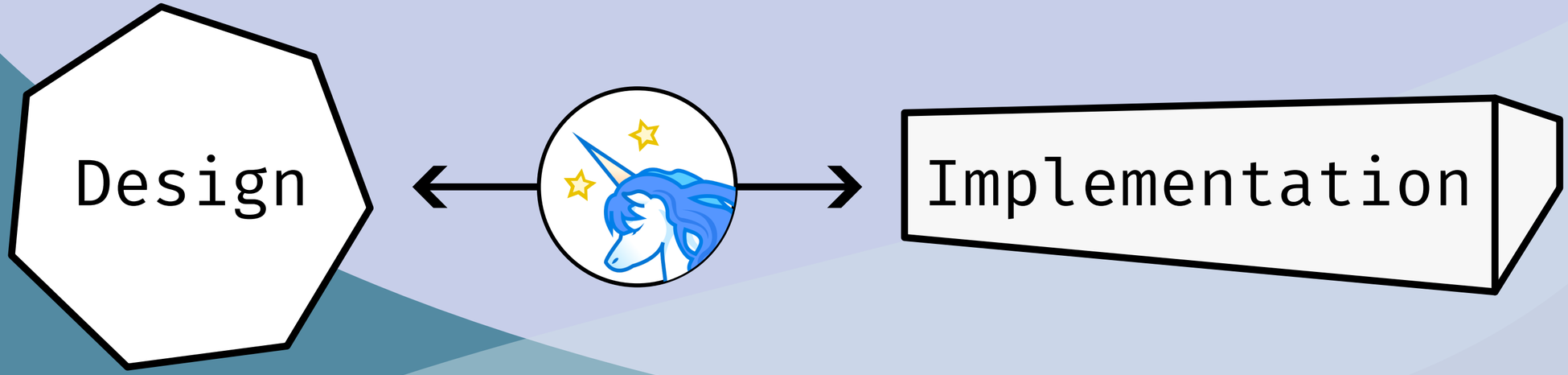
Promises and Challenges in Bridging TLA+ Designs with Implementations

A. Finn Hackett and Ivan Beschastnikh



Context: Who and What

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PhD Student

@ University of British Columbia

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PGo Compiler [ASPLOS'23]

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TLA+

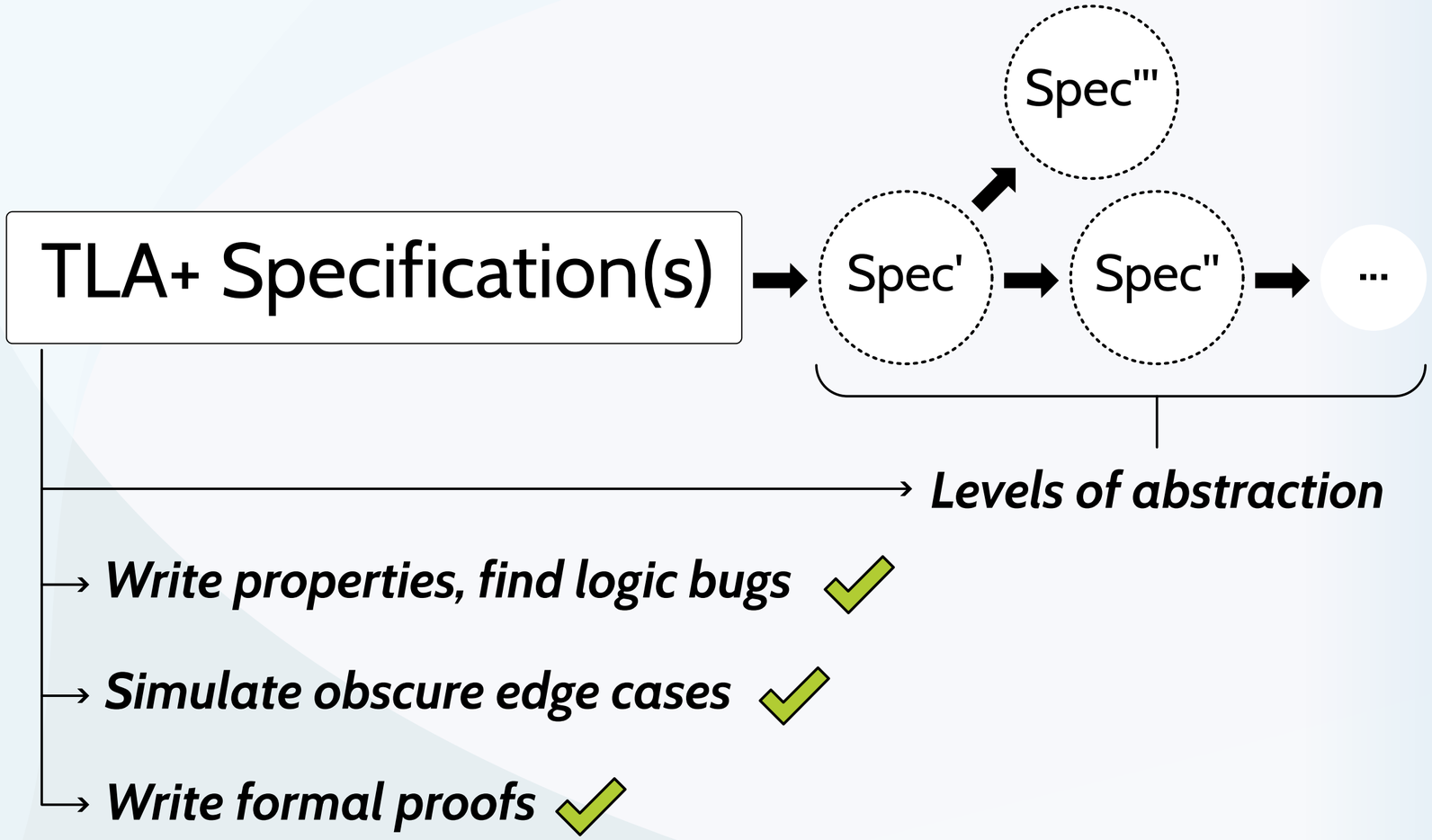
Understanding Inconsistency in Azure Cosmos DB with TLA+ [ICSE-SEIP'23]

