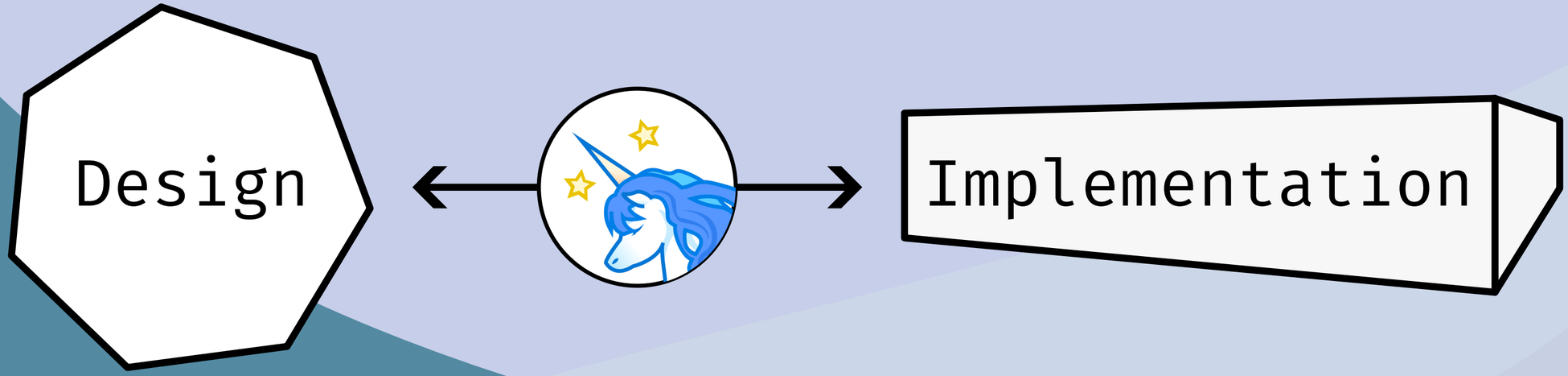
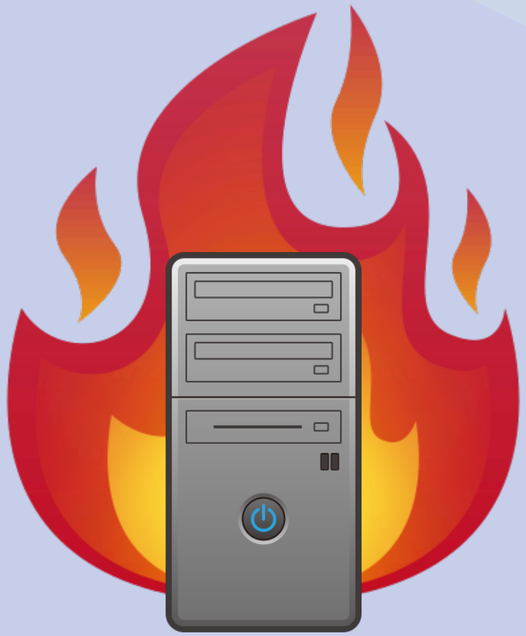
# Promises and Challenges in Bridging TLA+ Designs with Implementations

*A. Finn Hackett*



# Building and Running Distributed Systems is Notoriously Error-prone



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🚀 Analyzable designs

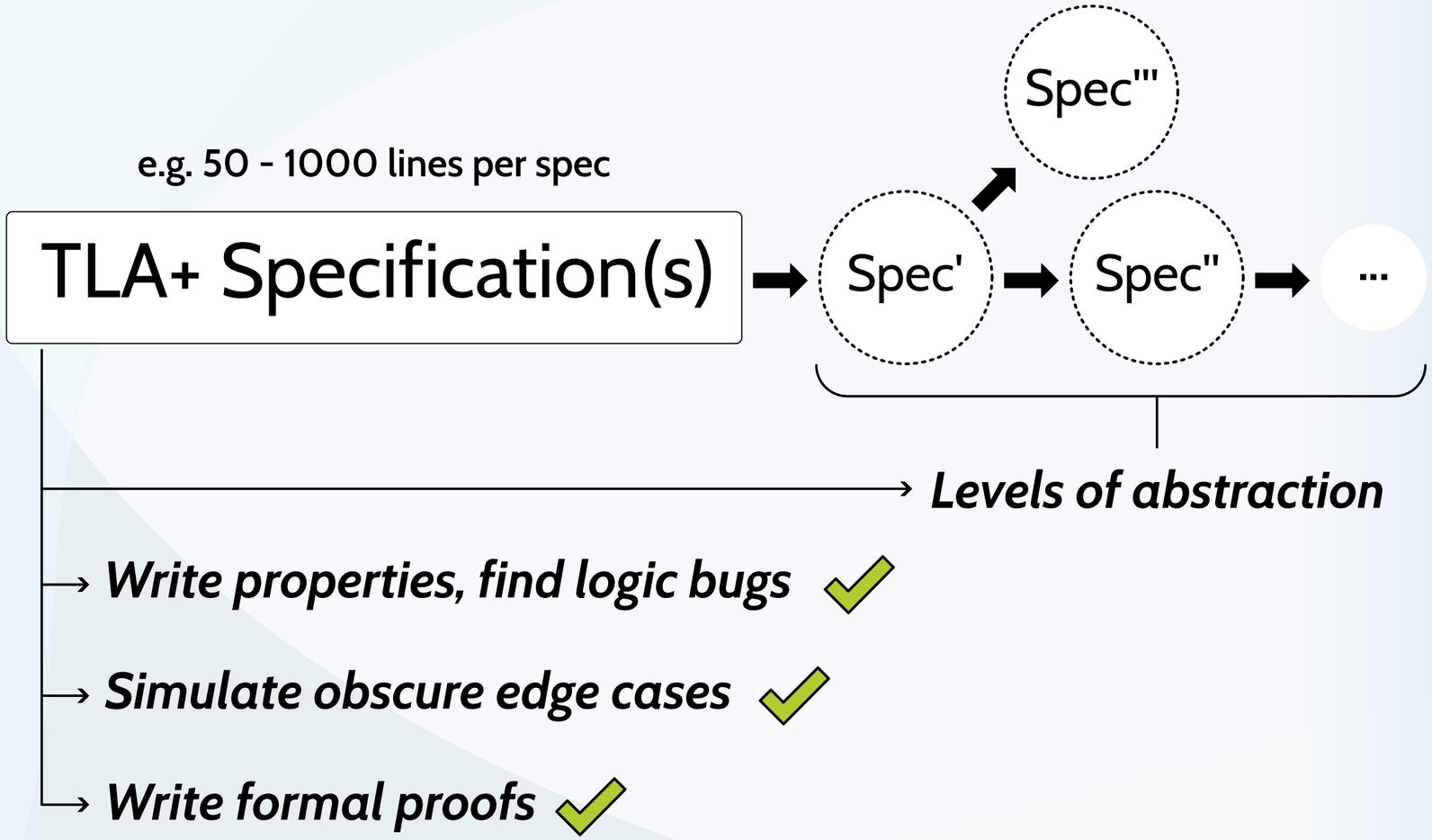

(or Alloy, P, Promela, Dafny, Verus, F*, Coq)

# Formal Methods

🚀 Find edge cases

🚀 Proofs

# Usage of TLA+


e.g. 50 - 1000 lines per spec
TLA+ Specification(s)
Spec'''
Spec'
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...
Levels of abstraction
Write properties, find logic bugs
Simulate obscure edge cases
Write formal proofs

# Usage of TLA+

e.g. 50 - 1000 lines per spec

TLA+ Specification(s) → Spec' → Spec" → ... → Spec'" → Implementation(s)

*Levels of abstraction*

- *Write properties, find logic bugs* ✓
- *Simulate obscure edge cases* ✓
- *Write formal proofs* ✓

**Recurring question:**
How can we be (more) sure impl and spec match?

# If We Were Sure Our Models and Implementations Matched...

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If we're really really sure, do we even need different spec + impl code?

