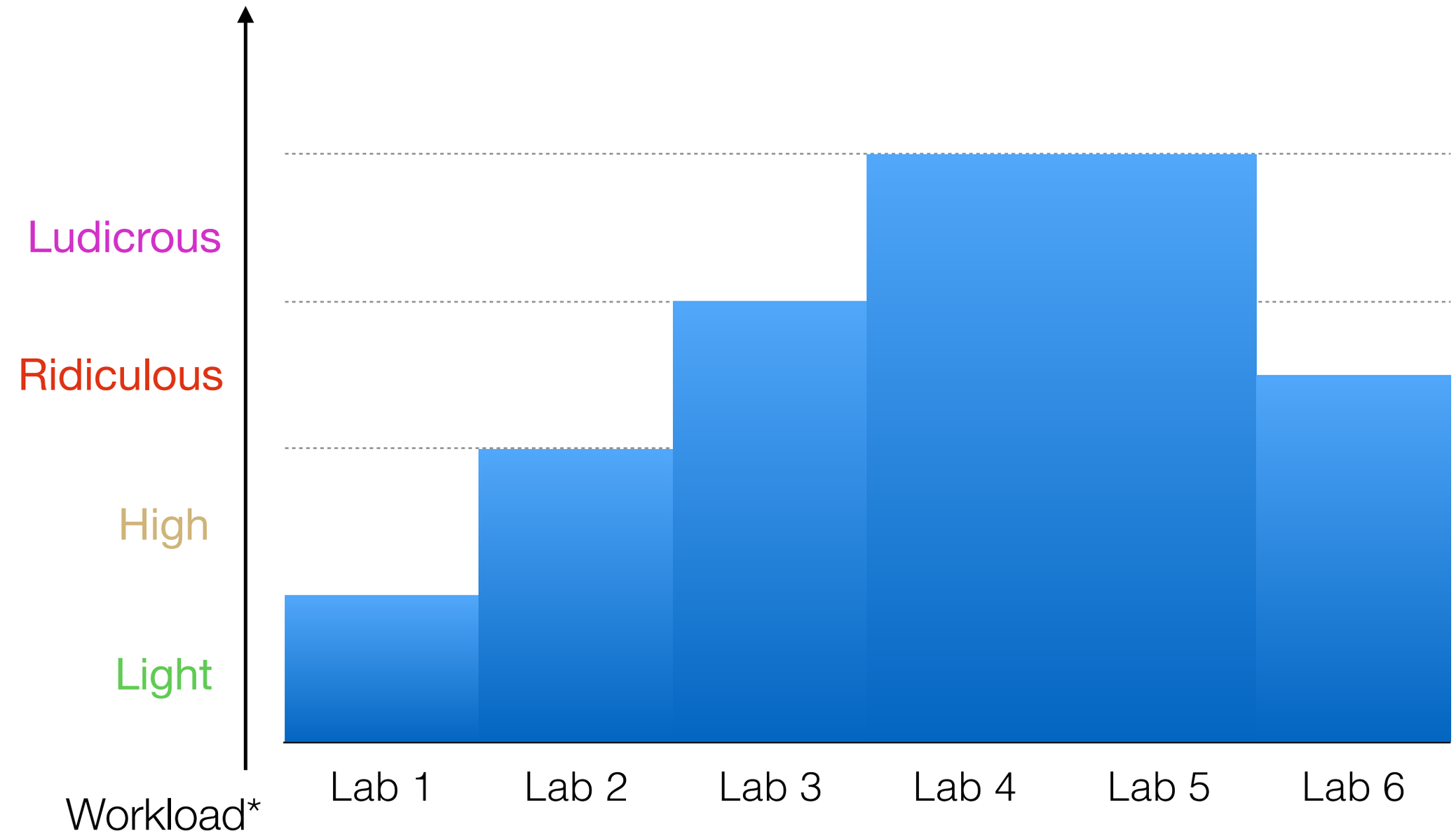

