

# Program Reasoning

## 1. Introduction

Kihong Heo

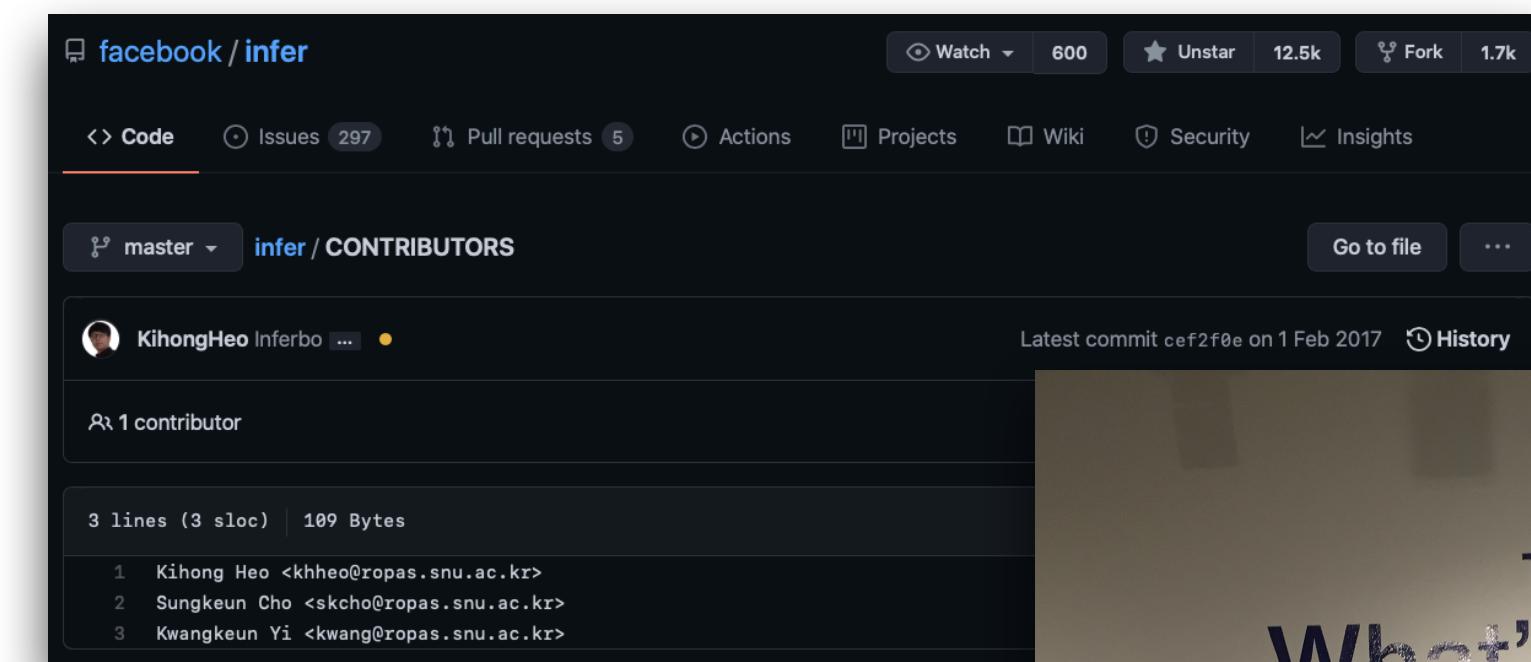


# About Me

- Instructor: Kihong Heo (허기홍, [kihong.heo@kaist.ac.kr](mailto:kihong.heo@kaist.ac.kr))
- KAIST CS / GSIS / Programming Systems Lab.
- Homepage: <https://kihongheo.kaist.ac.kr> / <https://prosys.kaist.ac.kr>
- Office: N5 2321
- Office Hours: after each class (by appointment)

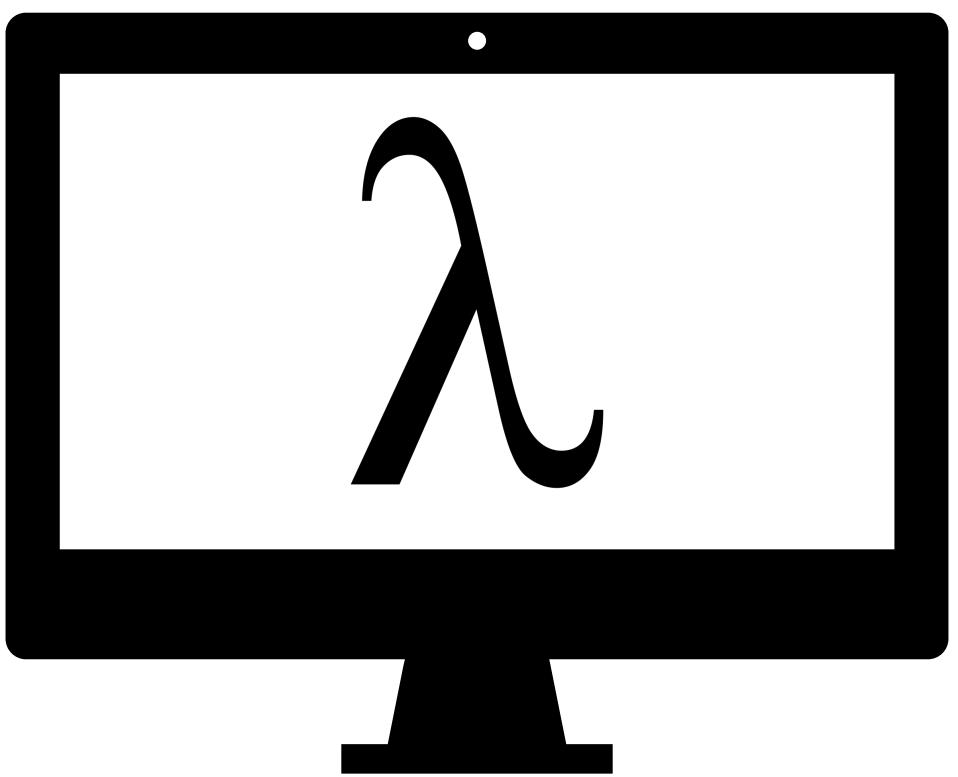
# My Research

- Goal: solid PL theories  $\Leftrightarrow$  powerful programming systems
- Keywords: programming language, program analysis, SW engineering, SW security
- Good memories:



\*<https://research.fb.com/blog/2017/02/inferbo-infer-based-buffer-overrun-analyzer/>