# How Have We Attempted Implementation Linking?

[@Confidential Consortium Framework @etcd]

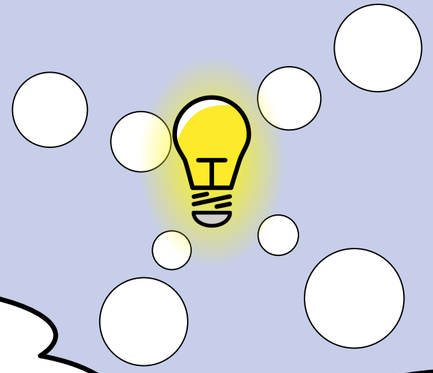
## Trace Validation

*e.g. collect structured logs + compare with TLA+*

## Compile the TLA+

*e.g. the PGo project, PlusPy, Elixir*

[Related to:
- Verdi
- IronFleet
- F*]



## Test Case Generation

*e.g. use execution traces as test scenarios*

## Runtime Monitoring

*e.g. put/compile the TLA+ assertions in your code*

[See: Choreographic PlusCal, Elixir ver.]

# Tradeoffs in Trace Validation

- ☑ Directly observes the implementation, could catch wide range of errors

  e.g. misconfiguration, wrong assumption in TLA+

- 🚀 Strictly beyond spec verification

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❌ Incomplete: if you don't see the implementation do it, you don't check it

🤷 Better than nothing to use it in your integration tests

# Generating Test Cases

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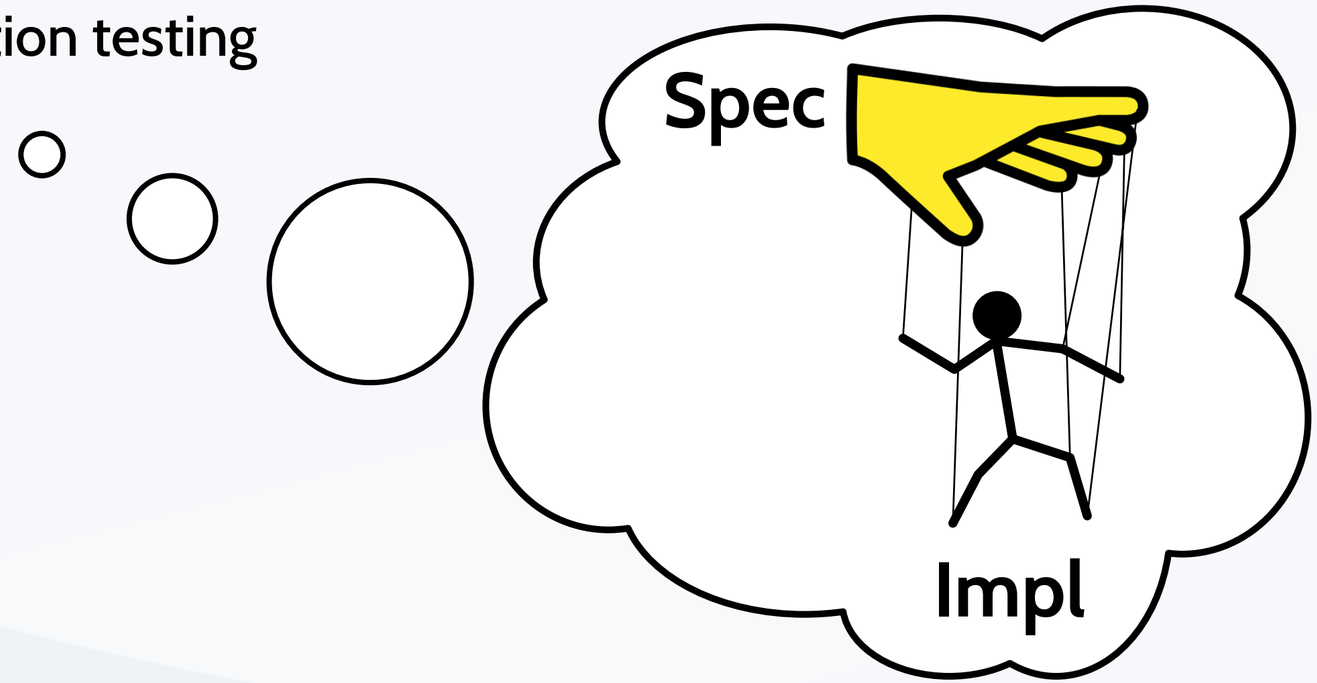
💡 Let the spec drive implementation testing



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  - 🚀 … can be partly automated, but fundamental refinement job remains

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🤔 Extracting implementation behavior and state is still non-trivial

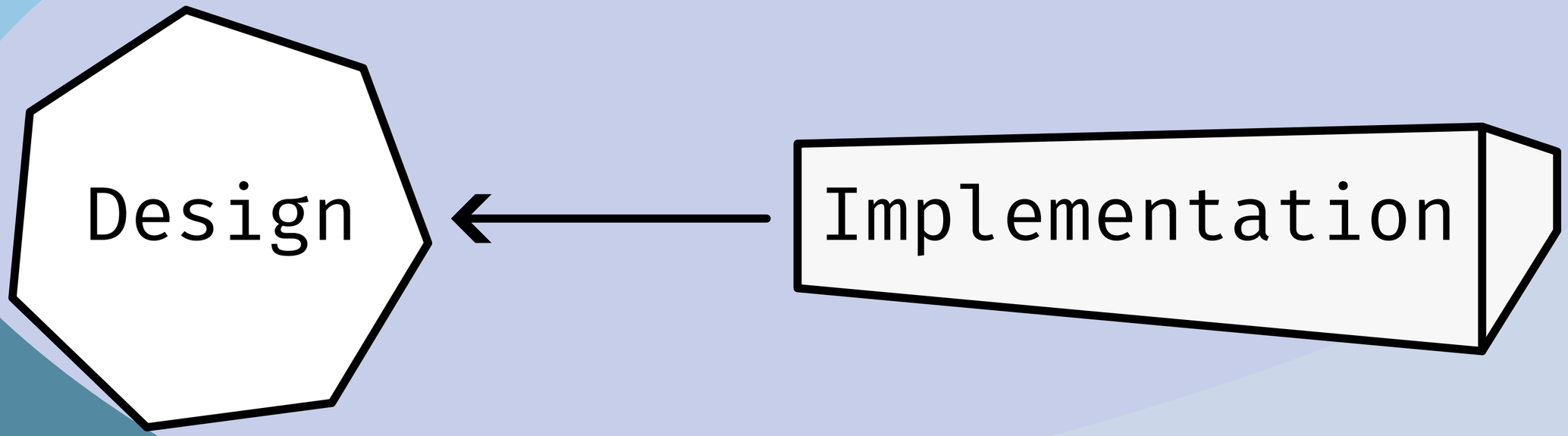
- 🚀 … can be partly automated, but fundamental refinement job remains

