

# Program Analysis

## 1. Introduction

Kihong Heo

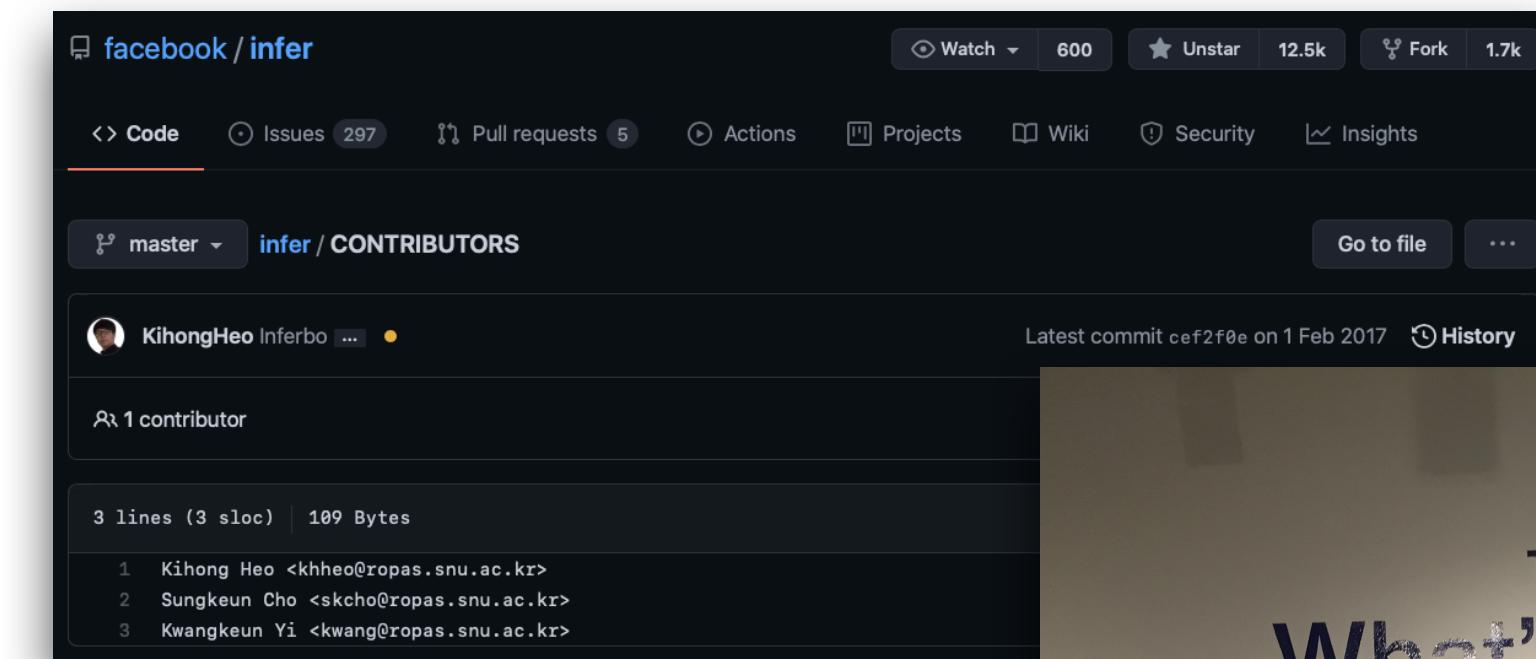


# About Me

- 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)