Markus Kuppe

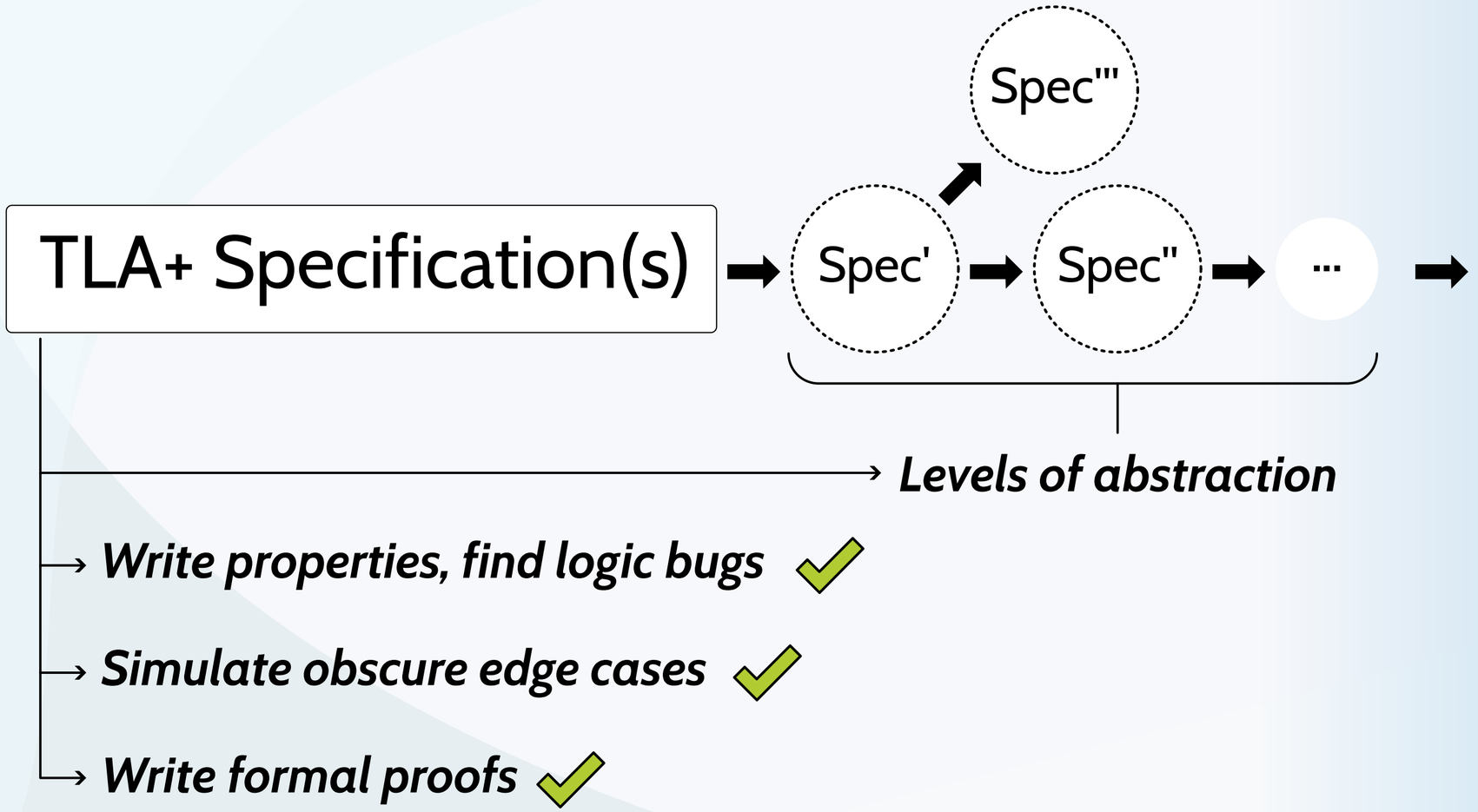
Principal Research Software Development Engineer

@ Microsoft

Usage of TLA+


TLA+ Specification(s)
Spec'''
Spec'
Spec''
...
Levels of abstraction
Write properties, find logic bugs
Simulate obscure edge cases
Write formal proofs

Usage of TLA+



Implementation(s)

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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Only bug possible is wrong correctness properties

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Unreasonably precise monitoring for free using verification tools

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

Goals of this Talk

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Preface: notes on logical refinement

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Summarize existing spec <-> code linkage work

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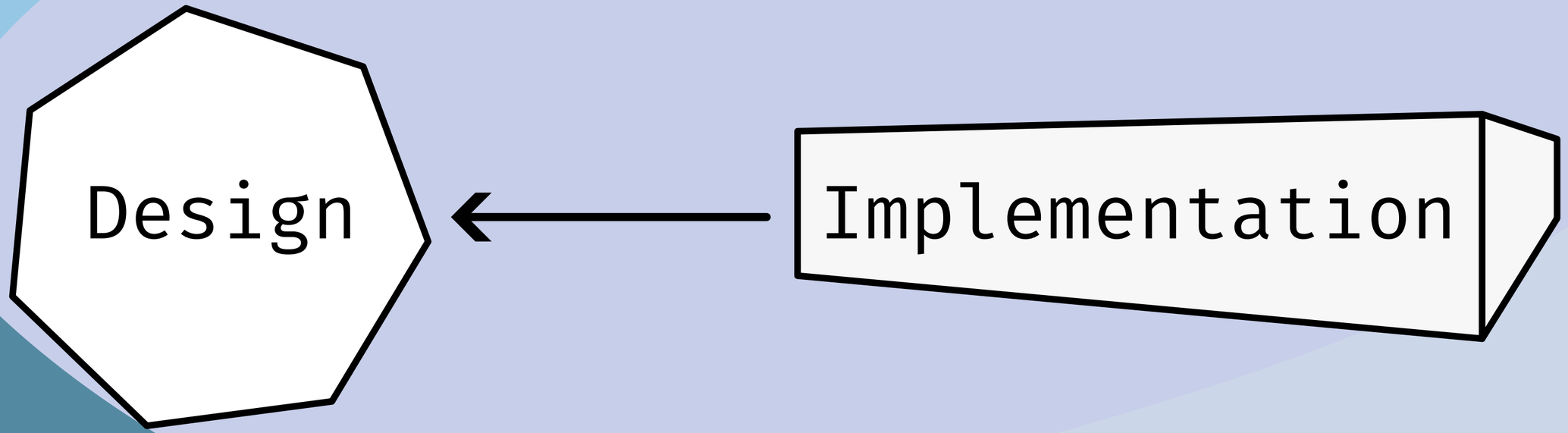
👉 Summarize existing spec <-> code linkage work

👉 Think aloud about what hasn't been tried and why

👉 Describe things we are working on

Why Are We Talking About Refinement?



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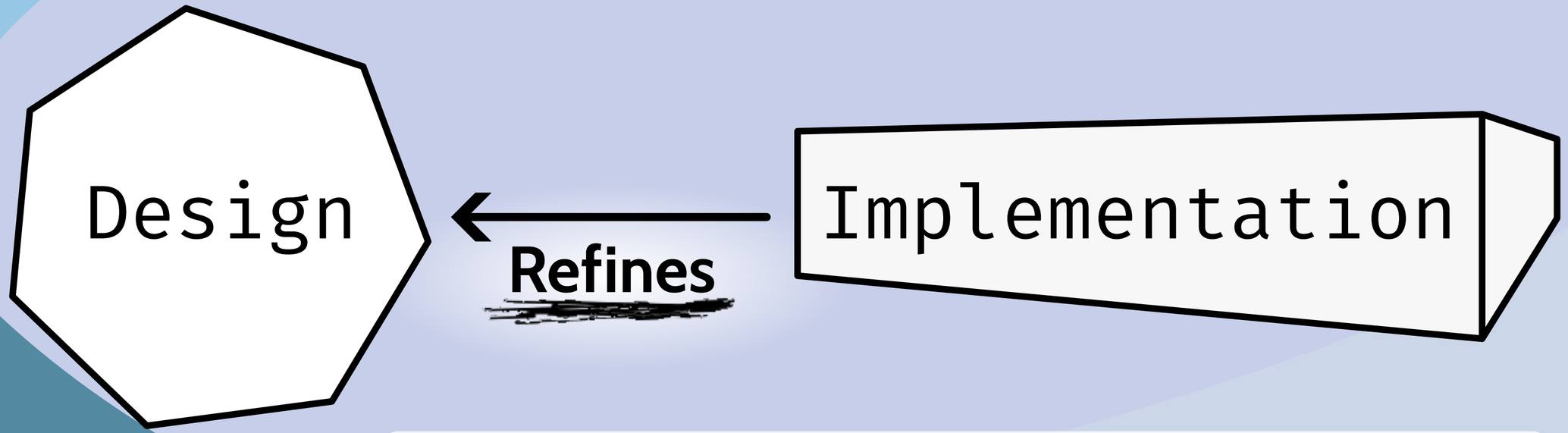

Underlying theory of linking design and impl.

Summary of Refinement

A logical relationship between a "less specific" spec and "more specific" spec

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

Atomic key-value write

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

Much more detailed view of "same" op

Conditions for Refinement

Question: how does that big trace relate to setting that one value on that dict?

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Use INSTANCE in TLA+

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- Use INSTANCE in TLA+
- How to match data?

  e.g. ignore everything except key-value bindings.