# My Research

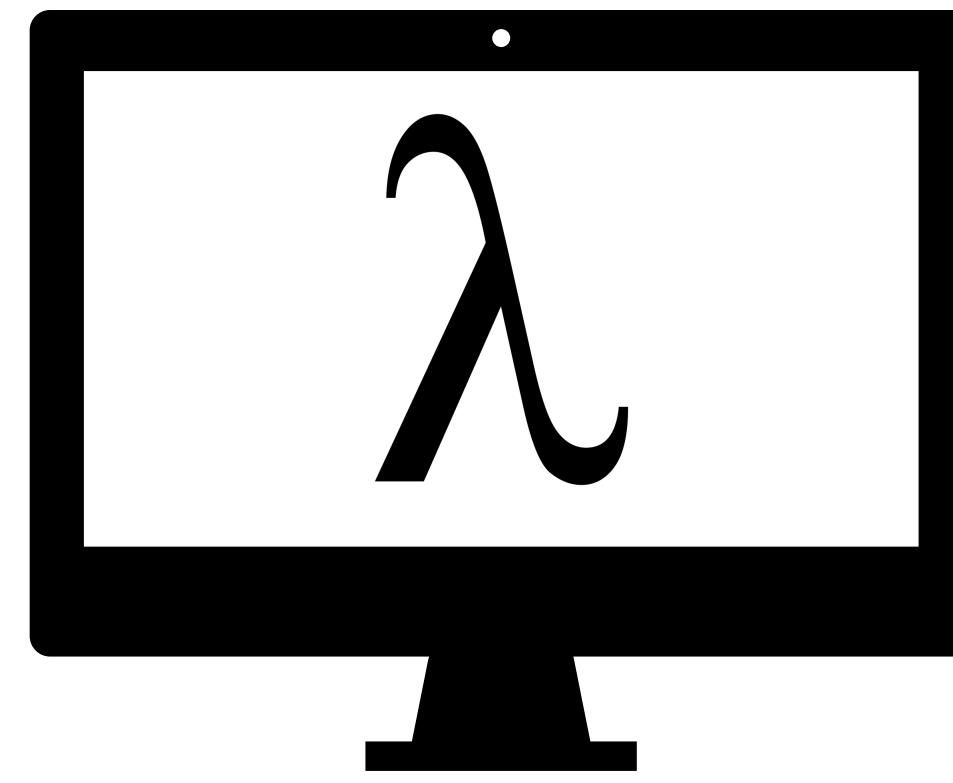


**Next-generation  
Programming Systems**

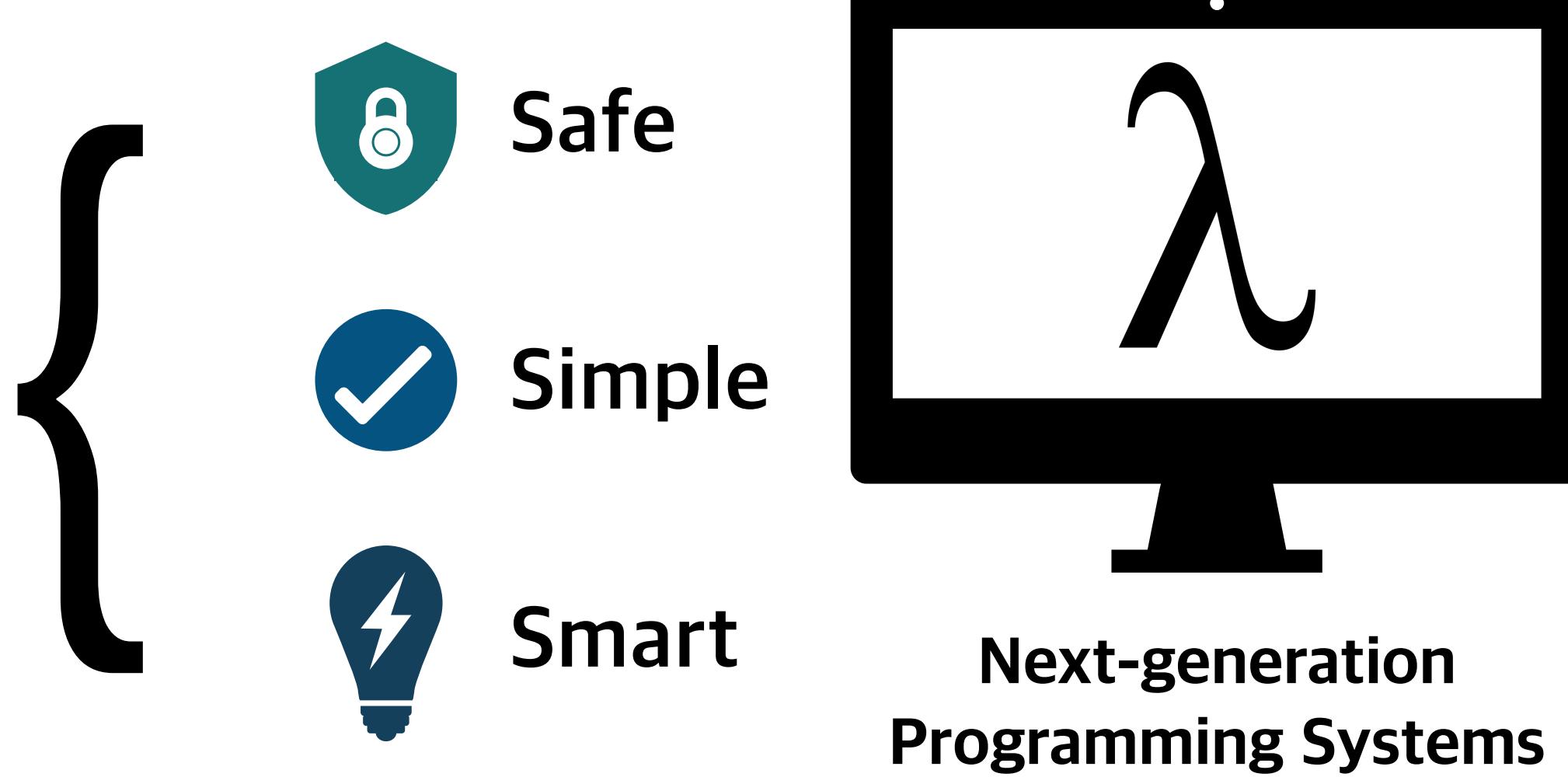
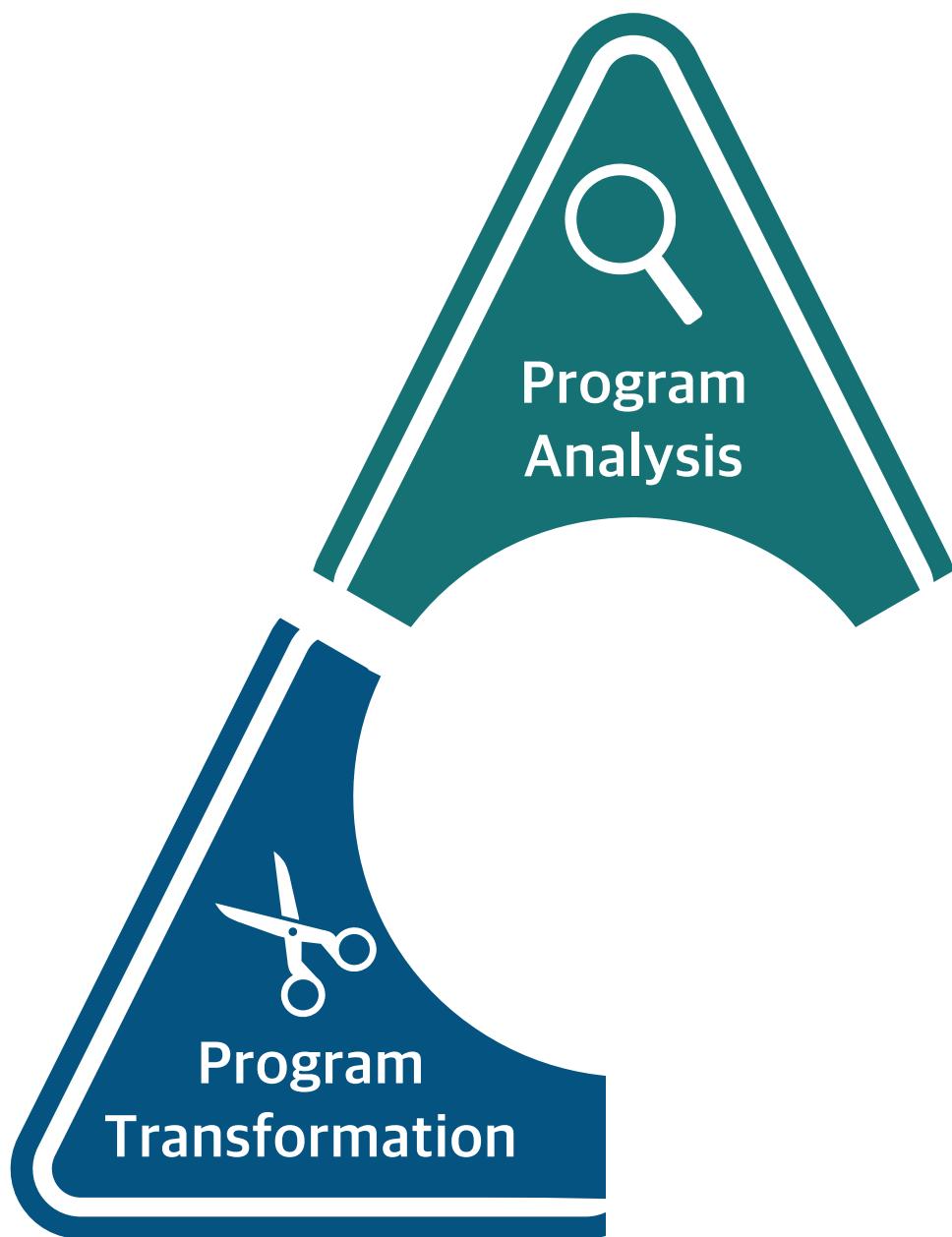
# My Research



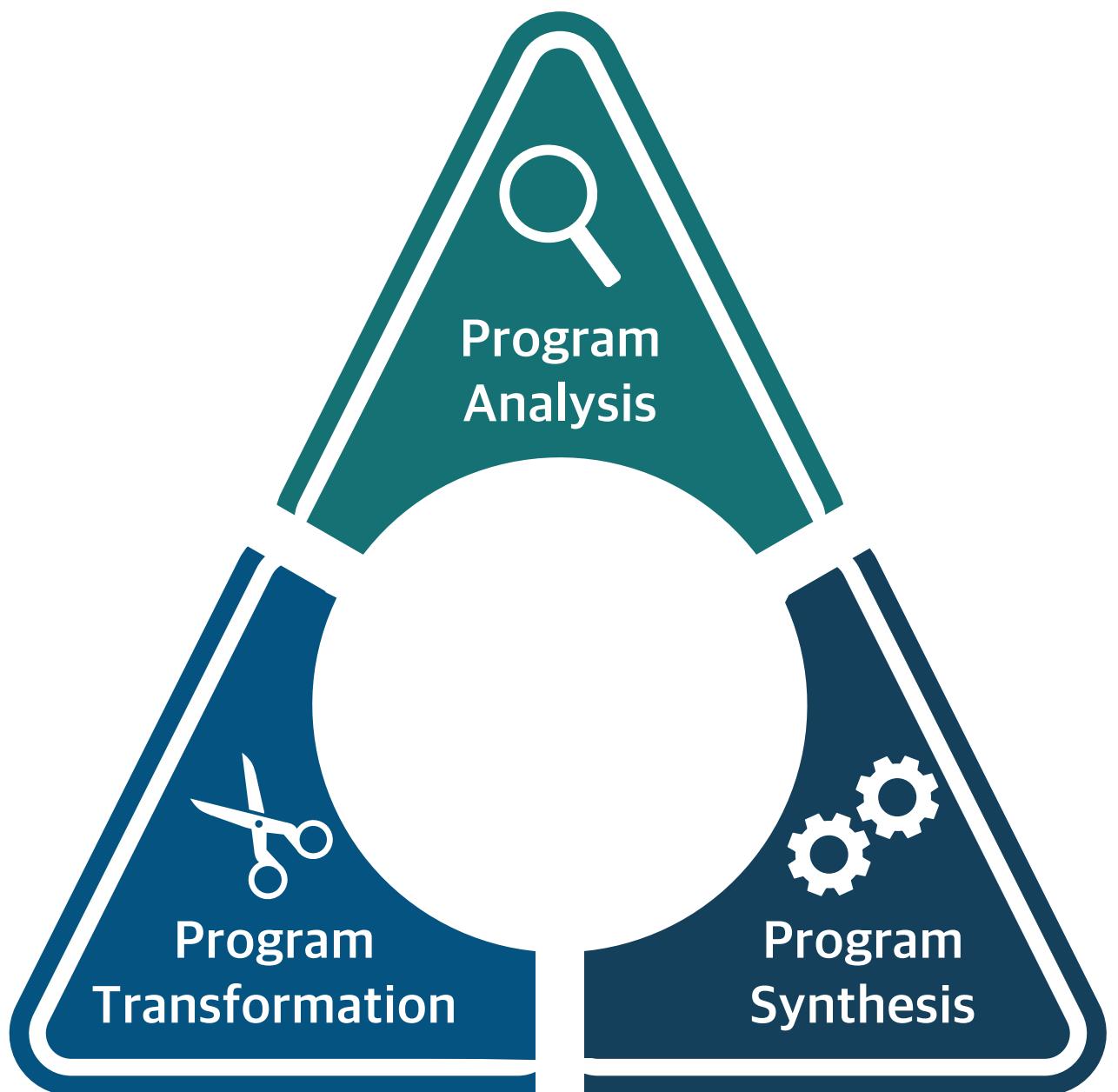
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**Safe****Simple****Smart****Next-generation  
Programming Systems**