🤔 For existing implementation, need to retrofit deterministic exploration

e.g. get a custom scheduler, or otherwise control all system actions

[See: Kani, Coyote, Chaos Engineering, Jepsen]

# Other Direction: Compile the Design



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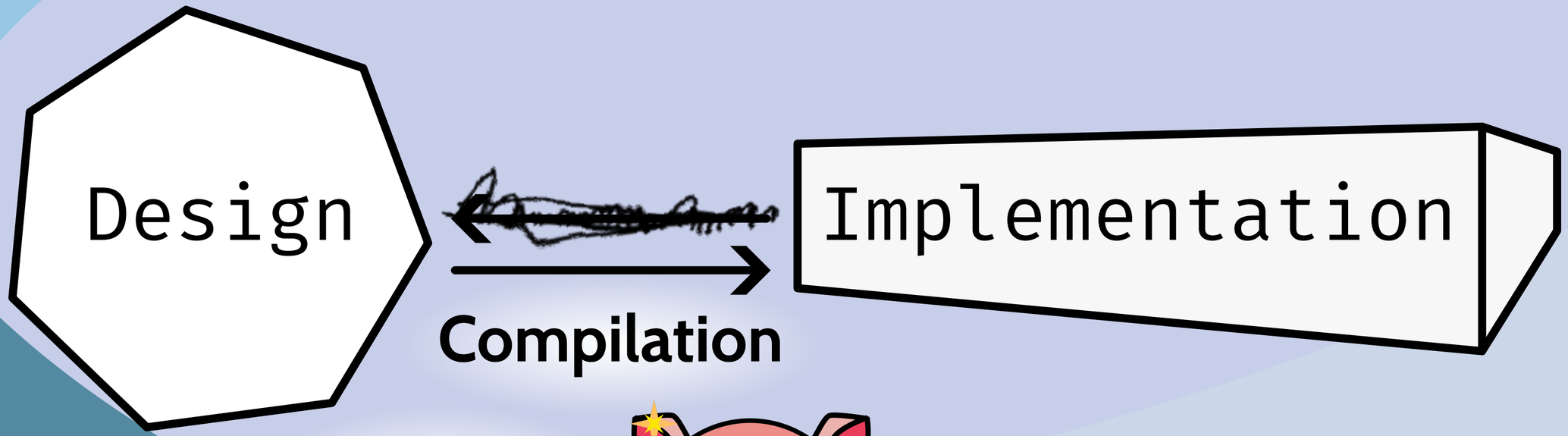


e.g. PGo
[ASPLOS'23]

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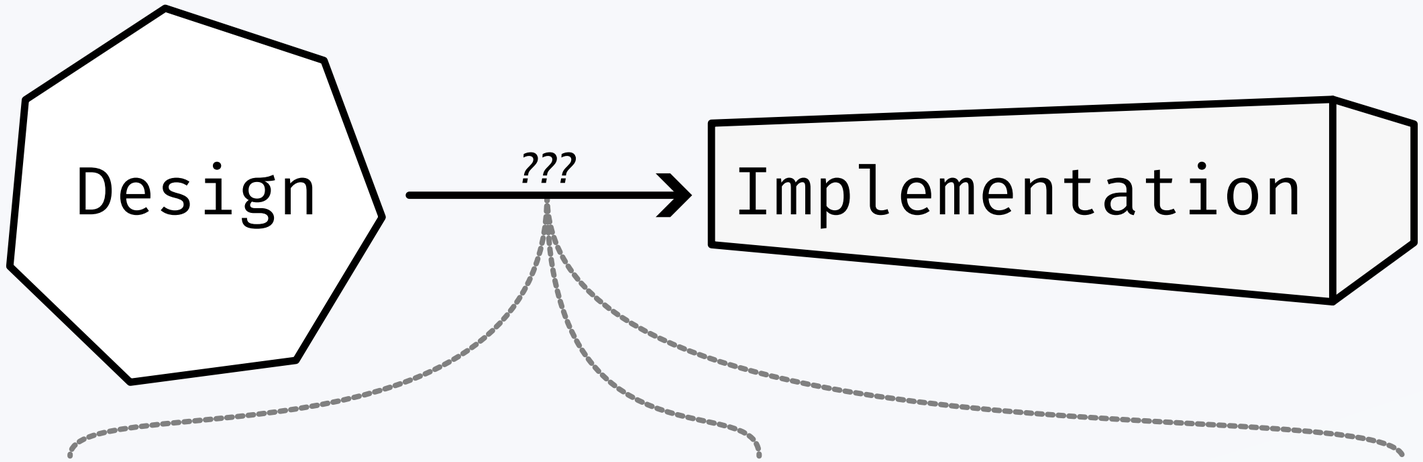