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Conditions for Refinement

Question: how does that big trace relate to setting that one value on that dict?

- Use INSTANCE in TLA+
- How to match data?

  e.g. ignore everything except key-value bindings.
- Choose "when" the write happened.

  e.g. when the server said "ok"?

  Shouldn't be able to tell anything apart from high-level model.

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Worked Example, from Azure Cosmos DB Modeling

1. Load 2 different specs

```
31
32      Impl == INSTANCE CosmosDBWithReads WITH
33          ReadConsistency <- ReadConsistencyImpl
34      ImplSpec ==
35         /\ ReadConsistencyImpl = StrongConsistency
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37         /\ Impl!RInit
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A

B

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Worked Example, from Azure Cosmos DB Modeling

1. Load 2 different specs

2. Here all vars match (see next slide if not)

3. HLSpec is a "property" of ImplSpec

./TheSpec.cfg

```
SPECIFICATION
    ImplSpec
```

```
PROPERTIES
    HLSpec
```

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Worked Example pt. 2: Mismatched Variables

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Define
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High-level spec uses defined vars like normal

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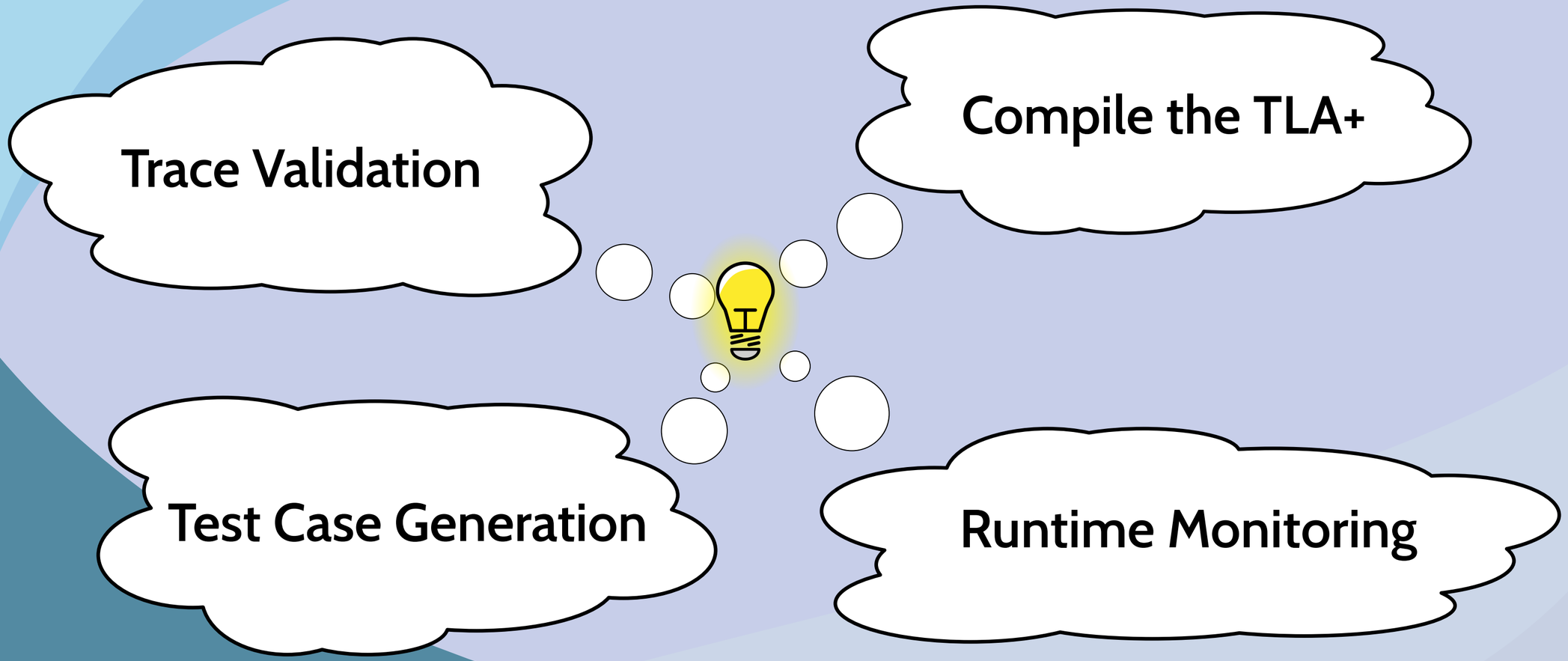
HL spec works like a property