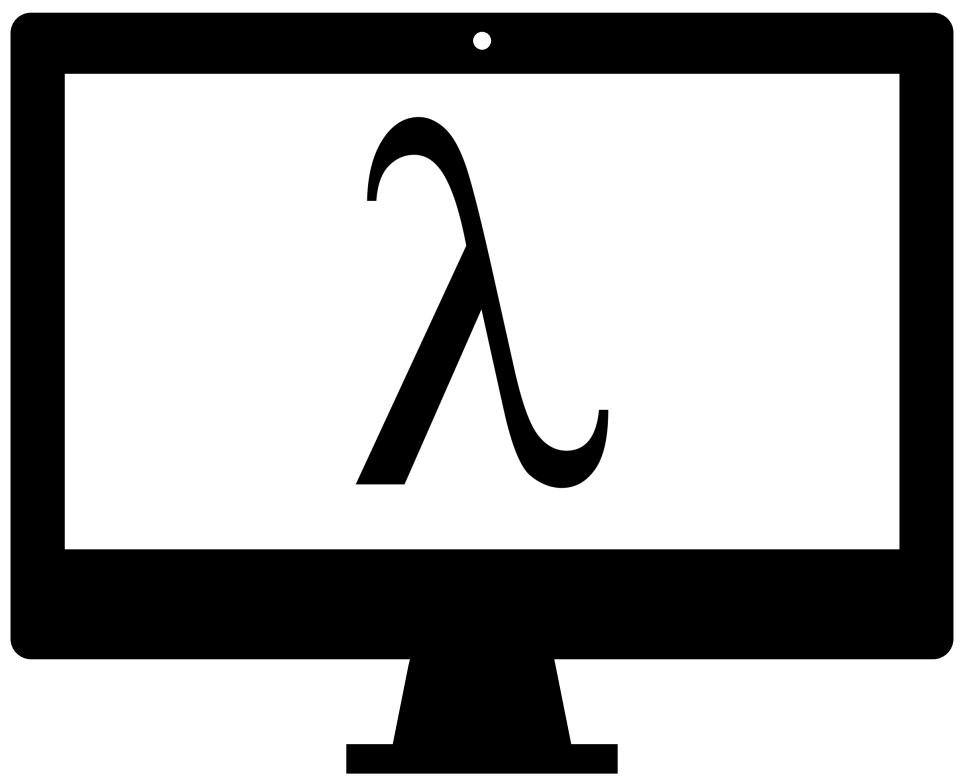
# My Research

- 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

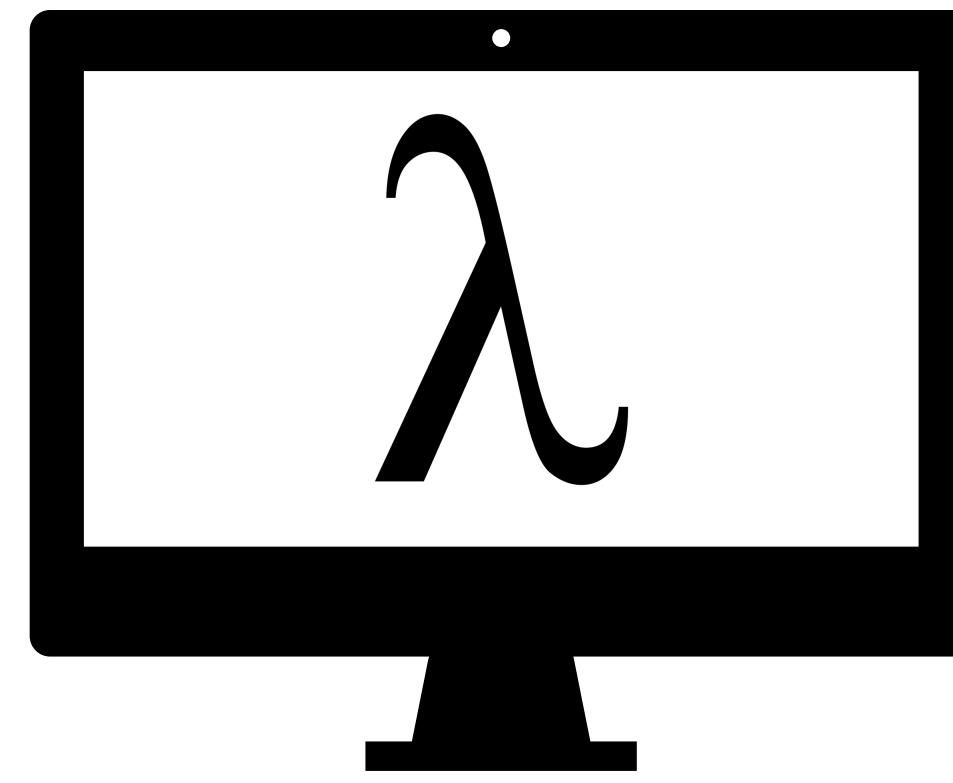


**Next-generation  
Programming Systems**

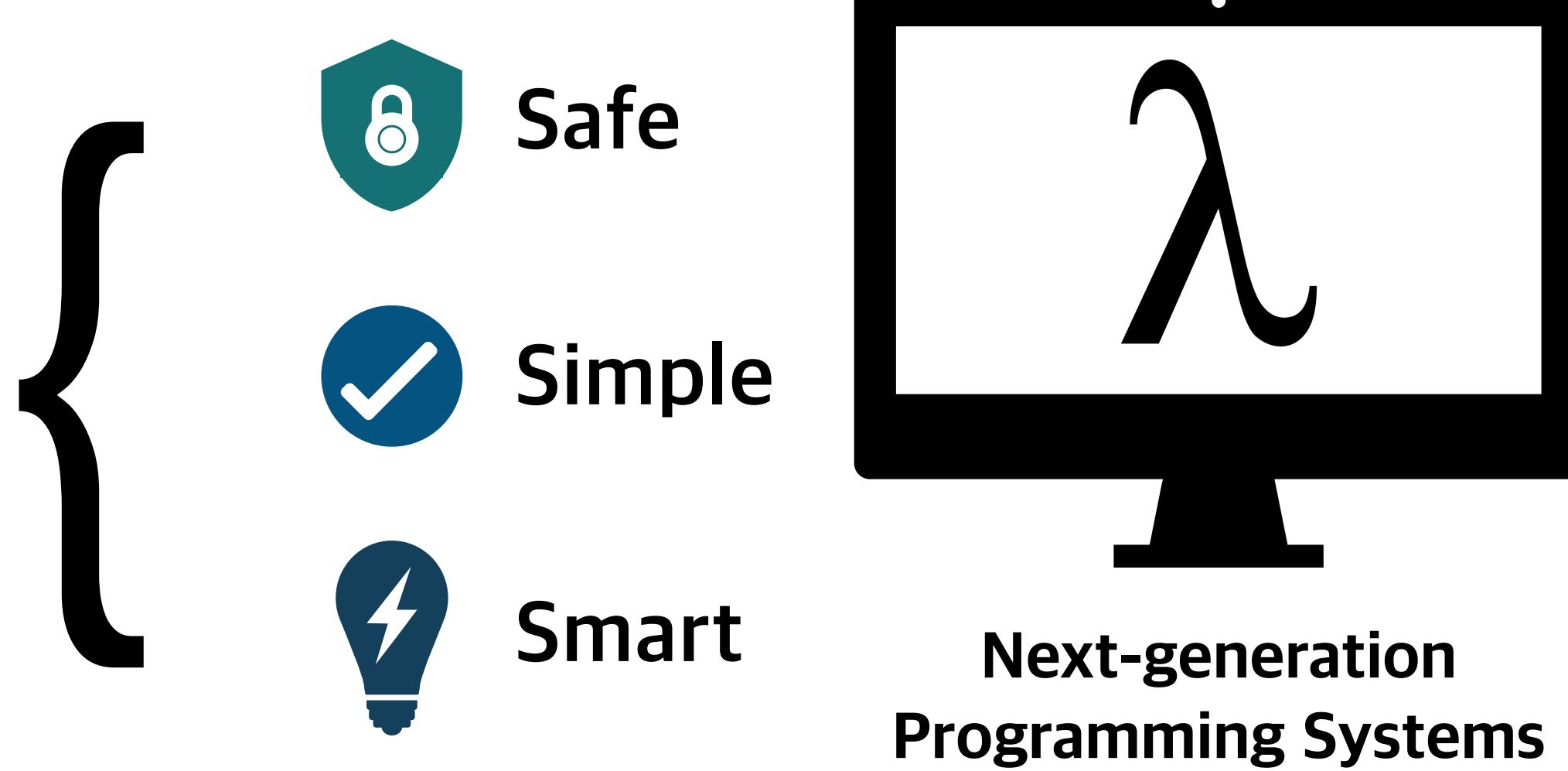
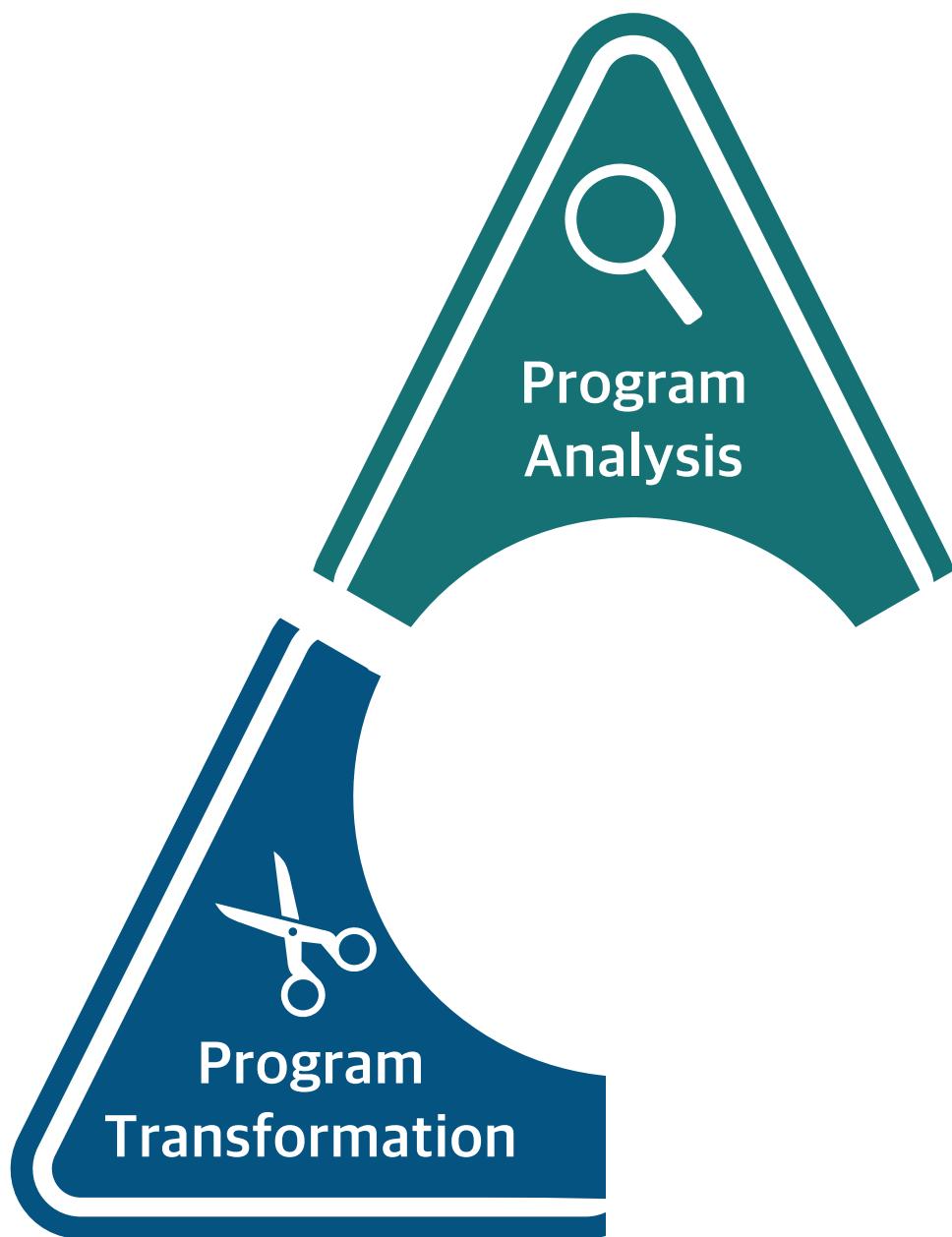
# My Research



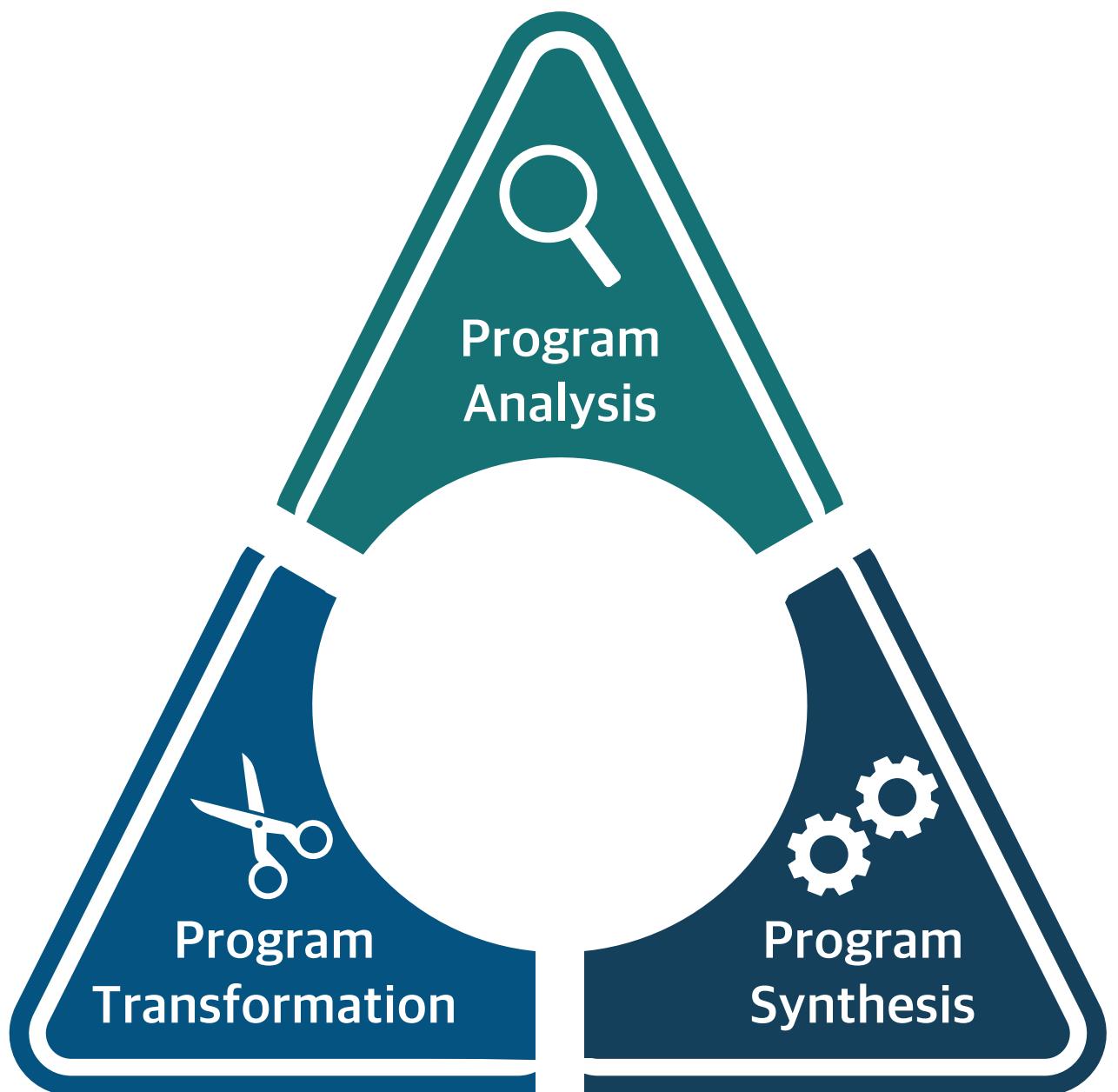
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**Safe****Simple****Smart****Next-generation  
Programming Systems**