Translating data structures right

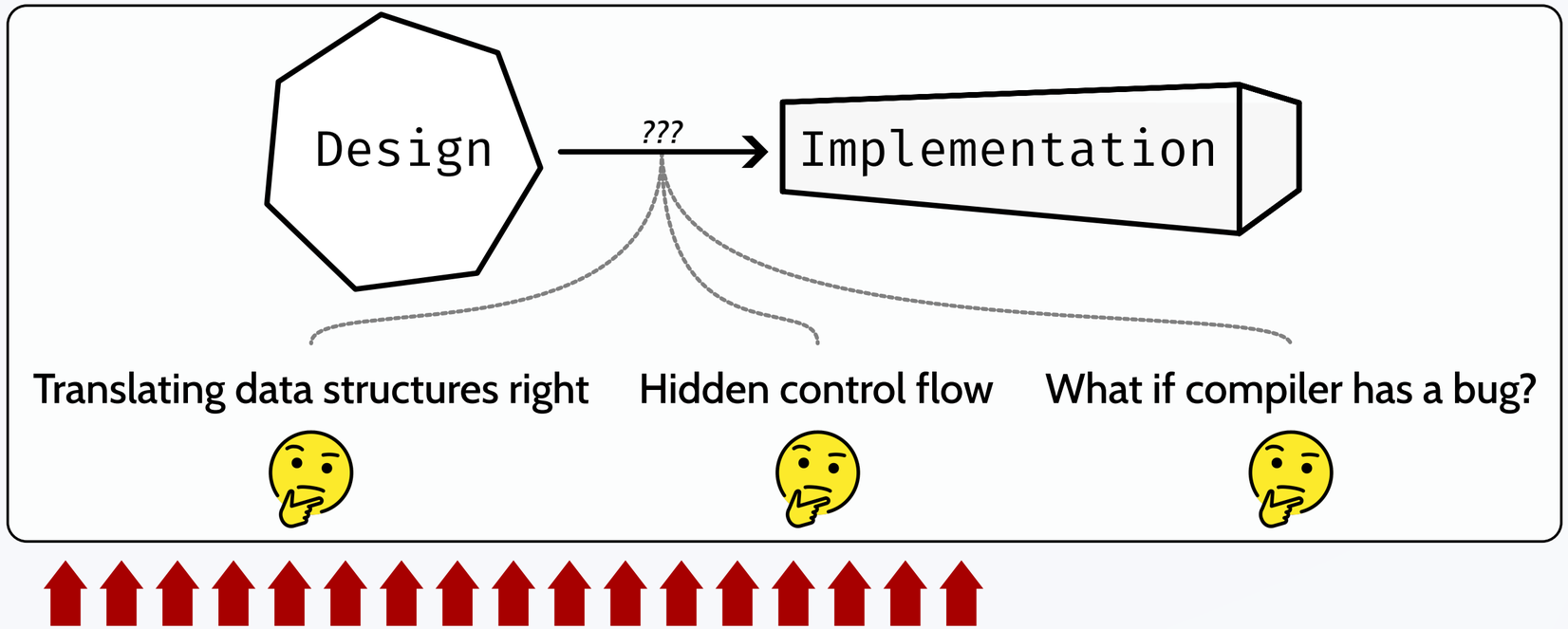
Hidden control flow

What if compiler has a bug?

# Ongoing Work...

# Ongoing Work: DCal, a More Customizable PGo

Move impl-oriented changes away from spec.



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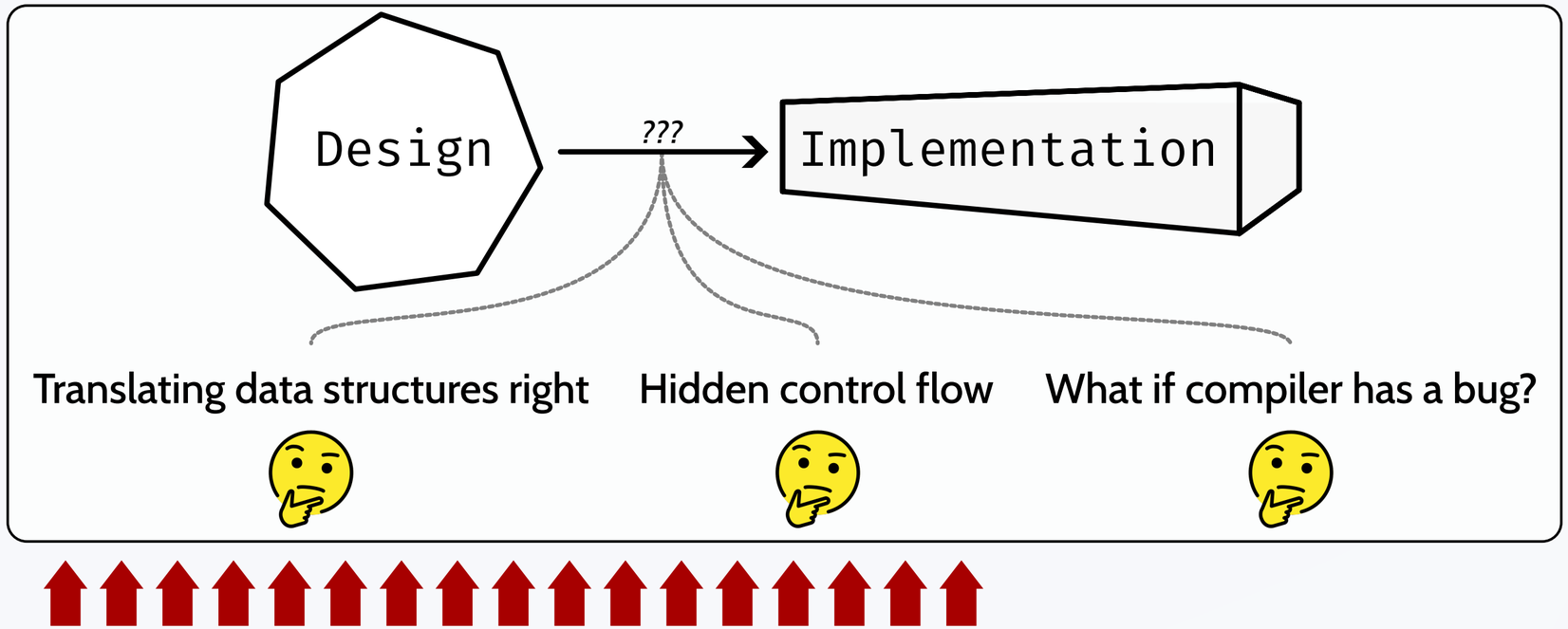
👉 **PGo uses fixed data structures.**
General-purpose, but can be inappropriate.

*e.g. log structures: often specialized in practice, but PGo forces general purpose sequence type.*