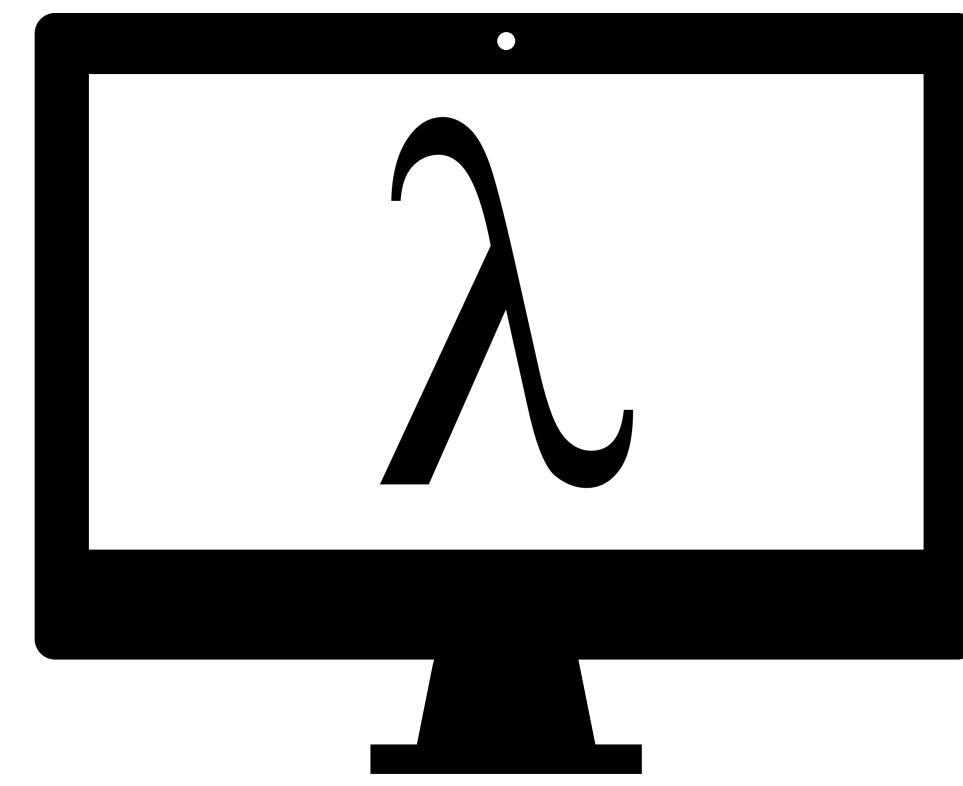
# My Research



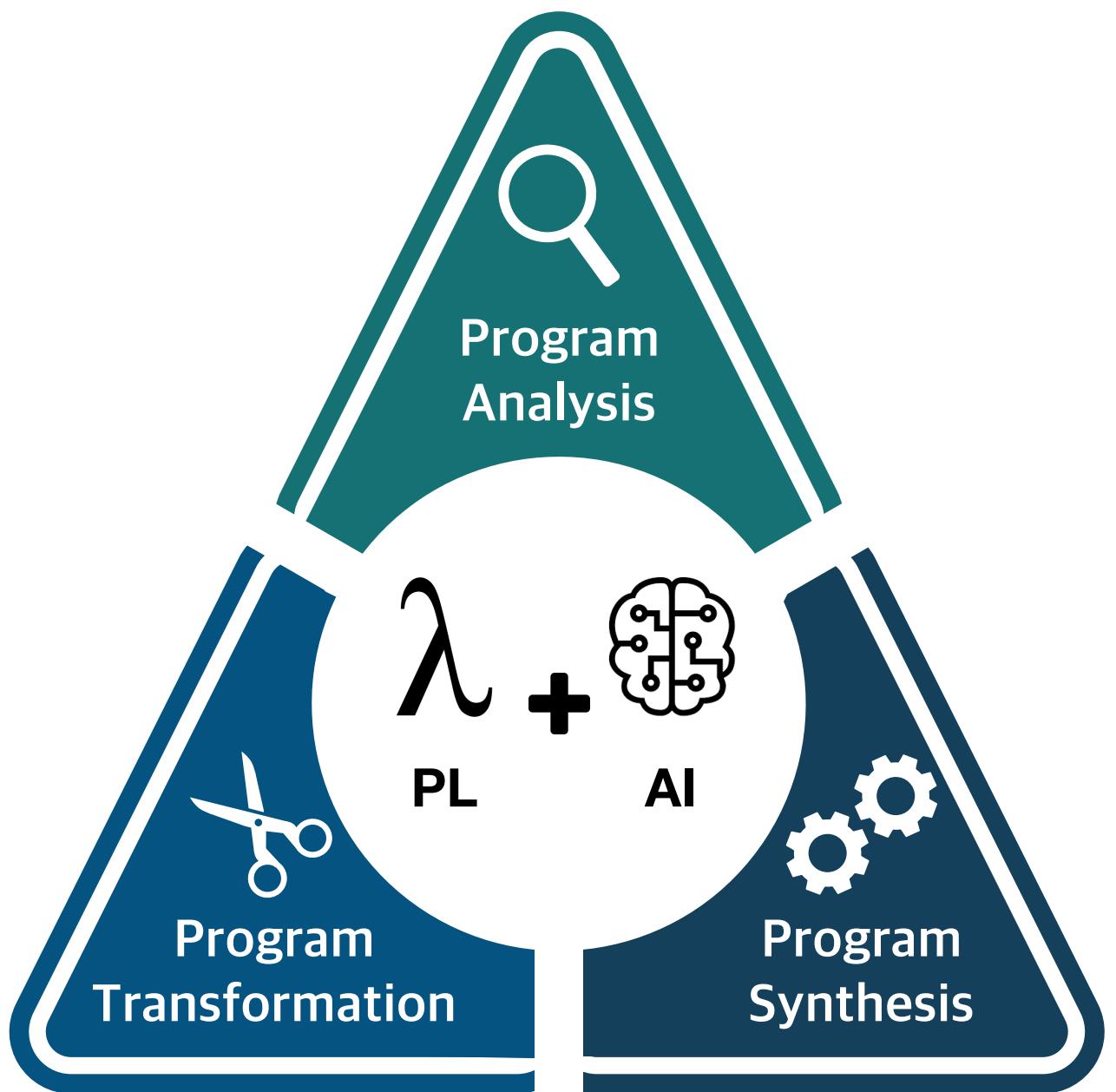
# My Research



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**Safe****Simple****Smart****Next-generation  
Programming Systems**

# My Research



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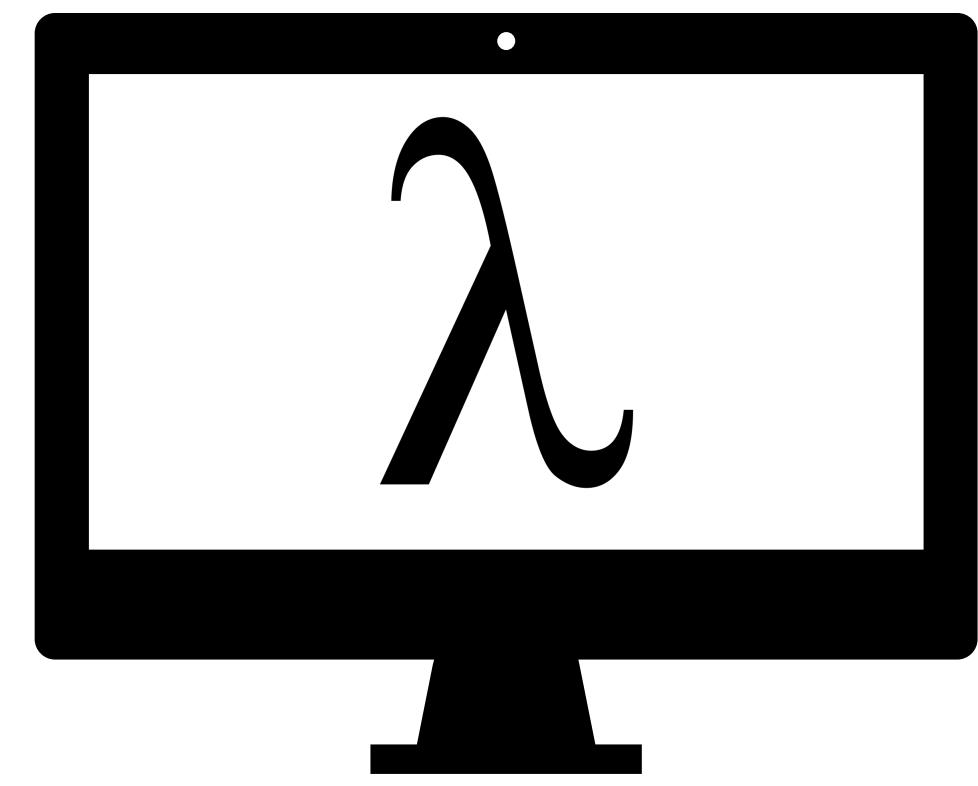
**Safe**



**Simple**



**Smart**



**Next-generation  
Programming Systems**

# Course Information

- Course Website: <https://github.com/prosyslab-classroom/cs492-program-reasoning>
- Q&A Board: <https://github.com/prosyslab-classroom/cs492-program-reasoning/issues>
- TAs (mailing list: [cs492.ta@prosys.kr](mailto:cs492.ta@prosys.kr))
  - Seungwan Kwon (권승완, [seungwan.kwon@kaist.ac.kr](mailto:seungwan.kwon@kaist.ac.kr))
  - Sujin Jang (장수진, [sujin.jang@kaist.ac.kr](mailto:sujin.jang@kaist.ac.kr))
- Textbook:
  - Lecture slides will be provided
  - See the course webpage

# Important Notice (1): Academic Integrity

- DO NOT share the course contents (e.g., assignments or exams) with others
  - Esp., Github public repository, chegg.com, etc
- DO NOT discuss the details of solutions with others
- DO NOT plagiarize
  - We keep all the submissions from previous years!
- Any integrity violation: at **LEAST F**
- If you have questions: QnA board > TAs > instructor