```
113   DictSpec == DictInit /\ [][DictNext]_<<dictView, commitIndex>>
```

```
15    PROPERTIES
16        DictSpec
```

How Have We Attempted Implementation Linking?



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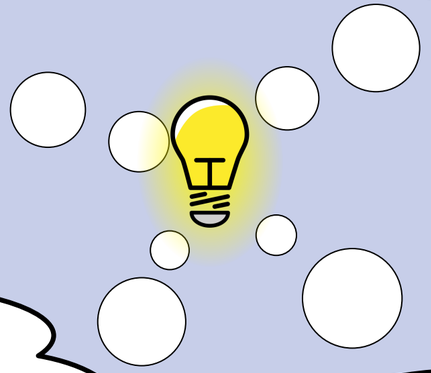
Trace Validation

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

Compile the TLA+



Test Case Generation

Runtime Monitoring

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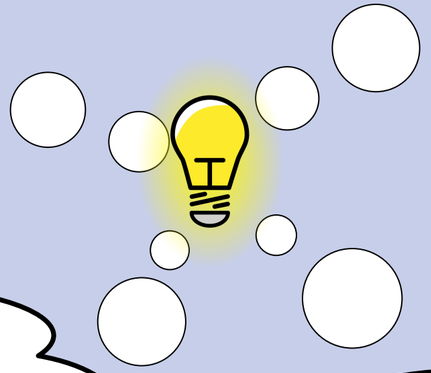

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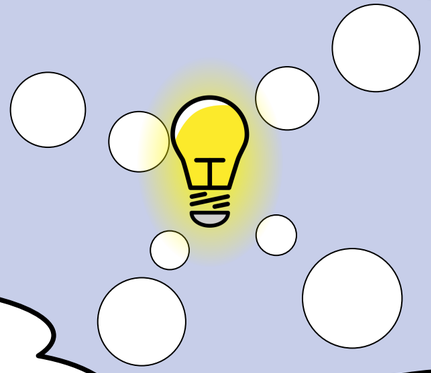

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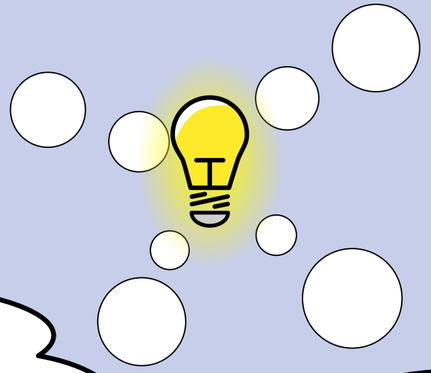

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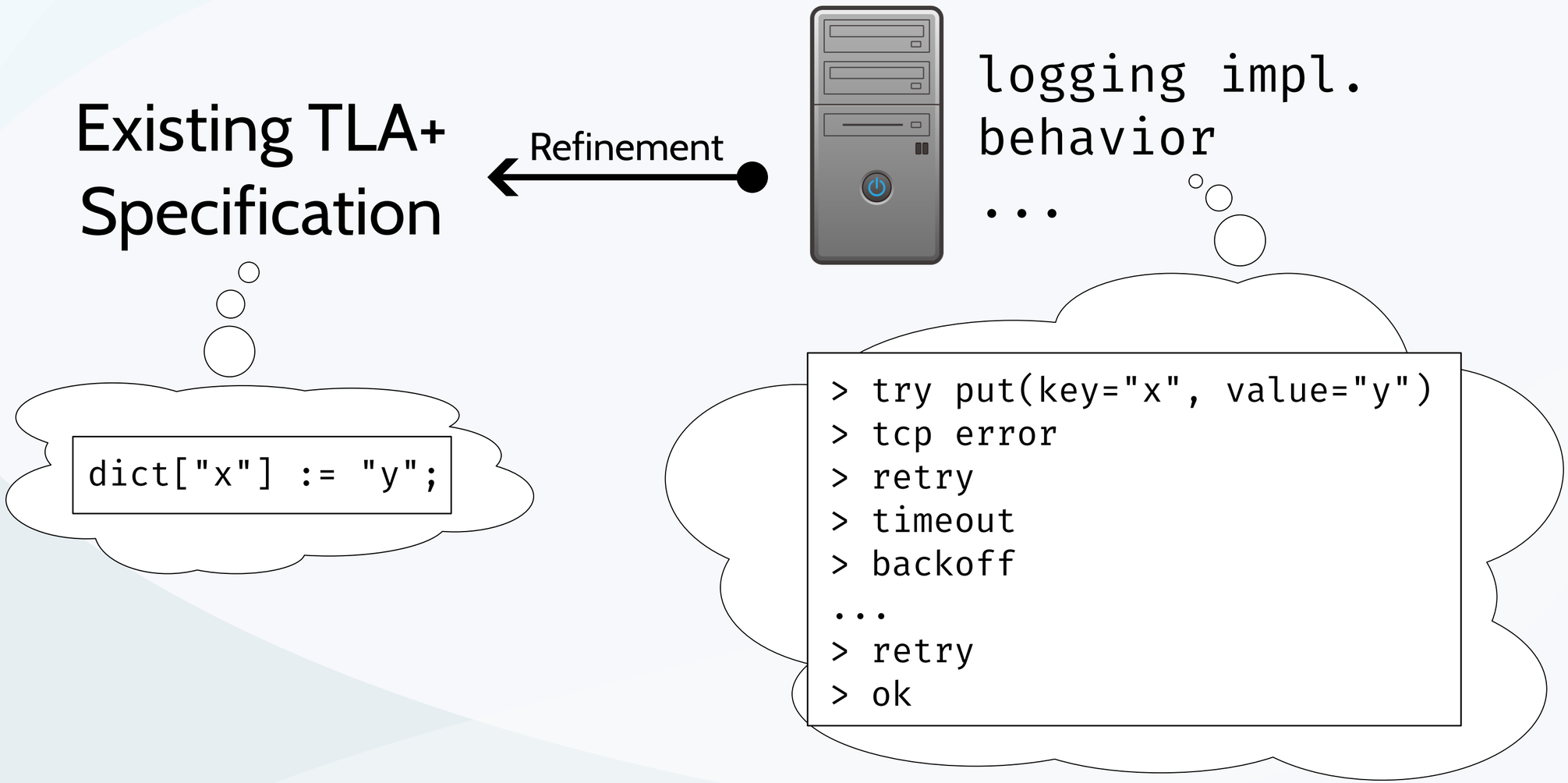
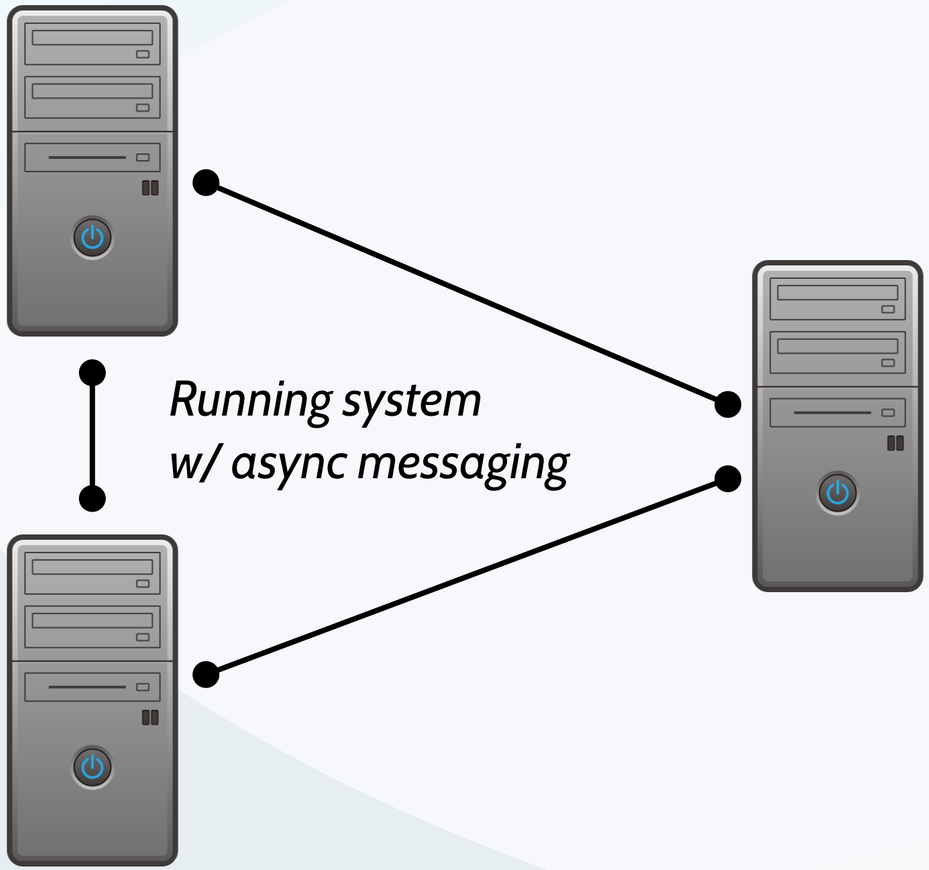
Runtime Monitoring

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

Trace Validation: Refinement w/ Implementation Traces



Trace Validation: the Order Problem



