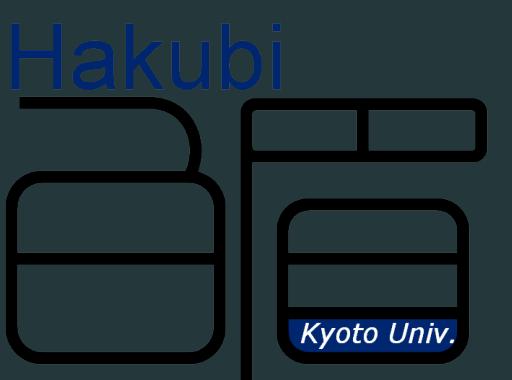


Science of Software, the Fun of Rust

Yusuke Matsushita Hakubi 15th

September 2, 2025 Hakubi Seminar



About me

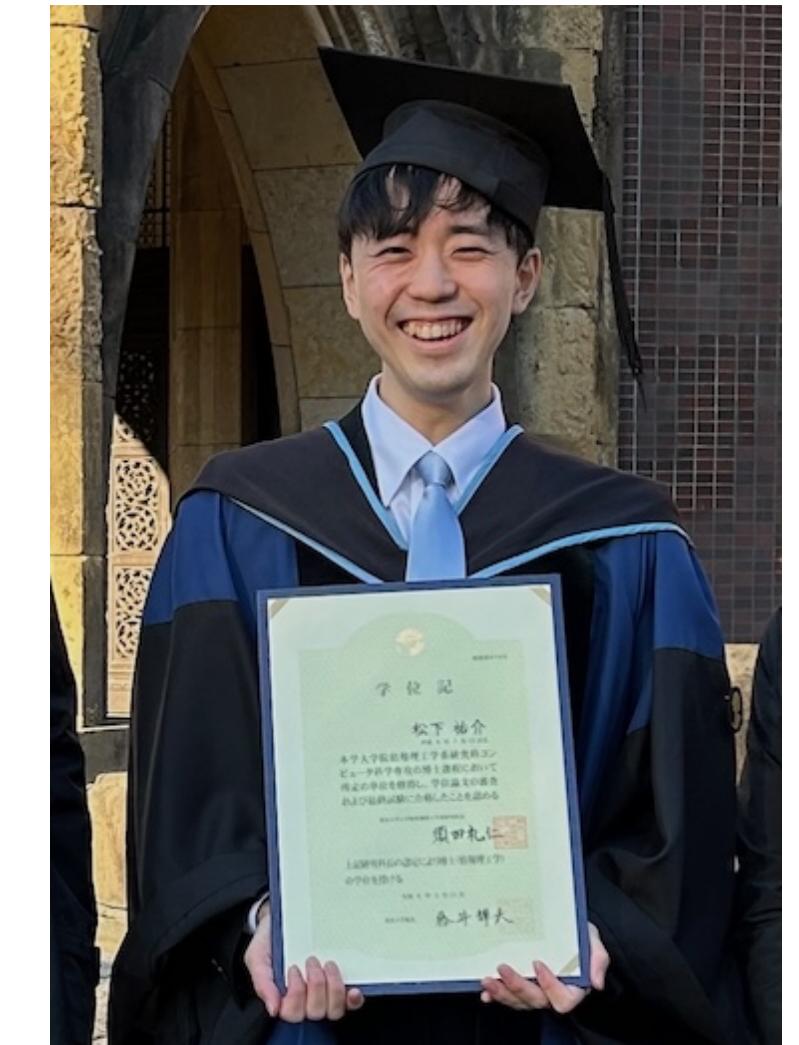


Awarded at ACM PLDI '22

◆ Yusuke Matsushita 松下 祐介

- ▶ '96 Born in Toyonaka, Osaka
- ▶ '09-'15 Nada Junior & Senior High School in Kobe
- ▶ '15-'24 University of Tokyo
 - Bachelor's, Master's & Ph.D.
 - Dept. of Info. Science, Sch. of Sci. / Dept. of Computer Science, Grad. School of Info. Sci. & Tech.
 - Supervisor: Naoki Kobayashi

*shiatsumat
.github.io*



My hobbies

♦ Music: Piano & Improvisation

- ▶ Mainly classical: Bach, Debussy, Chopin, ...
 - Was a leader of the UTokyo Piano-no-kai
- ▶ Also, jazz, celtic, techno, ...
 - Jazz at Zac Baran near Kumano Shrine



Gold prize at J.S.Bach concours '22

♦ Ballroom dance

- ▶ Started during my Ph.D.



Ballroom dance in Osaka



Jazz session at Zac Baran

Me as a computer scientist

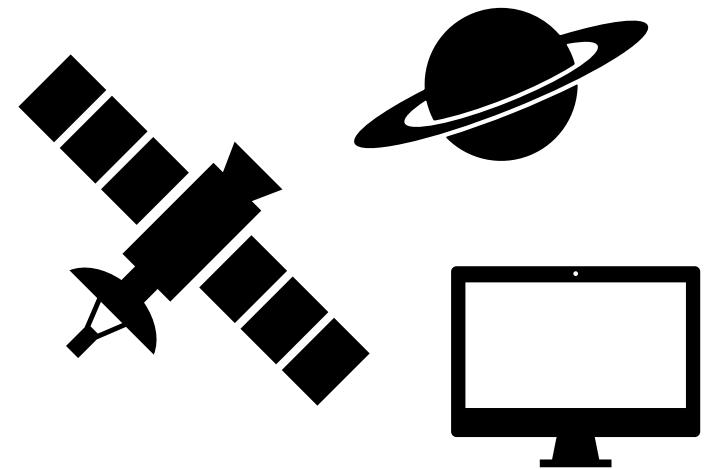
◆ Studies software science

- ▶ Esp. the **Rust** programming language
 - ▶ '20-'21 Intern at MPI-SWS, Germany
 - ▶ '25 Hakubi | 5th Prog.-Specific Assist. Prof.
 - “Exploring a new age of software development springing from Rust”
 - G.S. of Informatics, Igarashi & Suenaga Lab
 - '24 JSPS PD fellow
 - ▶ '24 & '25 Lecturer at IPA Security Camp

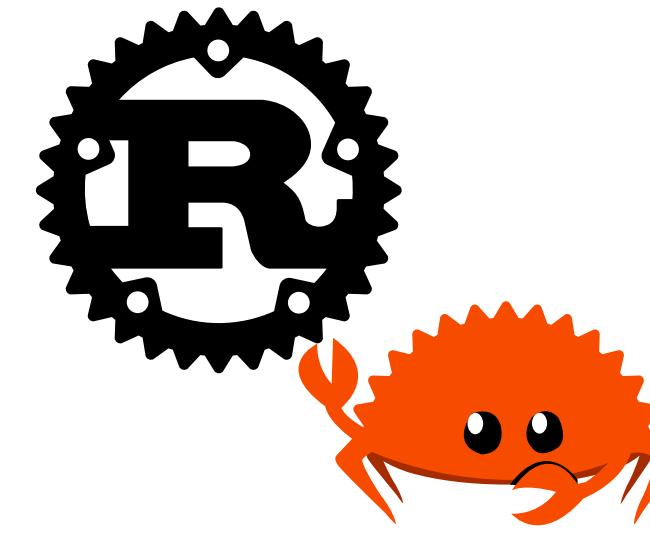


This talk

Science of Software

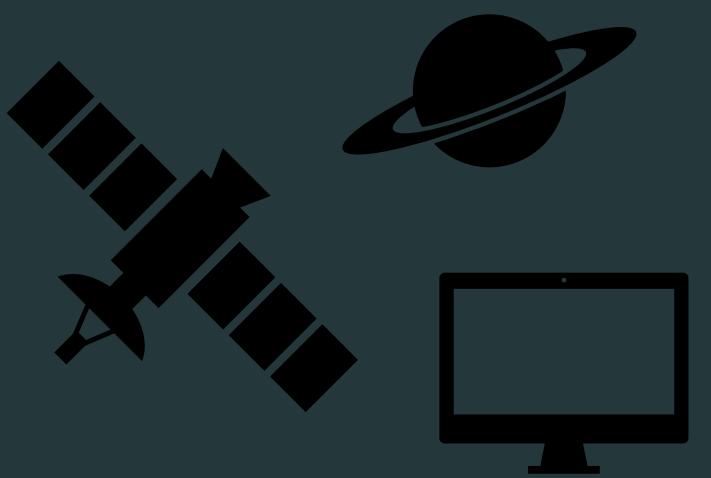


The Fun of Rust



*Your questions and comments
are always welcome!*

Science of Software



What was ancient human life like?

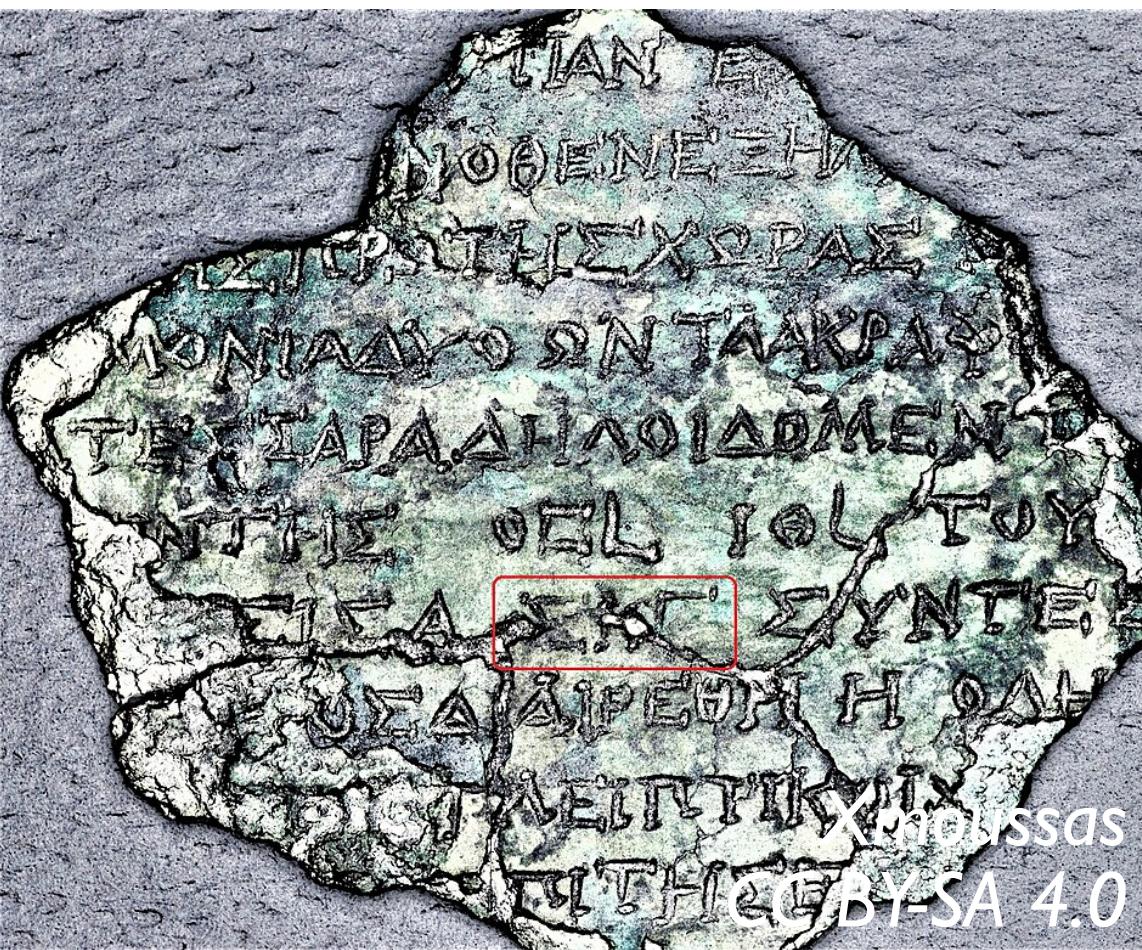


- ◆ Full of dangers & uncertainties in nature
 - ▶ Technologies were developed to just survive
- ◆ The stars in the sky move in a mysterious order

Antikythera mechanism

Ancient Greek, ~150 BC

- ♦ Oldest known analog **computer**
 - Models the solar system
 - Could be used to predict astronomical positions & eclipses



