Go is a programming language prominent in Cloud Computing.

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Since it is easy to make concurrency mistakes,
Go has a built-in data-race detector.

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Go has a built-in data-race detector.

```
go run -race my_program.go
```

Repairing the Go data-race detector.

A story on applied research.

Daniel S. Fava

danielsf@ifi.uio.no

Department of informatics
University of Oslo, Norway

Our *story* has a theoretical basis in two active areas of research.

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1. Memory model

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1. Memory model
2. Data-race detection

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1. Memory model

2. Data-race detection

What happens when a detector is at odds with the memory model

Our *story* also has real practical implications.

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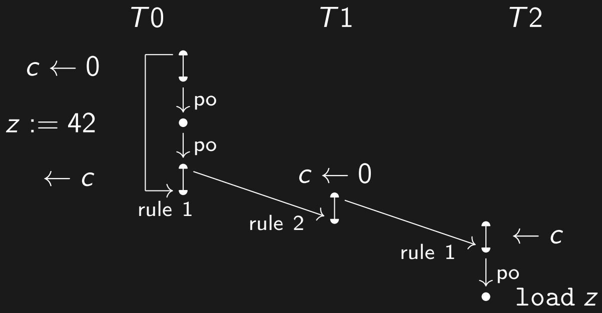
- Mismatch lead to the under-reporting of data-races
  - No warning about missing some synchronization
- A bug on a tool to find bugs (compound effect)
- Bug evaded Go maintainers for six years



T0
T1
T2
c ← 0
po
z := 42
po
← c
rule 1
c ← 0
rule 2
← c
rule 1
po
load z

We implemented a fix accepted by the Go community.
Here we share three main lessons learned.

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3. Bad news is good news

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Go memory model

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Go data-race detector

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Go memory model

- succinct document
- written in English
- technical vocabulary

Go data-race detector

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Go memory model

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Go data-race detector

- thousands of lines of code
- different projects & repos
- different languages
  (Go, C/C++, assembly)

1. Mind the Gap.

Go memory mod

- succinct d
- written in
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Formal model

Small-step operational semantics

[Fava et al., 2018a, Fava and Steffen, 2020]

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Formal model

Small-step operational semantics

[Fava et al., 2018a, Fava and Steffen, 2020]

- succinct
- executable
- formal: use logic to state and prove properties

detector

s of lines of code

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anguages

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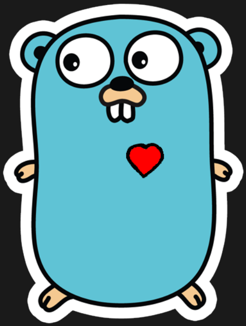

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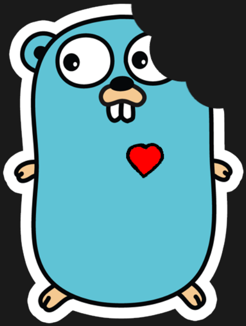

without interfaces

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without interfaces
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Goroutines	Channels
Concurrency	Synchronization

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Goroutines	Channels	Shared memory
Concurrency	Synchronization	

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Our operational-semantics was an approximation of the Go memory model

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The model was sufficiently accurate to be useful

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- ✓ Academia can develop valuable artifacts not common in industry.
- ✓ There is room for collaboration.

Three main open questions remain..

1. By taking channels seriously,
   can we improve data-race detection?

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- Most data-race detectors are based on locks (including Go's)
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"Channels at the head of the queue!"

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- Can we relax the model "all the way"?

  Without adding *out-of-thin-air* behavior into the model

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  across different compilation targets (HW)

In summary,

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Specification

Implementation

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Formal model

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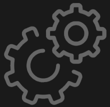
Implementation

- Abstraction

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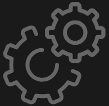

Implementation

- Abstraction
- Value-added

Questions?

Questions?

Thank you

References

- Go memory model (2014). The Go memory model.
  `https://golang.org/ref/mem`.
  Version of May 31, 2014, covering Go version 1.9.1
- Fava, D. (2020). Finding and fixing a mismatch between the Go memory model and data-race detector.
  Submitted for publication

References

- Fava, D. S. and Steffen, M. (2020). Ready, Set, Go!: Data-race detection and the Go language. *Science of Computer Programming*, 195:102473
- Fava, D., Steffen, M., and Stolz, V. (2018a). Operational semantics of a weak memory model with channel synchronization. *Journal of Logic and Algebraic Methods in Programming*. An extended version of the FM'18 publication with the same title

References

- GitHub (2020). [37355] runtime/race: running with -race misses races (mismatch with memory model).
  `https://github.com/golang/go/issues/37355`
- Gerrit (2020). [220419] runtime: swap the order of raceacquire() and racerelease().
  `https://go-review.googlesource.com/c/go/+/220419`
- Phabricator (2020). [d76322] tsan: Adding releaseacquire() to threadclock.
  `https://reviews.llvm.org/D76322`

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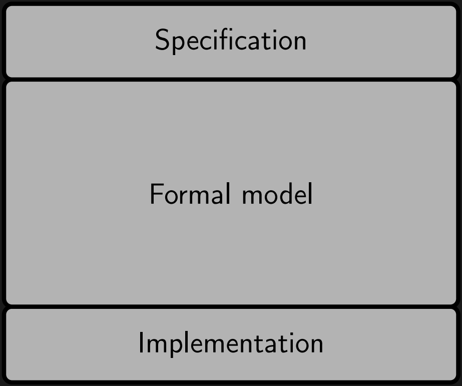

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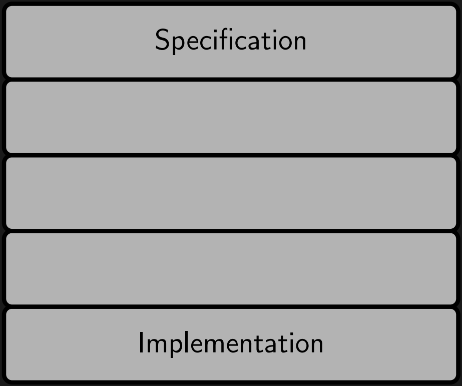

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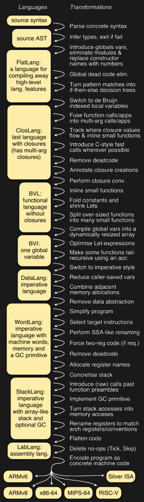


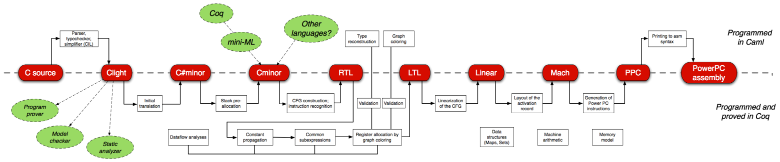
CakeML

verified compiler covering a *substantial* subset of Standard ML

3. How to automate bug finding?

CompCert

verified C compiler covering a *large* subset of C99



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GOBOT

TinyGo

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MAINFLUX