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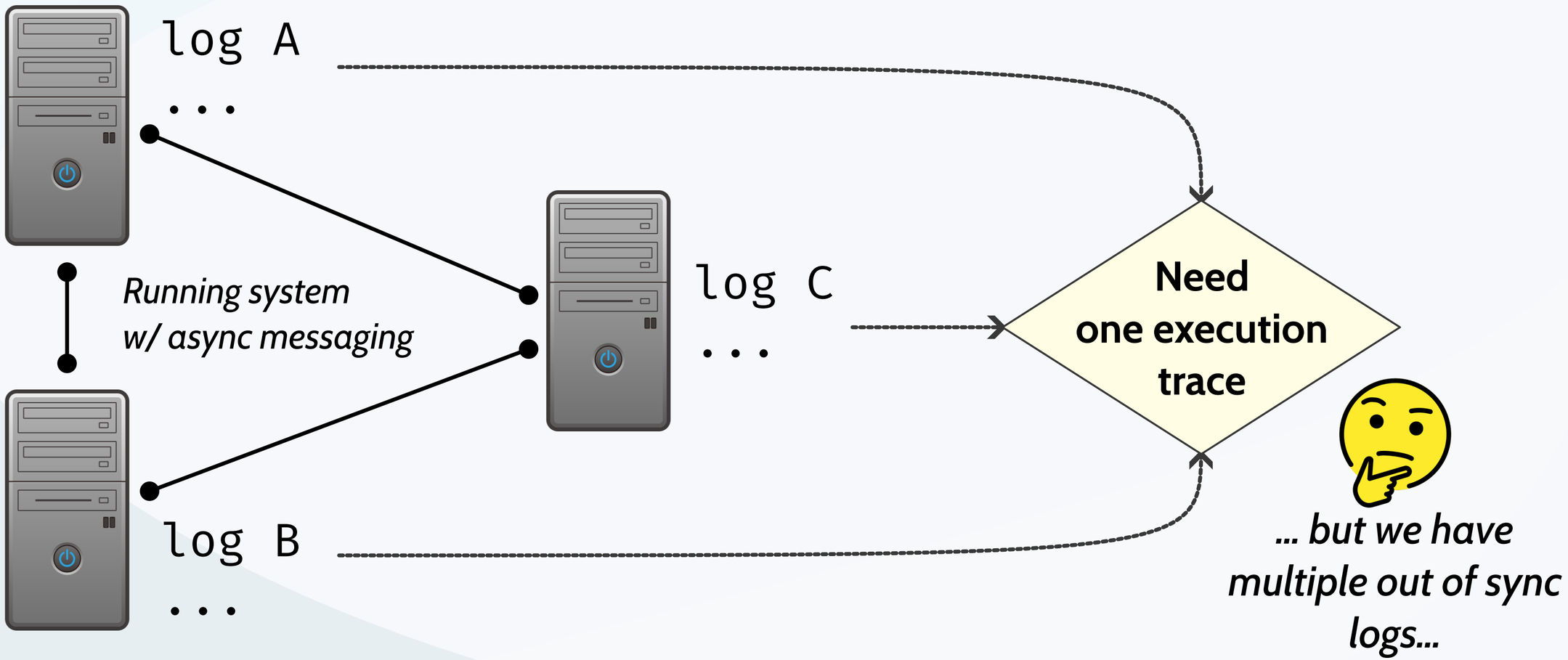

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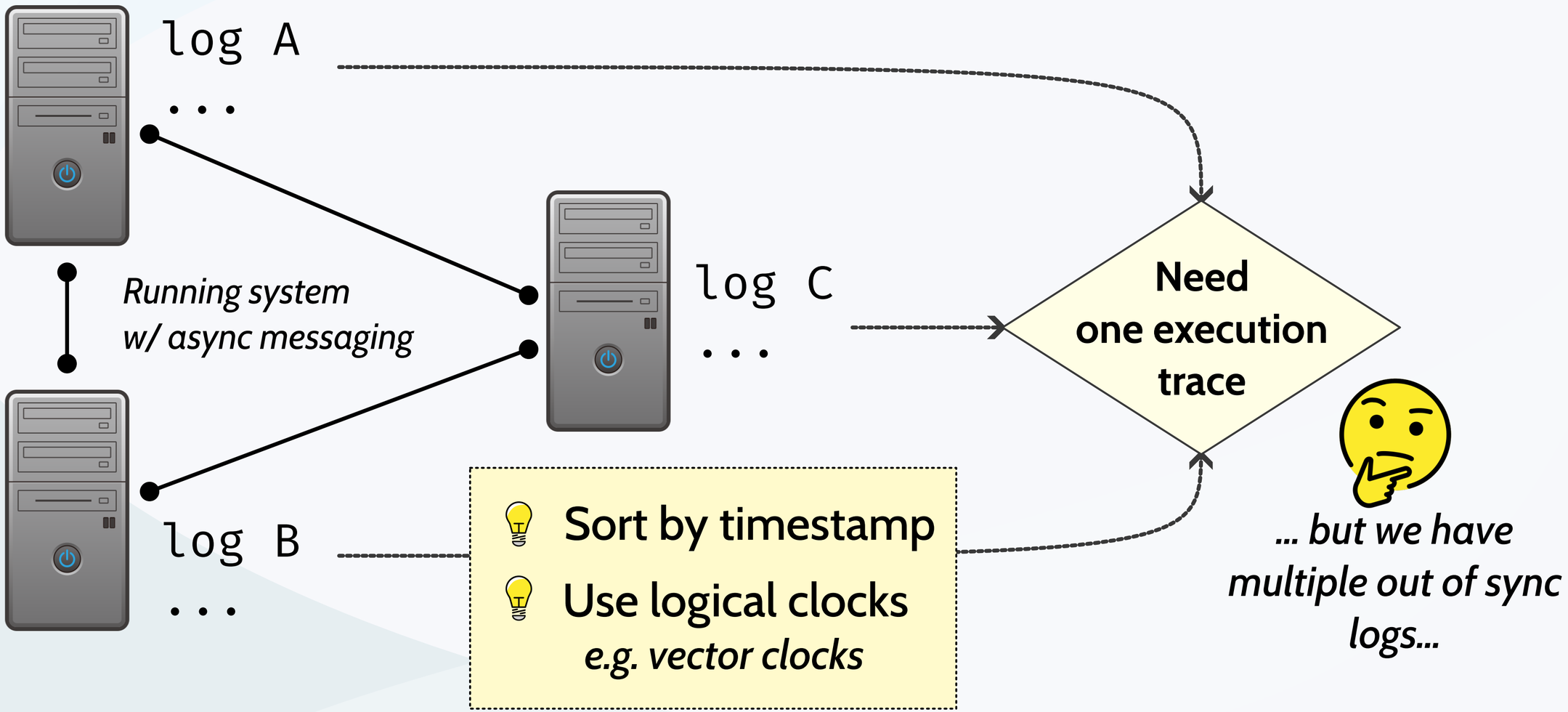

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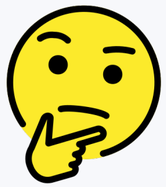

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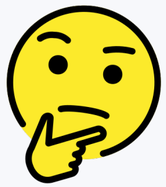

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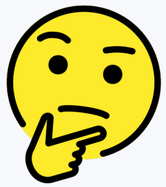

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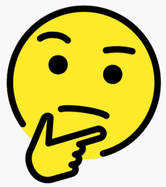

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Use symbolic reasoning to lazy-fill spec holes? Potential future work.

Trace Validation: In Practice

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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.

Tradeoffs in Trace Validation

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