Industrial Revolution

~1760 - ~1840, ~1870 - ~1914

♦ Great change in the global economy

- Water & steam power → Electricity
- **Machines** have become vital



Paris Expo in 1889

♦ Jacquard loom 1804

- Punch cards instruct complex weaving patterns
- Origin of **programming**



Jacquard loom



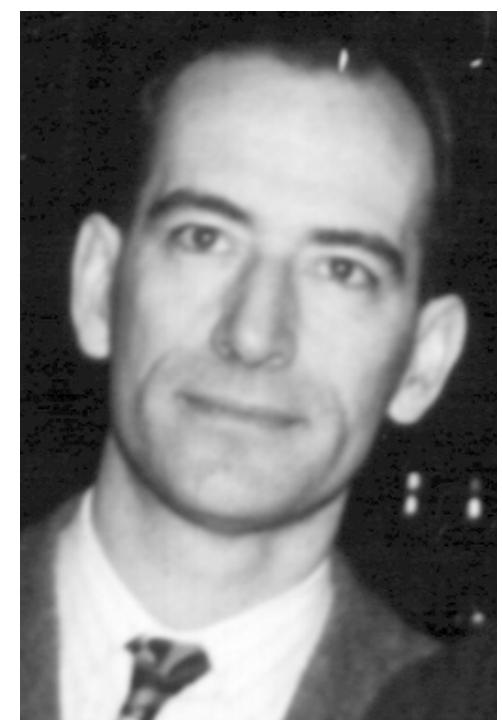
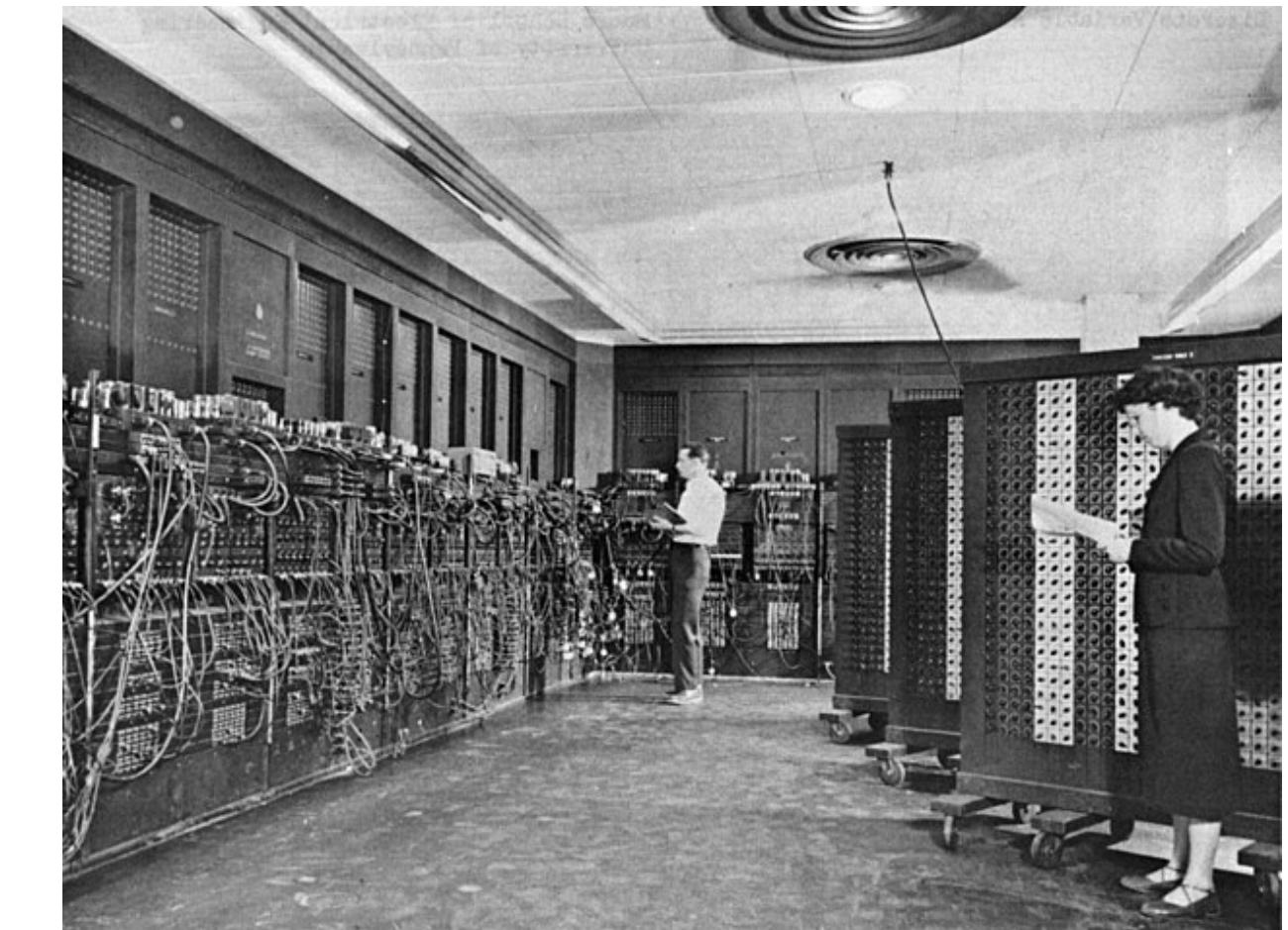
Punch for cards

Digital computers

1945 -

◆ ENIAC Electronic Numerical Integrator And Computer 1945

- ▶ First general-purpose digital computer
- ▶ Developed at the University of Pennsylvania
- ▶ Financed by the US Army
 - Used for research on building hydrogen bombs



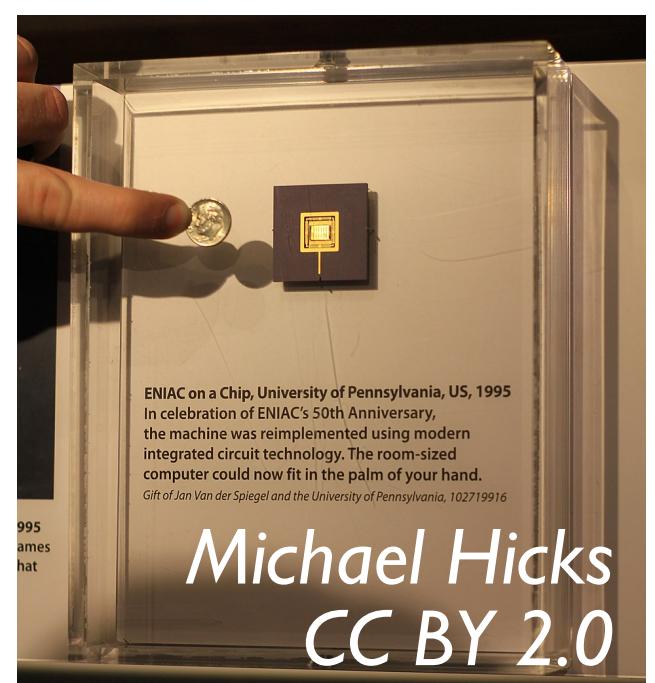
Physicist
John Mauchly



Engineer
J. Presper Eckert



Mathematician
John von Neumann



Michael Hicks
CC BY 2.0

ENIAC on a Chip, 1995

Software & Bugs

♦ Software = What instructs computers

- To achieve high-level goals for humans
- Built from programs & data

9/9

0800 anchor started
1000 " stopped - anchor ✓
13'00 (033) MP - MC
033 PRO 2 2.130476415
const 2.130676415
Relays 6-2 in 033 failed special sped test
in relay (Relay changed)
1700 Started Cosine Tape (Sine check)
1525 Started Multi Adder Test.
1545 Relay #70 Panel F (Moth) in relay.
1550 First actual case of bug being found.
1700 anchor started.
closed down.

Relay 2145
Relay 3370

♦ Bug = Design error in software

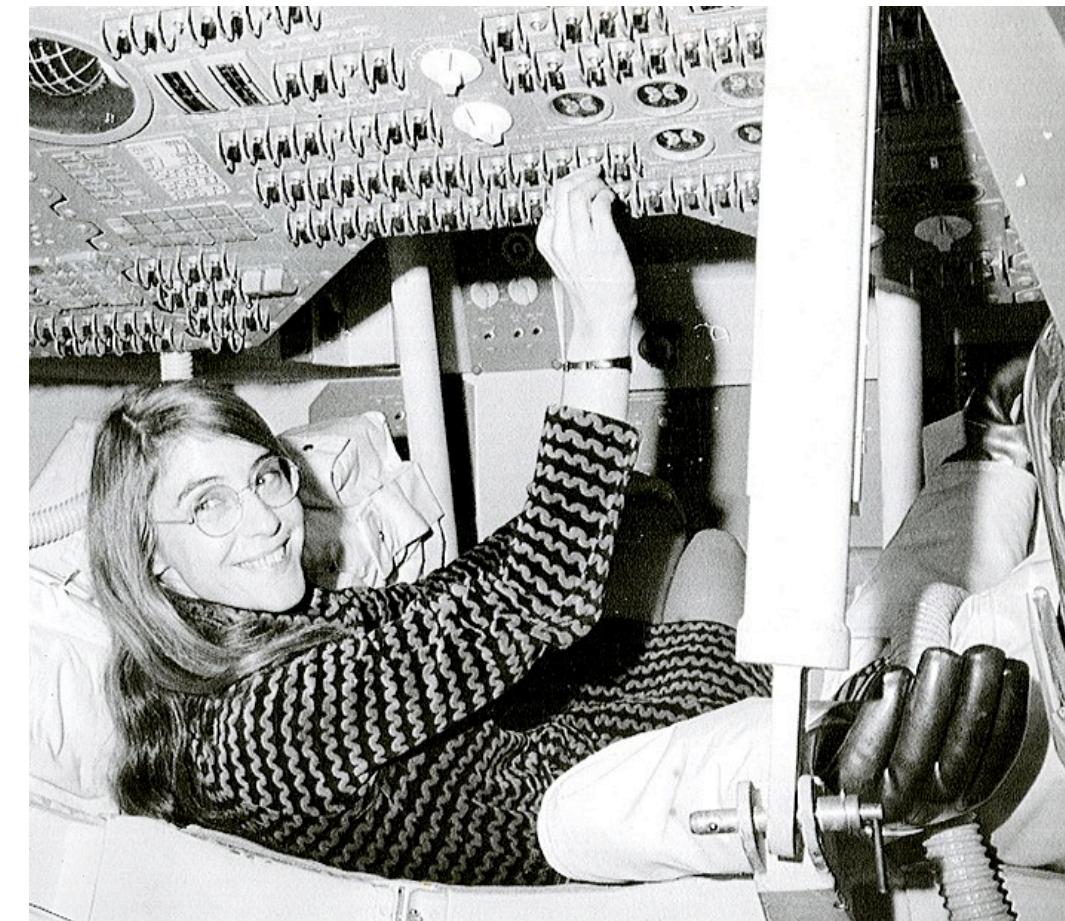
♦ Bugs can really cost

- Example: NASA's Venus flyby Mariner I in 1962
 - Launch failure due to a spec bug, ~\$200M loss

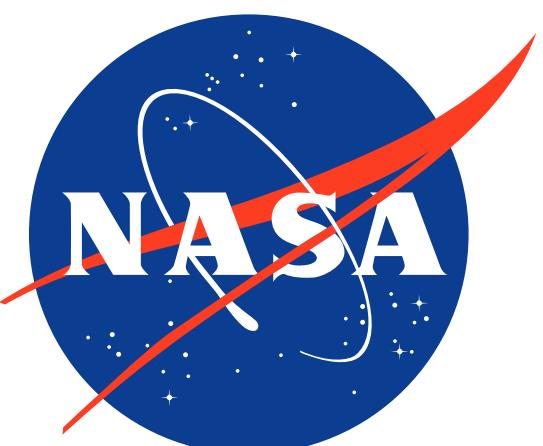


Software science & engineering

- ◆ Solid general methodologies to develop high-quality, bug-free software
 - ▶ M. Hamilton coined “software engineering”
 - She led the development of flight software for NASA’s Apollo 11 in the 1960s
 - ▶ Scientific curiosity & Pragmatic usability
 - ▶ Programming languages, types, testing & verification, fail-safety, ...

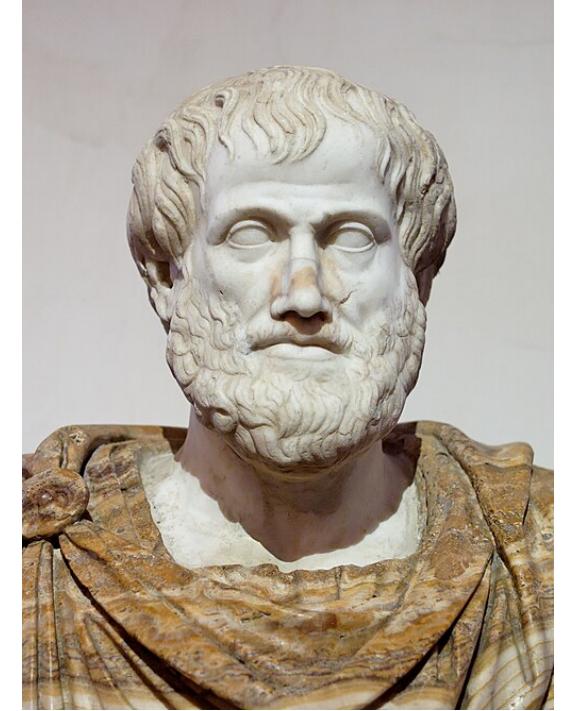


Margaret Hamilton
1936-



 LANGLEY FORMAL METHODS

History of logic – Philosophy & Mathematics



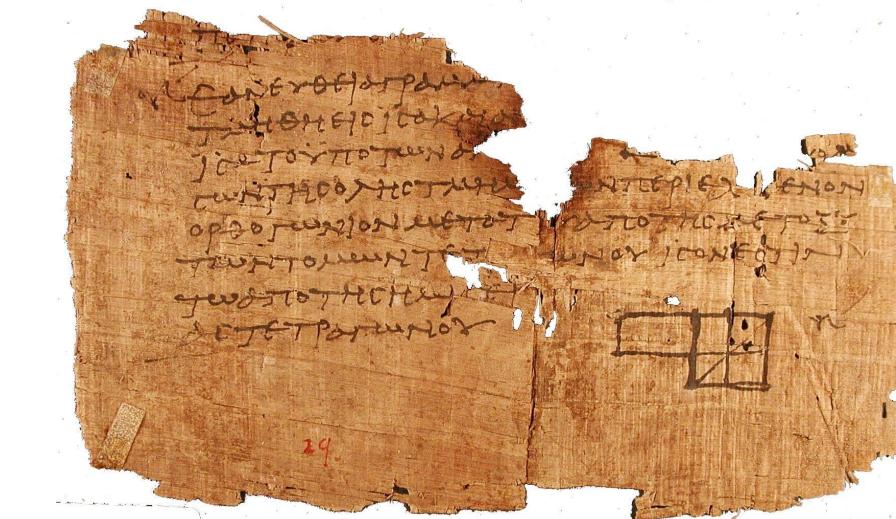
All men are mortal.
All Greeks are men.
Thus all Greeks are mortal.

$M \wedge P, S \wedge M; S \wedge P$
Syllogism

Aristotle 384-322BC



Euclid ~300BC



The Elements
Axioms

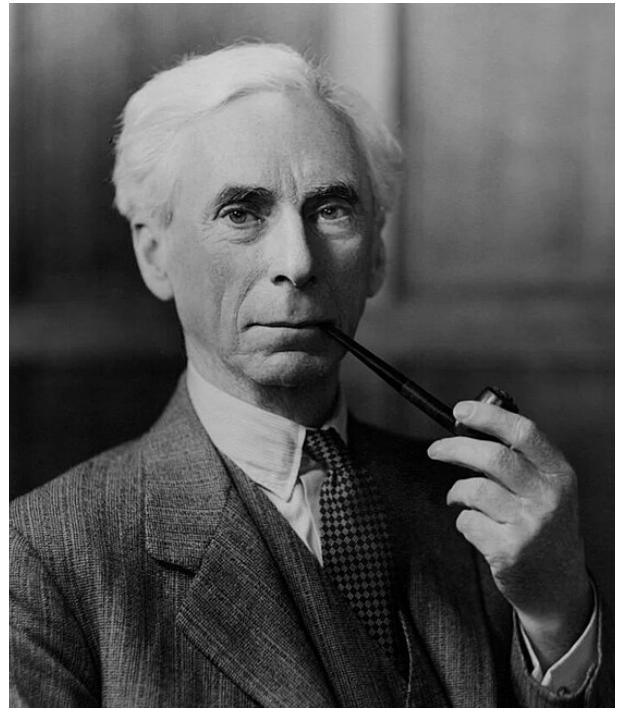


Gottlob Frege 1848-1925

BEGRIFFSSCHRIFT,
EINE DER ARITHMETISCHEM NACHGEBILDETE
FORMELSPRACHE
DES REINEN DENKENS.