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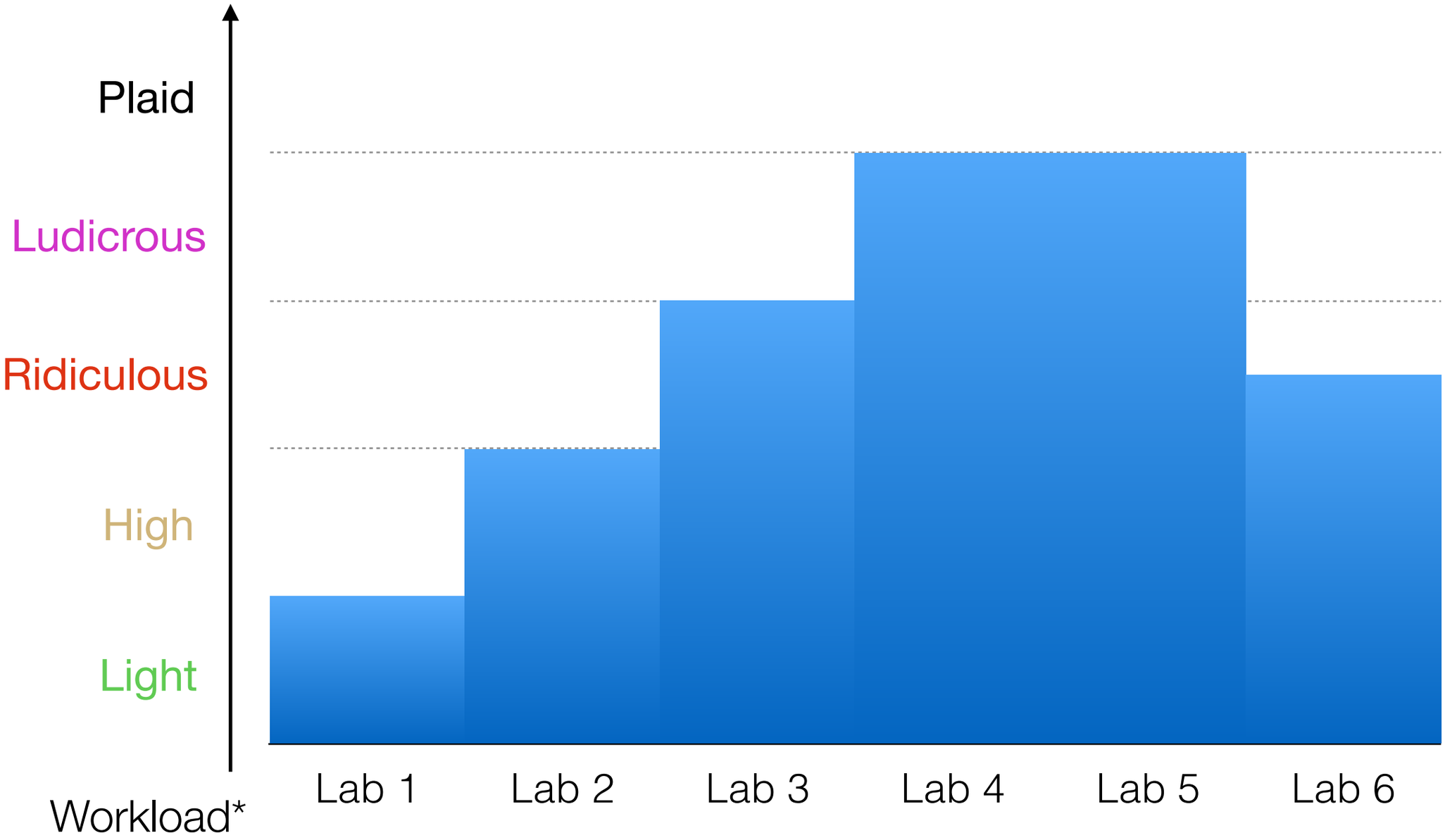