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- 🚀 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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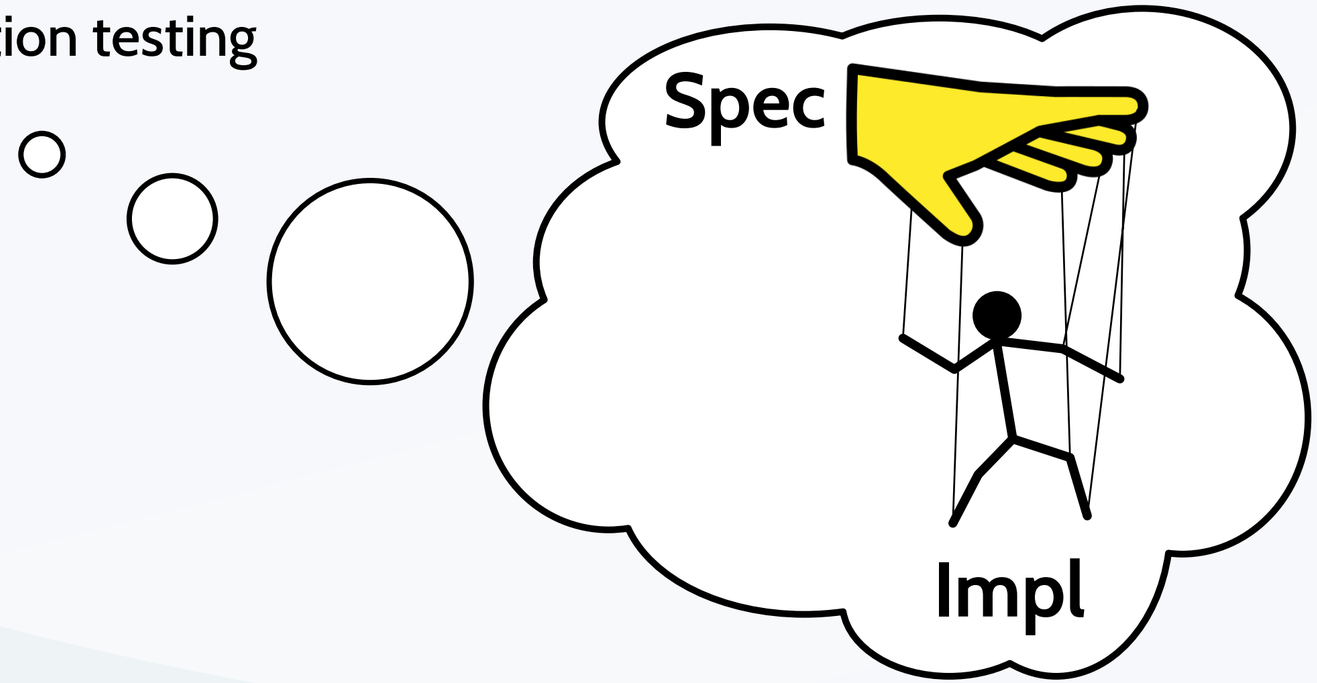
💡 Let the spec drive implementation testing



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

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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..

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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

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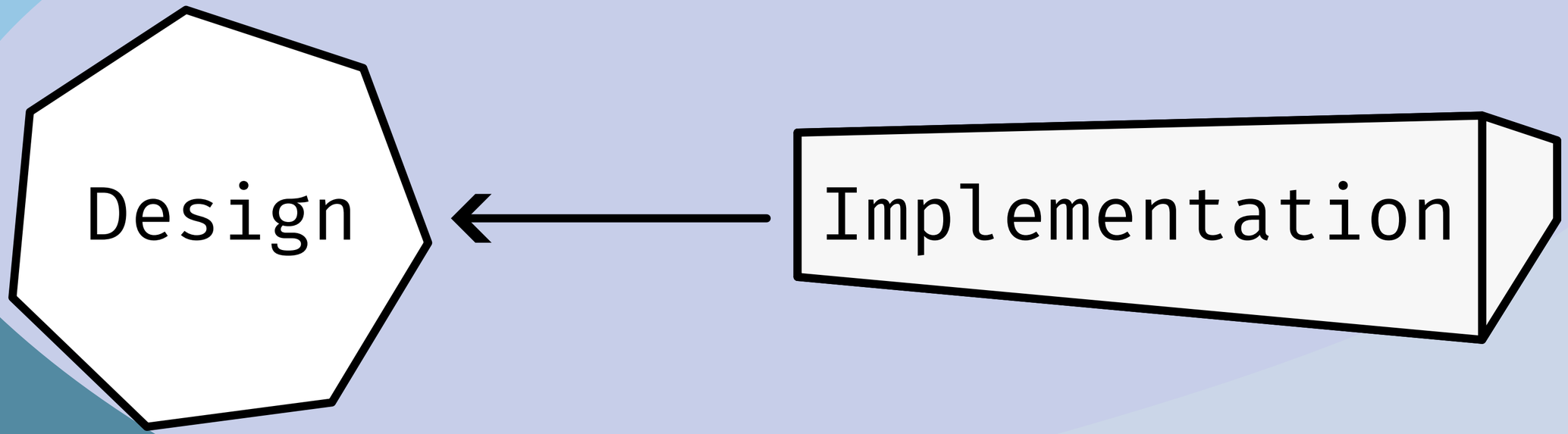
  - 💡 Different from implementation model checking, but similar effect
- 🤔 Extracting implementation behavior and state is still non-trivial
  - 🚀 … can be partly automated, but fundamental refinement job remains
- 🤔 For existing implementation, need to retrofit deterministic exploration

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

Other Direction: Compile the Design



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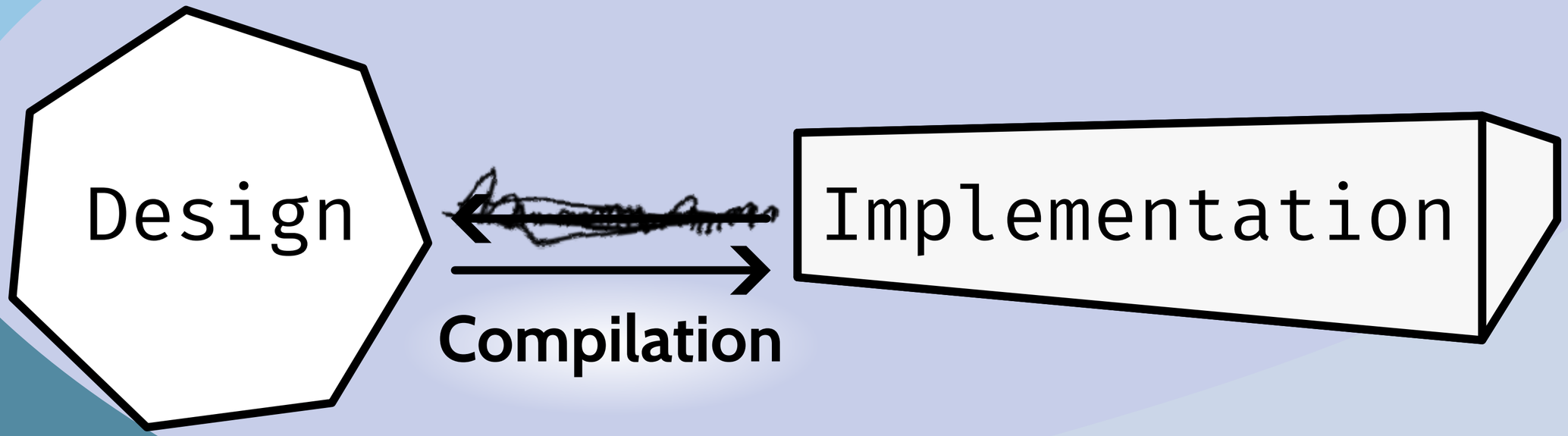