\overline{TT} A
 \overline{TT} B

Begriffsschrift



$\{S \mid S \notin S\}$
Russel's paradox

*54.43. $\vdash \alpha, \beta \in 1. \supset : \alpha \cap \beta = \Lambda \rightarrow \alpha \cup \beta \in 2$
Dem.
 $\vdash *54.26. \supset \vdash \alpha = t'x, \beta = t'y. \supset : \alpha \cup \beta \in 2 \equiv . x \neq y.$
[*51.231] $\equiv . t'x \cap t'y = \Lambda.$
[*18.12] $\equiv . \alpha \cap \beta = \Lambda$ (1)
 $\vdash (1). *11.11.35. \supset$
 $\vdash (x, y) . \alpha = t'x, \beta = t'y. \supset : \alpha \cup \beta \in 2 \equiv . \alpha \cap \beta = \Lambda$ (2)
 $\vdash (2). *11.54. *52.1. \supset \vdash \text{Prop}$
From this proposition it will follow, when arithmetical addition has been
defined, that $1 + 1 = 2$.

Bertrand Russell
1872-1970

Principia Mathematica



Kurt Gödel
1906-1978

Gödel's 2nd incompleteness theorem

Any consistent **formal system** cannot prove its consistency

Foundational crisis of mathematics

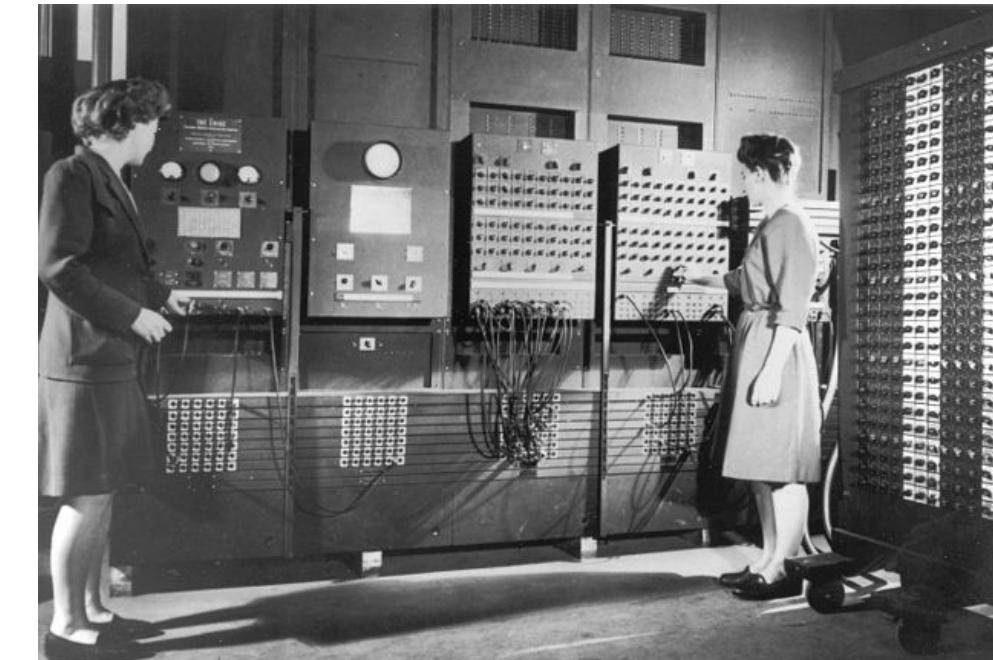
What is the mathematical **truth**?

What is a limit of a finite **machine**?

History of programming

◆ 1940's Physical settings

- ▶ Plugboard wiring & switches



◆ 1947 Assembly languages

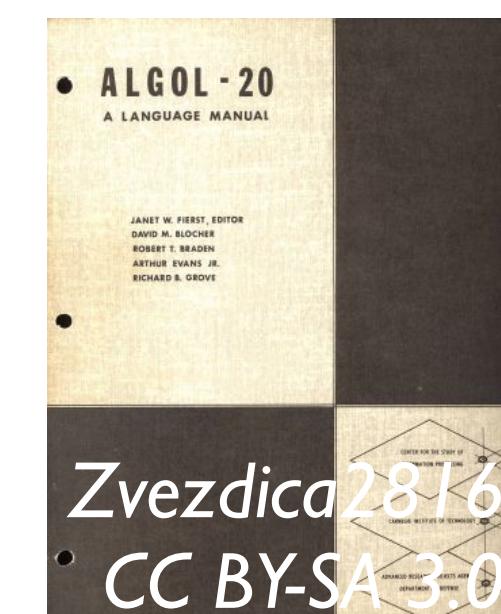
- ▶ Transliteration of machine code

0013	RESETA	EQU	%00010011
0011	CTLREG	EQU	%00010001
C003 86 13	INITA	LDA A	#RESETA
C005 B7 80 04		STA A	ACIA
C008 86 11		LDA A	#CTLREG
C00A B7 80 04		STA A	ACIA
C00D 7E C0 F1	JMP	SIGNON	

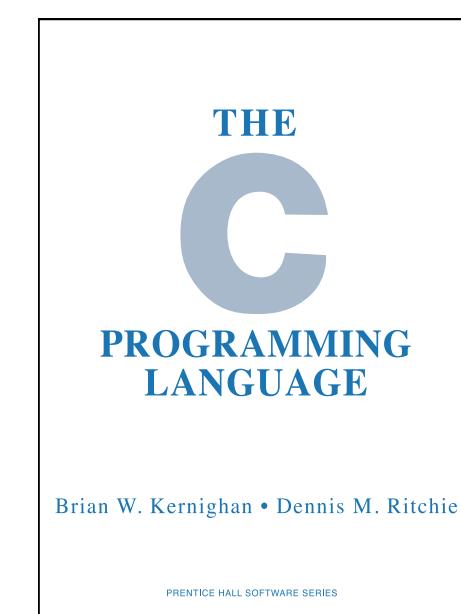
◆ 1952 Programming languages

- ▶ High-level abstraction
- ▶ Various designs explored

1958
ALGOL



1972
C



1991
Python



1995
Java



2009
Go



and so on ...

Types in programming languages

♦ Labels on data in computation

- ▶ Describe kinds, attributes, permissions, etc.
- ▶ Systematic way to **prevent bugs** in programs

123 : Int

"Hello" : String



History of types

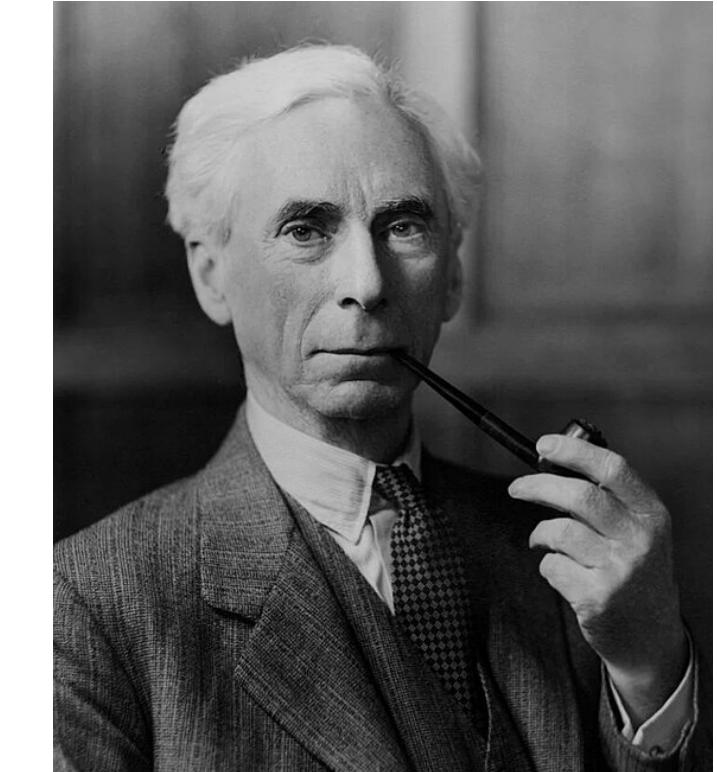
- ◆ 1903 Russel's work on types for logic
 - ▶ To avoid Russel's paradox $\{S \mid S \notin S\}$
- ◆ 1940 Church's simply typed lambda calculus
 - ▶ Types for a formal model of computation
- ◆ 1958 Types for programming languages
 - ▶ To prevent bugs in software

1. Type declarations

Type declarations serve to declare certain variables, or functions, to represent quantities of a given class, such as the class of integers or class of Boolean values.

Form: $\Delta \sim type (I, I, \dots, I, I[], \dots, I[,], \dots, I[, ,], \dots)$ where *type* is a symbolic representative of some *type* declarator such as *integer* or *boolean*, and the *I* are identifiers. Throughout the program, the variables, or functions named by the identifiers *I*, are constrained to refer only to quantities of the type indicated by the declarator. On the other hand, all variables, or functions which are to represent other than arbitrary real numbers must be so declared.

Algol 58 Report, CACM



Bertrand Russell



Alonzo Church

Formal verification

♦ Prove that the software satisfies the specifications

- ▶ Rigorously eradicate software bugs
- ▶ Real-world use in critical domains
 - Aerospace, automobile, finance, security, ...

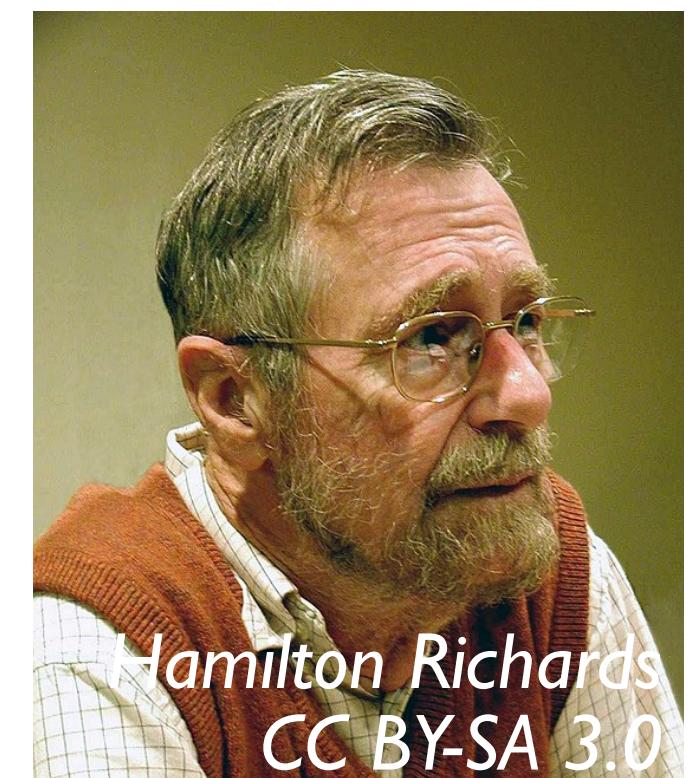


♦ Central topic in software science

- ▶ Program logics, especially Hoare Logic '69
 - Dijkstra's weakest precondition calculus '75
- ▶ Mathematical logic at work



Tony Hoare



Edsger Dijkstra

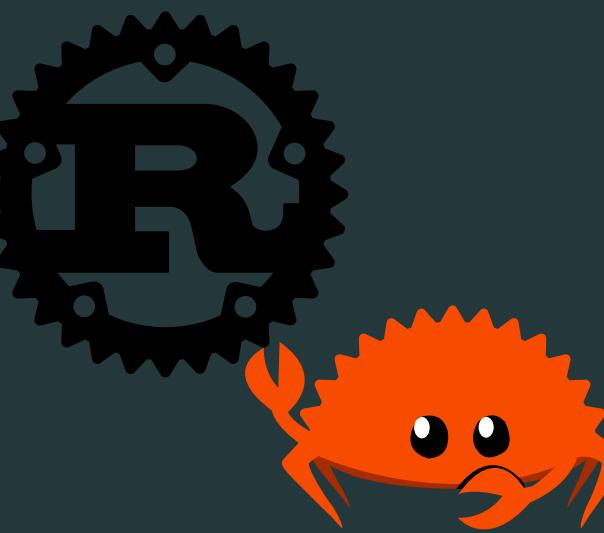
Now in the Information Age

1947 - Present

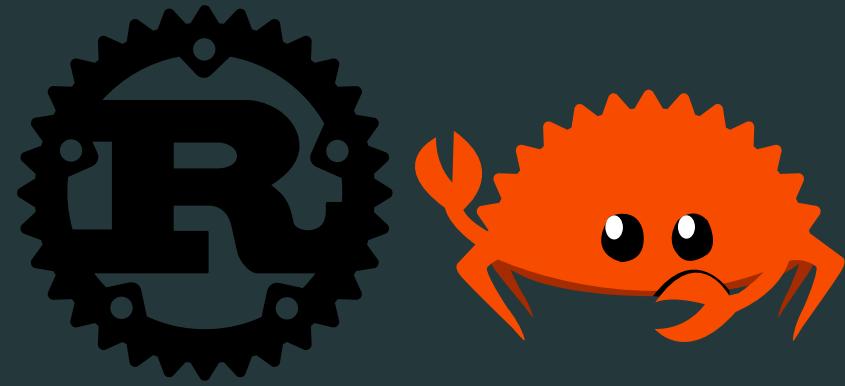


- ◆ **Software science & engineering can help shape a great future of information technology and our lives**

The Fun of Rust



The **Rust** programming language



♦ Rust makes the software:

- ▶ **Performative** — Low-level controls like C/C++
- ▶ **Secure** — High-level safety guarantees by **ownership types**
- ▶ **Developed fast** — Modern language features & ecosystem

Software science

is advancing the real world

Rust

[GET STARTED](#)

Version 1.83.0

A language empowering everyone to build reliable and efficient software.