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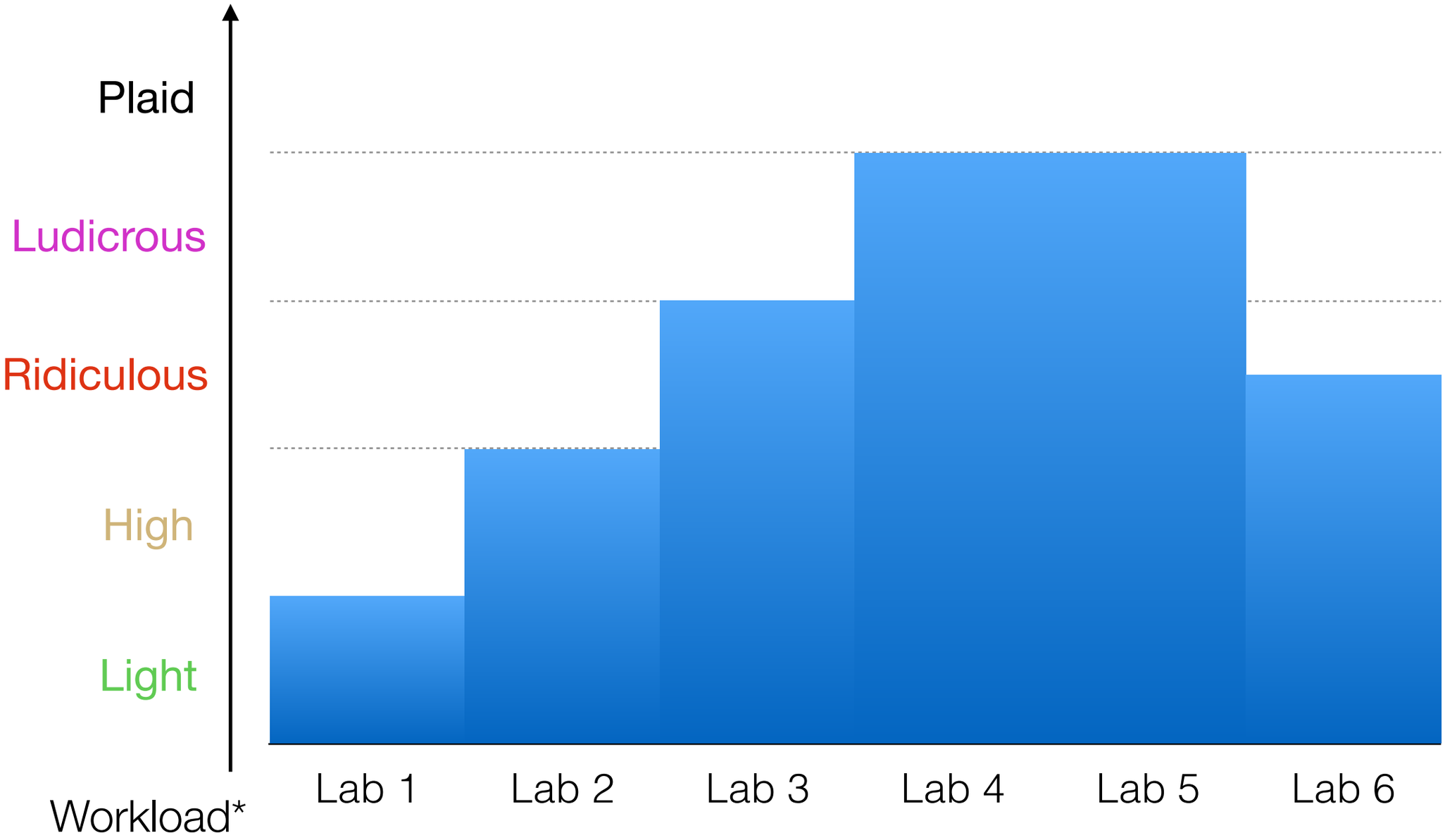