💡 *Constraint system to specialize abstract TLA+ data specs.*



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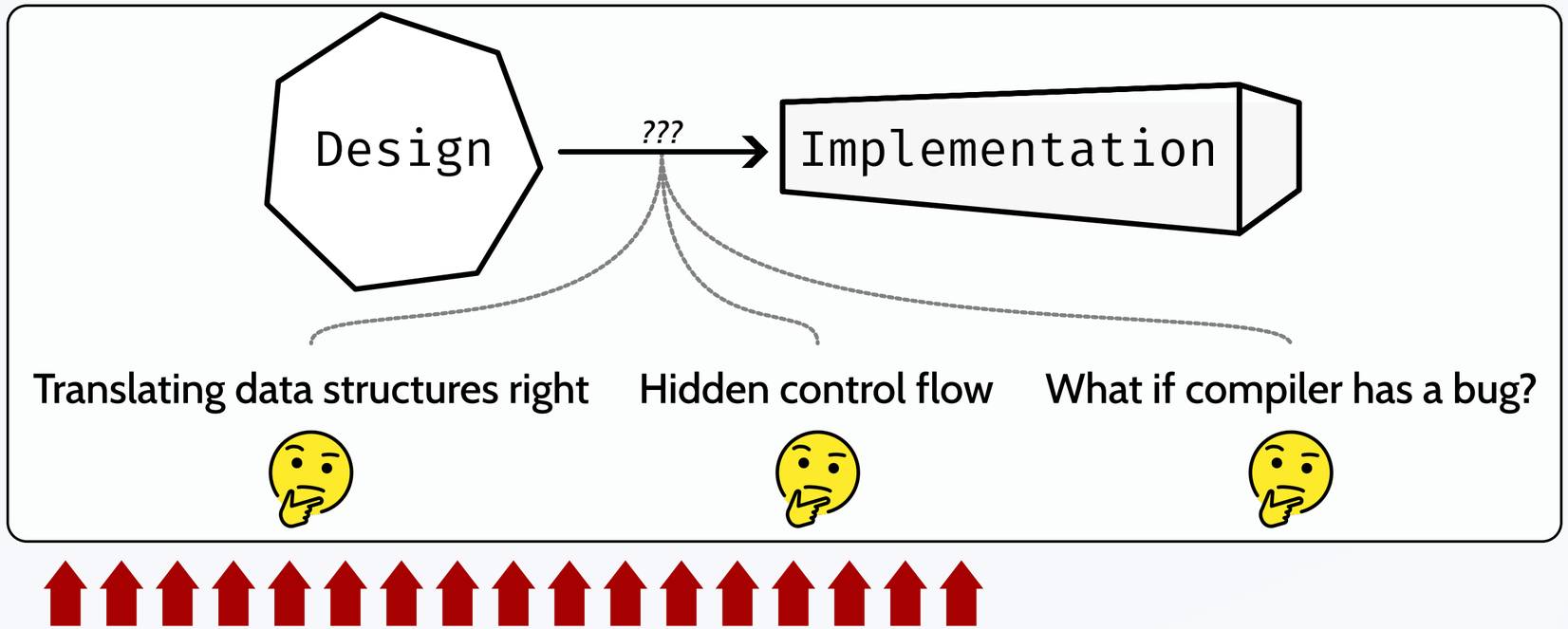



👉 **PGo's control flow impl is black-box and fixed.**
Difficult to specialize compiler's output.

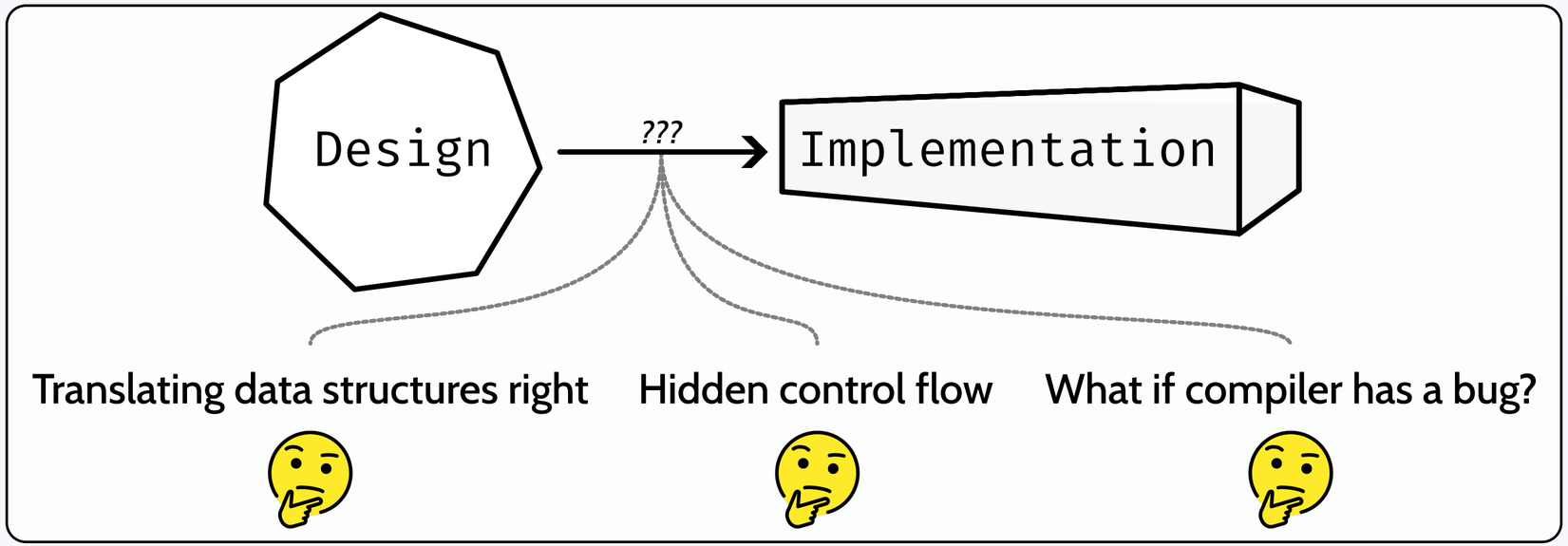
*e.g. can't compile disjunction to I/O select primitive.*

💡 Write specific strategies as meta-programs / compiler plugins.

# Ongoing Work: TraceLink, Compiler-assisted Trace Validation

🤔 **Trace Validation** → Manual effort needed to instrument + handle logs

… how much effort can we automate?



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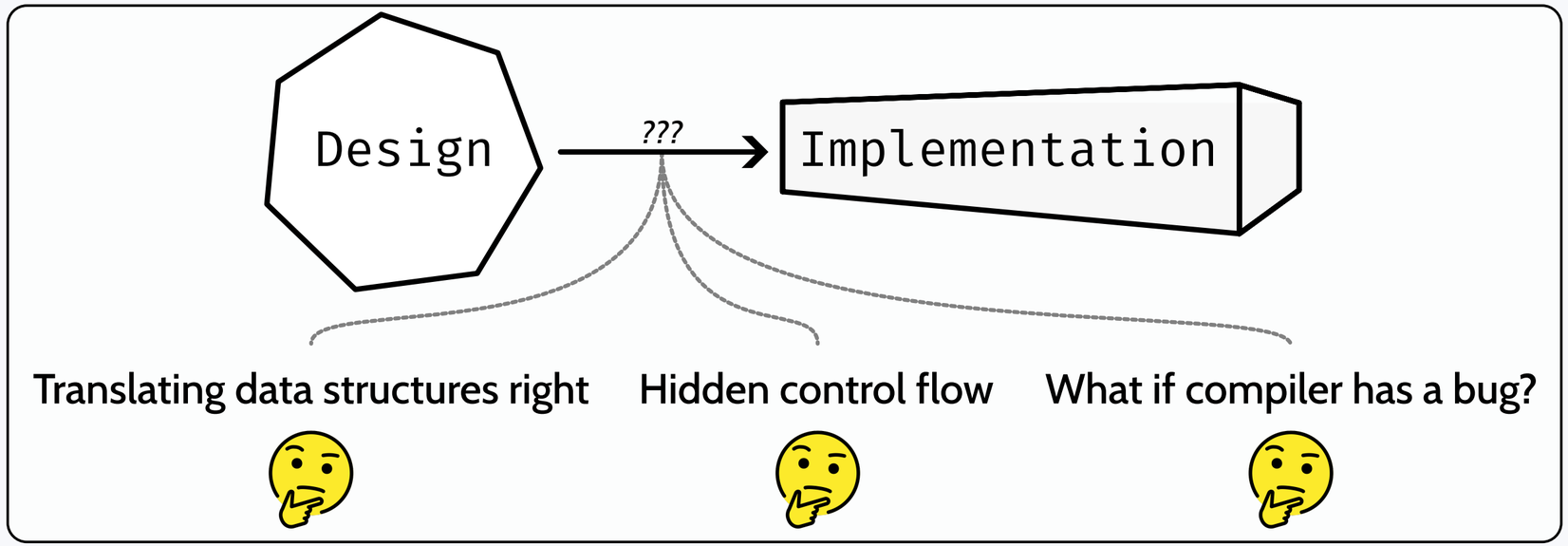
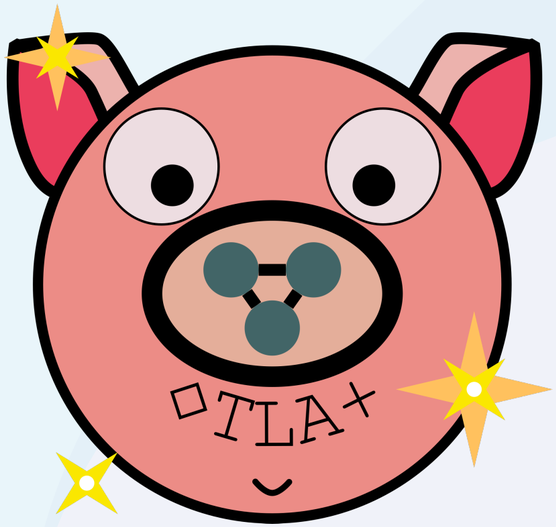
**How to find problems in the compiled system?**