Why Rust?

Performance

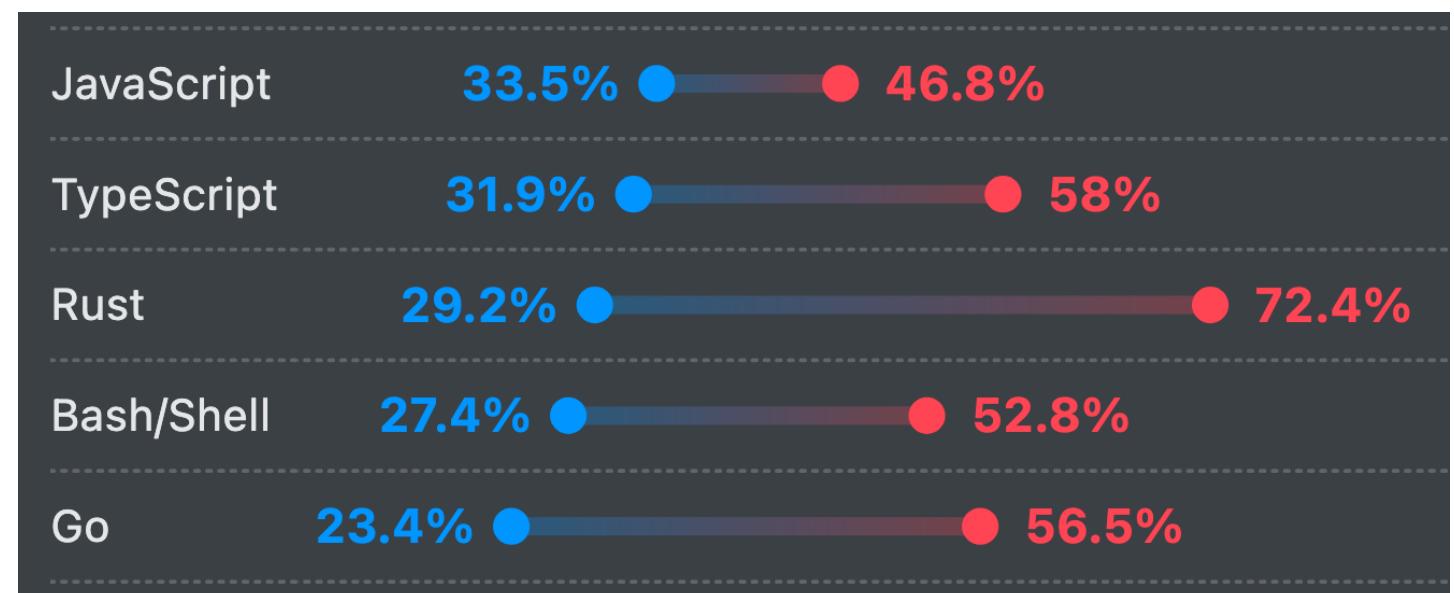
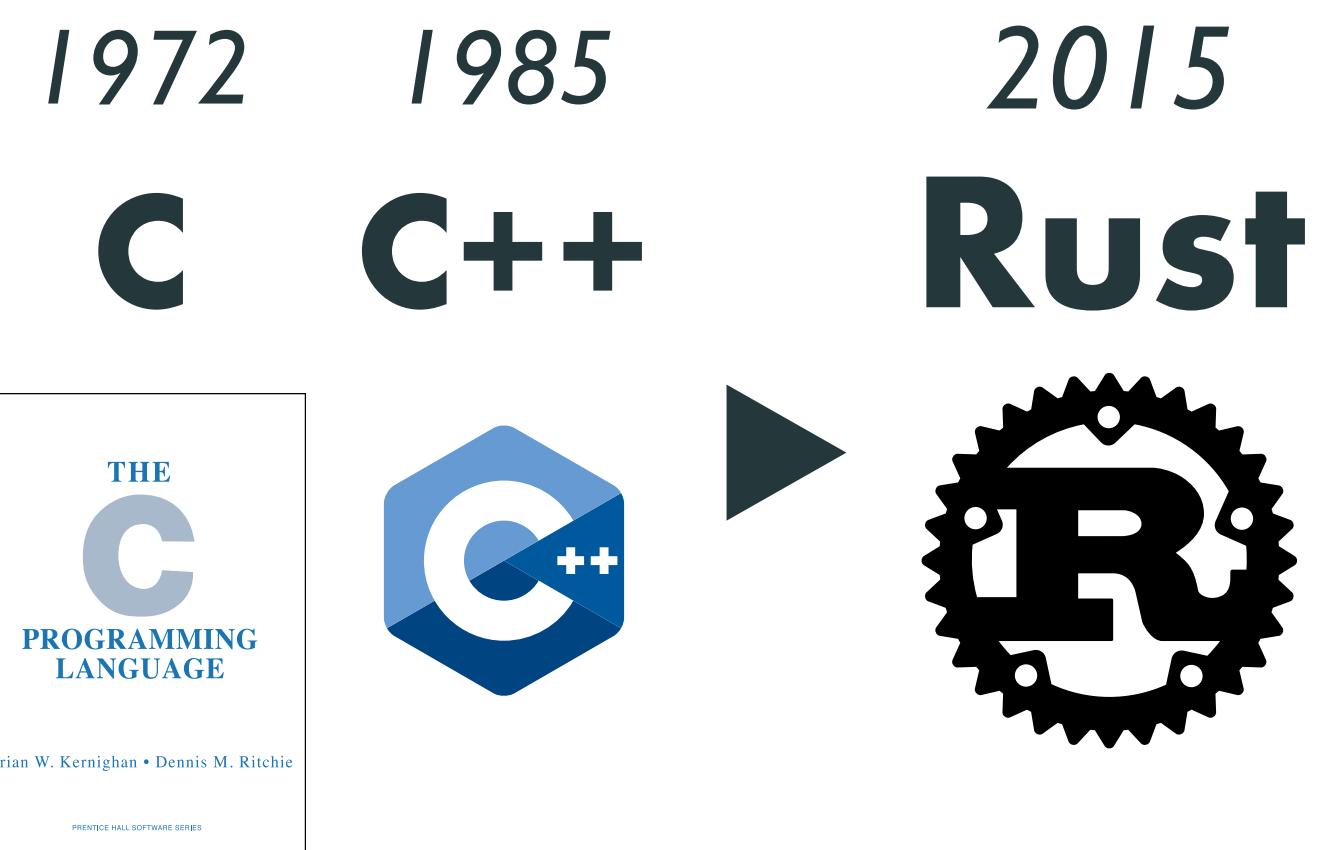
Rust is blazingly fast and memory-efficient: with no runtime or garbage collector, it can power performance-critical services, run on embedded devices, and easily integrate with other languages.

Reliability

Rust's rich type system and ownership model guarantee memory-safety and thread-safety — enabling you to eliminate many classes of bugs at compile-time.

Productivity

Rust has great documentation, a friendly compiler with useful error messages, and top-notch tooling — an integrated package manager and build tool, smart multi-editor support with auto-completion and type inspections, an auto-formatter, and more.

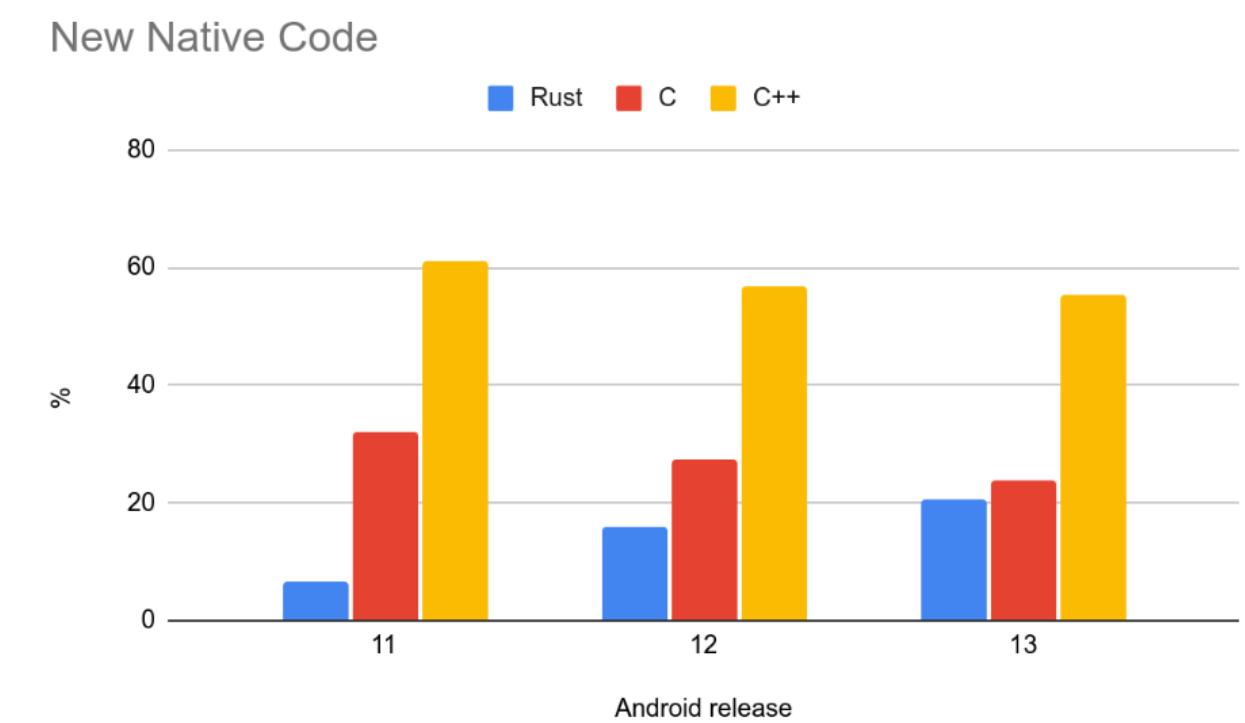


Rust has been the most admired language for 10 years

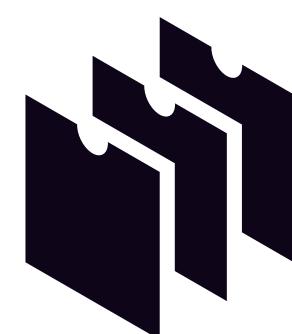
Rust in the real world

◆ Rust serves a lot in real-world software

- ▶ **Google's Android OS**
 - Rust reduced vulnerabilities
- ▶ **Mozilla's Firefox web browser**
 - Rust was born from and raised by Mozilla
- ▶ **Security & performance**
 - VMs: AWS's Firecracker, Google's crosvm
 - Language engines: Deno, Wasmer

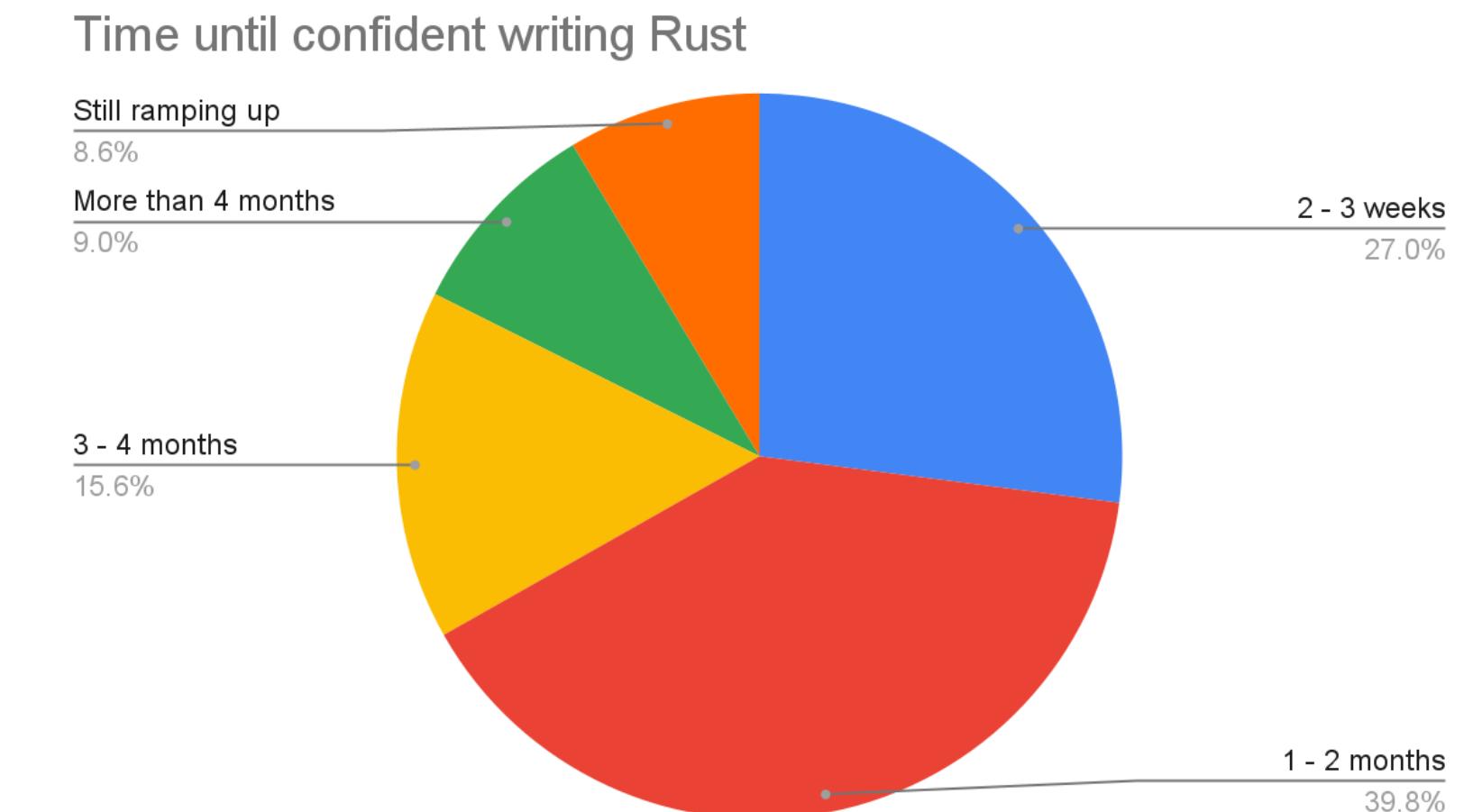
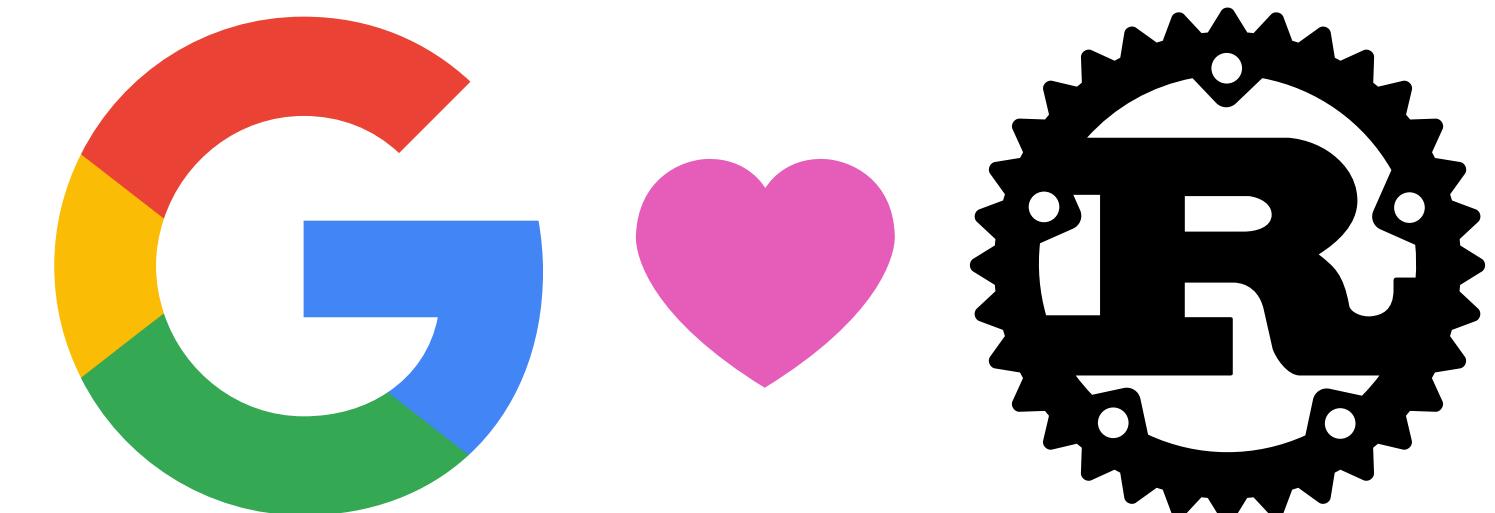