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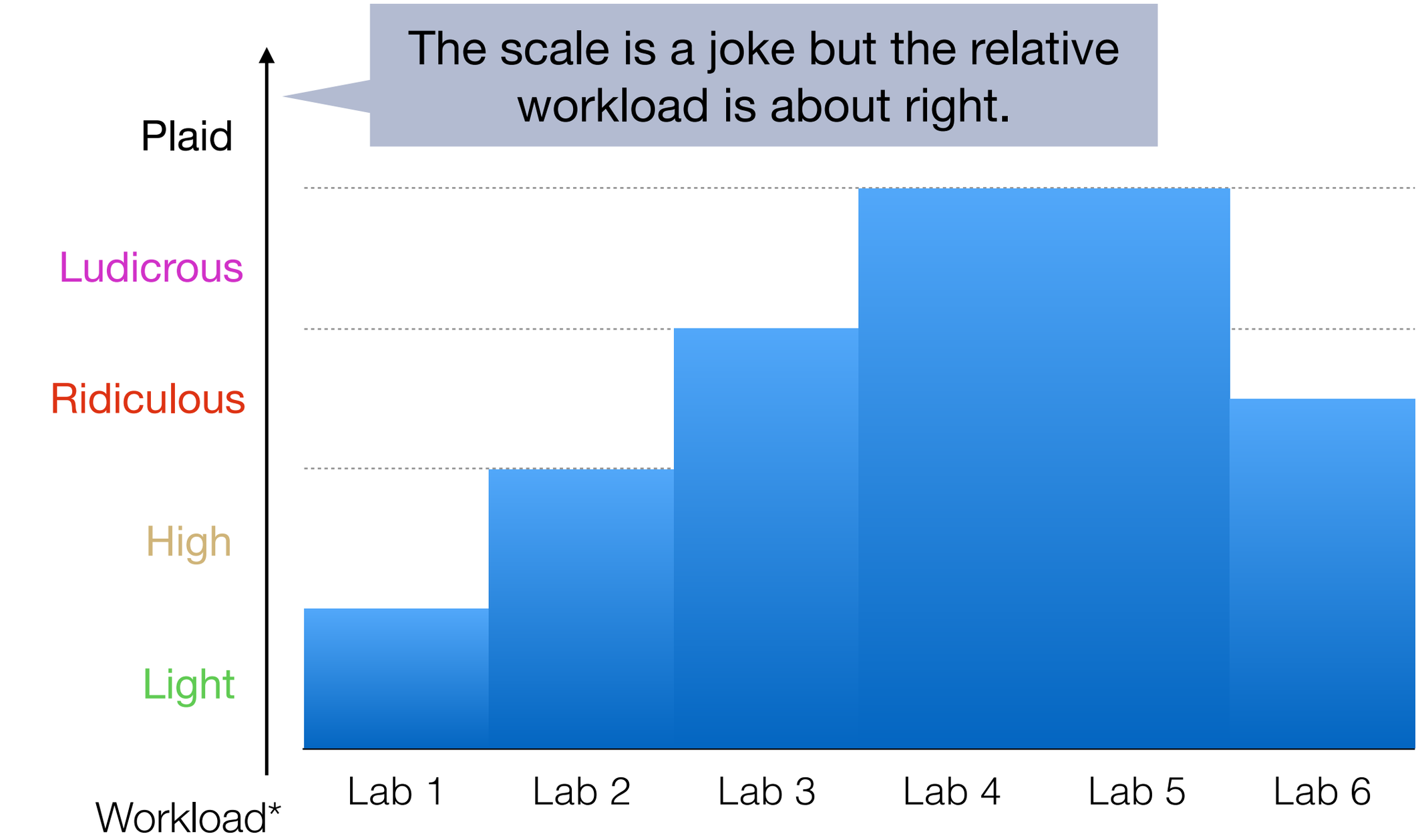