## 전산학부 명예규정 2022 봄학기 / School of Computing Honor Code 2022 Spring

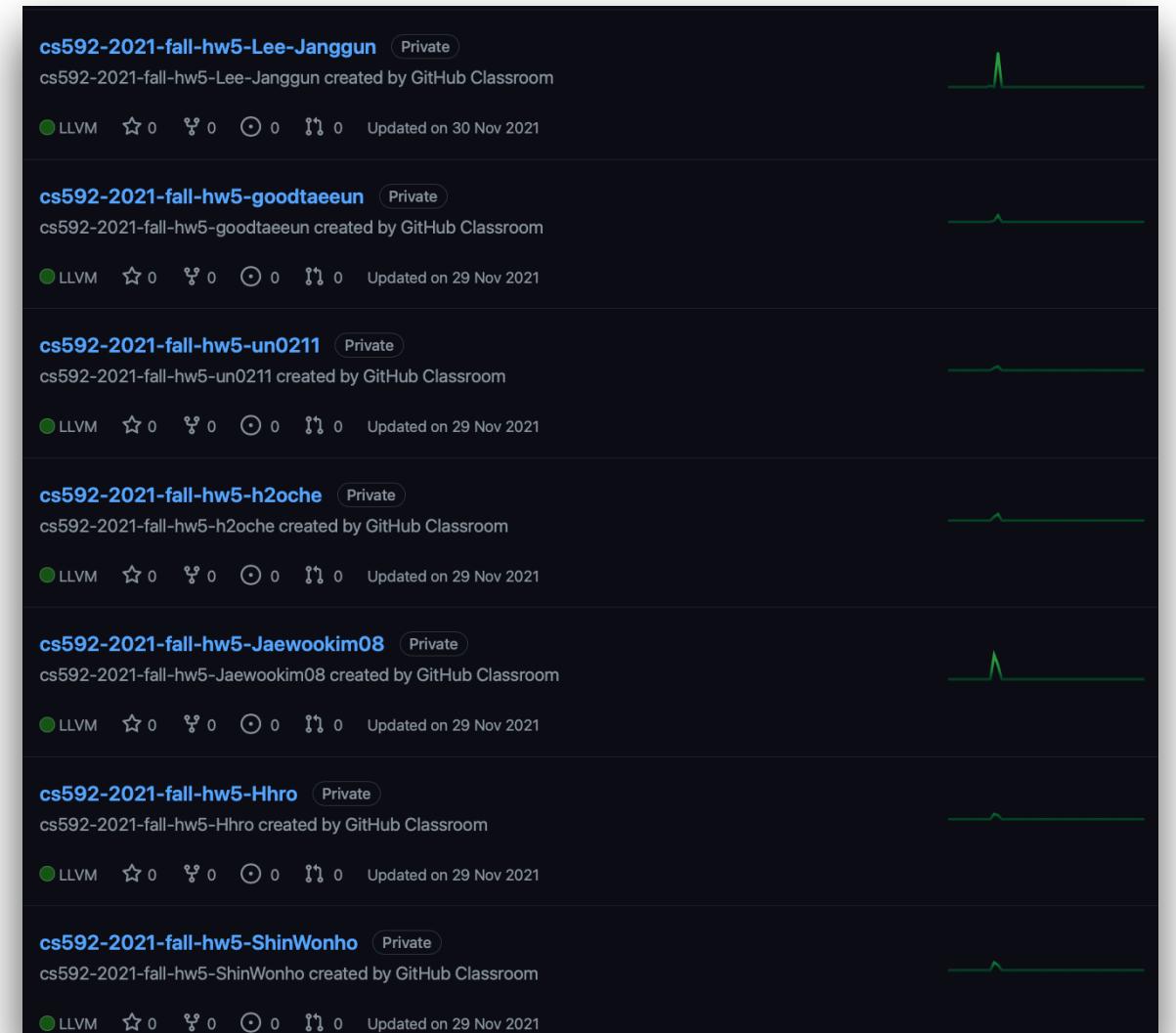
카이스트 전산학부가 운영하는 모든 수업에 참여하는 학생은 개인의 명예와 타인의 권리를 함께 존중하며 성실성과 정직성을 지키기 위하여 최선을 다합니다. 모든 시험 및 과제를 작성에 있어 허위되거나 다른 형태의 도움도 받지 않습니다. 다음의 행위들은 학생의 성실성과 정직성을 위반하는 것으로 간주됩니다:

- 본인 이외의 사람/기관이 작성한 답안지, 숙제, 프로그램 소스 코드, 보고서 등을 참고 및 이용하는 행위
- 시험 및 과제들과 관련해 [chegg.com](https://www.chegg.com)과 같이 정답을 공유하는 온라인 서비스를 이용하는 행위
- GitHub 등의 코드 저장소에 본인의 과제 답안을 공개하거나, 타인이 공개된 답안을 참고 및 이용하는 행위
- 다른 학생이 본인이 작성한 답안지, 숙제, 프로그램 소스 코드, 보고서 등을 참고하도록 용인하는 행위
- 다른 학생이 작성한 결과물을 자신의 것인 양 제출하는 행위
- 다른 학생을 대신해 시험을 치루는 행위
- 개인이 수행하도록 되어있는 take-home 시험이나 과제를 작성에 있어 허락 없이 공동 작업을 하거나 부적절한 도움을 받는 행위
- 표절, 길이와 무관하게 적절한 인용이나 언급 없이 타인의 창작물(참고서적, 문헌, 온라인상의 자료)을 무단으로 사용하는 행위

규정 위반 여부의 판단과 처벌 수위는 교과목 담당 교수에 의해 결정됩니다. 모든 부정행위는 전산학부 학사주임 교수 및 학부장님께 보고되어, 적발시 전산학부 내부적으로 아래와 같은 제재를 받습니다.

- 항후 2학기 동안 모든 포상 및 장학금 수여/추천 대상에서 제외함
- (주진공이 전산학부가 아닌 경우) 항후 2학기 동안 전산학부로의 전과 금지

위반의 심각성에 따라 학교 전체의 상벌위원회에 회부될 수 있습니다. 카이스트 학사규정이 적용하는 칭계의 범위는 아래 첨부된 학생 징계 일정 기준을 참고하세요 (학생 핸드북 한글판 67페이지, 다운로드는 [https://portal.kaist.ac.kr/ennotice/student\\_notice/11614934649338](https://portal.kaist.ac.kr/ennotice/student_notice/11614934649338))

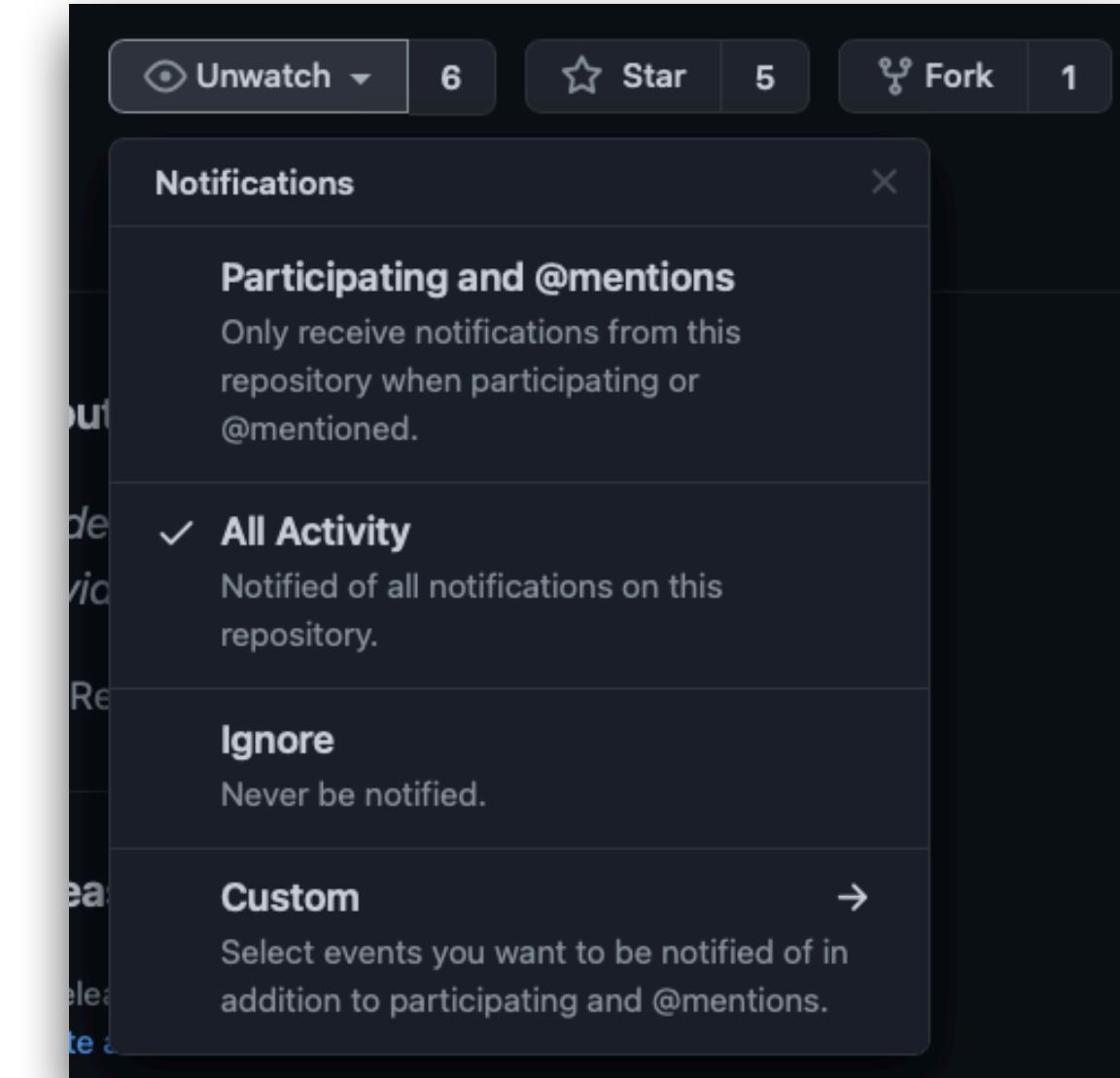


# Important Notice (2): In-class Operations

- Language: English (default), Korean (supplementary)
- Attendance: always (default), absence (if necessary)
  - No quantified attendance score
  - I expect you to be here, as you expect me to be here!
- Questions & discussion (either in Korean or in English): highly encouraged

# Important Notice (2): Out-of-class

- All Q&A and public notices: Github issue board
  - “Watch” all notifications
- Private notices (grading, etc): KLMS
- Questions are always welcome except for
  - Too detailed ones (TAs are not debuggers!)
  - Directly related to the solutions
- Actively discuss with your classmates



A long time ago  
in a galaxy far, far away....