Mozilla



Rust: Case for Googlers

- ♦ A survey on >1k Google software engineers in 2022
 - ▶ ~67% got confident in writing Rust just in 2 months
 - ▶ Over 50% felt as productive in Rust as in other languages in 4 months
 - ▶ ~85% felt more confident in correctness in Rust than in other languages
 - ▶ Top challenges in learning Rust: Macros, ownership/borrowing, async

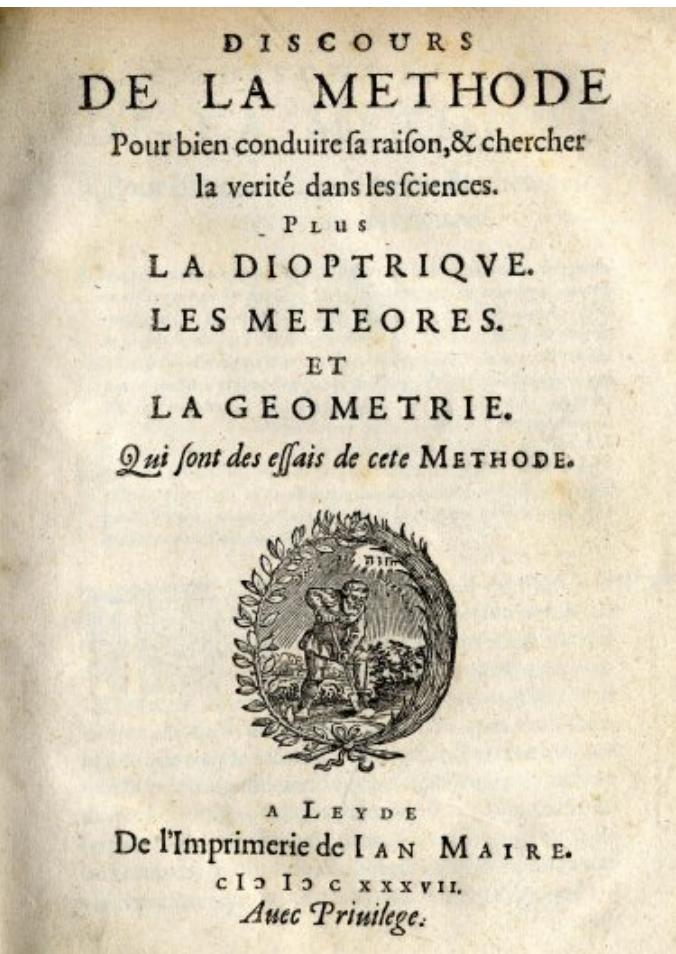


Rust, more technically

Divide the difficulties



René Descartes 1596-1650



The second: to divide each of the difficulties under examination into as many parts as possible, and as might be necessary for its adequate solution.

Discourse on the Method, Part II

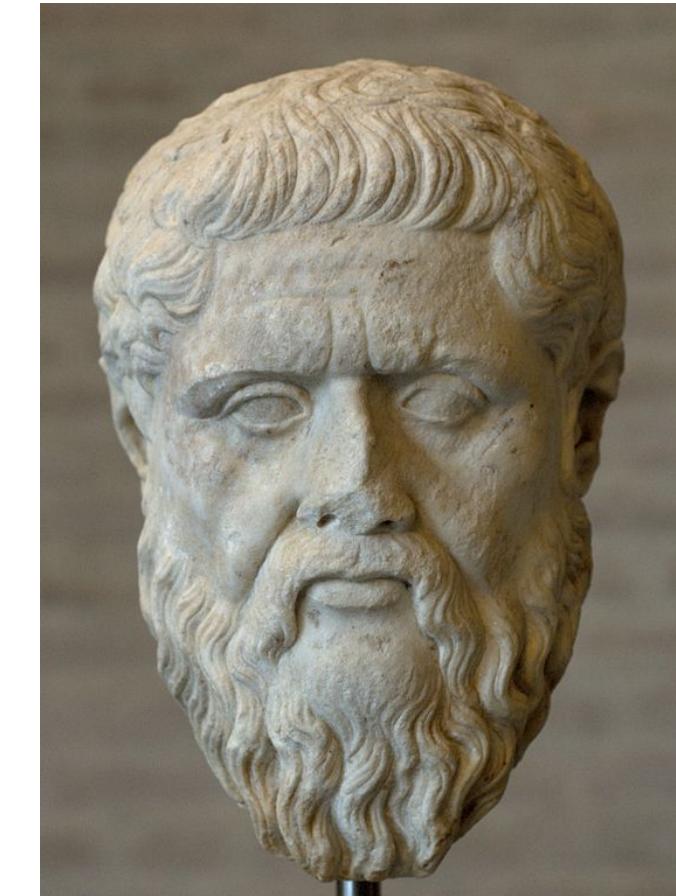
- ♦ To overcome the difficulties, divide them
 - Then compose the reasoning about the parts
 - Modularity & Composability → Scalability



Difficulties in computation

- ♦ Ideally, everything is just persistent

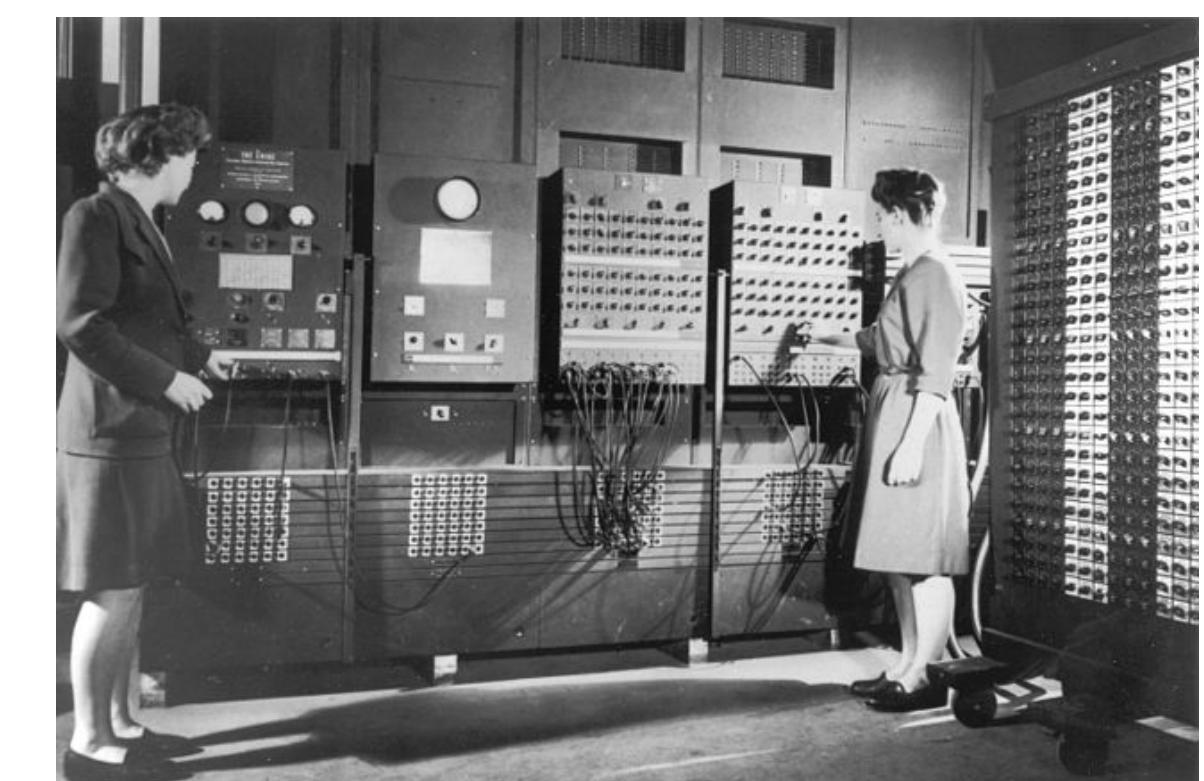
- ▶ Metaphysical world of Platonic Forms
- ▶ Usual mathematics works in this setting



Plato
~400BC

- ♦ Physical computation breaks things

- ▶ Inevitably deals with **mutable state**,
e.g., the memory and the environment
- ▶ Reasoning about mutable state is hard
 - Naive reasoning can break by state update



Girard's linear logic

1987

♦ Logic with non-persistent propositions

- ▶ Can reason about mutable state
- ▶ Applications to computer science



Jean-Yves Girard 1947-

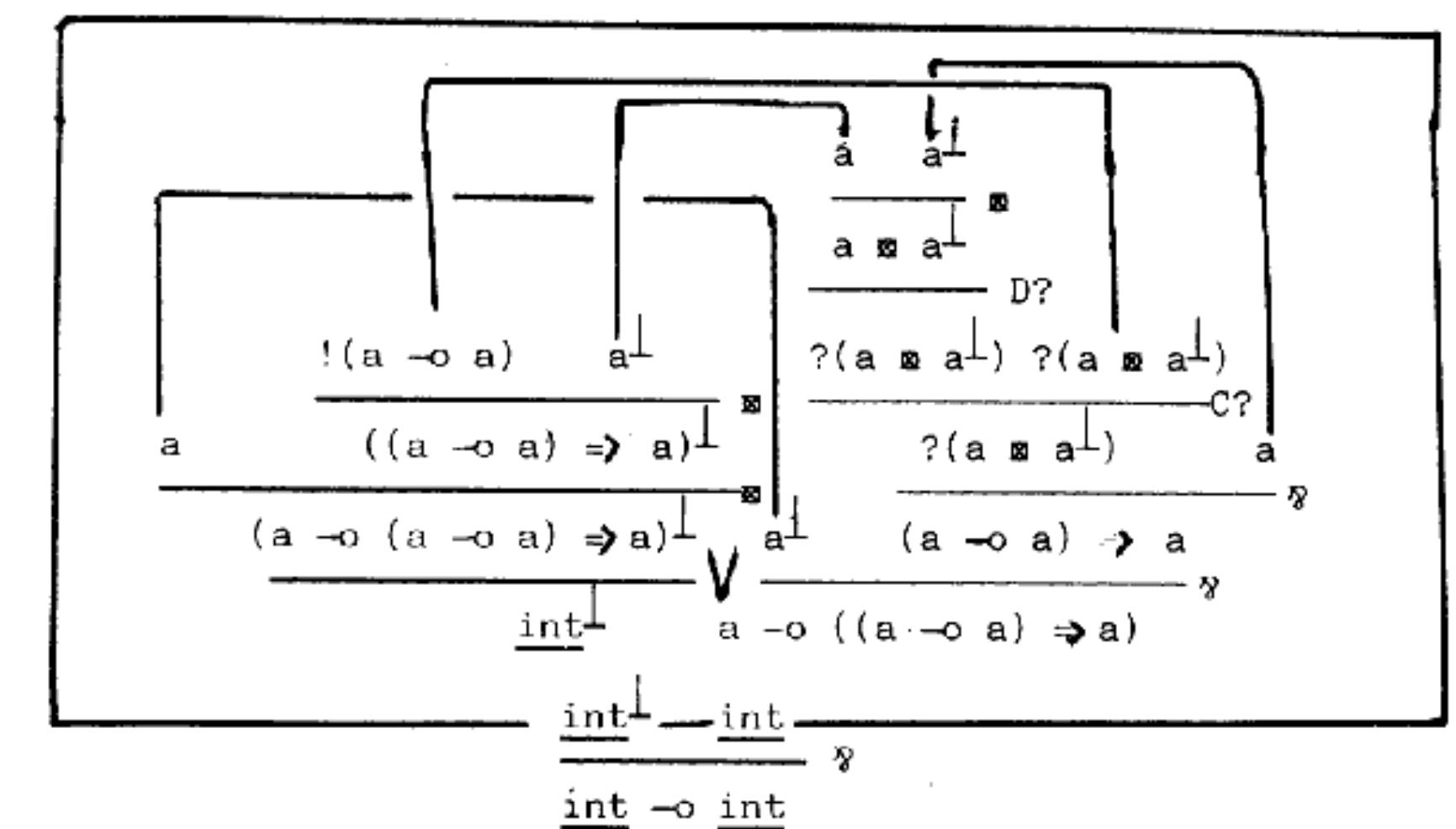
LINEAR LOGIC*

"La secrète noirceur du lait..."

