Programs and Proofs

KC Sivaramakrishnan

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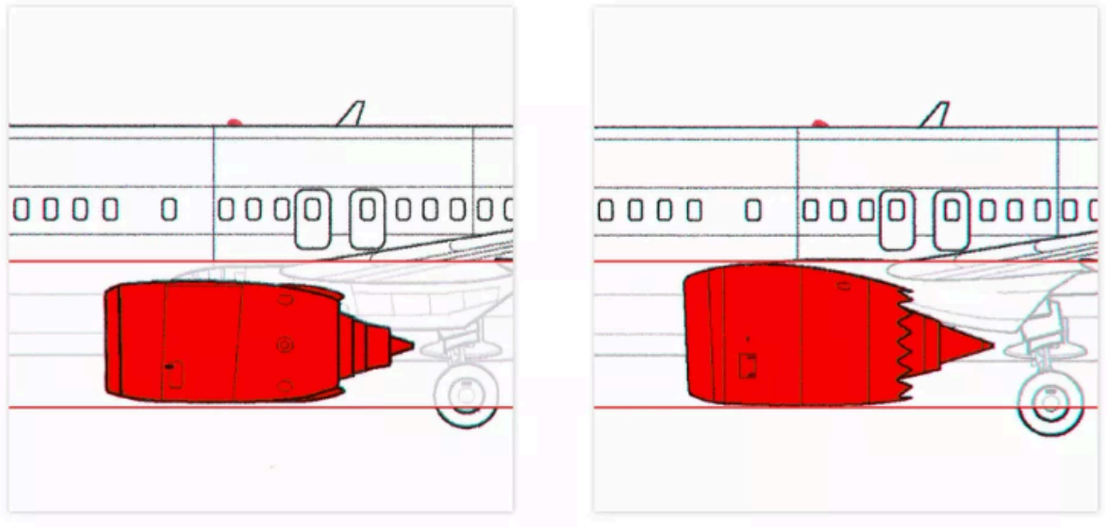
Building Reliable Software

- Suppose you run a software company
- Support you've sunk 30+ person-years into developing the "next big thing":
  - ★ Boeing Dreamliner2 flight controller
  - ★ Autonomous vehicle control software for Tesla
  - ★ Gene therapy DNA tailoring algorithms
  - ★ Super-efficient green-energy power grid controller
- How do you avoid disasters?
  - ★ Turns out software endangers lives

Boeing 737 Max Crashes

- Involved in two crashes
  - ✦ Lion Air Flight 610 on October 29, 2018 — 189 dead
  - ✦ Ethiopian Airlines Flight 302 on March 10, 2019 — 157 dead
- The crash is attributed to design errors including flight control software
  - ✦ The position of larger engines on 737 Max generated addition lift



Engine placement on the third-generation 737 NG (left) versus the MAX (right).

Boeing 737 Max Crashes

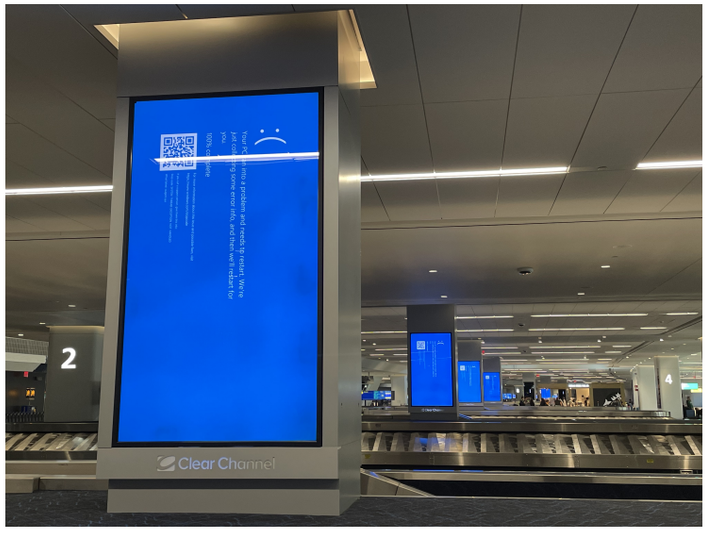
- Manoeuvring Characteristics Augmentation System (MCAS)
  - ✦ Software to sense angle of attack (AoA) from a sensor and automatically compensate
- Crashes due to faulty AoA sensor data but also due to MCAS software
- Every time MCAS was switched on and off again, it acted like first time pitching nose lower
  - ✦ *incorrect spec not including history*
- Max 0.8 degrees pitch during testing, which was changed to 2.4 after
  - ✦ *Executing conditions not reflective of testing*
- MCAS completely ignored that pilots were desperately pulling back on the yoke
  - ✦ *Incorrect spec not considering environment*