*Use the compiler to automate trace validation workflow.*

*Use model to analyze trace validation soundness.*






distcompiler.github.io

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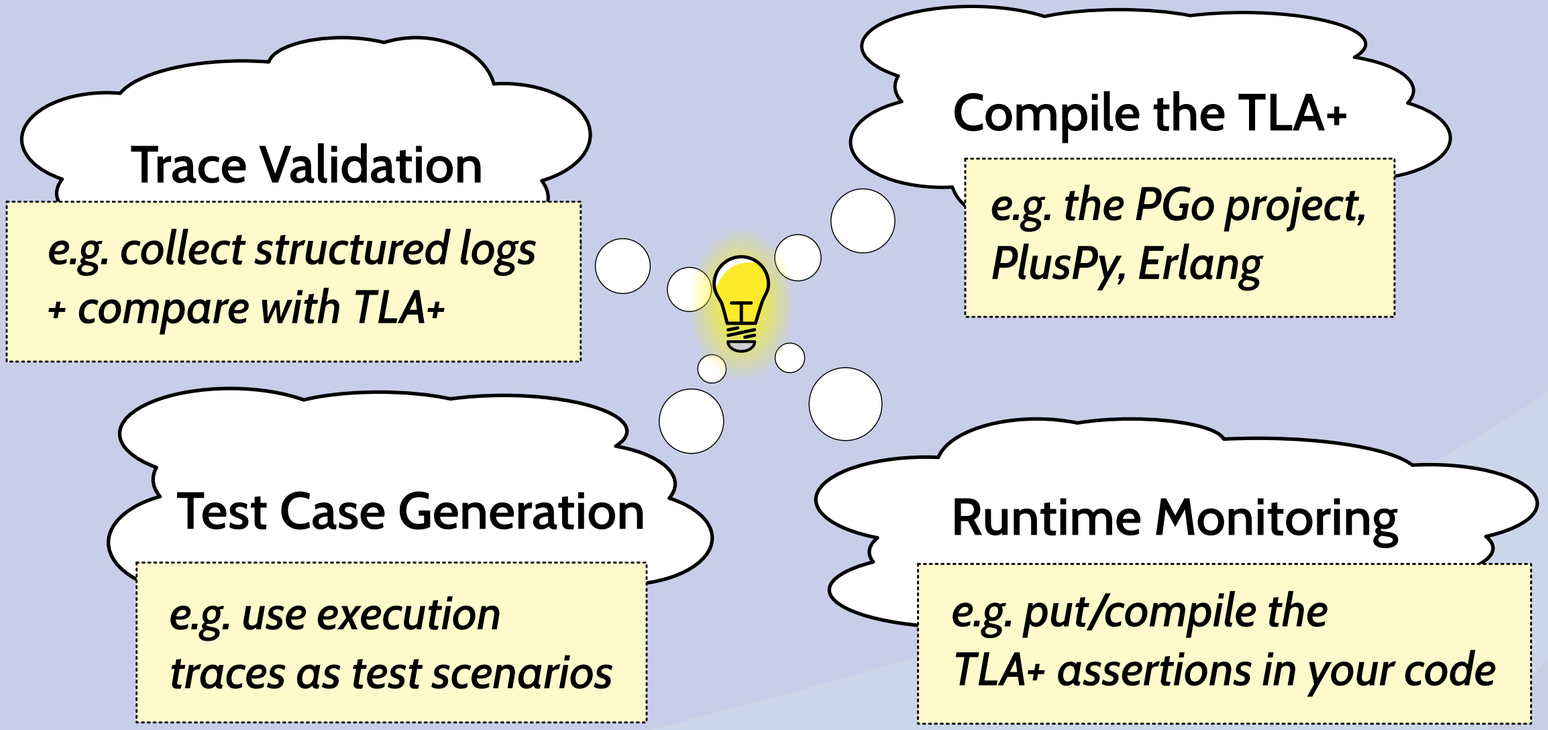