(Jacques Audiberti)

$$\vdash 1 \text{ (axiom)}, \frac{\vdash A}{\vdash \perp, A} \perp, \quad \frac{\vdash A, C \quad \vdash B, D}{\vdash A \otimes B, C, D} \otimes, \quad \frac{\vdash A, B, C}{\vdash A \wp B, C} \wp$$

* Because of its length and novelty this paper has not been subjected to the normal process of refereeing. The editor is prepared to share with the author any criticism that eventually will be expressed concerning this work.



From linear logic to Rust

- ♦ Rust's ownership types originate from academic studies
 - Rust is the first to put **ownership types** into full practice

Linear logic

Girard 1987



$$\frac{\vdash A, C \quad \vdash B, D}{\vdash A \otimes B, C, D} \otimes, \quad \frac{\vdash A, B, C}{\vdash A \wp B, C} \wp$$

Linear types

Wadler 1990

Region types

Tofte & Talpin 1994

Ownership types

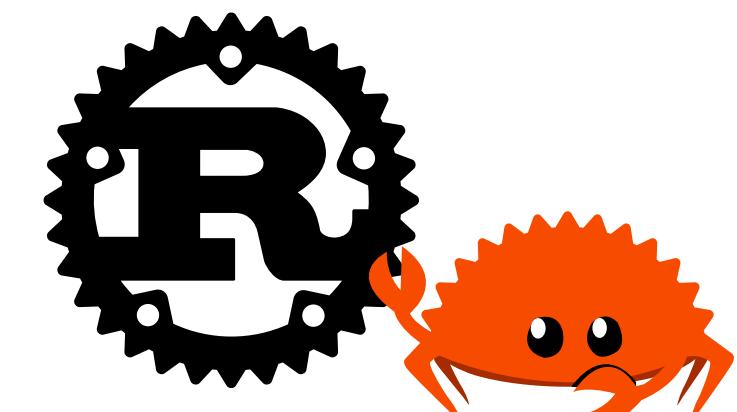
Clarke+ 1998

Cyclone

Grossman+ 2002

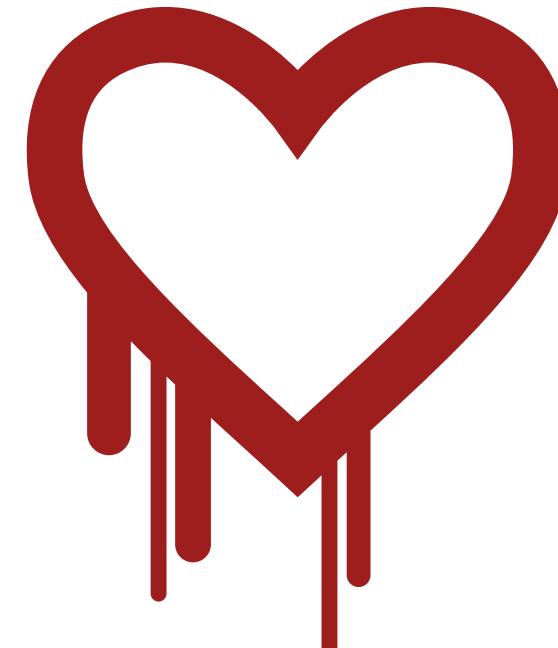
Borrows

Rust



Matsakis+ 2015

Days before Rust

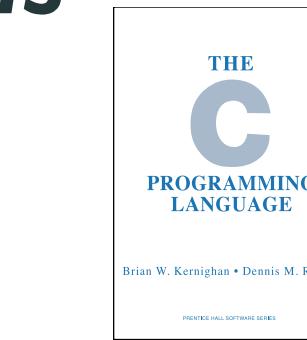


Heartbleed

'12 Introduced
'14 Disclosed & fixed

Severe bug in OpenSSL, a widely used library for secure communications

Memory corruption caused by C



Heartbeat – Malicious usage

Client

Server, send me this 500 letter word if you are there: "bird"

bird. Server master key is 31431498531054. User Carol wants to change password to "password 123"...

Server has connected. User Bob has connected. User Mallory wants 500 letters: bird. Server master key is 31431498531054. User Carol wants to change password "password 123".

♦ Severe vulnerabilities due to **memory corruption**

- Languages like C/C++ are **not** memory-safe!
- ~70% of zero-day attacks - '19 stem from **memory corruption** — Google Project Zero

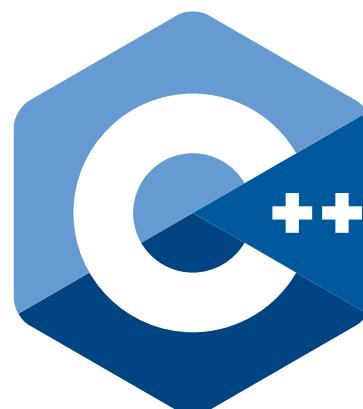
CVE	Vendor	Product	Type
CVE-2019-7286	Apple	iOS	Memory Corruption
CVE-2019-7287	Apple	iOS	Memory Corruption
CVE-2019-0676	Microsoft	Internet Explorer	Information Leak
CVE-2019-5786	Google	Chrome	Memory Corruption
CVE-2019-0808	Microsoft	Windows	Memory Corruption
CVE-2019-0797	Microsoft	Windows	Memory Corruption



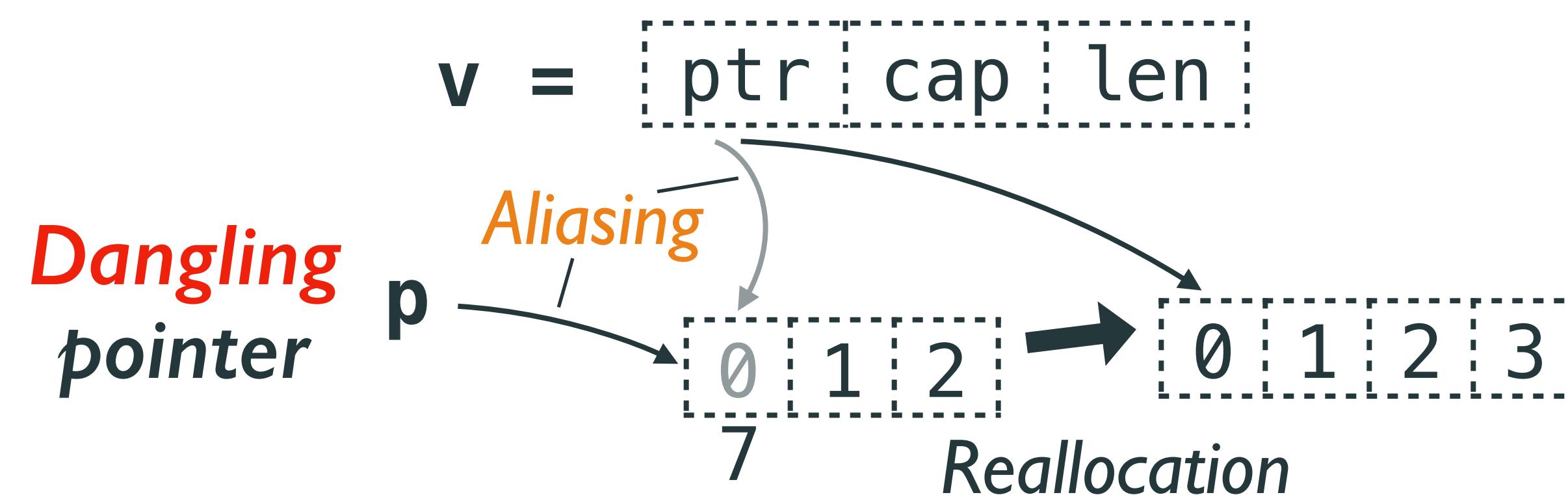
Aliasing AND Mutability is dangerous

- ♦ Aliased mutable state is the core source of bugs

Example A **dangling pointer** caused by a **data race**



```
vector<int> v { 0, 1, 2 }; int *p = &v[0];  
v.push_back(3); *p = 7; // Data race!  
printf("%d\n", v[0]); // Prints 0, not 7
```

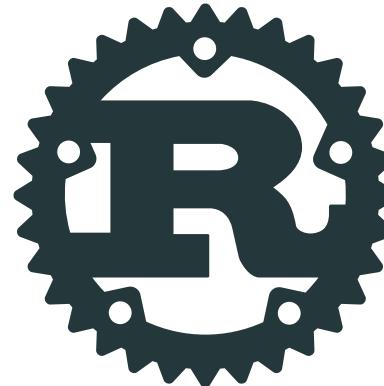


Even worse, this can cause
a buffer overflow, **leaking secrets!**

Rust bans Aliasing AND Mutability

- ◆ Rust's ownership types ban “Aliasing AND Mutability”

Example



```
let mut v = vec![0, 1, 2]; let p = &mut v[0];
v.push(3); *p = 7; // OWNERSHIP ERROR
println!("{}", v[0]);
```

error[E0499]: cannot borrow `v` as mutable more than once at a time

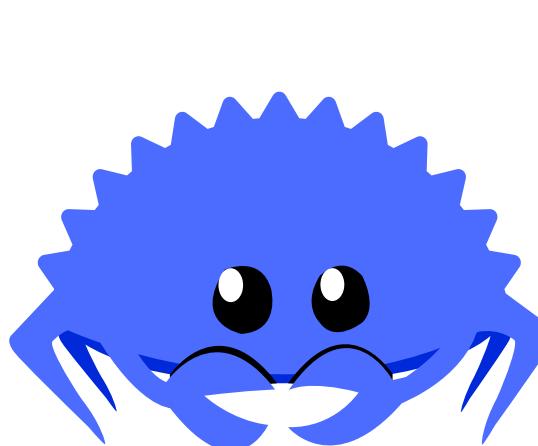
```
| ...; let p = &mut v[0];
|                               - first mutable borrow occurs here
| v.push(3); *p = 7; // Data race!
| ^
| ----- first borrow later used here
| second mutable borrow occurs here
```

Bug detected!

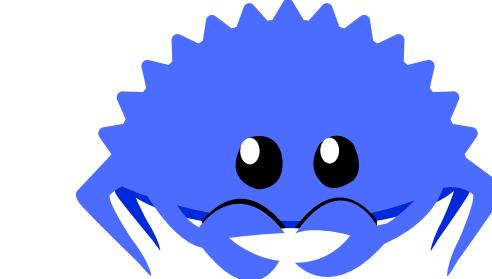
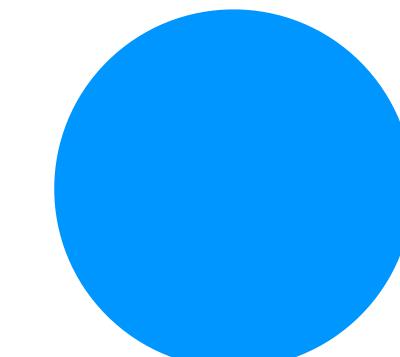
Ownership for Aliasing XOR Mutability

- ◆ Each resource is either aliased or mutable, never both
- ◆ Managed by **ownership** = access permission