Tradeoffs in Specification Compilation

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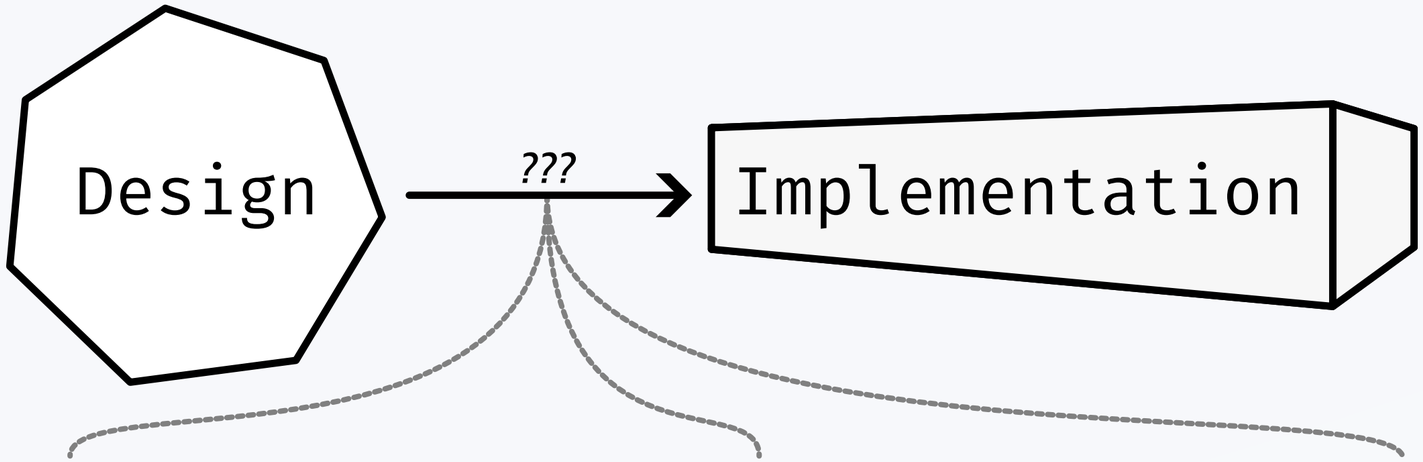

Translating data structures right

Hidden control flow

What if compiler has a bug?

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:
  msg := read from A;
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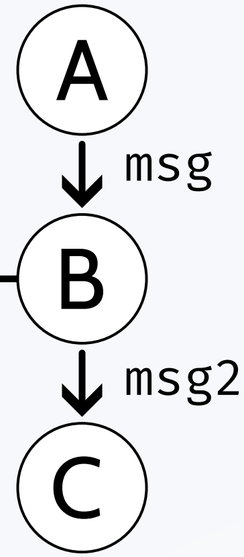

Thanks to Markus for finding a real example of this in a hand-translated impl.

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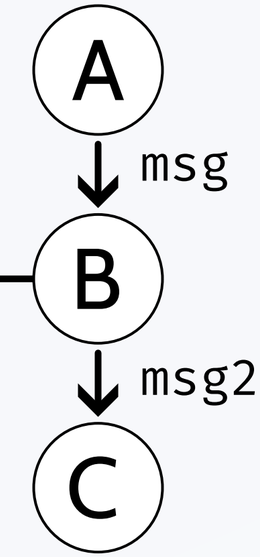

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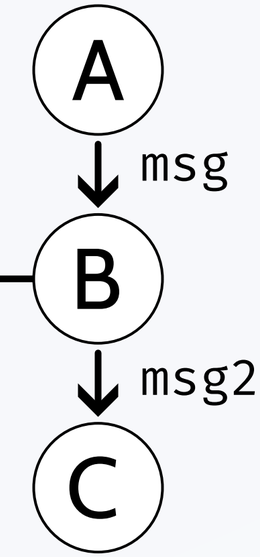

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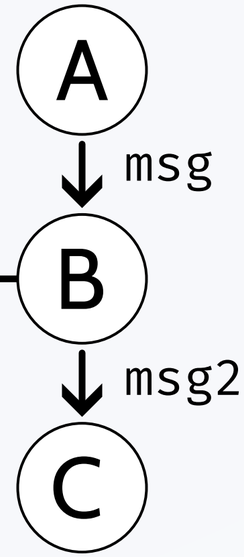

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A correct implementation must "remember" msg until it can send msg2!

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

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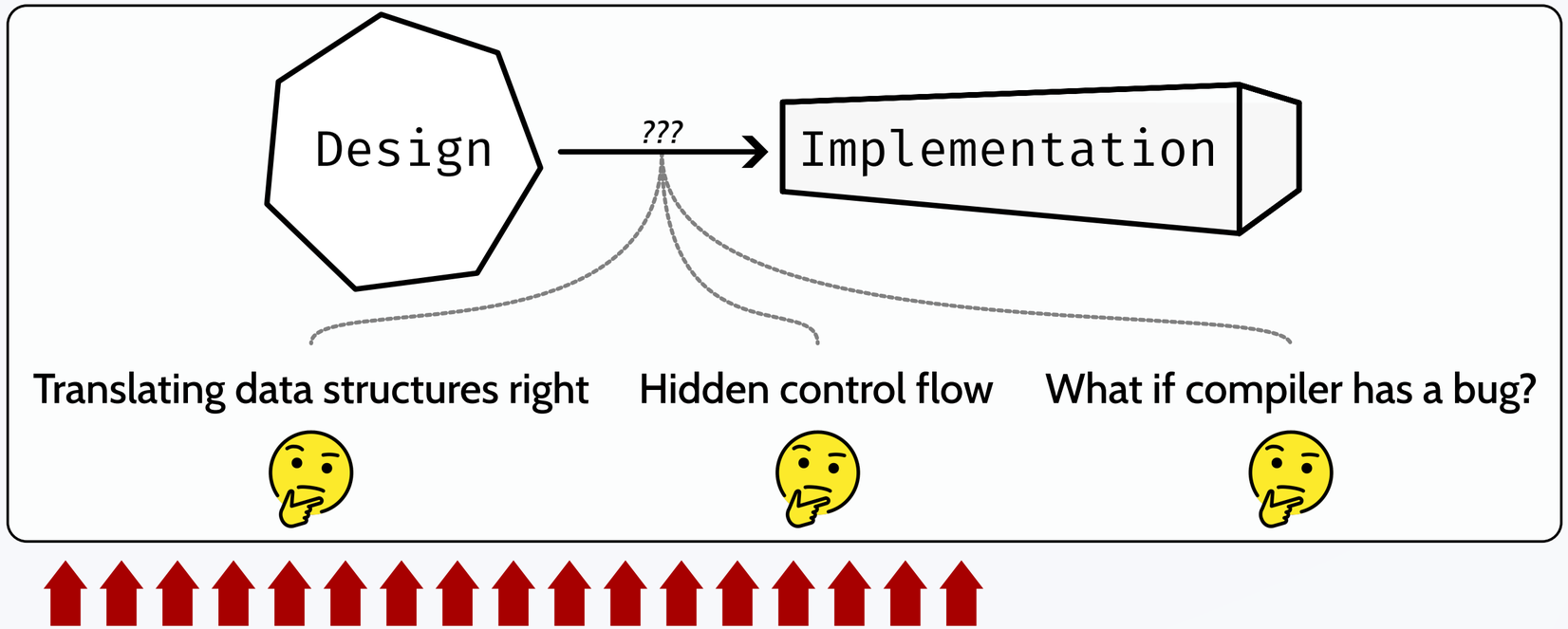