Not an isolated incident

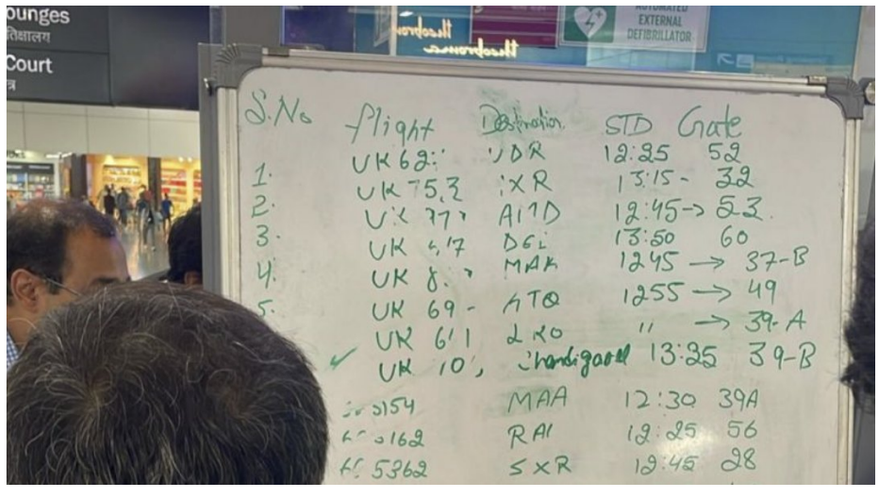
- NASA's Mars Climate Orbiter
  - ✦ A sub contractor on the engineering team failed to make a simple conversion from *English units to metric*
  - ✦ $125 million loss
- Ariane 5 Flight 501
  - ✦ The software had tried to *cram a 64-bit number into a 16-bit space.*
  - ✦ Crashed both the primary and the backup computer
  - ✦ $500 million payload lost + $XXX to fix the flaw.
- Hawaii Sends Out a State-Wide False Alarm About a Missile Strike
  - ✦ there were "troubling" design flaws in the Hawaii Emergency Management Agency's alert origination software.
- The Equifax social security hack
  - ✦ 143 million of their consumer records (names, SSN, credit card numbers) were stolen by attackers.

2024 Hall Of Fame: CrowdStrike

- CrowdStrike Falcon Sensor
  - ✦ Detects and prevents threats
  - ✦ Operated at OS kernel level
- A faulty update led to BSOD loop



- Impact
  - ✦ **Devices affected:** 8.5 million globally.
  - ✦ **Downtime:** Up to 72 hours for major organizations.
  - ✦ **Financial losses:** Estimated at $10 billion.
  - ✦ **Sectors impacted:** Banking (30%), healthcare (25%), transportation (20%).



CrowdStrike: Cause

- Software
  - ✦ The channel files were validated using *Regex patterns with wildcards* and loaded into an array instead of using a *parser* for this purpose.
  - ✦ In C, the *array length was not checked before access.*
    - ✤ An array with 21 fields was expected, but the channel file was in an older data format with only 20 fields.
  - ✦ In the unit tests, only the *happy path* was tested.
    - ✤ Regression tests for compatibility with the older data format were not conducted.
    - ✤ In manual tests, *only valid data* was tested.
  - ✦ The channel files did not contain a version number field that was checked.
- Process
  - ✦ There were *no staggered rollouts*, but the update was distributed to all customers simultaneously
  - ✦ Falcon run as driver at ring 0 in the OS!