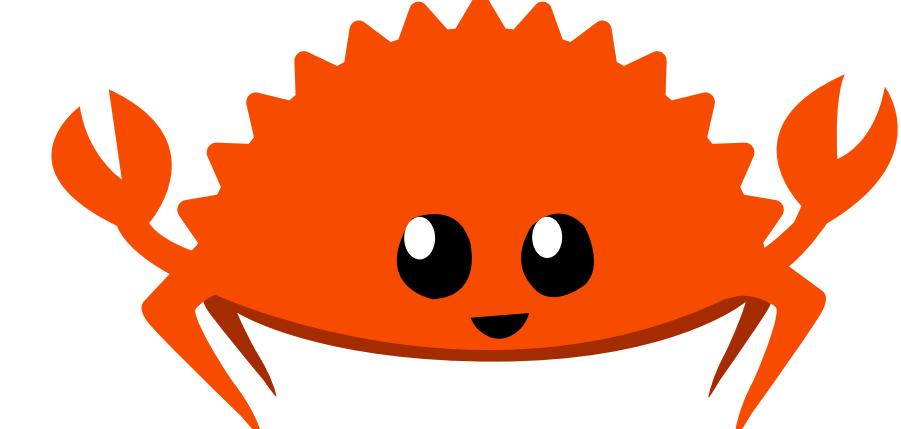
Aliased & Immutable



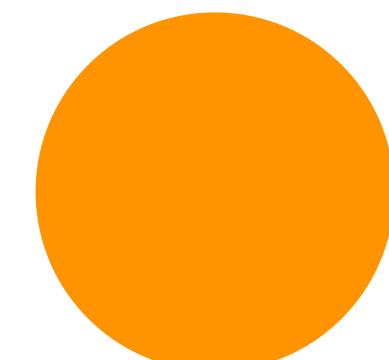
Read-only



Mutable & Exclusive



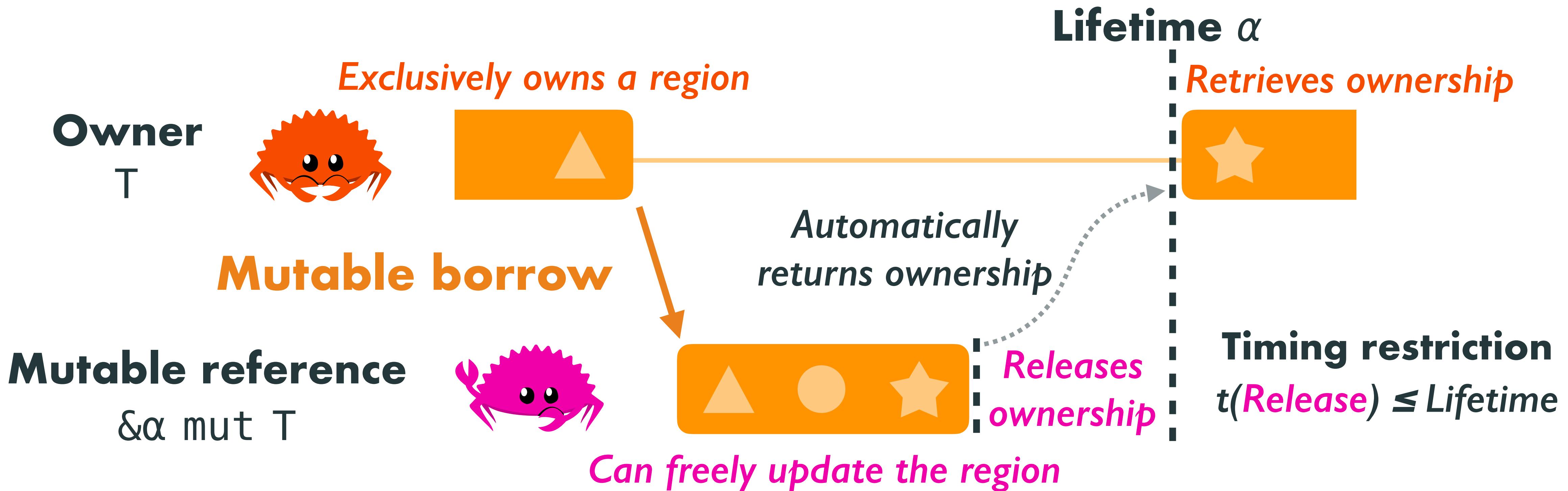
Writable



Unique

Rust's key idea: Borrowing

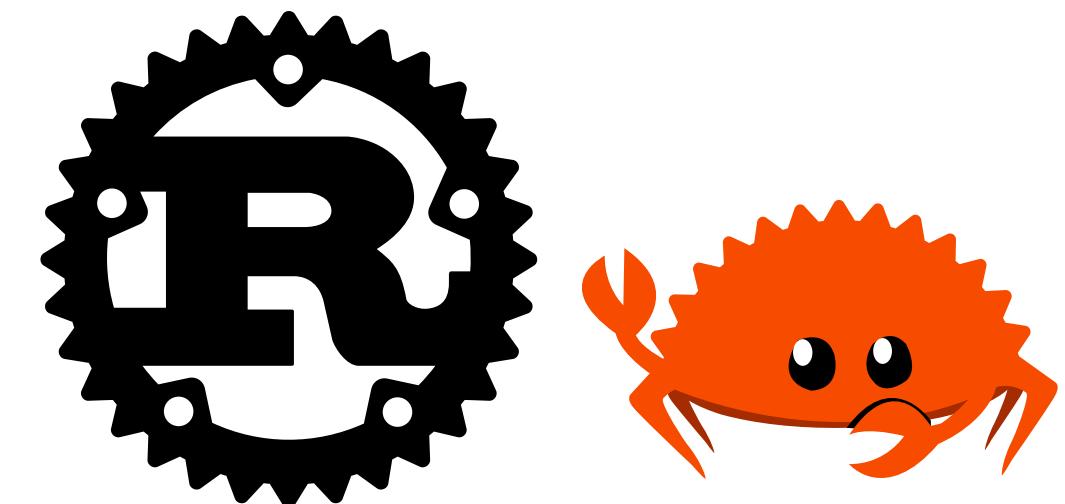
- ◆ To borrow ownership temporarily
 - No direct communications needed when releasing ownership



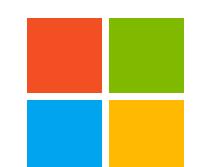
My research on Rust

Formal verification of Rust programs

- ♦ Significant in the real world
 - ▶ As Rust is widely used for foundational software
 - ▶ Operating systems, servers, crypto, ...
- ♦ Can take advantage of Rust's ownership types



Α Ε



Microsoft Research

Practical, High-
Performance
Verification in Rust

Rust Verification Workshop

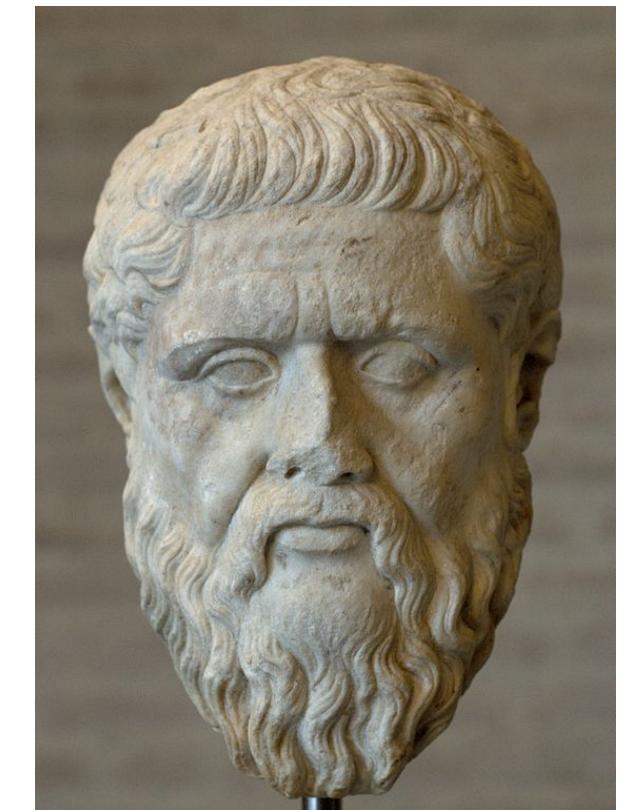
Fifth Rust Verification Workshop
(RW2025)

May 5-6, 2025

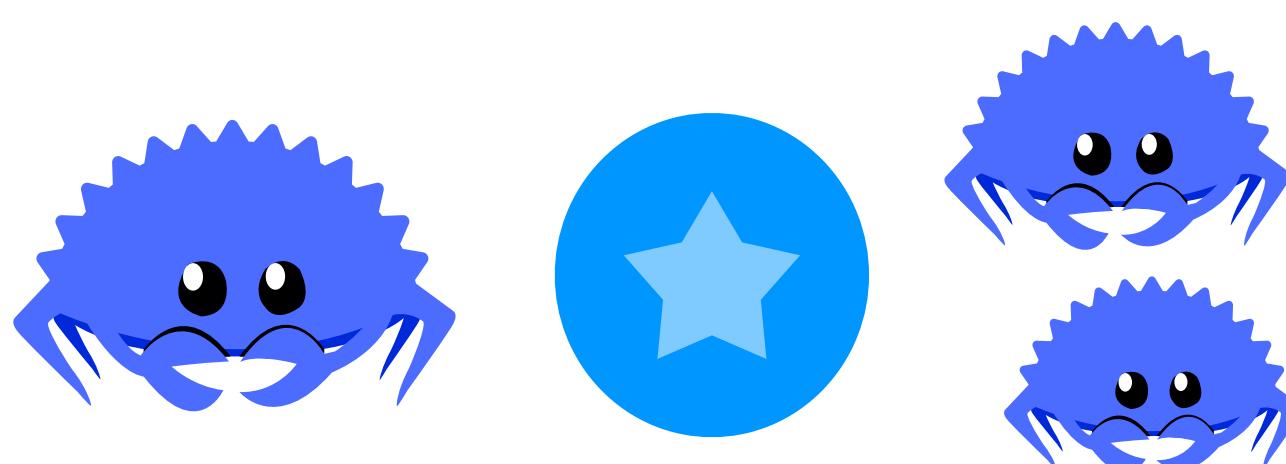
co-located with [ETAPS 2025](#), Hamilton, Canada

Basic idea: Rust into mathematical models

- ◆ Turn Rust programs into mathematical models
 - ▶ Leverage Rust's ownership types
 - ▶ To the “metaphysical” world where all is persistent



Aliased & Immutable



Just an immutable value

Fully own



Can track the value change

Challenge: Mutable borrows

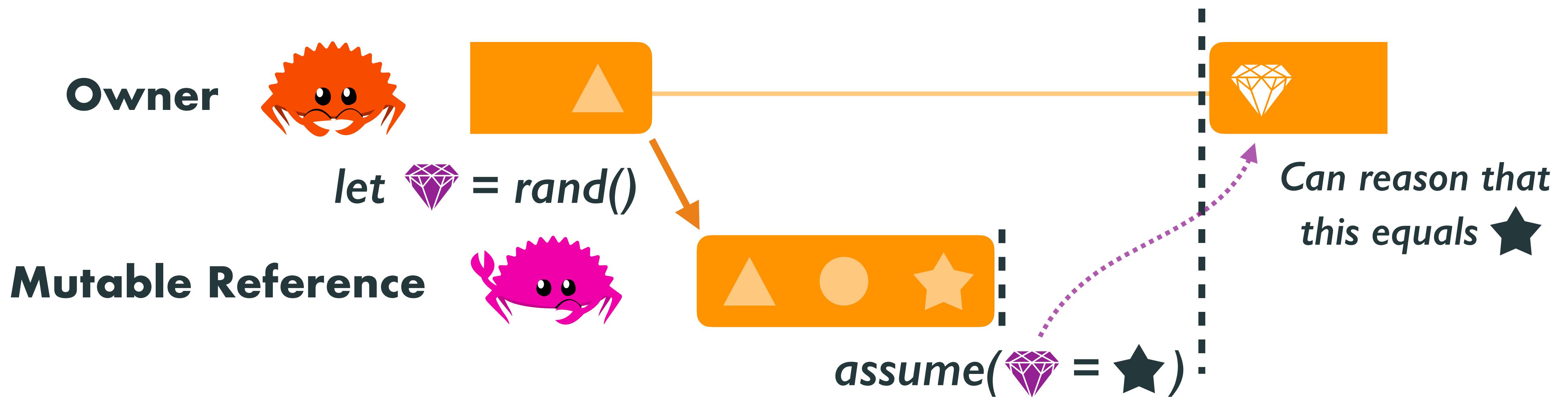
- ♦ **Mutable borrows are hard for functional reasoning**
 - How to “tell” the lender the result of the borrower’s mutation?





♦ Model mutable borrows by prophecy 💎

- ▶ Prophecy [Abadi & Lamport '88]: Fetches info about the **future**
 - Specifically, the result of the borrower's mutation



Power of RustHorn's approach

- ◆ Prophecy can naturally model various operations
 - ▶ By resolving prophecies just as ownership is released

Example

```
fn push<α, T>(v : &α mut Vec<T>, a : T)
```

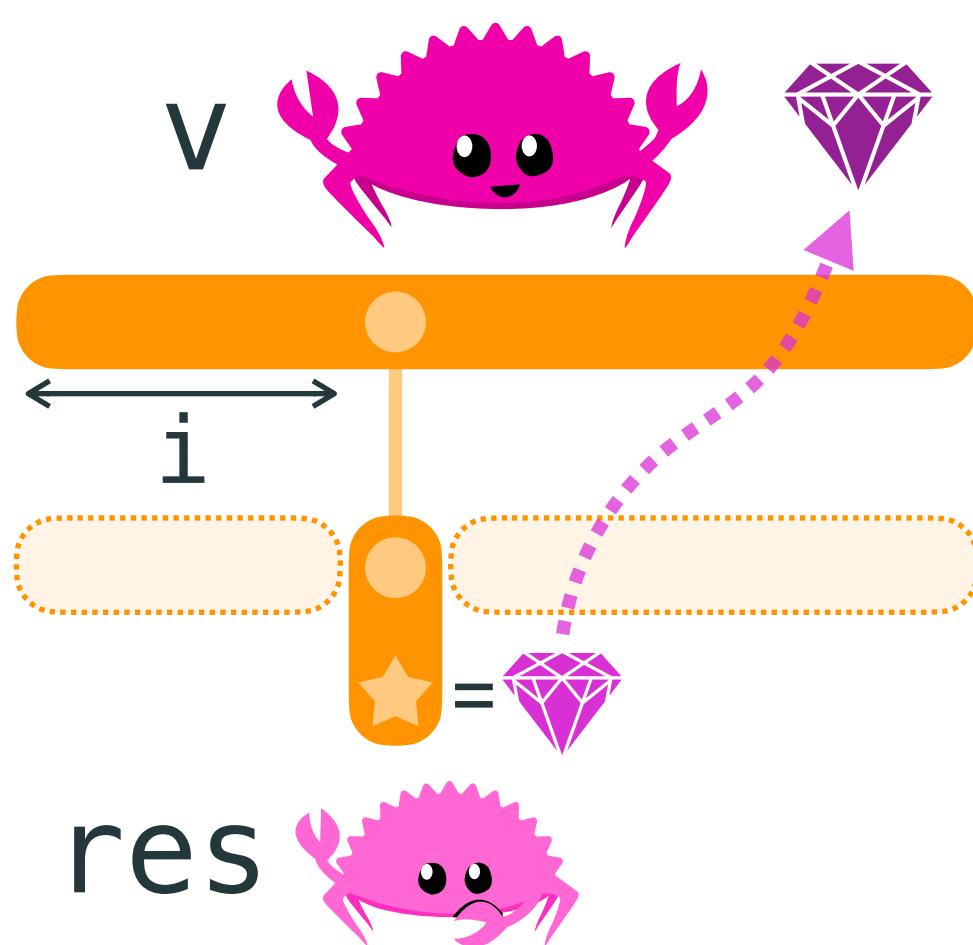
ensures $\hat{v} = *v + a$ *Resolve the prophecy* 

```
fn index_mut<α, T>(v : &α mut Vec<T>, i : uint) -> &α mut T
```

requires $i < v.\text{len}()$

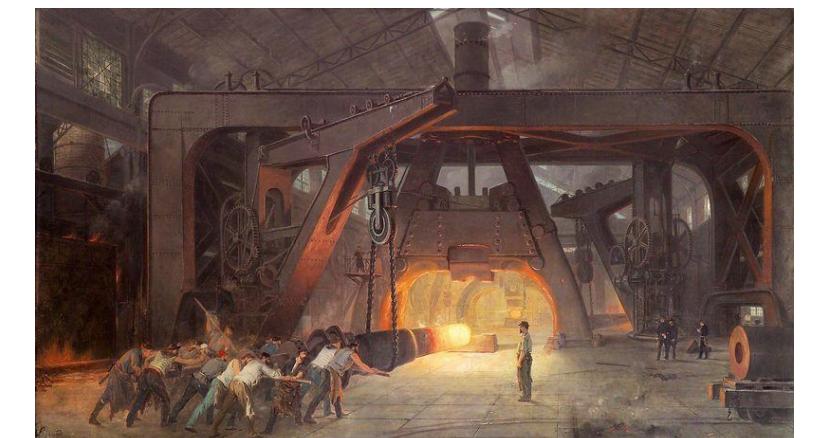
ensures $*res = v[i] \ \&& \ \hat{v} = *v \ \{ \ i := \hat{res} \}$