## Any Questions?

# Trace Validation: Refinement w/ Implementation Traces

Existing TLA+ Specification

Refinement

logging impl. behavior

...

```
dict["x"] := "y";
```

```
> try put(key="x", value="y")
> tcp error
> retry
> timeout
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...
> retry
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```
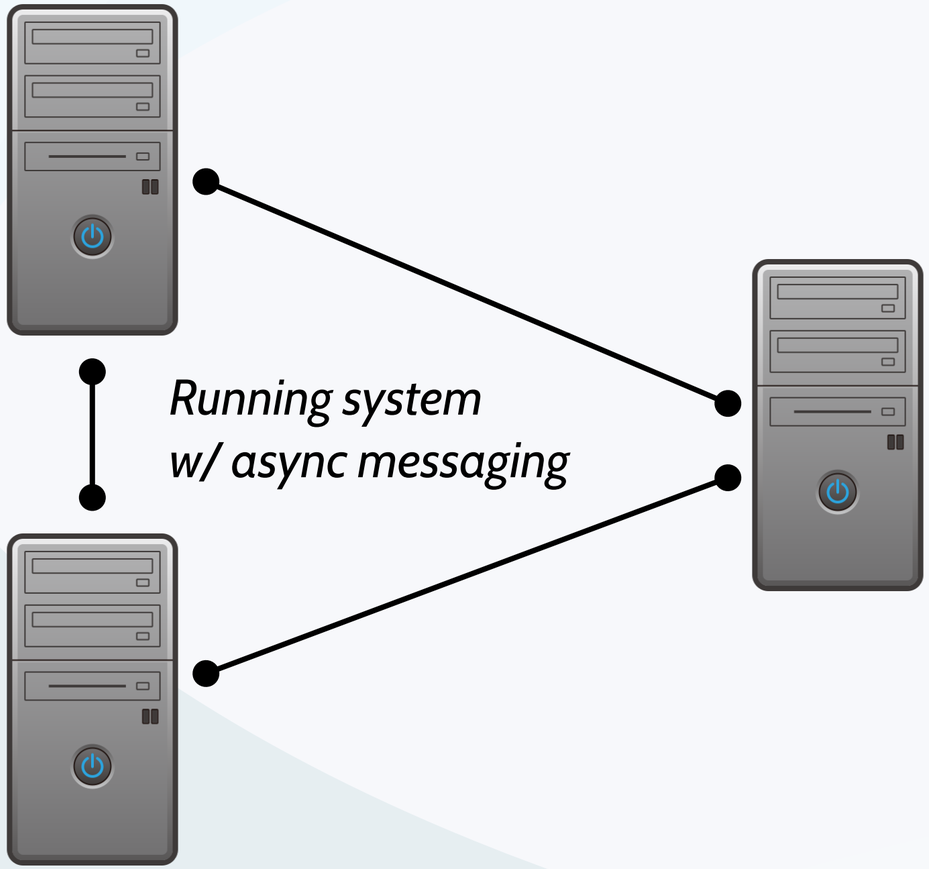

# Trace Validation: the Order Problem



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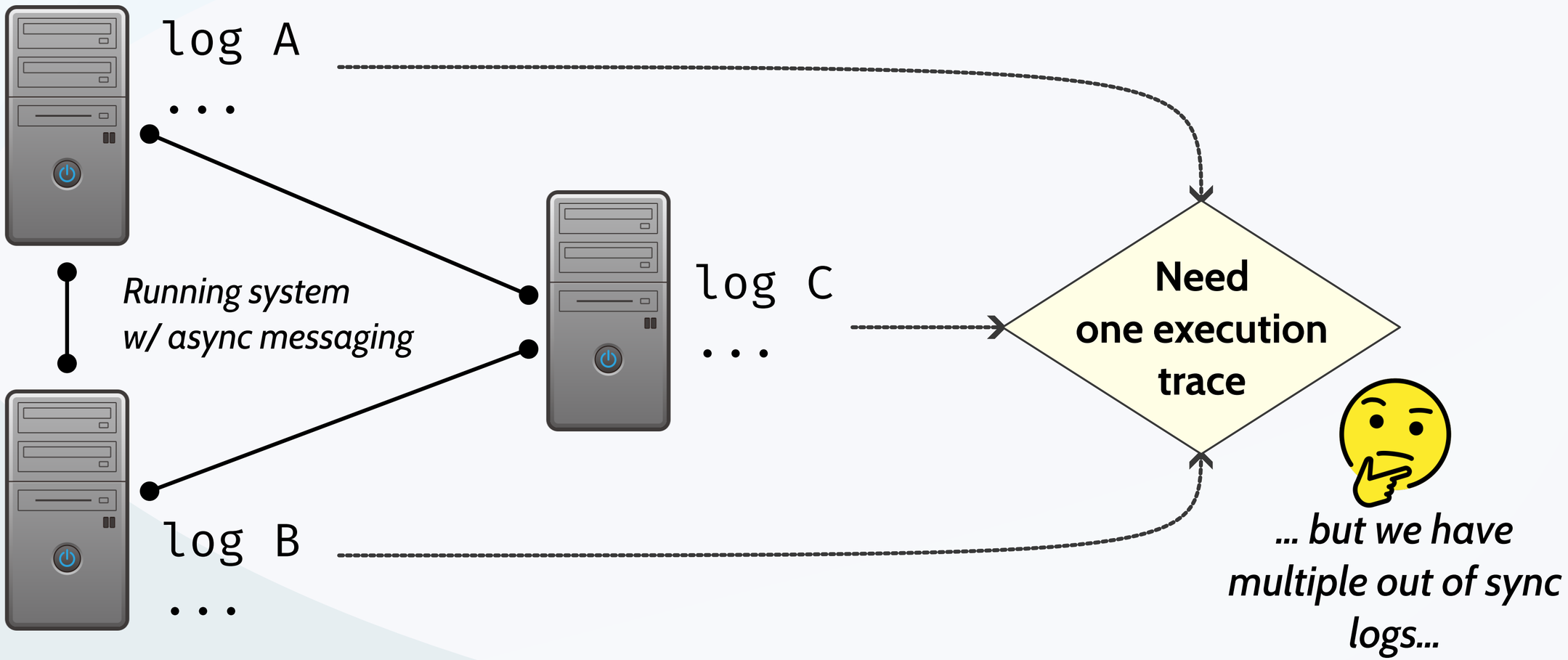

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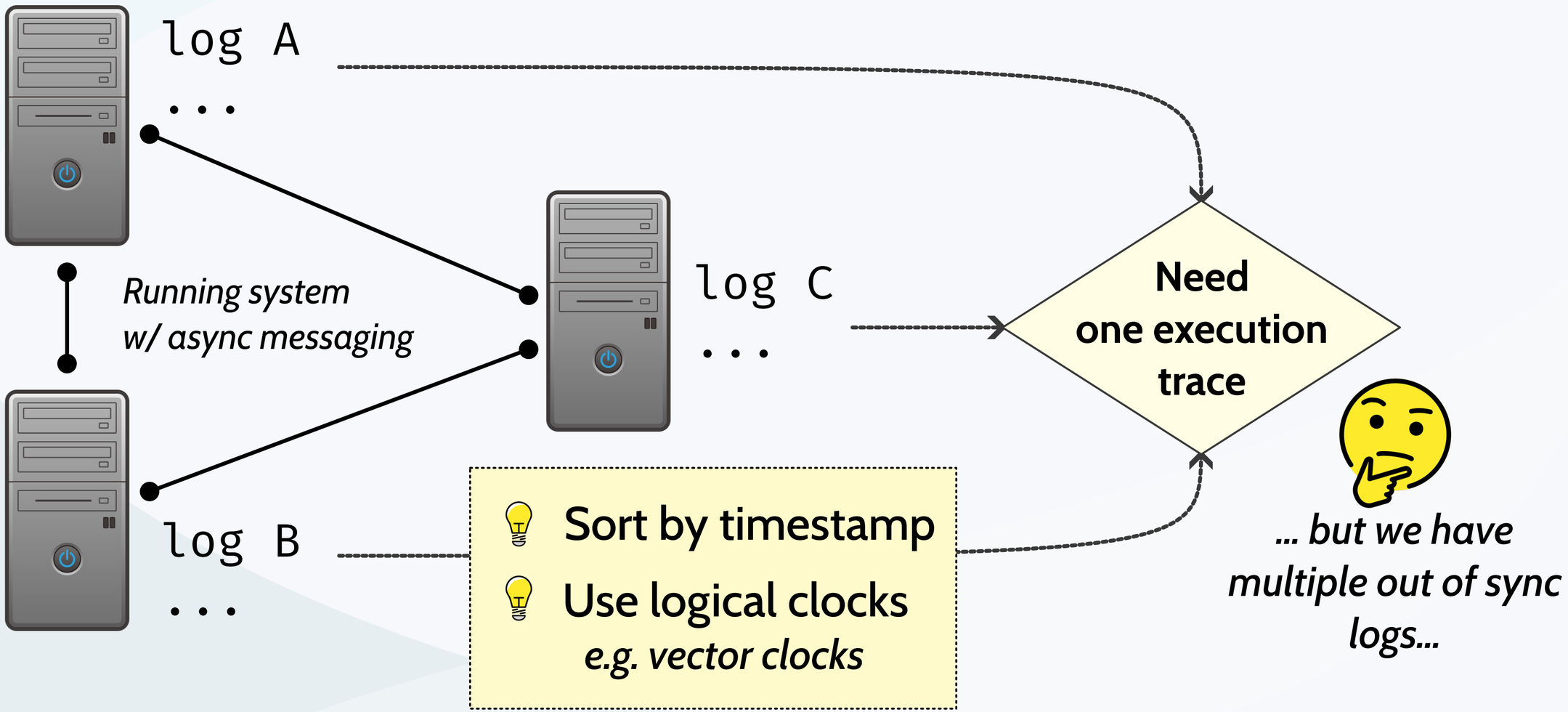

# Trace Validation: Trouble with Levels of Detail

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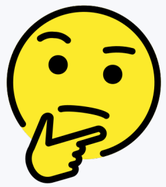

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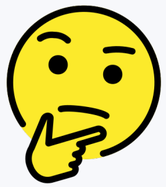

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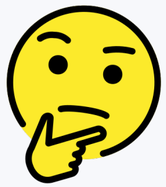

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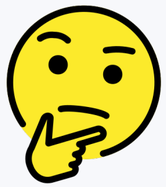

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Manually fix gaps in TLA+? Shown to work well, but not automatic.

Use symbolic reasoning to lazy-fill spec holes? Potential future work.

# Trace Validation: In Practice

**eXtreme Modelling in Practice @ MongoDB [VLDB '20]**

*Tried matching logs with a spec, ran into trouble relating the 2 in a strict sense.*

**INSIGHT:** strict, direct comparison works poorly for complex systems.

**Bridging the Verifiability Gap @ Open Networking Foundation [TLA+Conf '20]**

*Used TLA+ properties (not the whole spec) as assertions over captured traces.*

**INSIGHT:** for some cases, you don't need the whole spec or refinement.

**Validating System Executions* with the TLA+ Tools @ Microsoft [TLA+Conf '24]**

*Developed state-based logging discipline and method for indirect spec-trace relationship.*

**INSIGHT:** you can patch "holes" in the trace with more TLA+ if you're careful.

# Generating Test Cases: In Practice

**Kayfabe, Model-based testing with TLA+ and Apalache [TLA+Conf '20]**

*For systems co-written with specs, control and trace evaluation w/ Apalache.*

**INSIGHT:** can build systems w/ a control interface for testing; manual but effective

**Using Lightweight Formal Methods to Validate a KV Storage Node in Amazon S3 [SOSP '21]**

*Wrote Rust programs that acted like TLA+ specs, compared running spec- and real-programs..*

**INSIGHT:** concrete programs can act like specs, though without direct TLA+ link

**Model Checking Guided Testing for Distributed Systems [EuroSys '23]**

*Read TLC state graph, generate synthetic test sequences for auto-instrumented real systems.*

**INSIGHT:** given additional manual TLA+ work, can test-drive concrete system with TLC

# Specification Compilation: Translating Data Structures

***Abstract definition of a log structure (from e.g. Raft spec)***