Approaches to Validation

- Social
  - ✦ Code reviews
  - ✦ Extreme/pair programming
- Methodological
  - ✦ Design patterns
  - ✦ Test-driven development
  - ✦ Version control
  - ✦ Bug Tracking
- Technological
  - ✦ Static analysis
  - ✦ Fuzzers
- Mathematical
  - ✦ Sound Type Systems
  - ✦ Formal verification

Less formal: Techniques may miss problems in programs

All of these methods should be used!

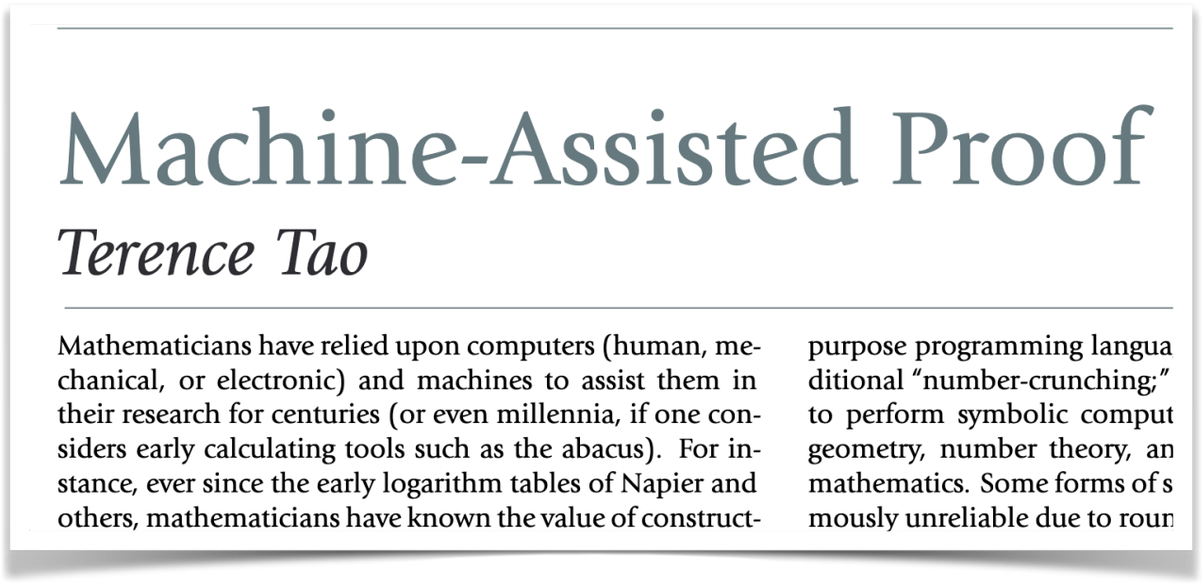
Even the most formal can still have holes:

- did you prove the right thing?
- do your assumptions match reality?

More formal: eliminate *with certainty* as many problems as possible.

Verification

- Scaled to 10s of lines of code in 1970s
- Now, research projects scale to real software:
  - ✦ CompCert: A verified C compiler (done in Coq)
  - ✦ seL4: verified microkernel OS
  - ✦ Ynot: verified DBMS, web services
  - ✦ Verified Crypto using F* in Microsoft Windows, Mozilla Firefox, etc.
- In another ~~40~~ **5** years?
  - ✦ LLMs!
  - ✦ *Verification to avoid hallucination*



Machine-Assisted Proof

Terence Tao

Mathematicians have relied upon computers (human, mechanical, or electronic) and machines to assist them in their research for centuries (or even millennia, if one considers early calculating tools such as the abacus). For instance, ever since the early logarithm tables of Napier and others, mathematicians have known the value of construct-

purpose programming langua
ditional "number-crunching;"
to perform symbolic comput
geometry, number theory, an
mathematics. Some forms of s
mously unreliable due to roun