Partially resolve the prophecy 



RustHorn's approach at work

- ♦ **Demonstrated in diverse contexts**
 - ▶ **Fully automated Rust verifier RustHorn [Matsushita+ '20/21]**
 - Automatically find invariants with CHC solvers [Bjørner+ '15]
 - ▶ **Semi-automated Rust verifier Creusot [Denis+ '22]**
 - Used for verifying a SAT solver written in Rust [Skotåm '22]
 - ▶ **Rust program synthesizer RusSOL [Fiala+ '23]**
 - Synthesizes to satisfy **RustHorn-style specs & ownership constraints**
 - ▶ **Refinement-type based verifier Thrust [Ogawa+ '25]**



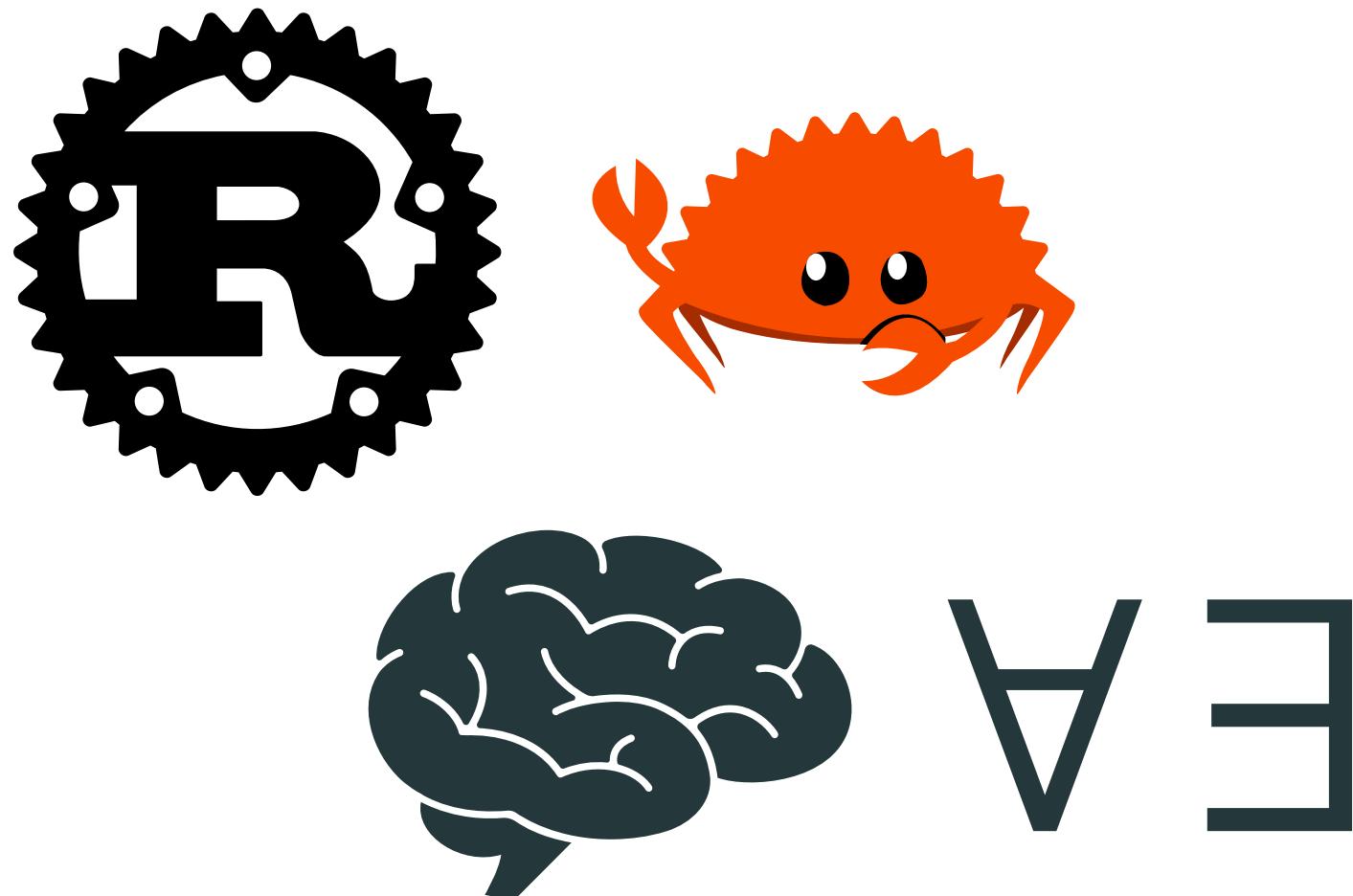
Foundational verification of Rust

- ◆ Metatheory on Rust's core features
 - ▶ Ownership types + Extension by Rust APIs
 - ▶ RustBelt [Jung+ '18]  — Foundation for Rust
 - Memory & thread safety of Rust's ownership types
 - Modeling types in separation logic [O'Hearn+ '01], a variant of linear logic
 - ▶ RustHornBelt [Matsushita+ '22]  — Foundation for RustHorn
 - Extended RustBelt to prove RustHorn-style reasoning sound
 - Modeled nestable prophecies in separation logic

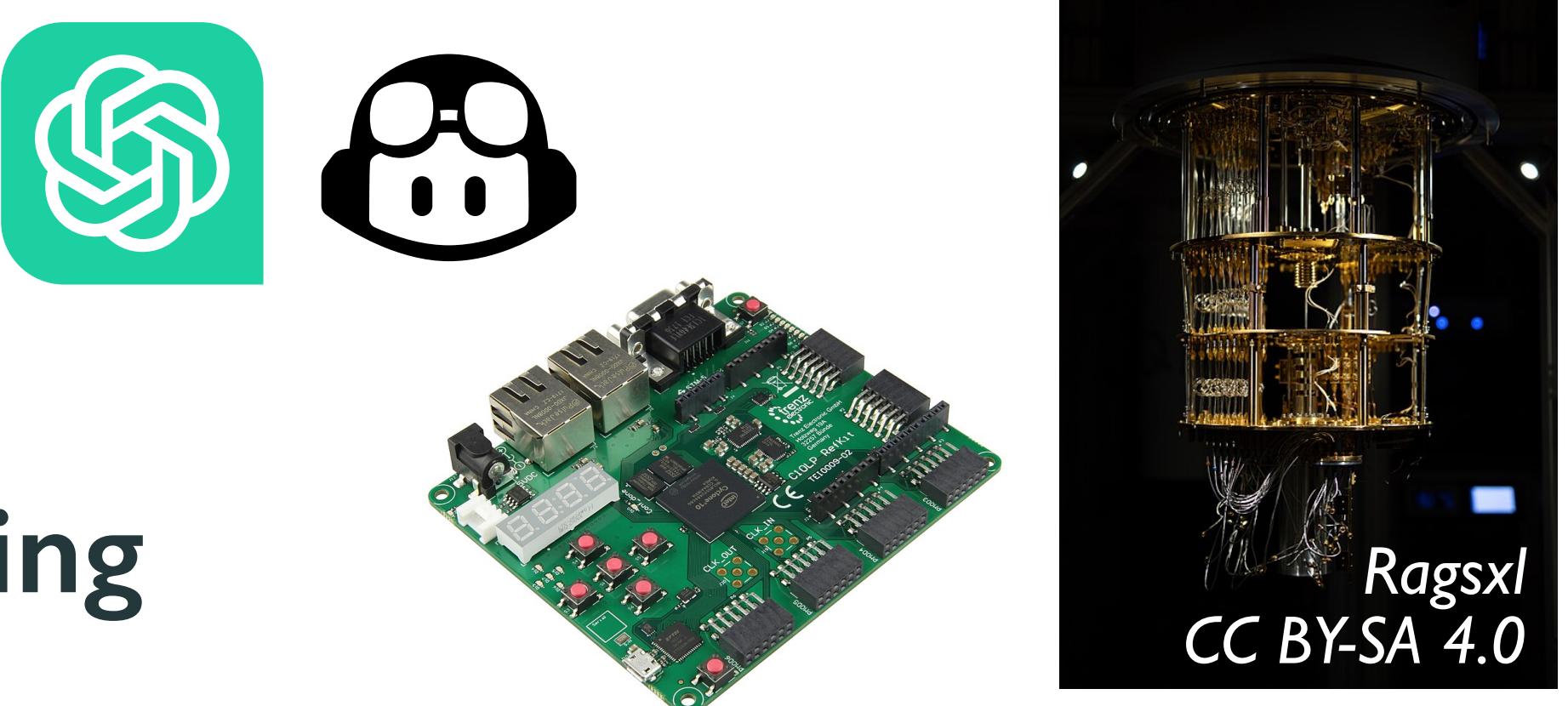


Future research topics

- ◆ **Beyond Rust's ownership types**
 - ▶ Practically verify more low-level code
 - ▶ Reason about shared mutable state
 - ▶ Prove contextual refinement & equivalence
 - Compare program behaviors under Rust's types

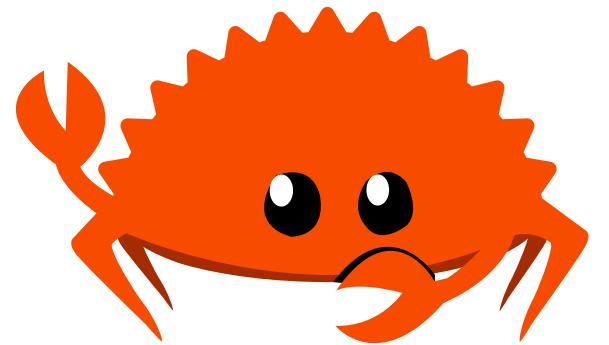
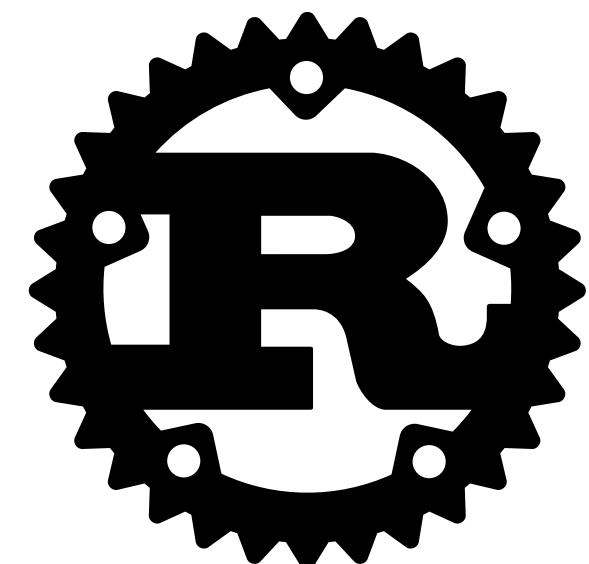


- ◆ **Different angles**
 - ▶ Synthesize programs & proofs with AI
 - ▶ Apply to hardware & quantum computing

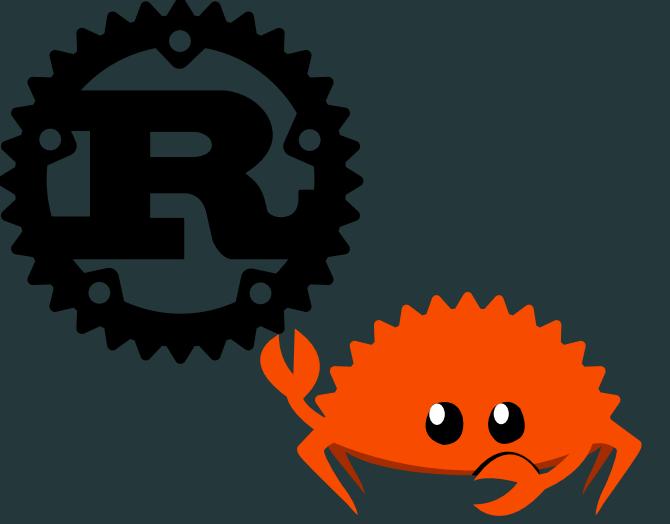
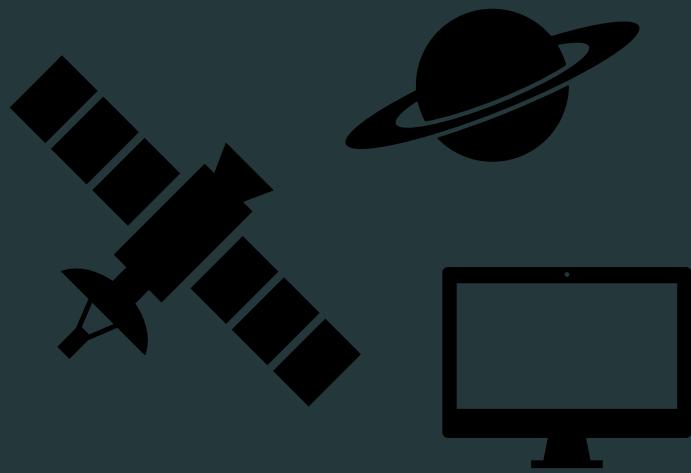


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Creating the new age with Rust



EVA



Software science & Rust
can take us to
a great future of
information technology