# My Research



# My Research



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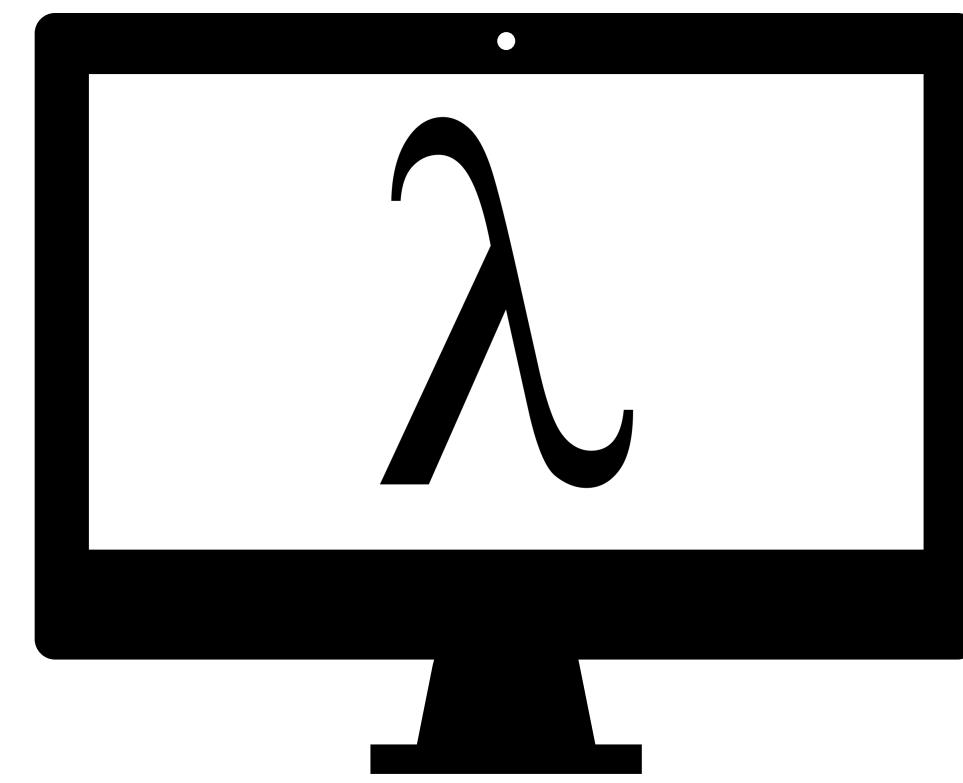
Safe



Simple

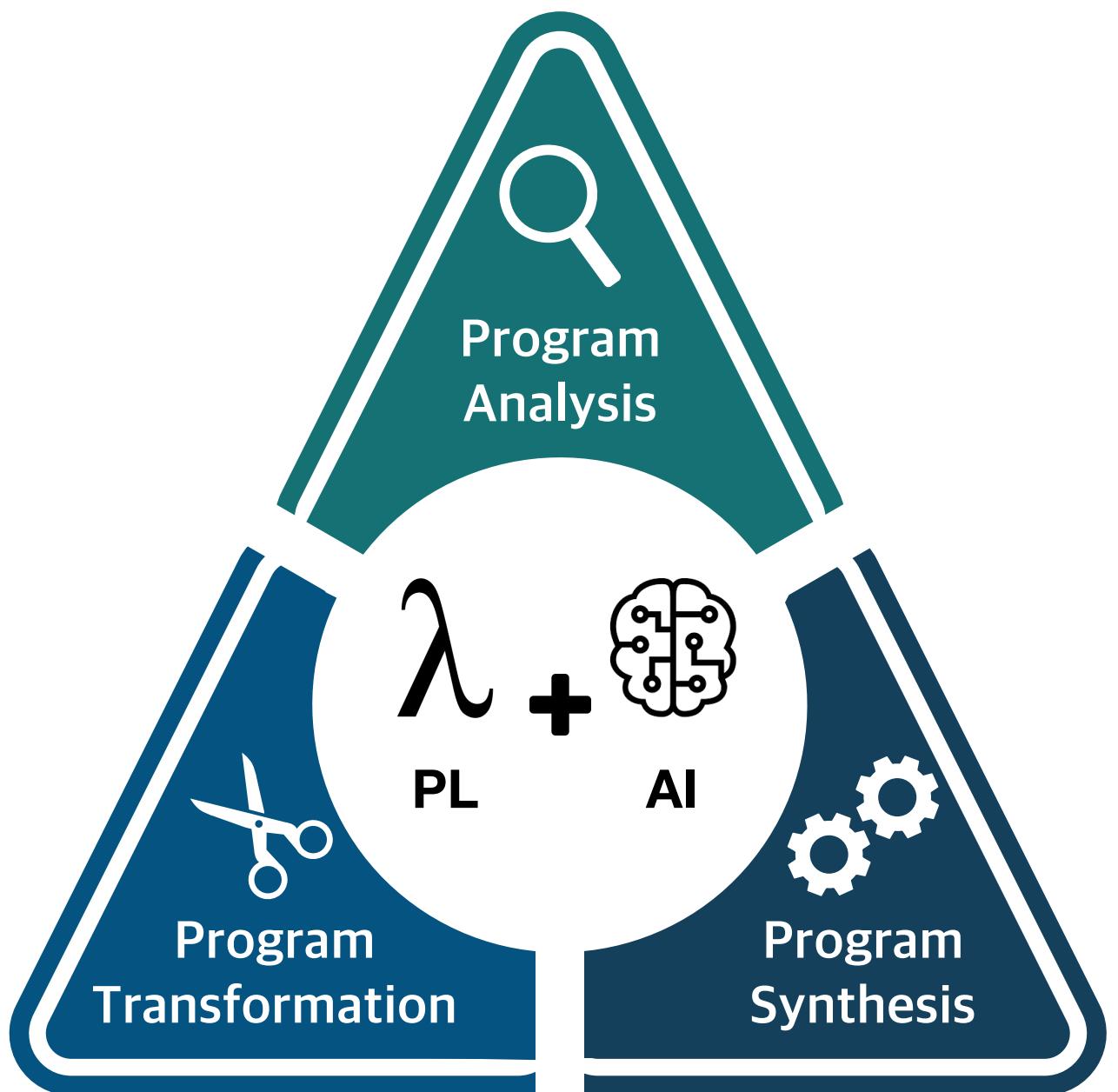


Smart



Next-generation  
Programming Systems

# My Research



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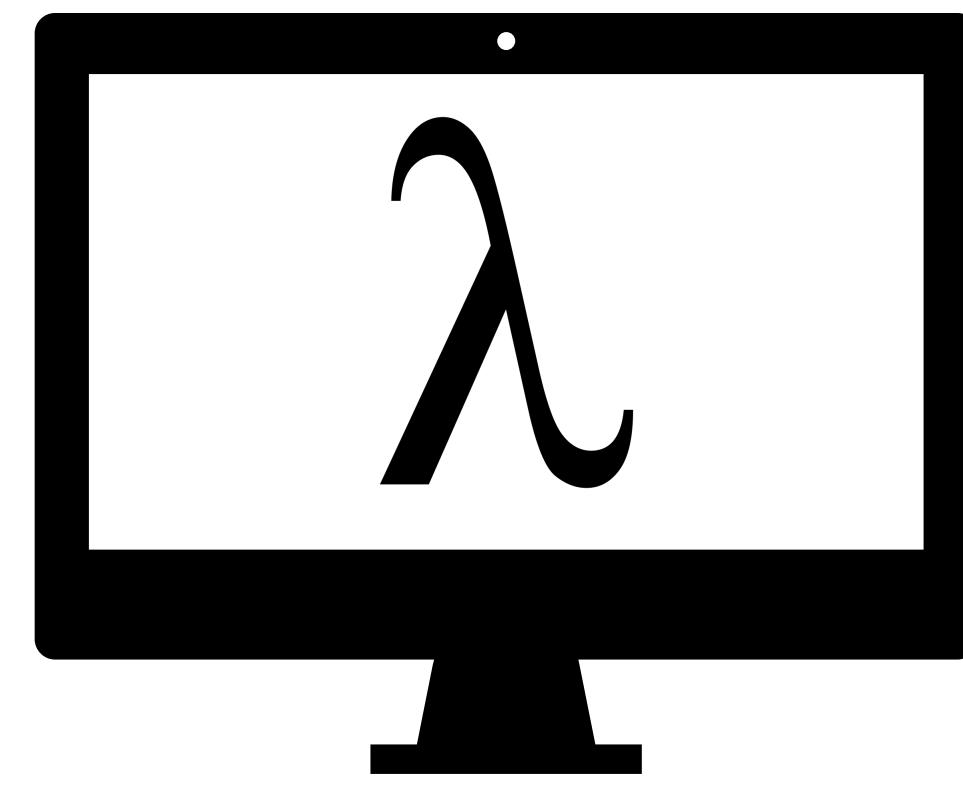
**Safe**



**Simple**



**Smart**



**Next-generation  
Programming Systems**

# Course Information

- Course Website: <https://github.com/prosyslab-classroom/cs524-program-analysis>
- Q&A Board: <https://github.com/prosyslab-classroom/cs524-program-analysis/issues>
- TAs (mailing list: [cs524.ta@prosys.kr](mailto:cs524.ta@prosys.kr))
  - Yeonhee Ryou(류연희)
  - Jaeseong Kwon (권재성)
- Textbook:
  - Lecture slides will be provided
  - Xavier Rival and Kwangkeun Yi,  
Introduction to Static Analysis: an Abstract Interpretation Perspective, MIT Press, 2020

# Grading

- Homework: 50%
- Final exam: 40%
- Participation: 10%
  - Active participation including questions or discussions (online or offline)
- DO NOT allow for P/NR grading
- NOTE: **nonnegotiable!**
  - DO NOT send an email for a negotiation (cheating)