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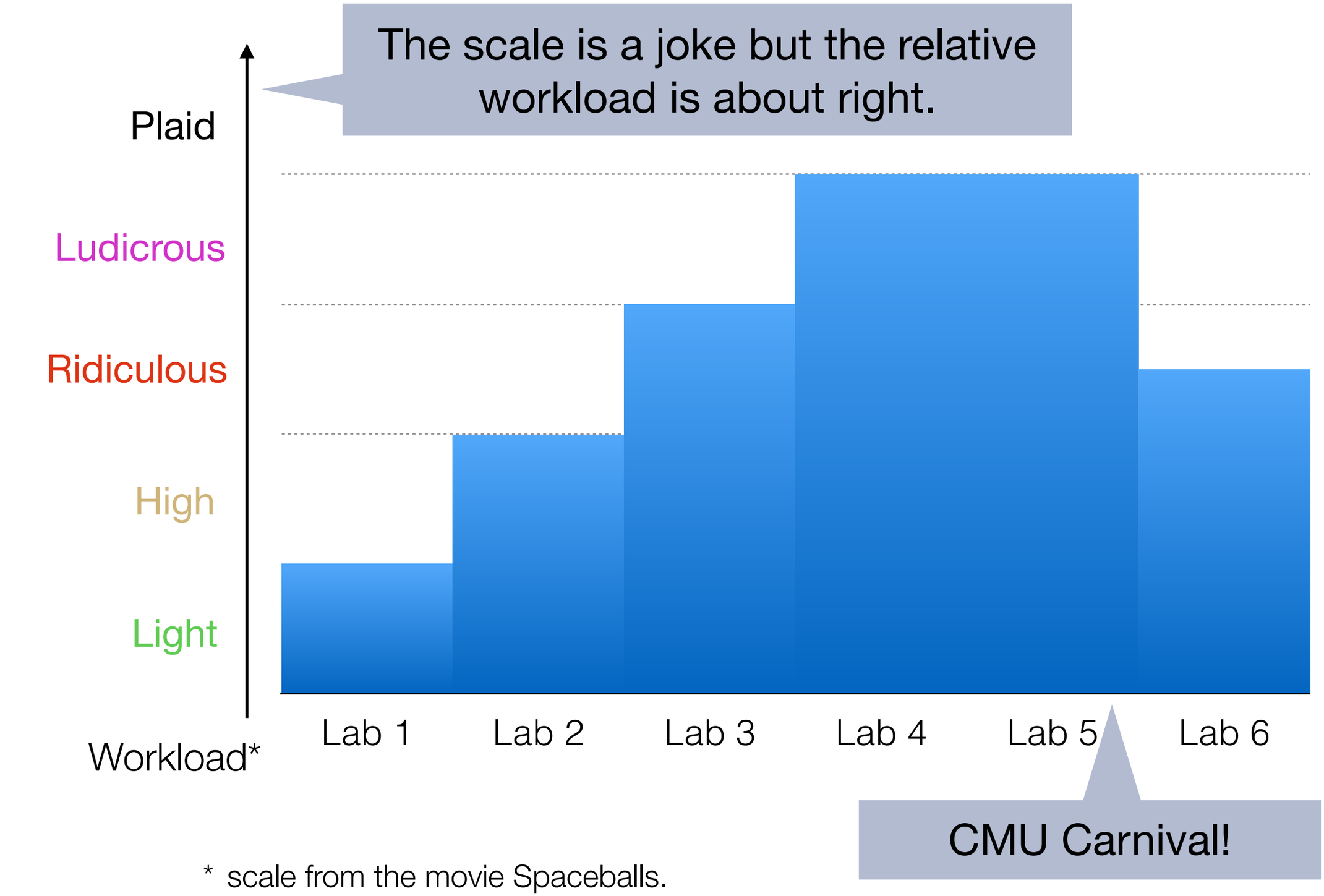

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This Year's Theme

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(Famous) Mathematicians

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Deadlines and Academic Integrity

- **Deadlines are at midnight; being late results in a late day**
  - You have six (6) late days for the labs (see details online)
  - You have three (3) late days for the assignments (details online)
- **Talk to me or your undergrad advisor if you cannot make a deadline for personal reasons (religious holidays, illness, …)**
- **Don’t cheat! (details online)**
  - Use code only from the standard library, add to Readme
  - Don’t use code from other teams, earlier years, etc.
  - If in doubt talk to the instructor
  - The written assignments need to be completed individually (1 person)

Things you Should Use

- Debugger
- Profiler
- Test programs
- Standard library
- Lecture notes

Well-Being

- **This is only a course!**
  - Take care of yourself
  - Watch out for others
- **Get help if you struggle or feel stressed**
  - If you or anyone you know experiences any academic stress, difficult life events, or feelings like anxiety or depression seek support
  - Counseling and Psychological Services (CaPS) is here to help:
    Phone: 412-268-2922
    Web: http://www.cmu.edu/counseling/

Who should take this course?

15-411 in the Curriculum

- **15-213 Introduction to Computer Systems**
- **15-411 Compiler Design**
  - How are high-level programs translated to machine code?
- **15-410 Operating System Design and Implementation**
  - How is the execution of programs managed?
- **15-441 Computer Networks**
  - How do programs communicate?
- **15-417 HOT Compilation**
  - How to compile higher-order typed languages?

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System requirement

- **15-417 HOT Compilation**
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Things you Should Know (Learn)