```
Record == [term: Nat, cmd: String, client: Nat]
Log == Seq(Record)
```

What data structure should the implementation use?
"Good enough" general structure?

... needs fast append, access to tail...
**!! must persist to disk**

# Specification Compilation: Hidden Control Flow

**Consider: critical section receives msg from node A, then sends msg2 to node C.**

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MyCriticalSection:
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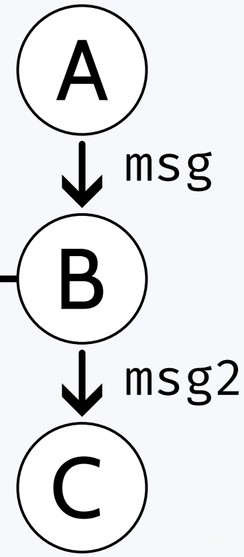


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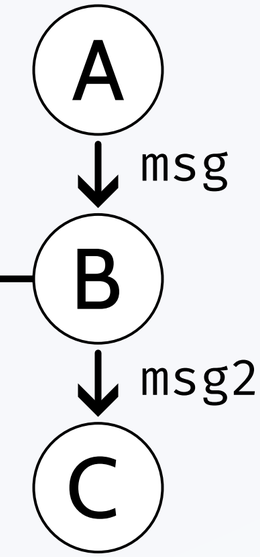


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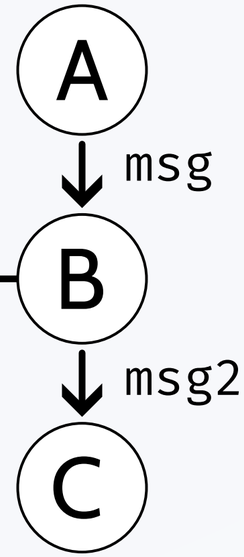


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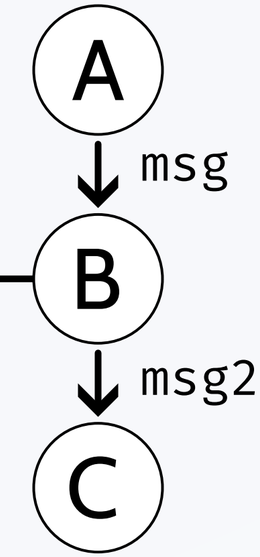


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A correct implementation must "remember" msg until it can send msg2!

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Can do trace validation on compiled system. Might be easier to automate?

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**tlaplus/PlusPy:** *evaluates TLA+ actions and expressions. Ignores hidden control flow.*

**Elixir Translator [SAST, TLA+Conf '22]:** *translates TLA+ actions into Elixir code.*

*Translation is literal, primarily for monitoring.*

**PGo [ASPLOS '23, TLA+Conf '22 '19]:** *compiles Modular PlusCal into Go w/ custom IO options.* 

*Uses special protocol to auto-implement hidden control flow; evaluated on full-scale systems.*

**Choreographic PlusCal [TASE '23]:** *compiles TLA+ actions into Go monitors.*

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👉 *Currently, only full Spec2Code attempt.*

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