# 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

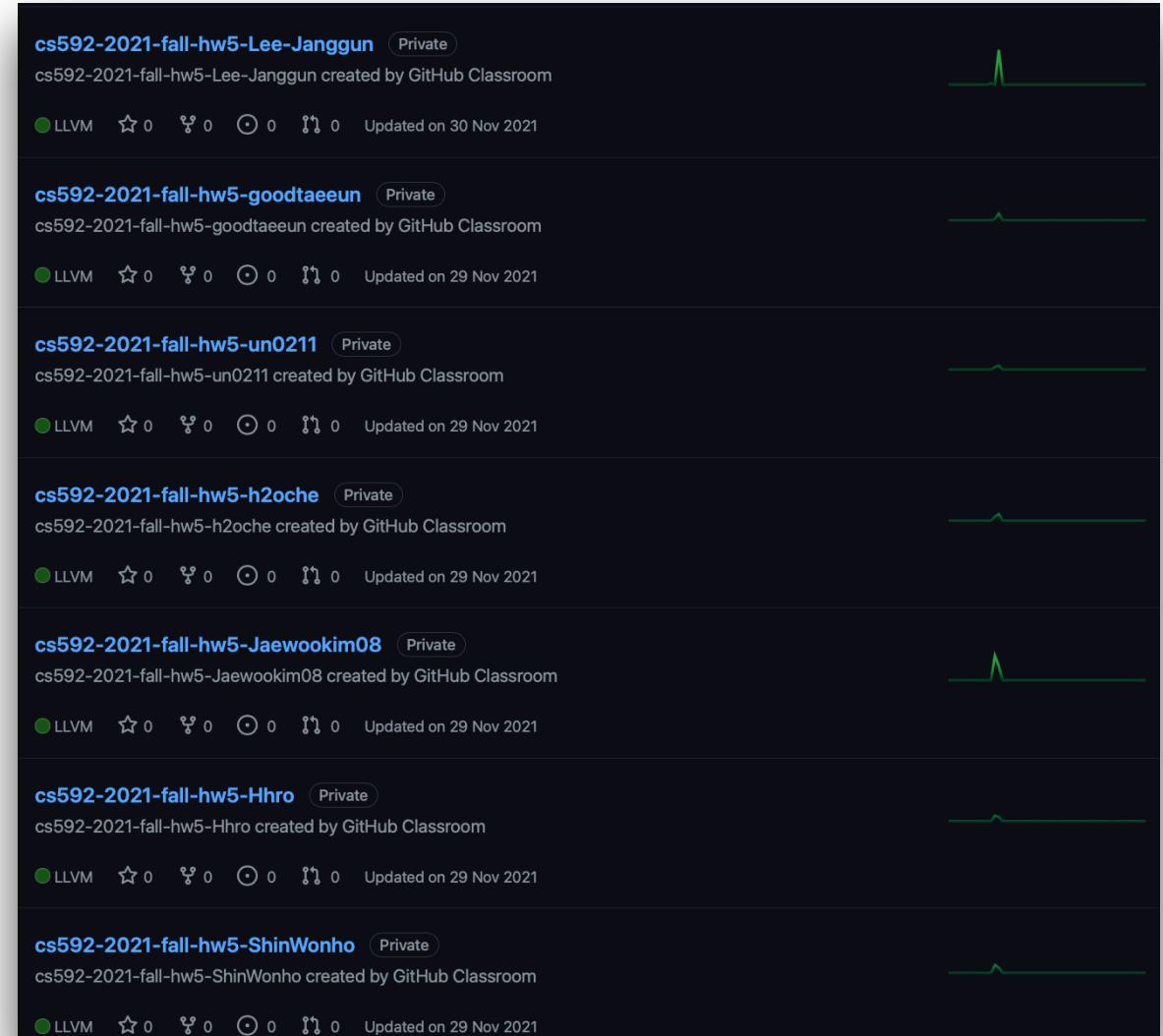
카이스트 전산학부가 운영하는 모든 수업에 참여하는 학생은 개인의 명예와 타인의 권리를 함께 존중하며 성실성과 정직성을 지키기 위하여 최선을 다합니다. 모든 시험 및 과제를 작성에 있어 허위되거나 다른 형태의 도움도 받지 않습니다. 다음의 행위들은 학생의 성실성과 정직성을 위반하는 것으로 간주됩니다:

- 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 실각성에 따라 학교 전체의 상별위원회에 회부될 수 있습니다. 카이스트 학자규정이 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))

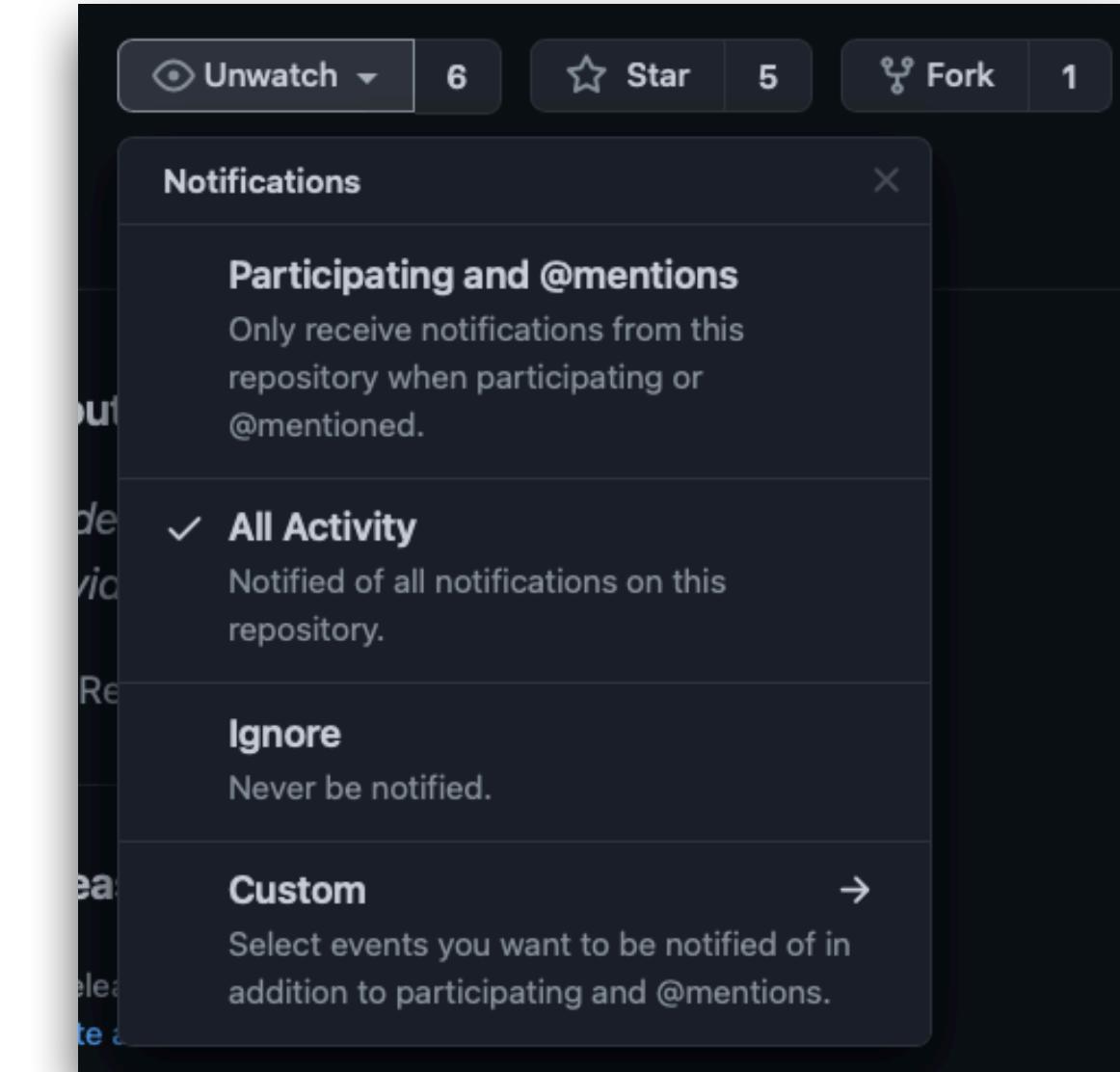


# Important Notice (2): In-class

- Language: English (default), Korean (supplementary)
- Attendance: always (default), absence (if necessary)
  - No quantified attendance score
  - “What is **essential** is **invisible** to the eye” - The Little Prince
  - 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 (3): 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 the aircraft's grounding due to software issues.

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

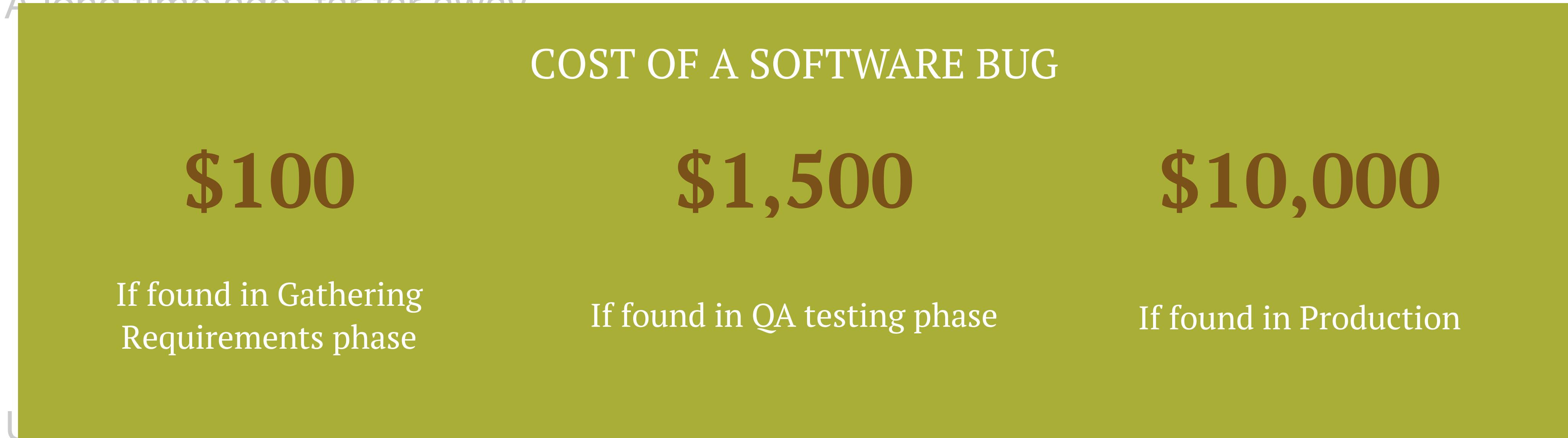
6 ways to celebrate Valentine's Day in Lake Geneva 8:55 AM