**SOFTWARE  
BUGS**

# Software Bugs: A Persistent Problem

- A long time ago, far far away



The Patriot Missile (1991)  
Floating-point roundoff  
28 soldiers died



The Ariane-5 Rocket (1996)  
Integer Overflow  
\$100M



NASA's Mars Climate Orbiter (1999)  
Meters-Inches Miscalculation  
\$125M

- Unfortunately, it becomes your own problem now

**CNN** U.S. | World | Politics | Money | Opinion | Health | Entertainment | Tech | Style | Travel | Sports | Video | Live TV | **US**

The 'Heartbleed' security flaw that affects most of the Internet

By Heather Kelly, CNN  
Updated 5:11 PM ET, Wed April 9, 2014

A large red heart icon with liquid dripping down from it, symbolizing the 'Heartbleed' bug.

This dangerous Android security bug could let anyone hack your phone camera

By Anthony Spadafina November 23, 2019

Camera app vulnerabilities allow attackers to remotely take photos, record video and spy on users

A smartphone displaying a green binary code pattern over a keyboard background, symbolizing a security vulnerability in mobile devices.

AERIAN MARSHALL / TRANSPORTATION 06:30 2019 07:00 AM

**What Boeing's 737 MAX Has to Do With Cars: Software**

Investigators believe faulty software contributed to two fatal crashes. A newly discovered fault will likely keep the 737 MAX grounded until the fall.

A Boeing 737 MAX airplane flying through a cloudy sky, symbolizing a major aviation safety issue due to software bugs.

Homeland Security warns that certain heart devices can be hacked



New in Life & Style

Interfaith 4th-graders bond through poetry, art and Steph Curry 2:03 PM

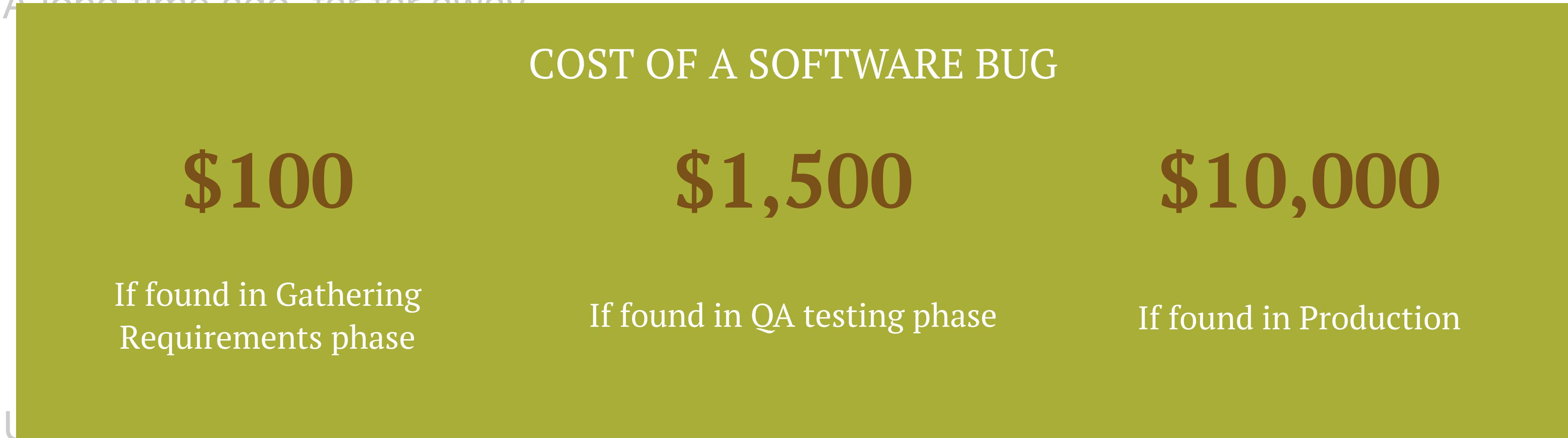
6 ways to celebrate Valentine's Day in Lake Geneva 8:55 AM

Six ways to keep your kids healthy during winter 8:56 AM

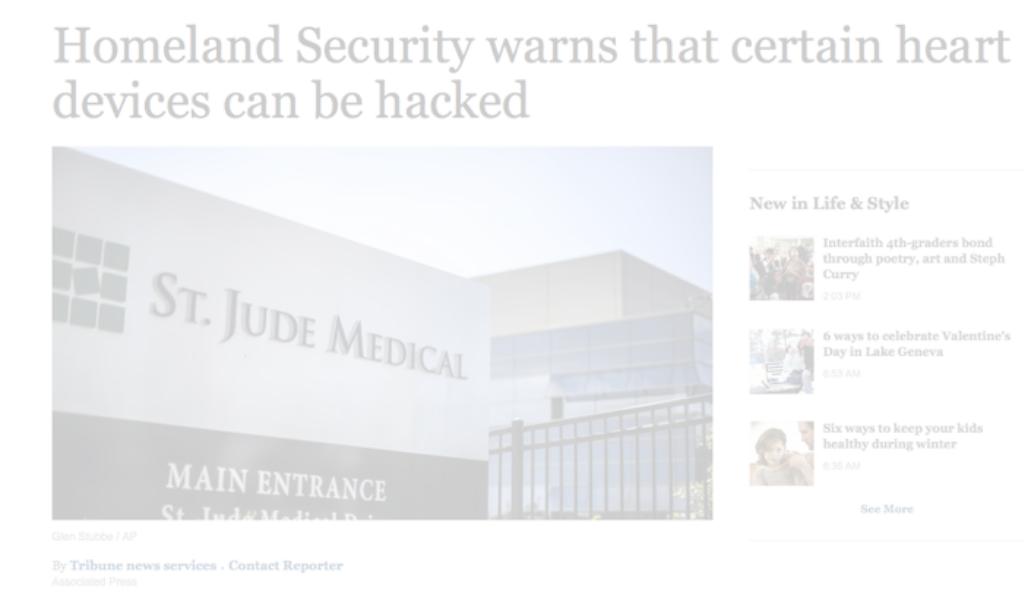
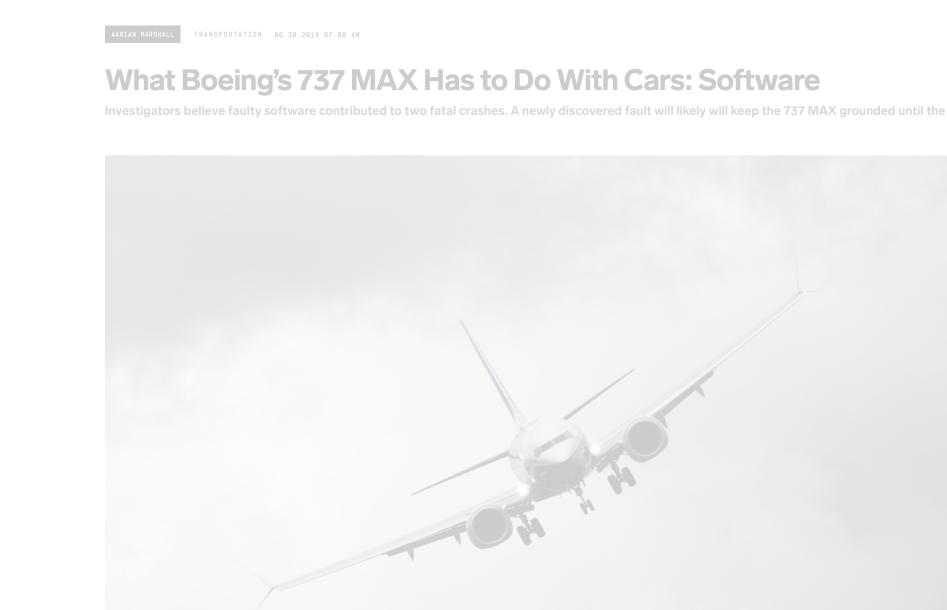
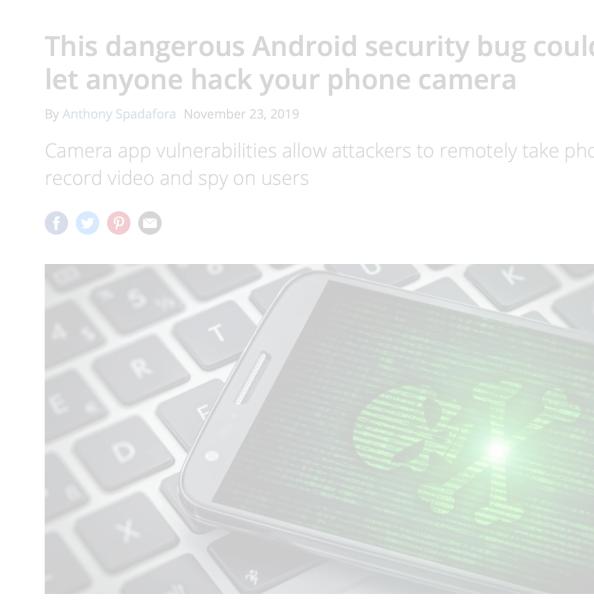
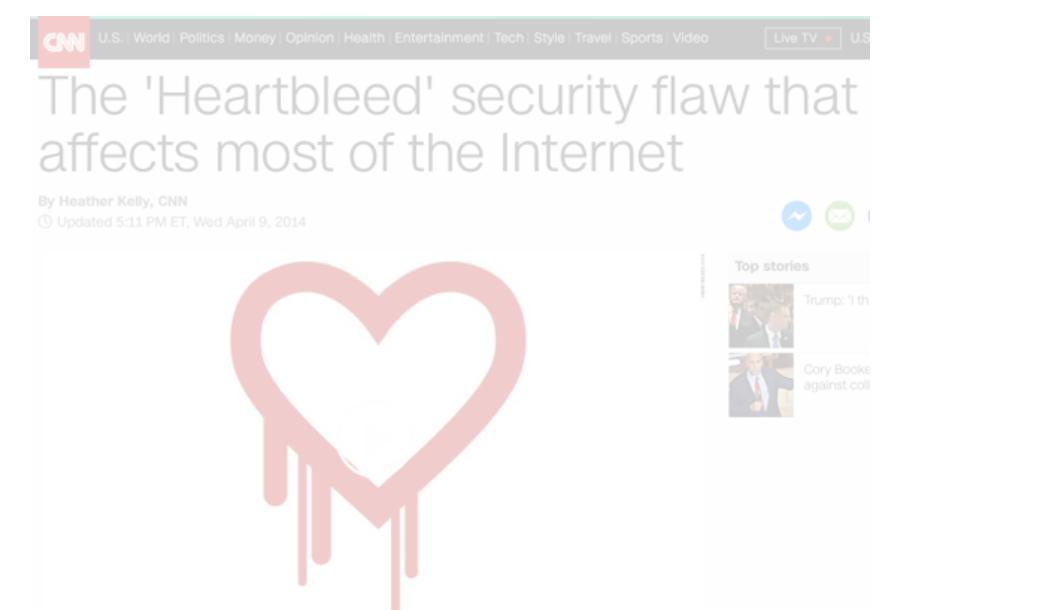
See More

# Software Bugs: A Persistent Problem

- A long time ago, far far away...