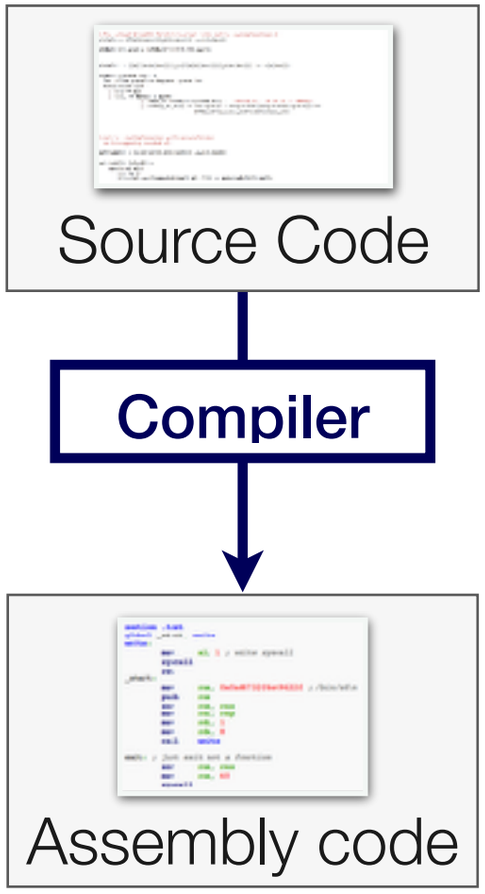
- **C0 programming language**
  - The source language
- **x86-64 assembly**
  - The target language
- **Functional programming**
  - Highly recommend
- **Git version control**
  - For submitting labs

A closer look at a compiler

Source Code

Assembly code

Compiler in Context



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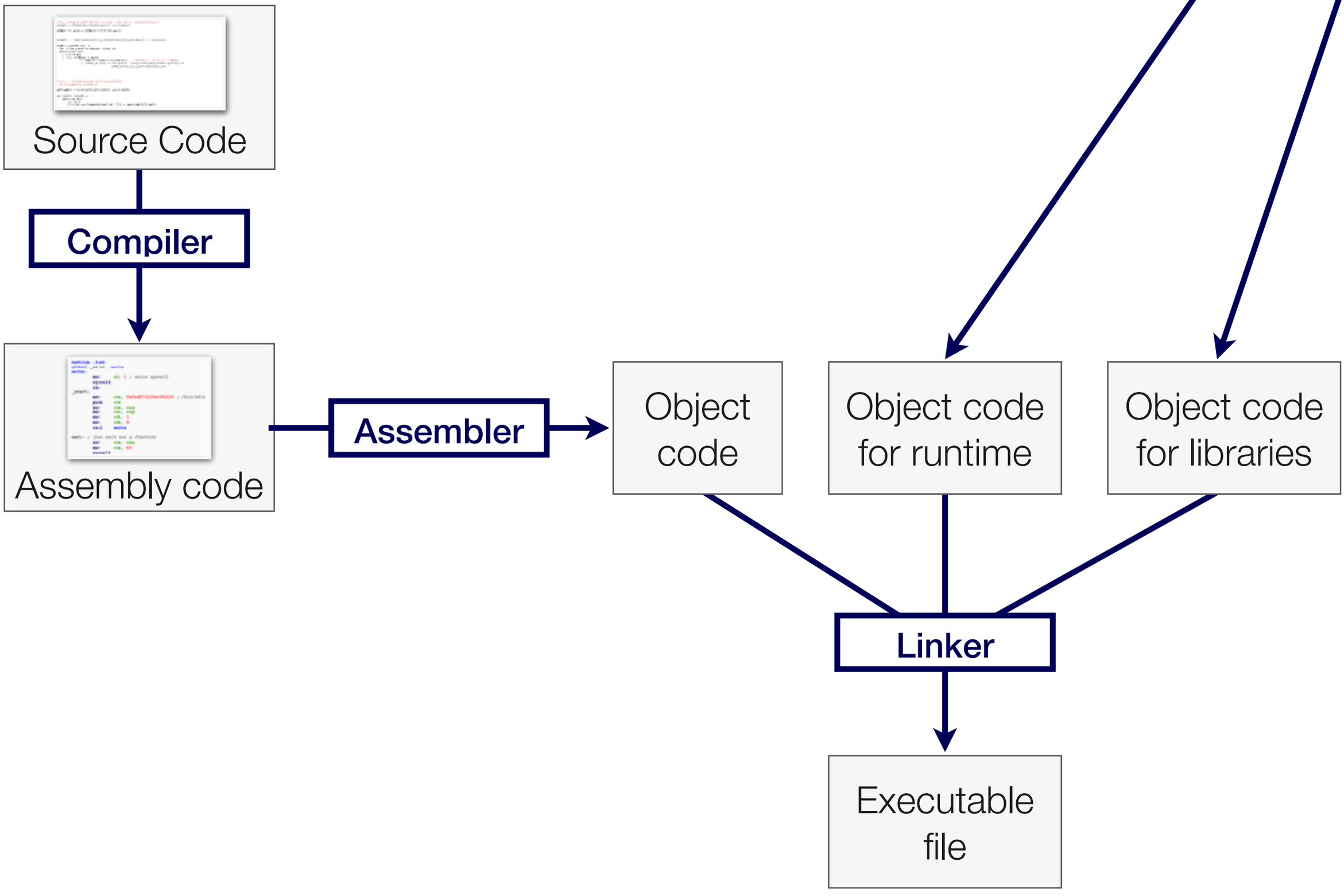