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

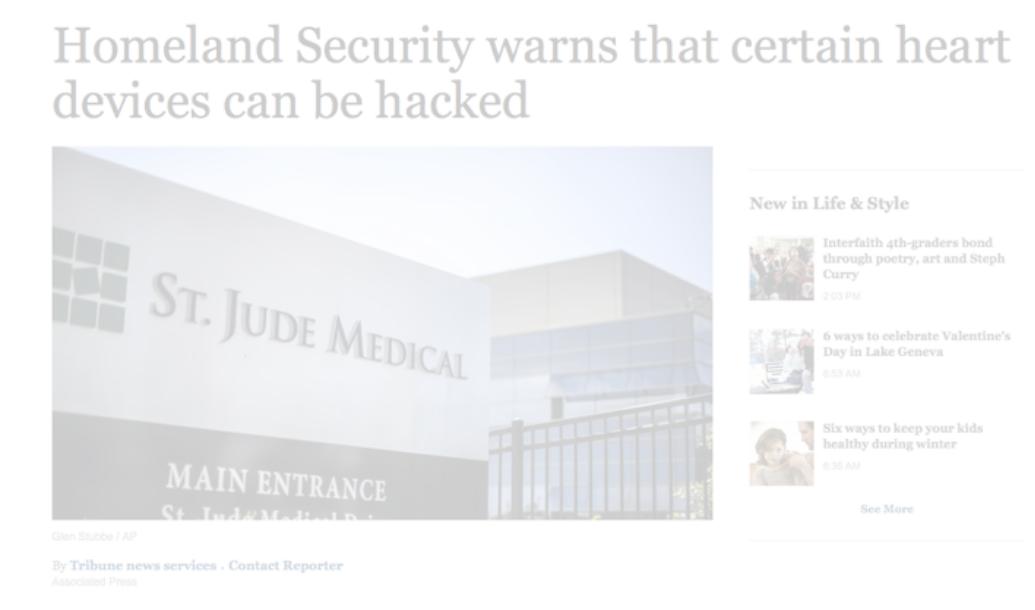
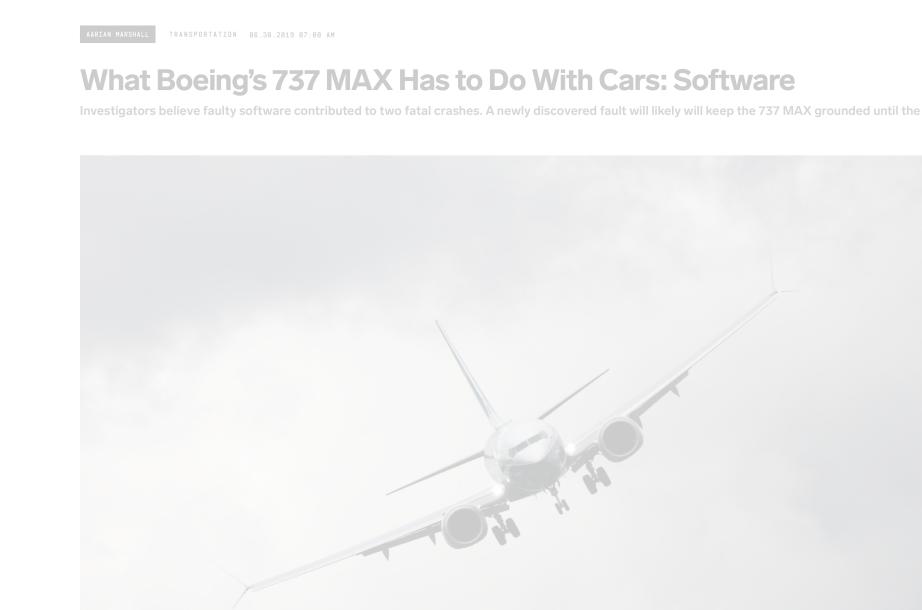
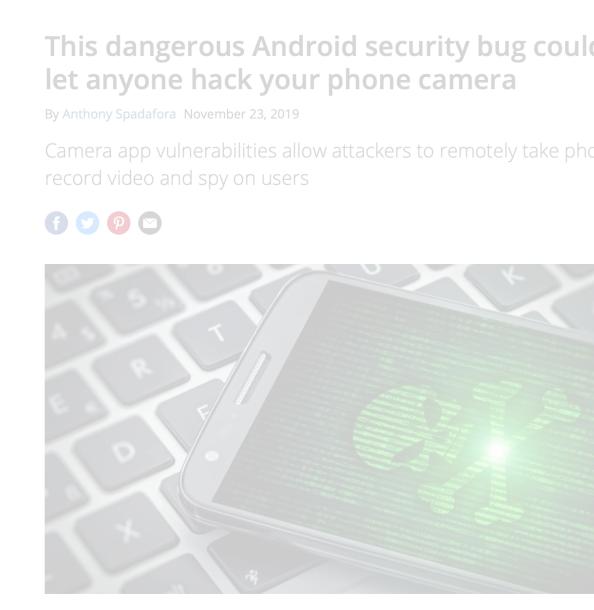
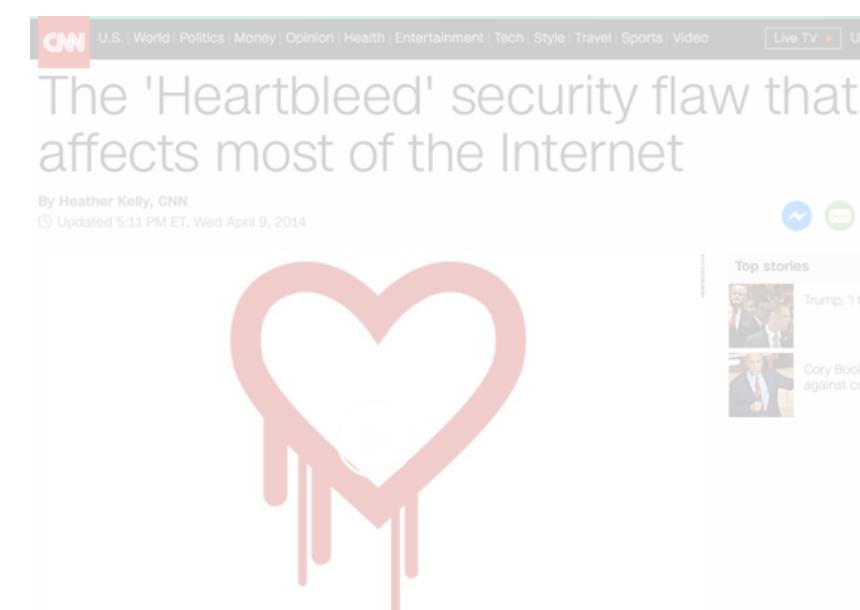
See More