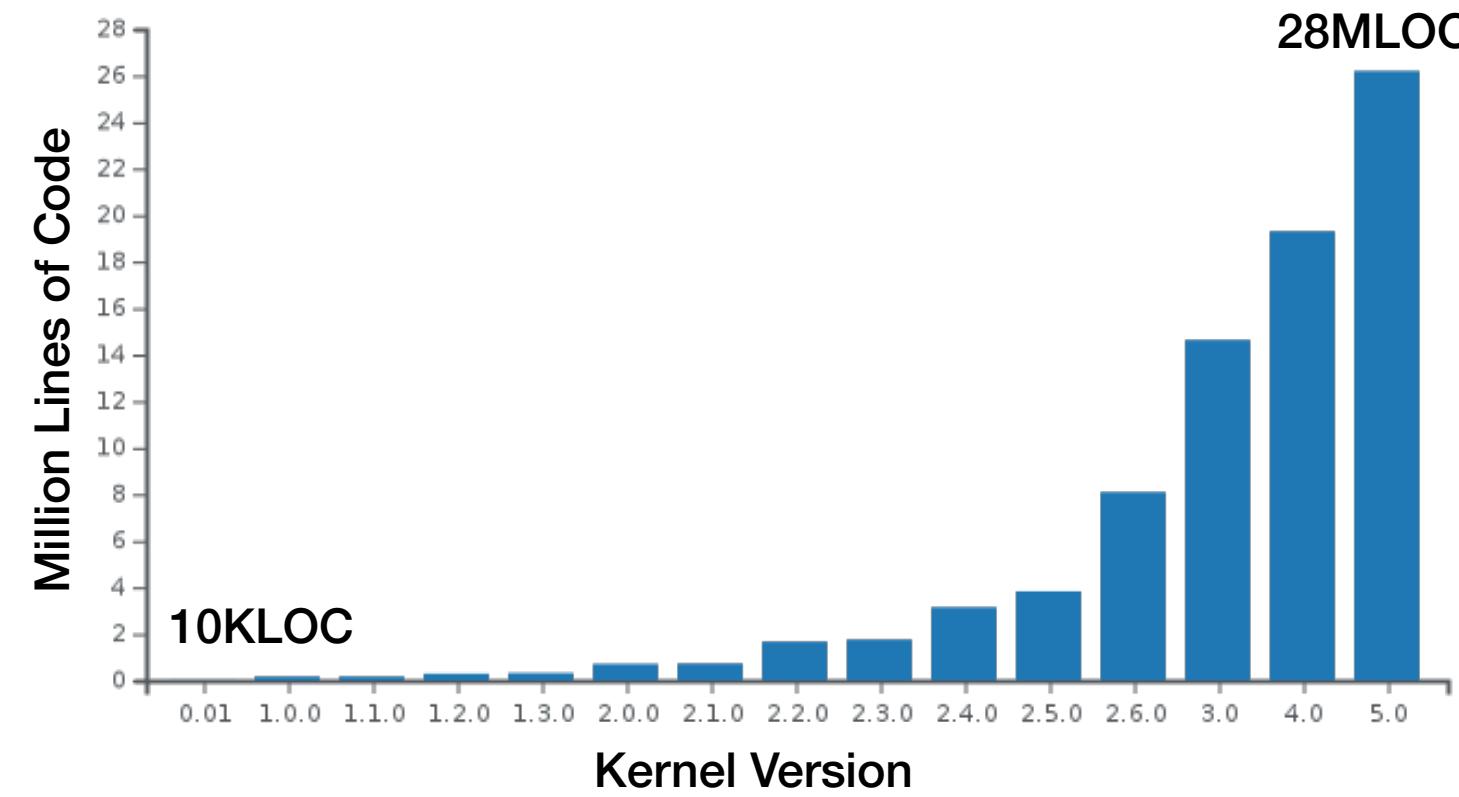


- IBM Systems Sciences Institute, 2015

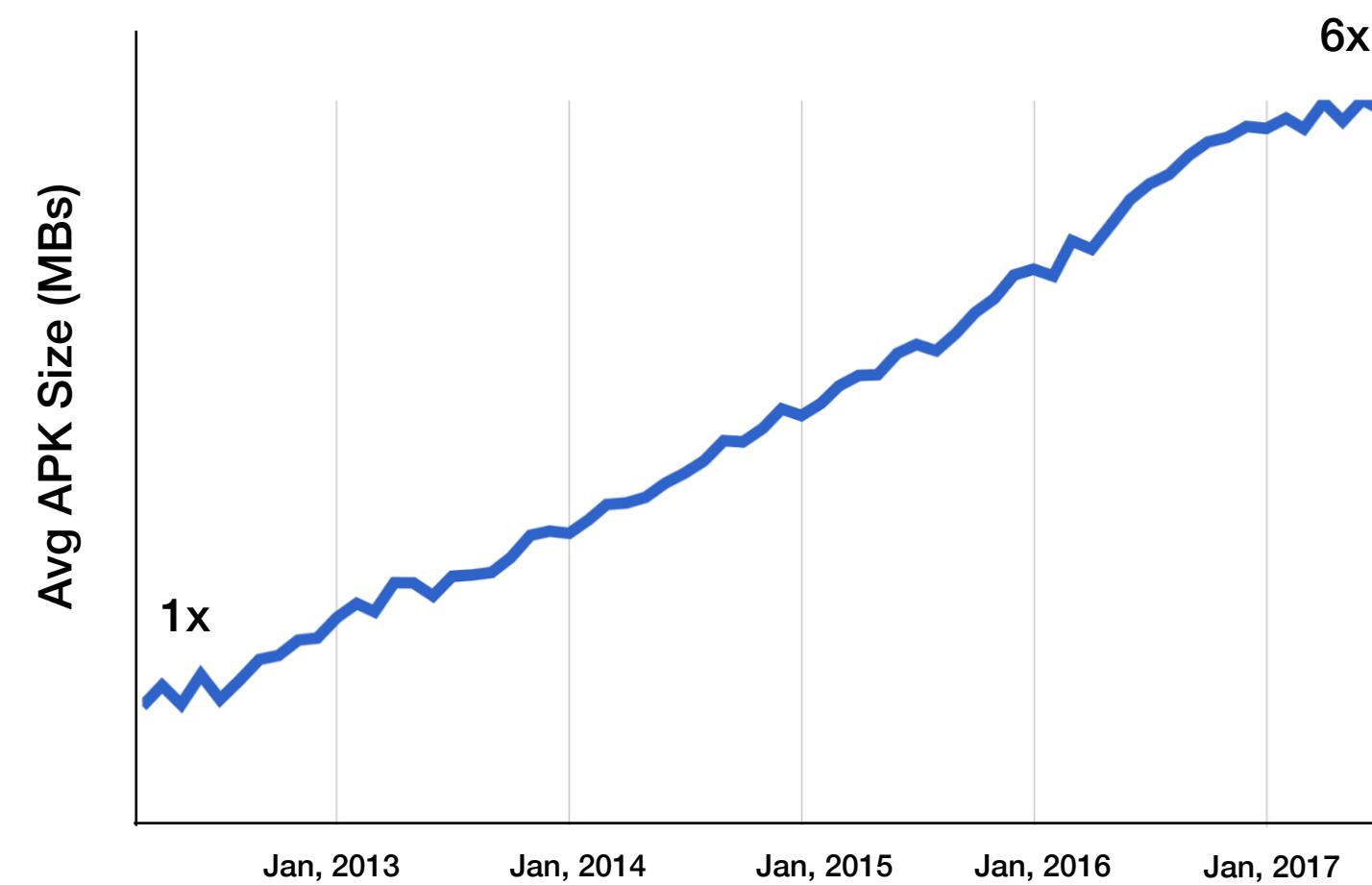


# Why Software Still Fails?

**Size of Linux Kernel**



**Avg. Size of Android Apps**



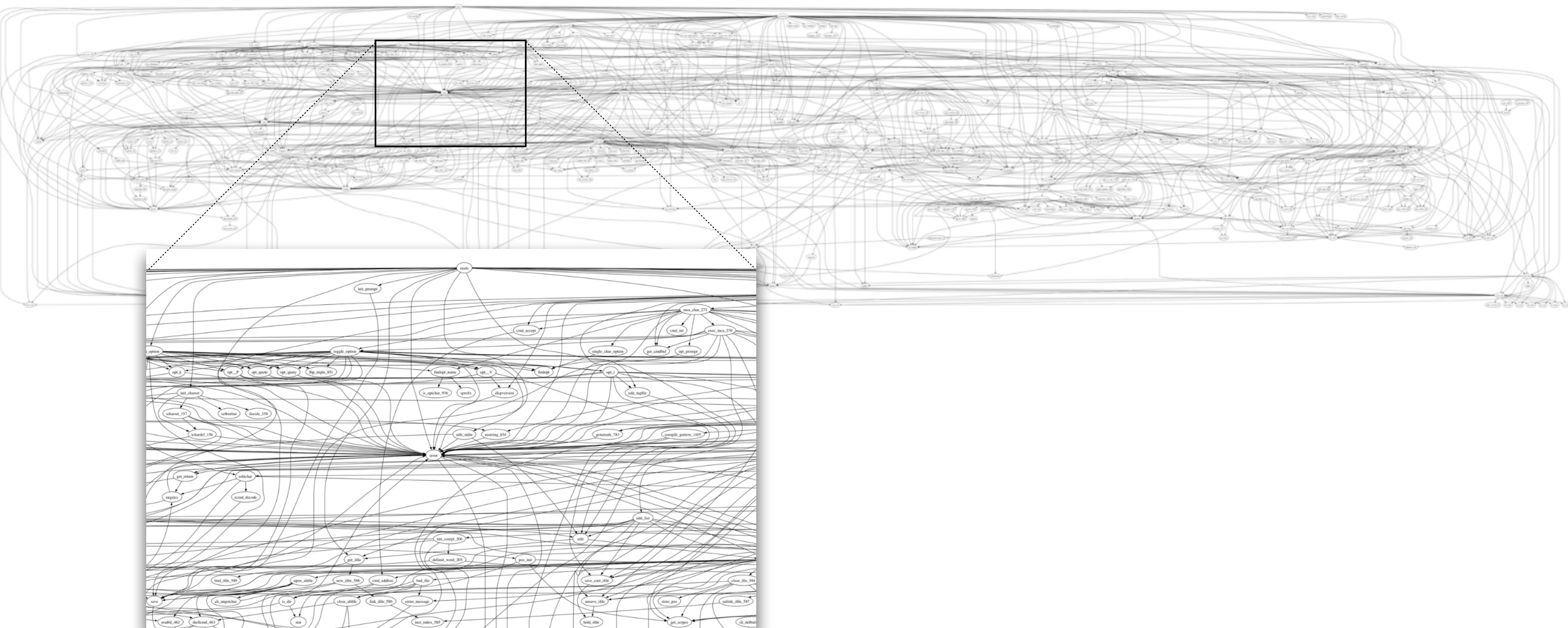
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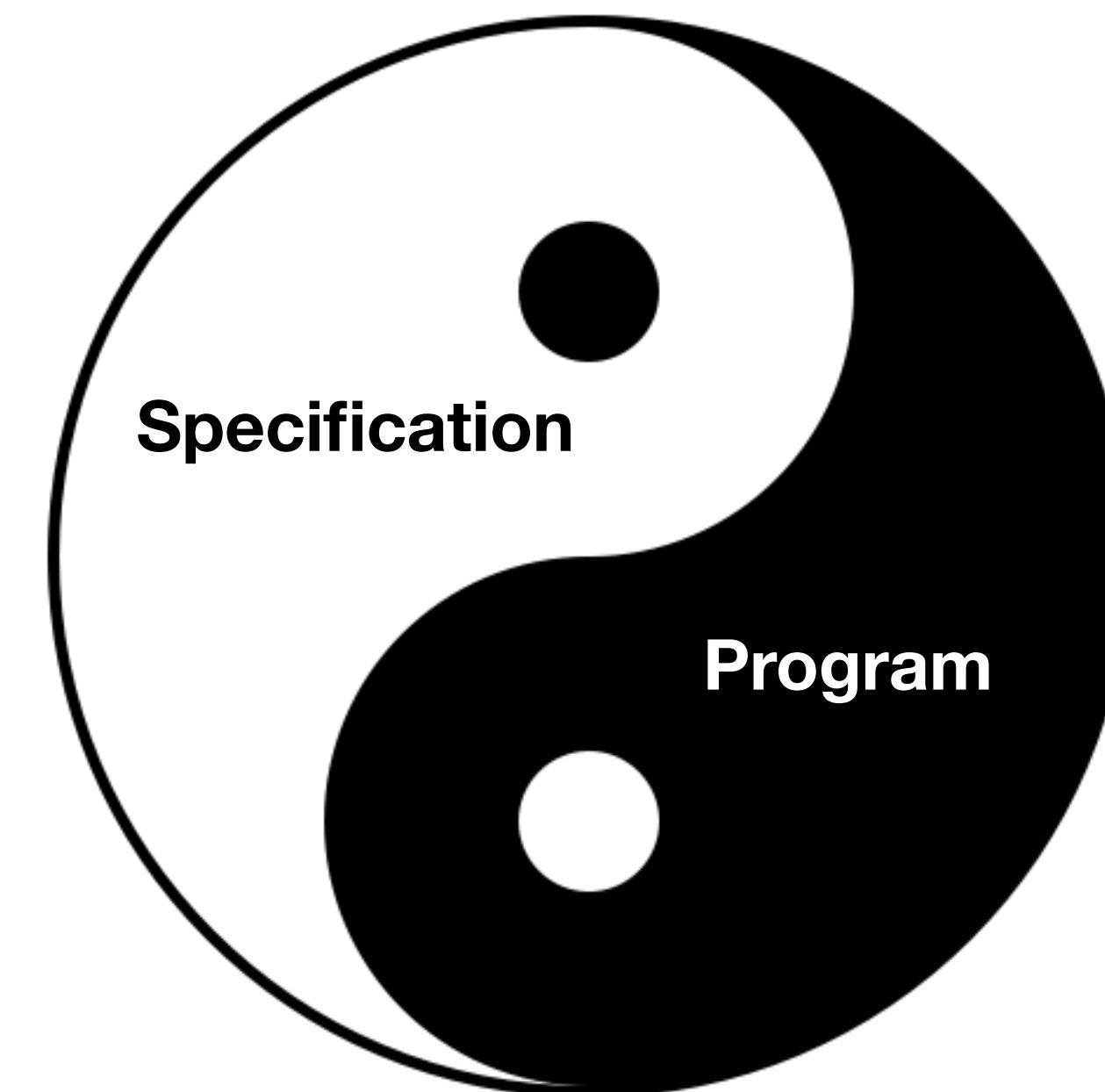
**10M+ New Developers  
44M+ New Repositories  
87M+ New Pull Requests  
in 2019**

# Software Complexity

less-382 (23,822 LOC)



# What is the Future of Programming?



How to automatically **generate** a program  
that satisfies the specification?

How to automatically **prove** if a given program  
satisfies the specification?



# Course Objectives: Principles

- Program verification
  - How to specify specification?
  - How to generate a correctness proof?
- Program synthesis
  - How to specify specification?
  - How to generate a correct program?

# Success Stories

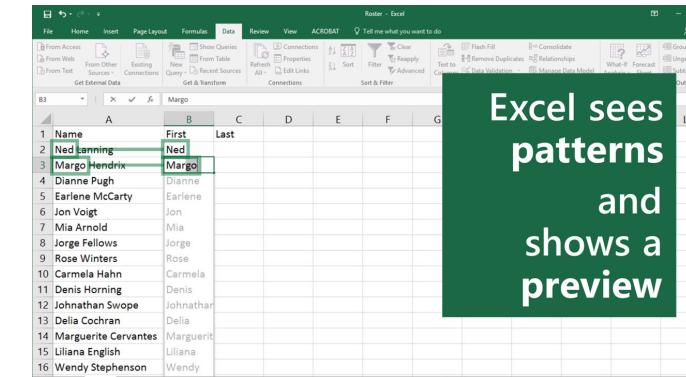
## Program Verification



Windows Device Driver

*Microsoft*

## Program Synthesis



Excel FlashFill

*Microsoft*

Astrée  
Airbus Controller  
*ENS / AbsInt*

A screenshot of a GitHub Copilot interface showing a snippet of Node.js code for sentiment analysis.

Copilot  
*Github*

# Course Objectives: Opportunities

- What is the state-of-the-art? What are the applications?
  - Program verification: API protocol, compiler, web browser, OS, DNN, ...
  - Program synthesis: cryptography, de-obfuscation, programming-by-example, ...
- What is your own application?

# Course Objectives: Practice & Challenge

- Homework: **design & implement** program analyzers
  - 6 (main) + 3 (dummy) assignments
- Programming assignments in OCaml using LLVM & Z3
  - You will write your verifier & synthesizer in OCaml
  - Your verifier will analyze LLVM IR code
  - You will utilize Z3 in your verifier & synthesizer
- Why LLVM? (<https://llvm.org>)
- Why OCaml? (<https://ocaml.org>)
- Why Z3? (<https://github.com/Z3Prover/z3>)



# The LLVM Compiler Infrastructure

- The de-facto standard & well-structured compiler toolchain
  - parser, code optimizer, linker, loader, debugger, etc