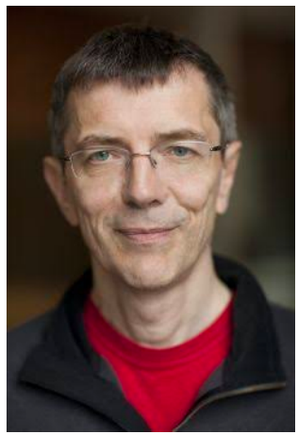
Proof Assistants

- You give assistant a theorem
- You and assistant cooperate to find the proof
  - ✦ Human guides the construction
  - ✦ Machine does the low-level details
- **Examples:** Coq, NuPRL, Isabelle HOL, Lean

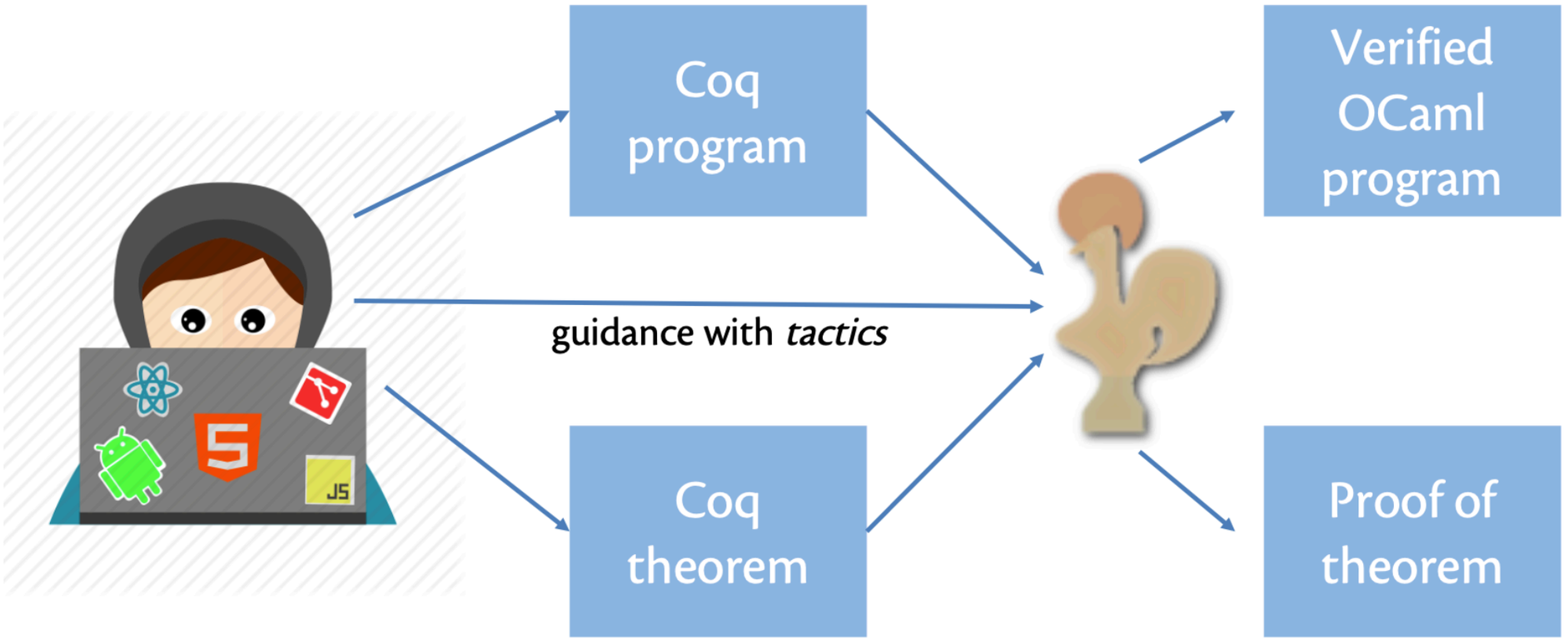
Coq

- 1984: ***Coquand*** and ***Huet*** implement Coq based on *calculus of inductive constructions*
- 1992: Coq ported to Caml
- Now implemented in OCaml