# Software Bugs: A Persistent Problem

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

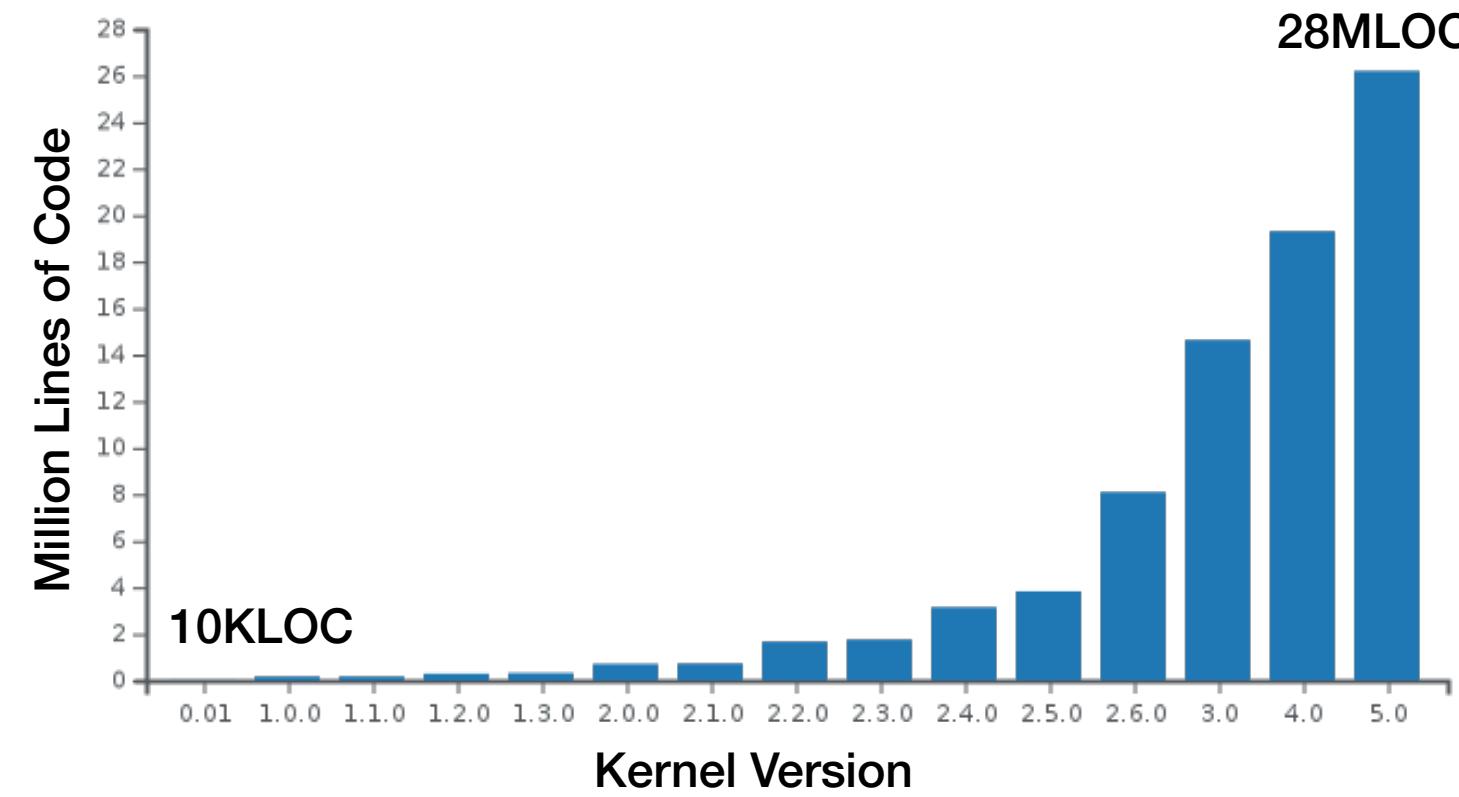


- IBM Systems Sciences Institute, 2015

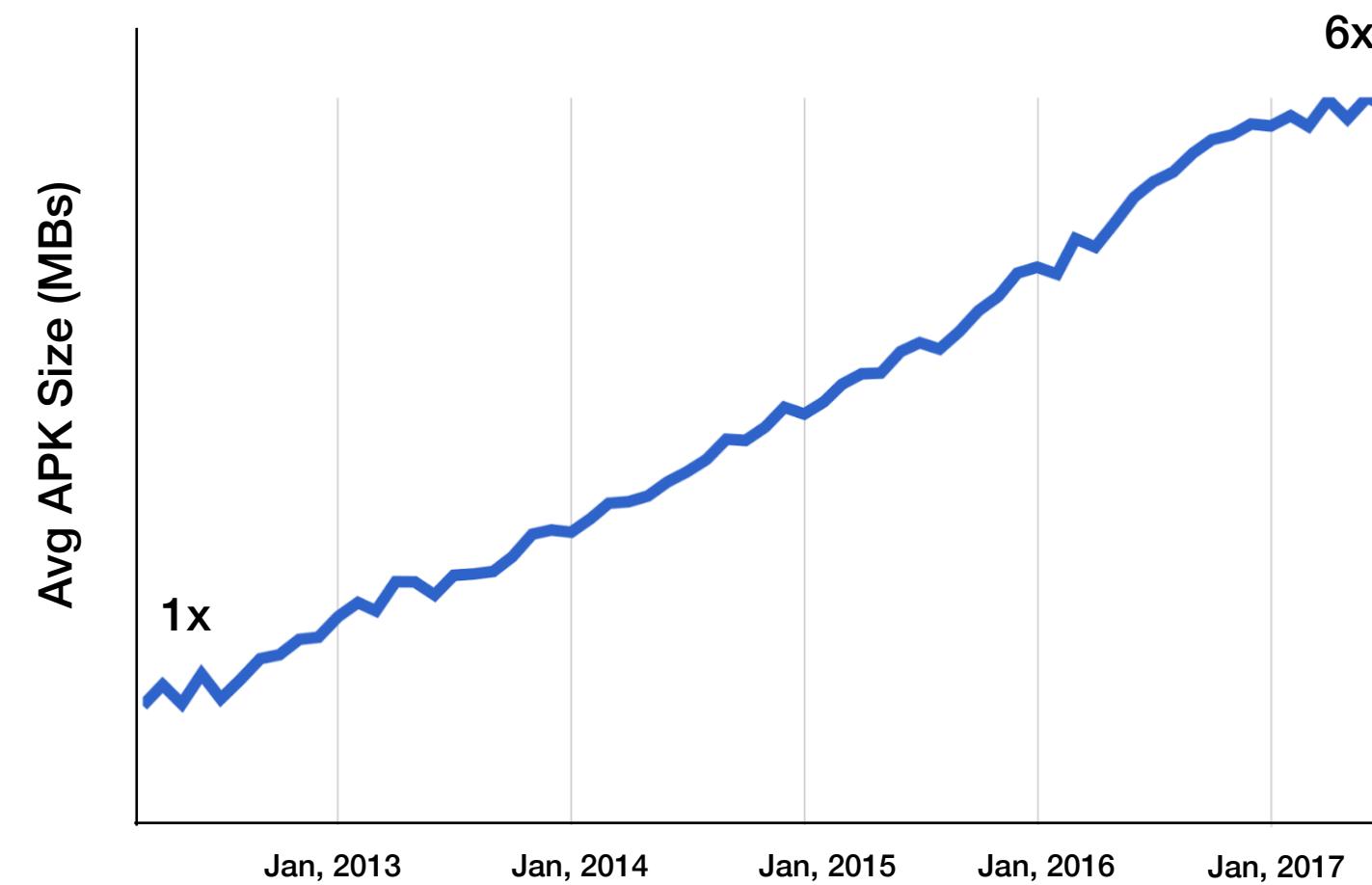


# Why Software Still Fails?

**Size of Linux Kernel**



**Avg. Size of Android Apps**



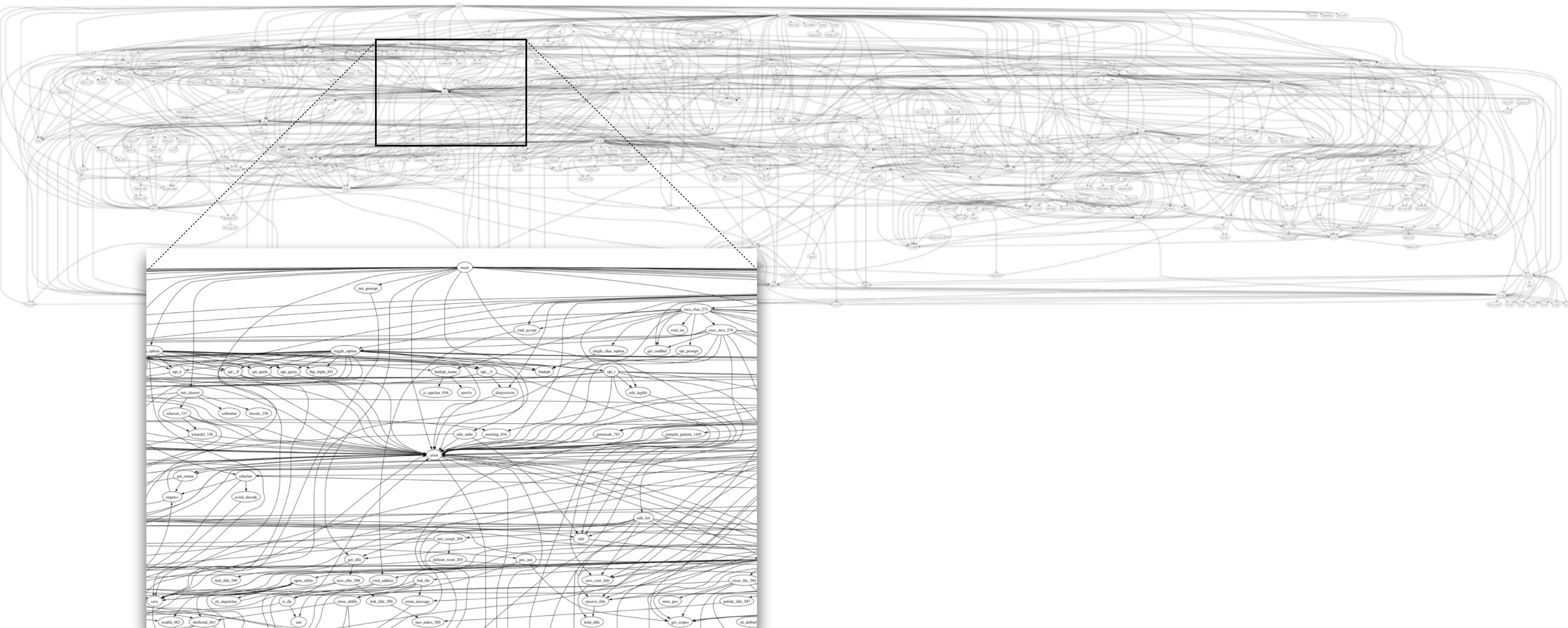
X



**20M+ New Developers  
85M+ New Repositories  
227M+ New Pull Requests  
in 2022**

# Software Complexity

less-382 (23,822 LOC)



# Course Objectives: Principles

**Q:** How to **formally estimate** software behavior automatically before its execution?

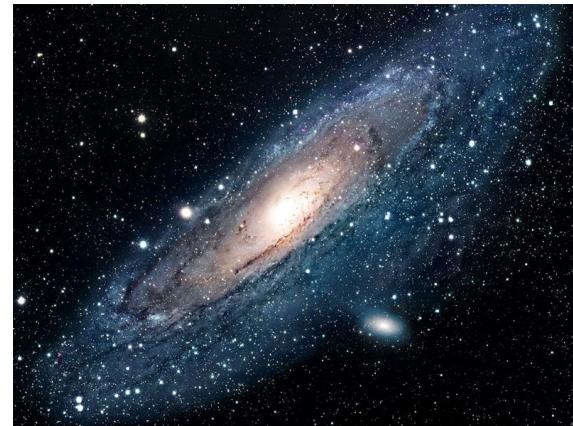


# Course Objectives: Principles

## Artifact



## Subject



## Principle

$$\vec{F} = m\vec{a}$$



$$\nabla \cdot E = 0 \quad \nabla \times E = -\frac{1}{c} \frac{\partial H}{\partial t}$$

$$\nabla \cdot H = 0 \quad \nabla \times H = \frac{1}{c} \frac{\partial E}{\partial t}$$



# Static Program Analysis

- General methodology to predict software behavior
  - **static**: before execution
  - **automatic**: software is analyzed by software (program analyzer)
  - **systematic**: foundational theory (Abstract Interpretation)
- Applications:
  - bug-finding, verification, code optimization, etc