- A wide variety of frontends: C/C++, Obj-C, Swift, Fortran, etc
  - translated to the LLVM IR (intermediate representation)



**Apple's other open secret: the LLVM Compiler**

By Prince McLean

Friday, June 20, 2008, 04:10 am PT (07:10 am ET)

SproutCore, profiled earlier this week, isn't the only big news spill out from the top secret WWDC conference due to Apple's embrace of open source sharing. Another future technology featured by the Mac maker last week was LLVM, the Low Level Virtual Machine compiler infrastructure project.

Like SproutCore, LLVM is neither new nor secret, but both have been hiding from attention due to a thick layer of complexity that has obscured their future potential.

**Looking for LLVM at WWDC**

Again, the trail of breadcrumbs for LLVM starts in the public WWDC schedule. On Tuesday, the session "New Compiler Technology and Future Directions" detailed the following synopsis:

Google Chrome is replacing Microsoft's C++ compiler with Clang

By Muhammad Jarir Kanji · Mar 6, 2018 14:06 EST · HOT!

Alongside bringing better touch support and automatic ad-blocking for 'intrusive' ads to the desktop version of Chrome, Google is also making some changes to its browser under the hood. The company is now starting to build Chrome for Windows using the Clang compiler which it already uses for other platforms like macOS and Linux.

IBM Developer

Power developer portal Blogs Feedback

Announcements Compilers

## IBM C/C++ and Fortran compilers to adopt LLVM open source infrastructure

SiyuanZhang

Published on February 23, 2020 / Updated on February 26, 2020

# The OCaml Language

- Simple, safe, and realistic programming language
  - Strong type system, higher-order functions, etc
- Official OCaml bindings to LLVM and Z3 API supported
- A lot of growing demands from academia and industry
- See the materials on the course webpage



# The Z3 Theorem Prover



- State-of-the-art automated theorem prover by Microsoft Research
- Solving satisfiability modulo theory (SMT) problems
  - first-order logic with background theories  
(e.g., arithmetic, bit-vectors, arrays, datatypes, uninterpreted functions, etc)