Thierry Coquand



Gérard Huet



Automated Theorem Proving

- You give the prover a theorem
- The prover either:
  - ✦ Finds a proof
  - ✦ Finds a counter example
  - ✦ Times out
- Eg,
  - ✦ Z3: Microsoft has started shipping with device driver developer kit since Windows 7
  - ✦ ACL2: used to verify AMD chip compliance with IEEE floating point specification, as well as parts of the Java virtual machine

F*

- A solver-aided (Z3) general purpose programming language
- Write programs and write theorems about the programs
  - ✦ F* will discharge the proof obligations to the Z3 solver, but proofs can also be interactive
- Programs can be extracted to OCaml, F#, C, WASM and ASM.
- Main use case is Project Everest at Microsoft — a drop in replacement for HTTPS stack
  - ✦ Verified implementations of TLS 1.2 and 1.3, and underlying cryptographic primitives.

This course

- *Providing a mathematical foundation for rigorous analysis of realistic software systems*

  ✦ Increasingly on demand as almost everything humans interact with is increasingly mediated by software

- We will look at

  ✦ Formal logical reasoning about **program correctness** through

  ✦ **Coq proof assistant**, a tool for machine checked mathematical theorem proving and

  ✦ **F***, a general-purpose programming language aimed at program verification

Why Proof Assts / Solver-aided PLs?

- Reasoning about program correctness presupposes the ability to read and write mathematical proofs
  - ✦ Humans are bad at writing proofs with pen-and-paper — terribly buggy!
- Proof assistants allow humans to carefully construct machine checked proofs
  - ✦ "obvious to see that it holds" is no longer possible
- Proof assistants = 1 TA per student!
- Homework
  - ✦ Watch "Lambda: the Ultimate TA" by Benjamin Pierce
    - ✤ https://vimeo.com/6615365

Course Contents

- Basics of mathematical logic
  - ✦ Logic::CS = Calculus::EE,Civil,Mech
- Functional Programming
  - ✦ Programs as data, polymorphism, recursion
  - ✦ Specification and verification
- PL theory
  - ✦ transition systems, operational semantics, lambda calculus, Hoare logic, separation logic, weakest precondition, dependent types, monadic effects, etc.

Course Details

- Lectures will be mostly developing programs and proofs interactively
  - ✦ In Coq and F-star
  - ✦ Students are encouraged to bring their laptops and follow along.
- CS3100 OCaml portions are a pre-requisite
  - ✦ If you aren't comfortable with functional programming, please review the lecture materials (available on my website).
- *Weekly assignments*
  - ✦ Expect them to consume 8-10 hours (but may take significantly longer/shorter).
- Collaboration encouraged but not plagiarism.
  - ✦ For example, OK to discuss intermediate lemma, but no copying of proof is allowed.
  - ✦ Will follow the institute policy on plagiarism

Course Details

- Grading: 60% assignments, 20% mid term, 20% final exam
- Exams will take home
  - ✦ Programming and proving
- See the course website http://kcsrk.info/cs6225_s21_iitm for topics and announcements
- Would like to get continual and honest feedback
  - ✦ This is not an easy course, but hopefully should be quite fun!

Textbooks

- For Coq, we will be following
  - ✦ Adam Chlipala, **Formal Reasoning about Programs**
  - ✦ Freely available here: http://adam.chlipala.net/frap/
- For F*, there is a in-progress book
  - ✦ Nik Swamy et al., **Proof-oriented Programming in F***
  - ✦ Freely available here: http://fstar-lang.org/tutorial/proof-oriented-programming-in-fstar.pdf

Fin!