# Success Stories

Domain-specific  
Verification



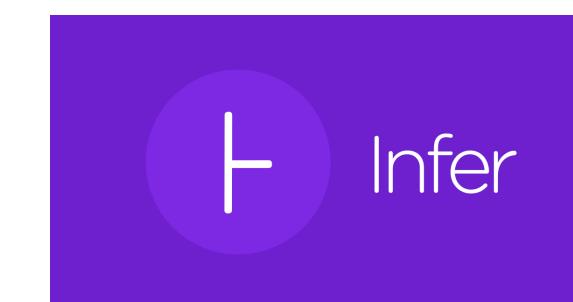
Windows Device Driver  
*Microsoft*

Astrée

Airbus Controller  
*ENS / AbsInt*



*Stanford / Synopsys*



*Facebook*



*SNU / Fasoo.com*



*Mathworks*



*GrammaTech*



*Semmle / Github*



*JuliaSoft*



*GCC*



*LLVM/Clang*

# Course Objectives: Practice & Challenge

- Homework: **design & implement** program analyzers
  - 7 (main) + 2 (dummy) assignments
- Programming assignments in OCaml using LLVM & Z3
  - You will write your analyzers in OCaml
  - Your analyzer will analyze LLVM IR code
  - You will utilize Z3 in your analyzers
- 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

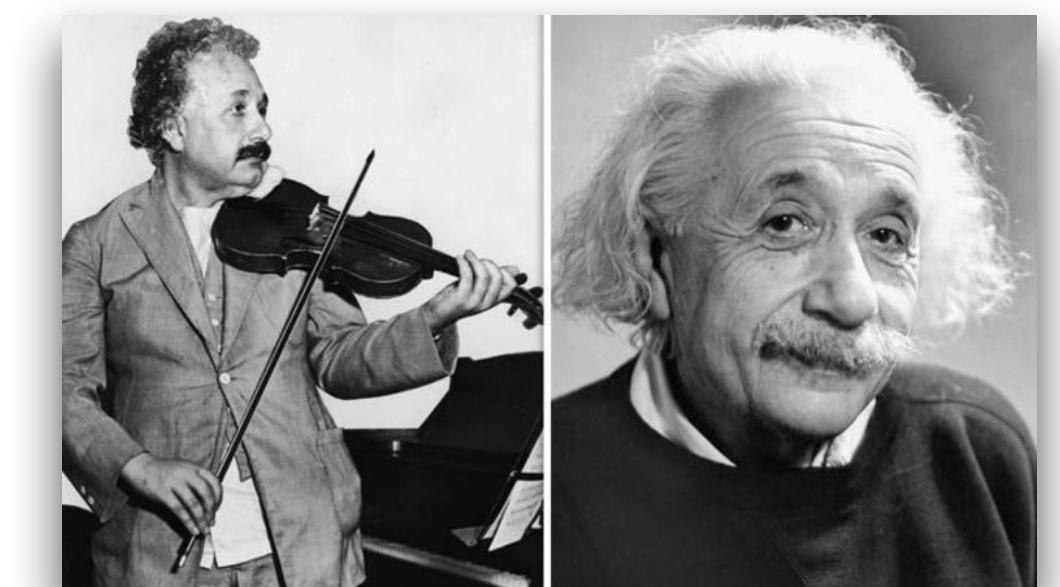
# Course Objectives: Active Learning

- The era of AI: NO free lunch and requires more creative thinking
  - Naively understanding & memorizing knowledge becomes obsolete
  - Creativity comes from “pain” (창의력은 노가다에서 나온다)
    - Training GPT-3: 355 yrs on a single GPU (2020)
- Three levels of knowledge

- Understandable knowledge (이해 가능)
- Explainable knowledge (설명 가능)
- Artifiable knowledge (예술로 승화 가능)

by lecture, exam,  
programming assignment

by various activities



“The greatest scientists are  
artists as well”  
- A. Einstein

# Activity (1): Writing

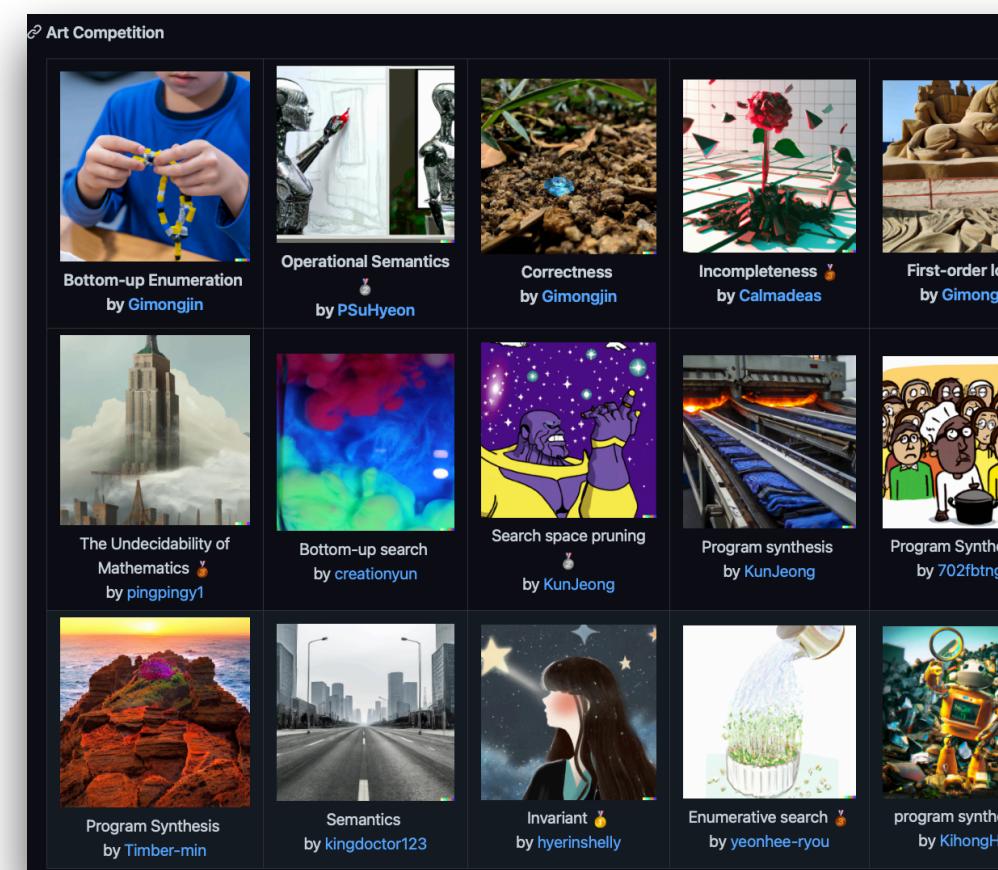
- Science is communication
  - Writing: main communication tool
- Roles of KAIST folks
  - World-leading researcher (in English)
  - Inspiring communicator to the community (in Korean)
    - For newcomers, public officials, etc

The screenshot shows a Twitter feed with the following tweets:

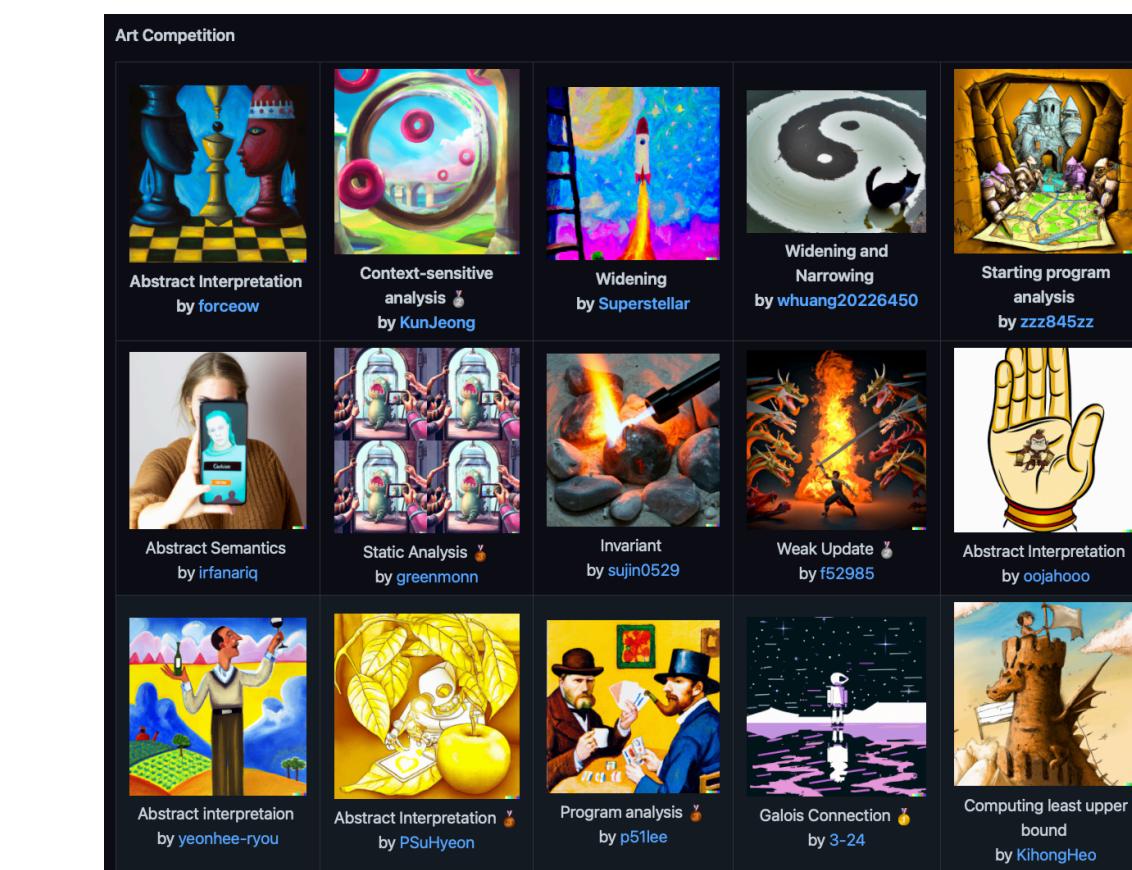
- 국립국어원 (@urimal365)** [우리말 다듬기] '변이 지방'은 '트랜스 지방'을 다듬은 말입니다. "이 과자에는 변이 지방이 들어 있지 않다."처럼 다듬은 말 '변이 지방'을 쓸 수 있습니다. #다듬기  
오전 9:01 · 2013년 3월 19일 · twtkr  
44 리트윗 9 인용한 트윗 6 마음에 들어요
- 田舎暮らしアコア (@hanaosakas)** 여행가고싶다 @urimal365 님에게 보내는 답글  
@urimal365 트랜스 지방의 트랜스는 "변이"라는 의미가 아닙니다.. trans-/cis-로 구조체의 형태가 다른 것입니다... 굳이 번역할 필요도 다듬을 필요도 없는 과학용어입니다.. 과학과 관련된 말을 다듬을 때는 과학계에 자문을 구해보심이  
1 27 4
- 국립국어원 (@urimal365)** 건의하실 의견은 공식적인 민원(j.mp/zUyQoR)을 통하여 주시거나, '우리말 다듬기(malteo.net)'를 이용해 주시기 바랍니다. #순화  
6
- PYLON / 수정탑 (@Pylon\_kr)** @urimal365 님에게 보내는 답글  
@urimal365 trans가 변이면 cis는 뭐라고 해야하나요? 유기화학 책 좀 보고 오세요.  
2 6