## Boolean Satisfiability Problem (SAT)

$$(\neg A \vee B) \wedge (\neg B \vee C) \wedge (A \vee \neg C \vee B)$$

Satisfiable when

$A = \text{false}$

$B = \text{true}$

$C = \text{true}$

## Satisfiability modulo theory (SMT)

$$x + 2 = y \implies f \text{read } write(a, x, 3, y - 2) = f(y - x + 1)$$

Arithmetic

Array

Uninterpreted Functions

# Homework

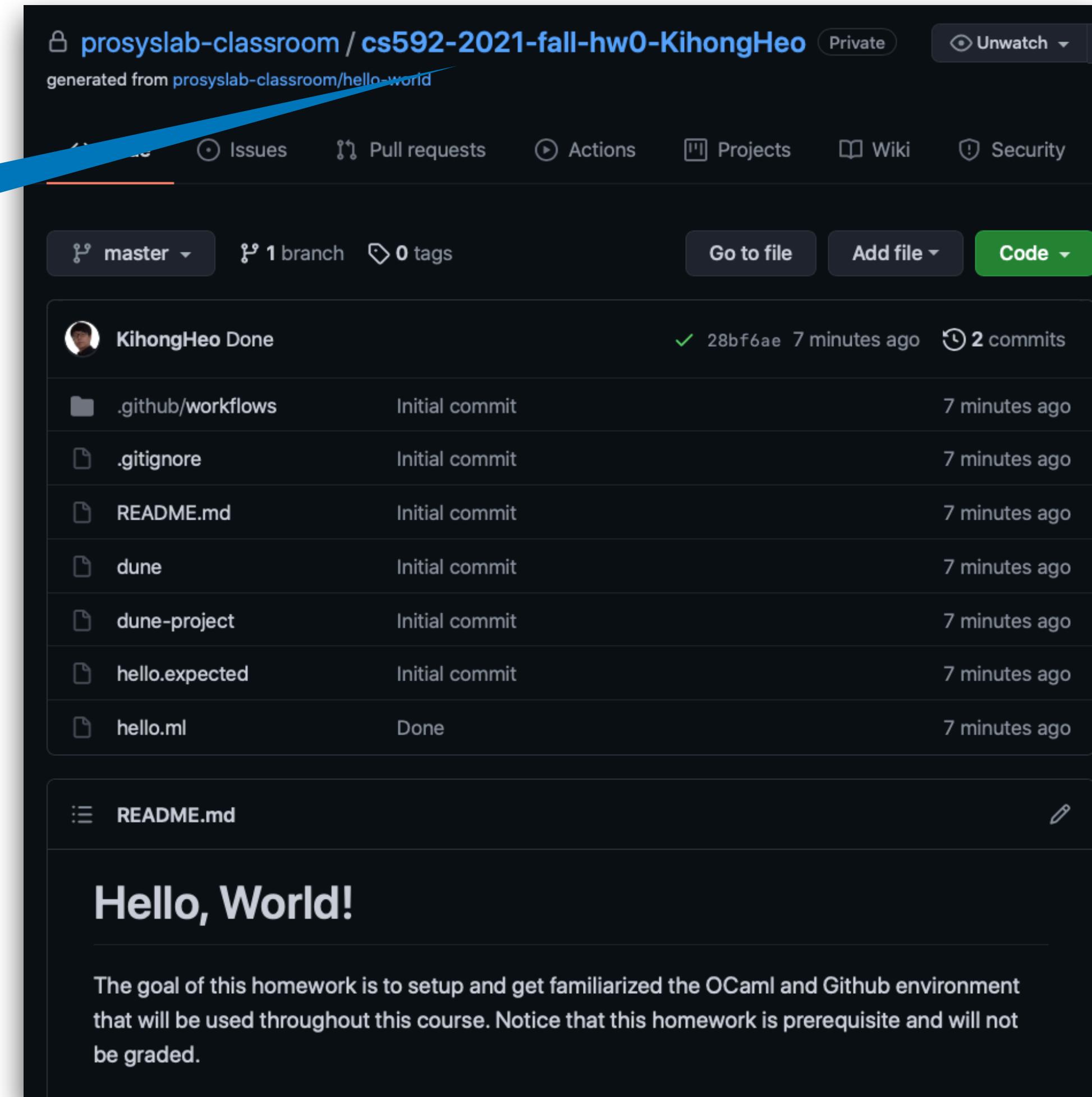
- All submissions will be managed using Github / Github Classroom
  1. For each HW, a unique invitation URL will be posted on the issue board
  2. Once you accept, a private repo for your assignment will be created
  3. You can push as many commits as you want before the deadline
  4. The final commit of your master branch will be graded
- Gradescope will be used for some assignments and exams
- 80% credit for 1-day late, 50% credit for 2-days late, NO credit otherwise

# Homework 0.1: Hello, World!

- Goal: setting up and getting familiarized with OCaml and Git environments
  - Implement your “hello-world” program in OCaml
  - Test on your machine
  - Push to your Github repository
  - See the result in Github Action
- The invitation URL will be posted on the course webpage
- Will not be graded

# Homework 0.1: Hello, World!

1. Accept the invitation  
and have your repository



# Homework 0.1: Hello, World!

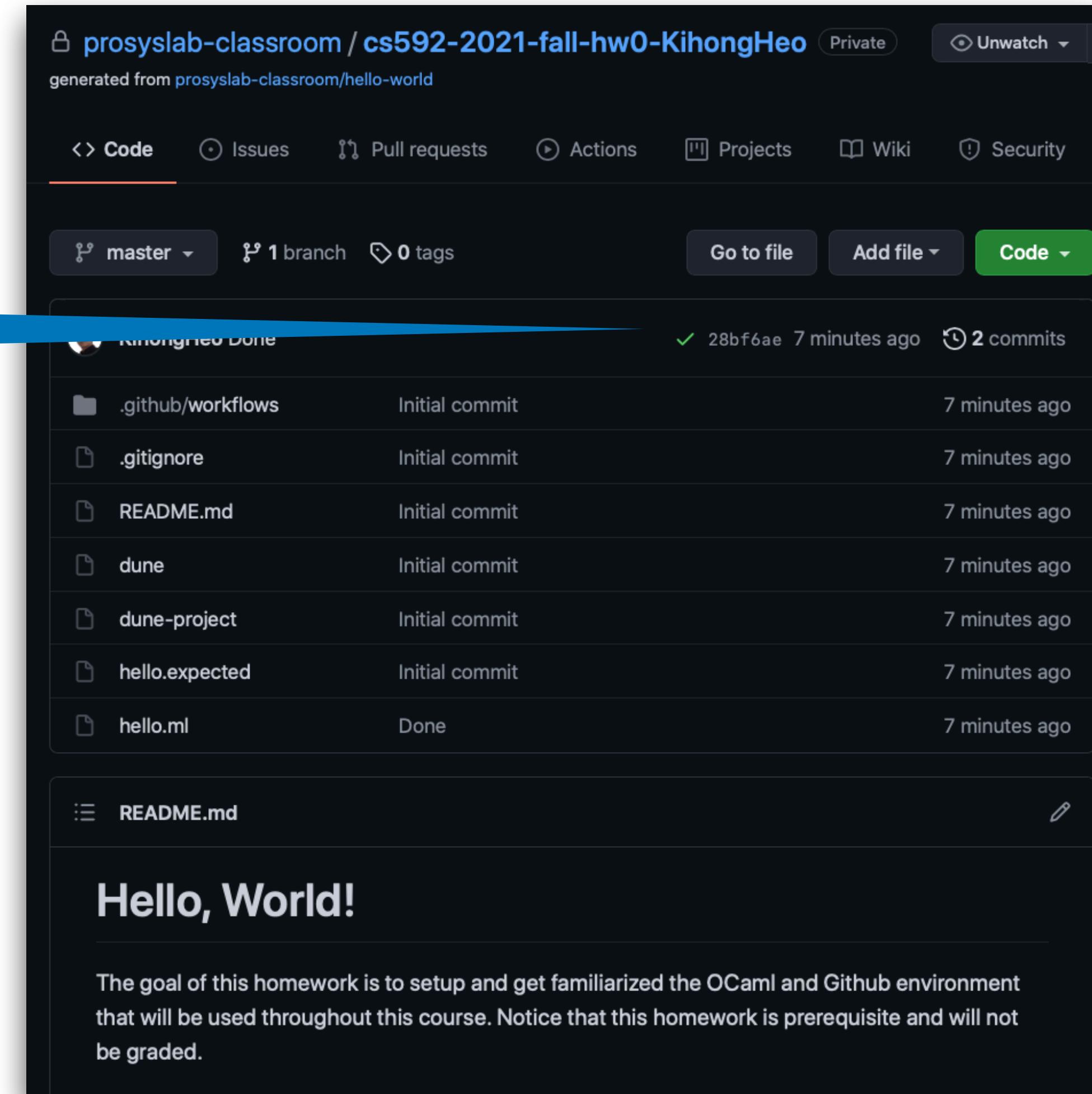
A screenshot of a GitHub repository page for "prosylab-classroom / cs592-2021-fall-hw0-KihongHeo". The repository is private and was generated from "prosylab-classroom/hello-world". The "Code" tab is selected, showing the master branch with 1 branch and 0 tags. A commit by "KihongHeo Done" was made 7 minutes ago, containing 2 commits. The commit details show files like .github/workflows, .gitignore, README.md, dune, dune-project, hello.expected, and hello.ml. The README.md file contains the text "Hello, World!". Below the README, a note states: "The goal of this homework is to setup and get familiarized the OCaml and Github environment that will be used throughout this course. Notice that this homework is prerequisite and will not be graded."

2. Commit your code

File	Type	Commit Message	Time
.github/workflows		Initial commit	7 minutes ago
.gitignore		Initial commit	7 minutes ago
README.md		Initial commit	7 minutes ago
dune		Initial commit	7 minutes ago
dune-project		Initial commit	7 minutes ago
hello.expected		Initial commit	7 minutes ago
hello.ml		Done	7 minutes ago

# Homework 0.1: Hello, World!

## 3. See your result



# Homework 0.2: OCaml Programming

- Goal: getting familiarized with basic OCaml programming
  - Solve a few programming problems in OCaml
  - Test on your machine
  - Push to your Github repository
  - See the result in Github Action
- The invitation URL will be posted on the course webpage
- Will not be graded but highly recommended if you are not familiar with OCaml

# Homework 0.3: Watching the Video

- Watch the Youtube video about “Undecidability” vis the course webpage
- Think about the followings:
  - What is the fundamental limitation of SW?
  - Why is it difficult to prove the correctness of SW?
  - How can we overcome the above challenges?
- Provide your opinion and write an essay
  - Not mandatory but a reward might be given depending on the quality
  - E.g., participation point, questions for the final exam, drink, fame, etc

# Writing

- Syntactic requirements
  - Typeset your document in Latex using a provided template (maximum 2 pages)
  - Korean (if you are a native Korean speaker), English (otherwise)
- Semantic requirements: Top-down (두괄식)
  - For each paragraph, write the topic sentence first followed by the details.
- See the README for the details
- The invitation URL will be posted on the course webpage

# Misc

- Submit your Github account via the google form (see the Github issue board)
- Join Gradescope (see the Github issue board)
  - For written assignments and the final exam
- Rules for programming assignments
  - Preserve the structures (directories, files, types, etc)
  - Don't install further Github App