Compiler in Context

Organizing a Compiler

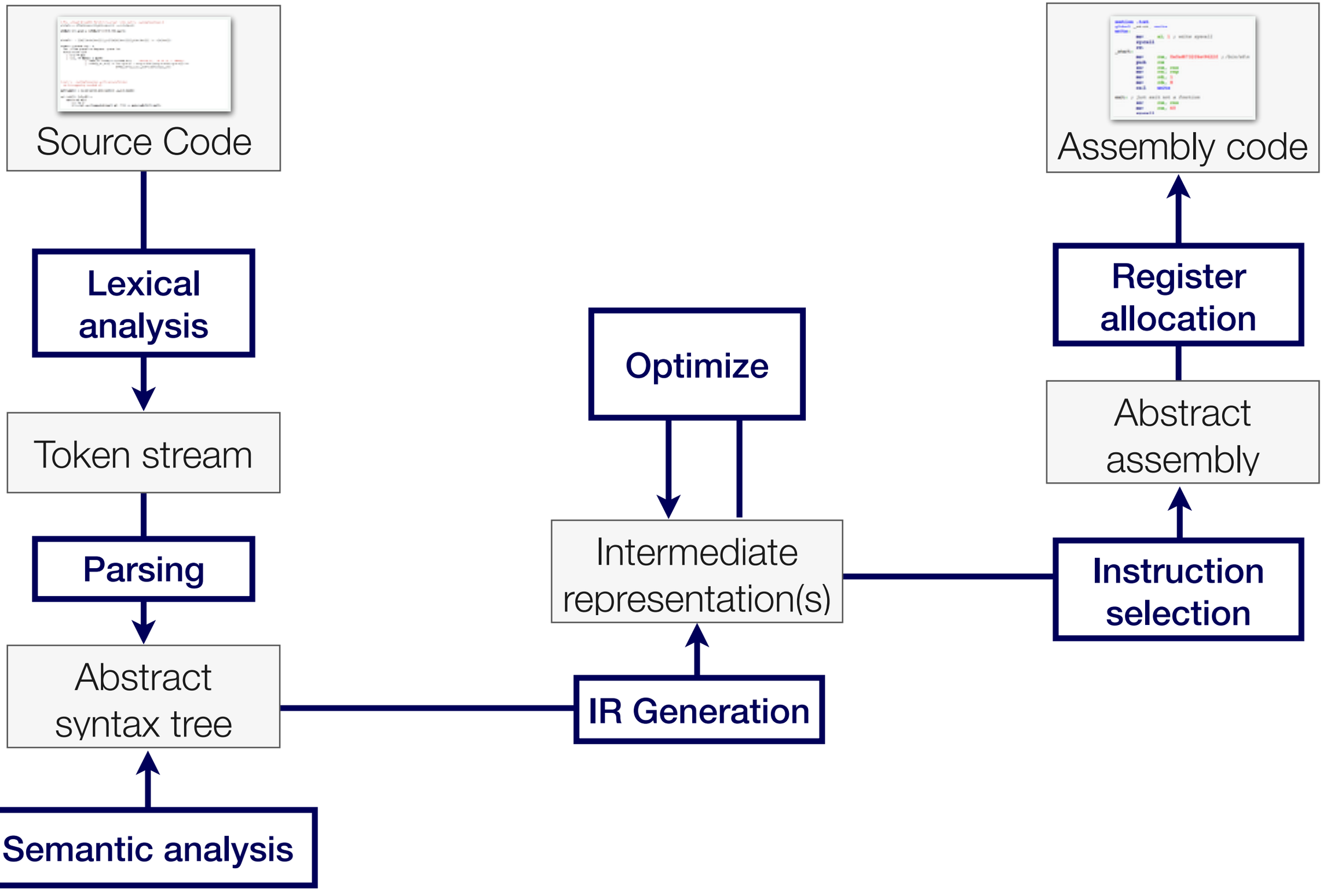
- **Split work into different compiler phases !!**