# Activity (2): Art Competition (천하제일 그림대회)

- What does X mean to you?
- Pick a concept X you have learned in this class such as cryptography, program analysis
- Draw a picture that succinctly represents the concept using DALL-E (or similar tools)
- Detailed instructions will be announced later



CS492: Program Reasoning, 2022



CS524: Program Analysis, 2022

# Homework

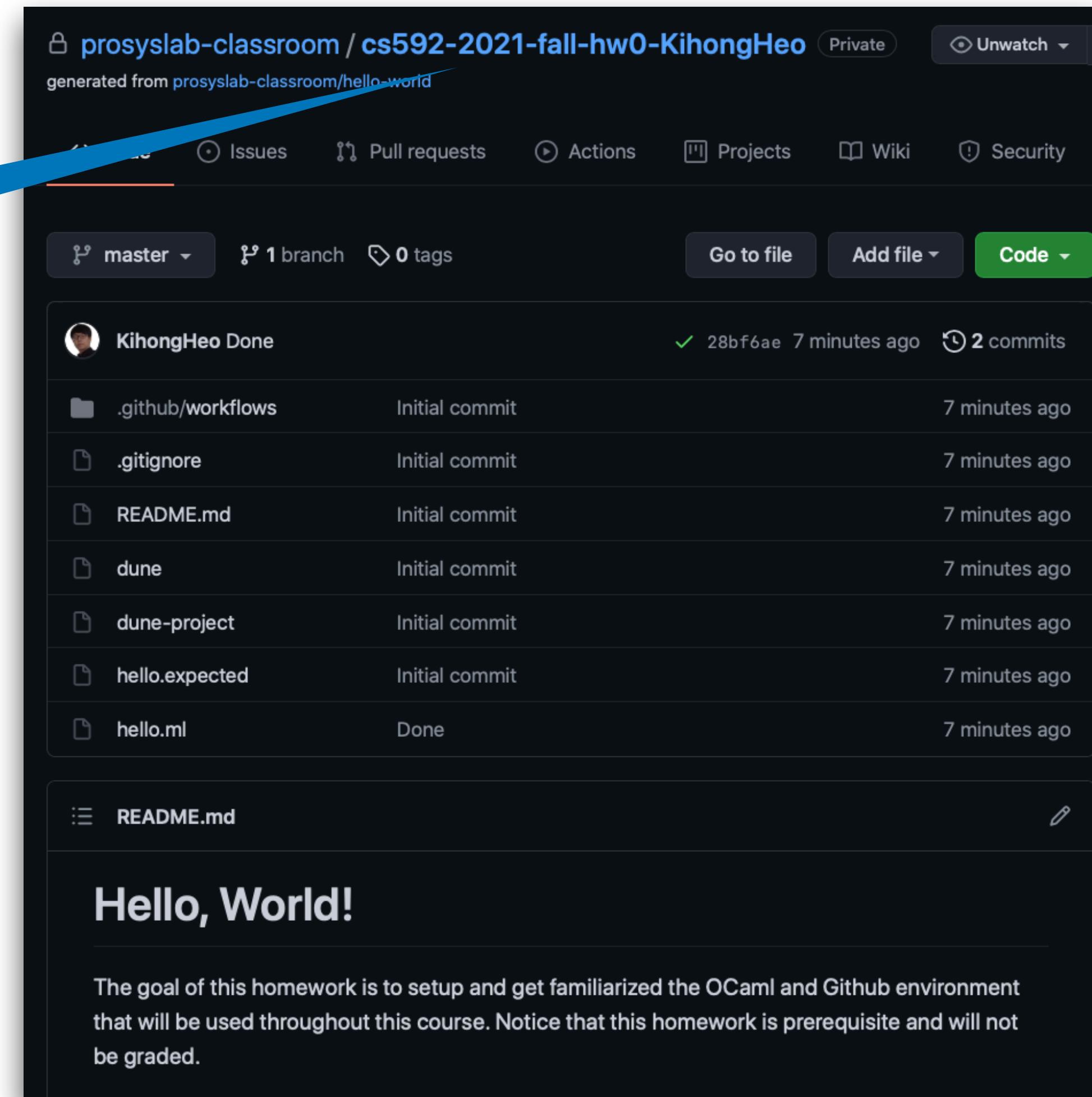
- All submissions will be managed using Github / Github Classroom
  1. For each HW, a unique invitation URL will be posted on the issue board
  2. Once you accept, a private repo for your assignment will be created
  3. You can push as many commits as you want before the deadline
  4. The final commit of your main branch will be graded
- Gradescope will be used for written 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!". A blue callout box on the left points to the commit history with the text "2. Commit your code".

2. Commit your code

prosylab-classroom / cs592-2021-fall-hw0-KihongHeo Private

generated from prosylab-classroom/hello-world

Code Issues Pull requests Actions Projects Wiki Security

master 1 branch 0 tags Go to file Add file Code

KihongHeo Done 28bf6ae 7 minutes ago 2 commits

| File              | Type           | 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 |

README.md

Hello, World!

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.

# Homework 0.1: Hello, World!

## 3. See your result

The screenshot shows 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 main navigation bar includes Code, Issues, Pull requests, Actions, Projects, Wiki, and Security. Below the navigation, it shows 1 branch and 0 tags. A prominent green button labeled "Code" is visible.

The commit history lists the following files and their initial commits:

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

The `README.md` file contains the following content:

```
Hello, World!
```

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.

# 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

# Requirement: Software Engineering Practices

- All programming assignments submissions must follow basic SE practices

- Remove all compile errors and warning

- Remember: warning is error

- Clean code via formatting

- Acceptable code coverage

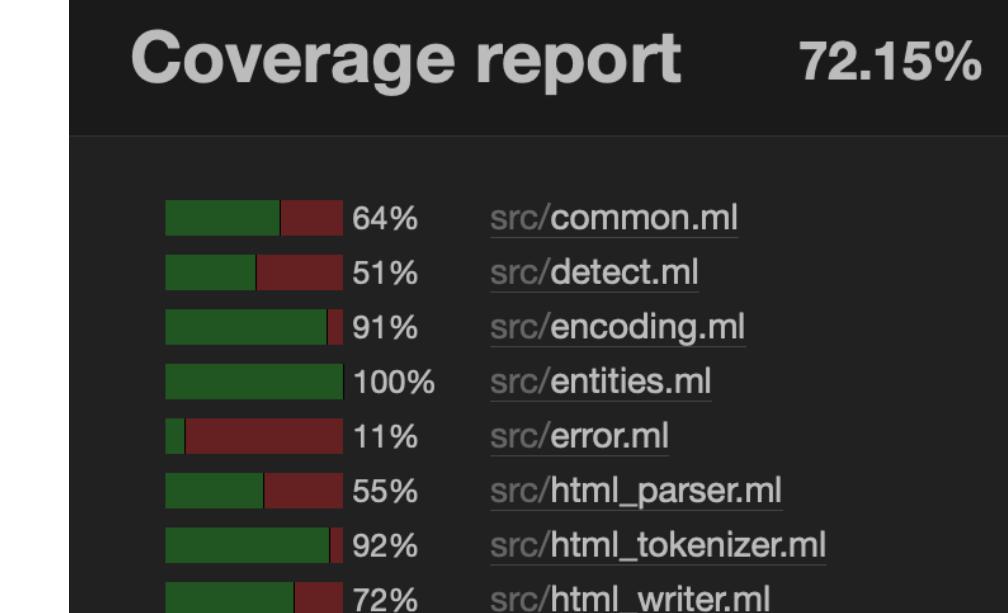
- Otherwise, NO points will be given

- Detailed instructions will be provided

```
File "src/semantics.ml", line 39, characters 6-11:  
39 |   let count = 1 in  
      ^^^^  
Warning 26 [unused-var]: unused variable count.
```

```
let rec  
  fact n =  
    match n with  
    | 0 | 1 -> 1  
    | _ -> n *  
        fact (n - 1)
```

```
let rec fact n =  
  match n with  
  | 0 | 1 -> 1  
  | _ -> n * fact (n - 1)
```



```
14 module Ns :  
15 sig  
16   val to_string : ns -> string  
17 end =  
18 struct  
19   let to_string = function  
20   | HTML -> html_ns  
21   | MathML -> mathml_ns  
22   | SVG -> svg_ns  
23   | Other s -> s  
24 end
```

# Homework 1: Essay

- Read the stories of Google, Facebook, and Apple (available from the course webpage)
- Write a critique essay
- 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