- Phases transform one program representation into another

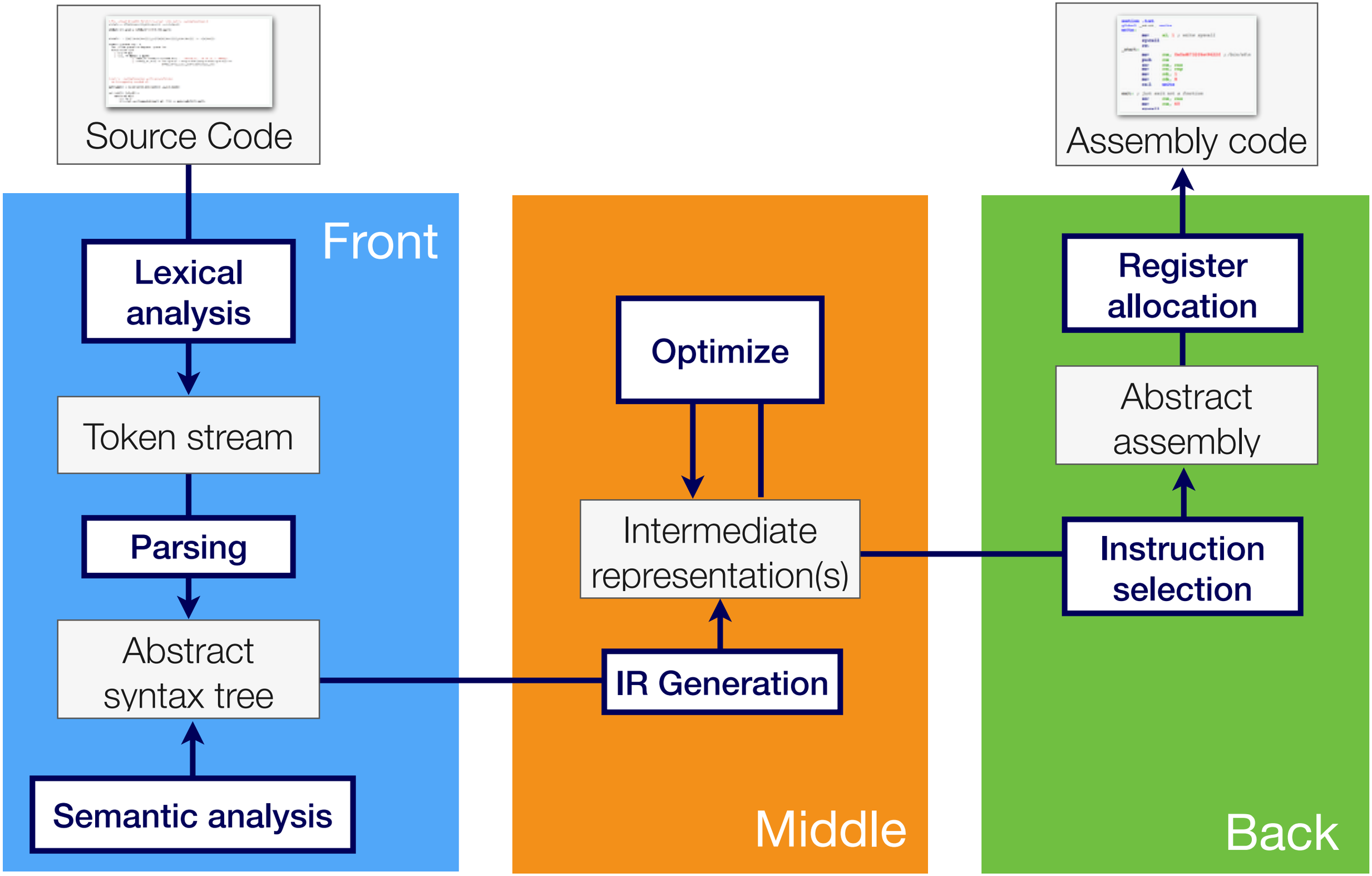
- Every phase is as simple as possible

- Phases can be between different types of program representations

- Phases can be on the same program representation



Compiler Phases



Compiler Phases