🤔 **... compilation seems popular for monitoring implementations ...**

Ongoing Work...

Ongoing Work: DCal, a More Customizable PGo

Move impl-oriented changes away from spec.



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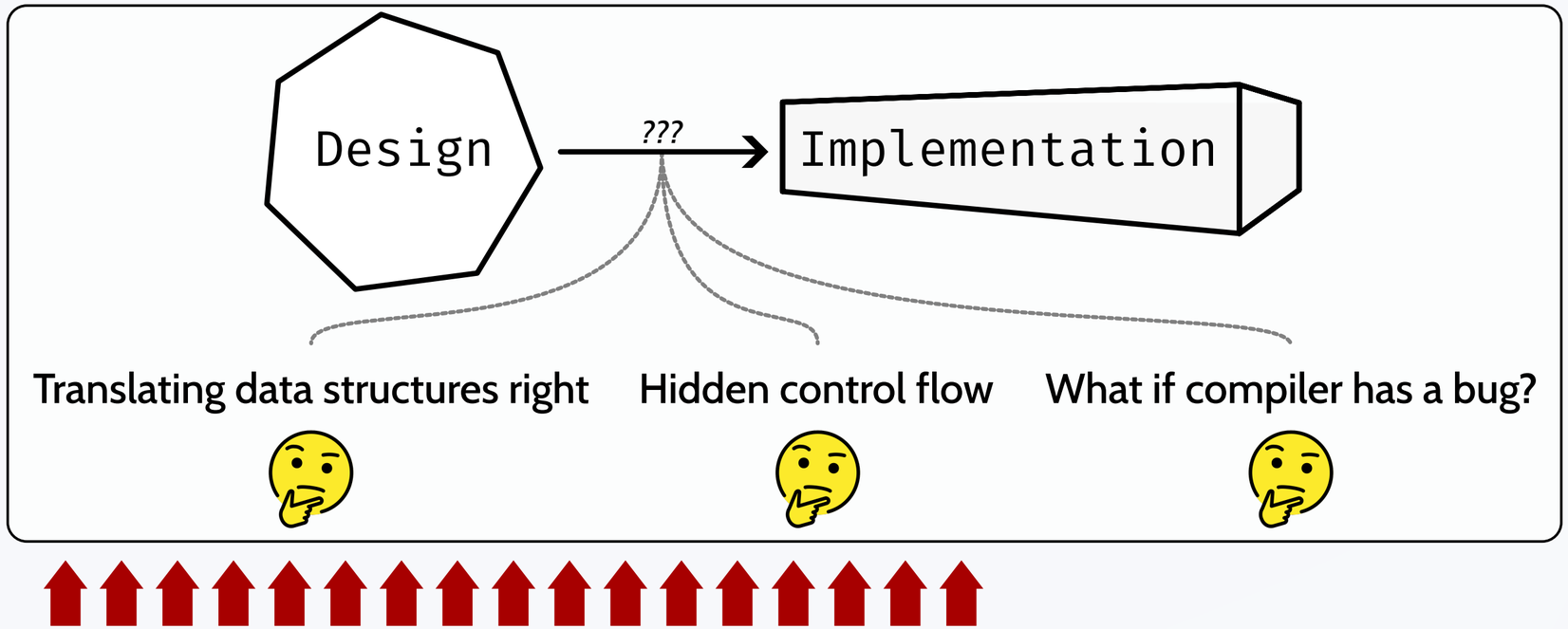
👉 **PGo uses fixed data structures.**
General-purpose, but can be inappropriate.

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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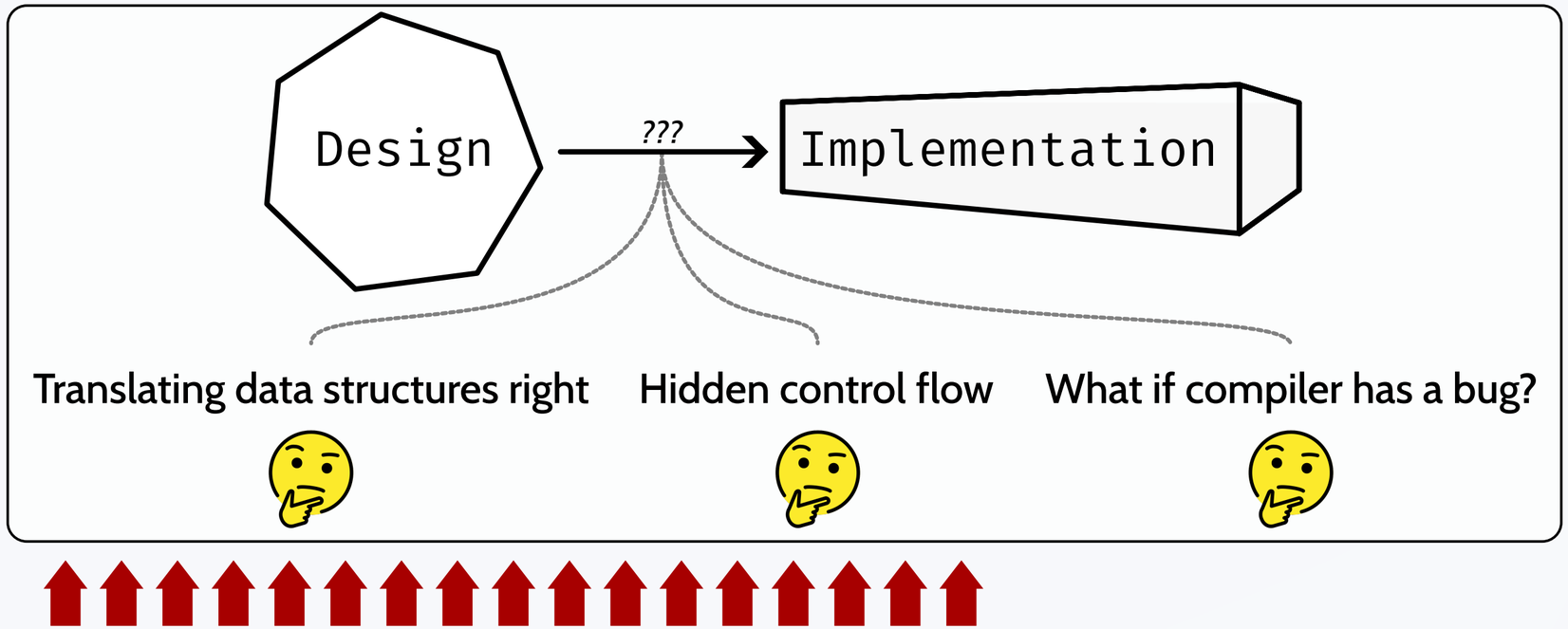


👉 **PGo's control flow impl is black-box and fixed.**
Difficult to specialize compiler's output.

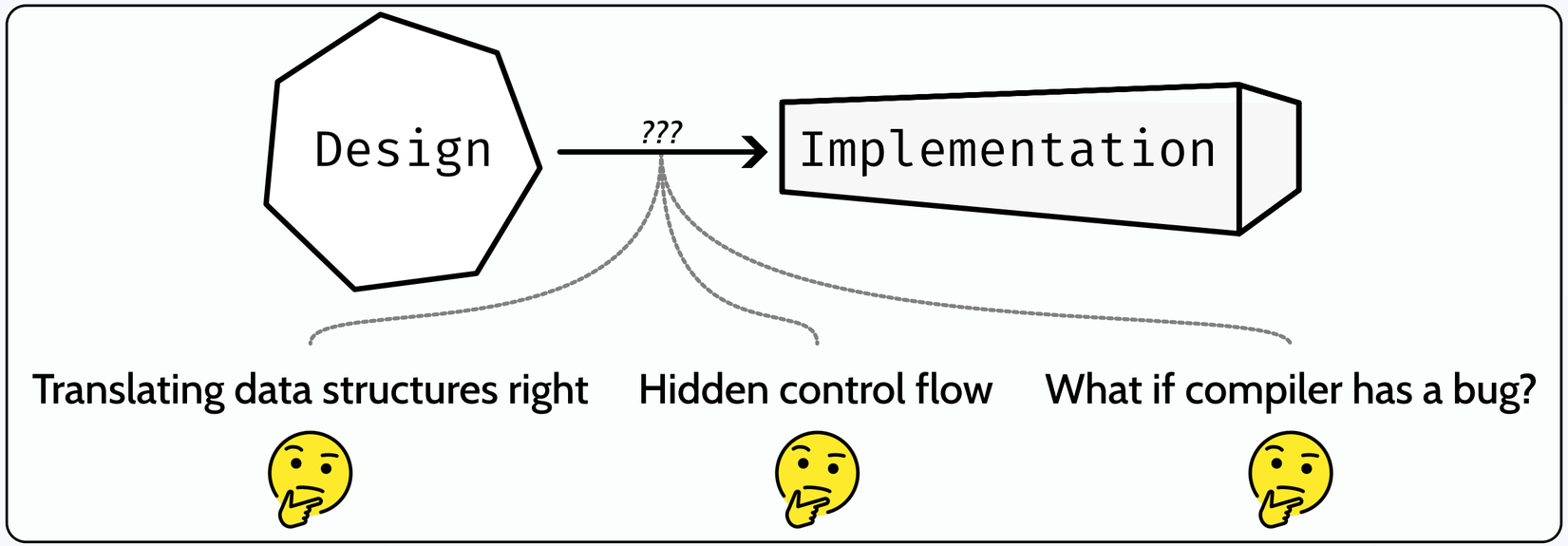
e.g. can't compile disjunction to I/O select primitive.

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

Ongoing Work: TraceCheck, Compiler-assisted Trace Validation

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

… how much effort can we automate?



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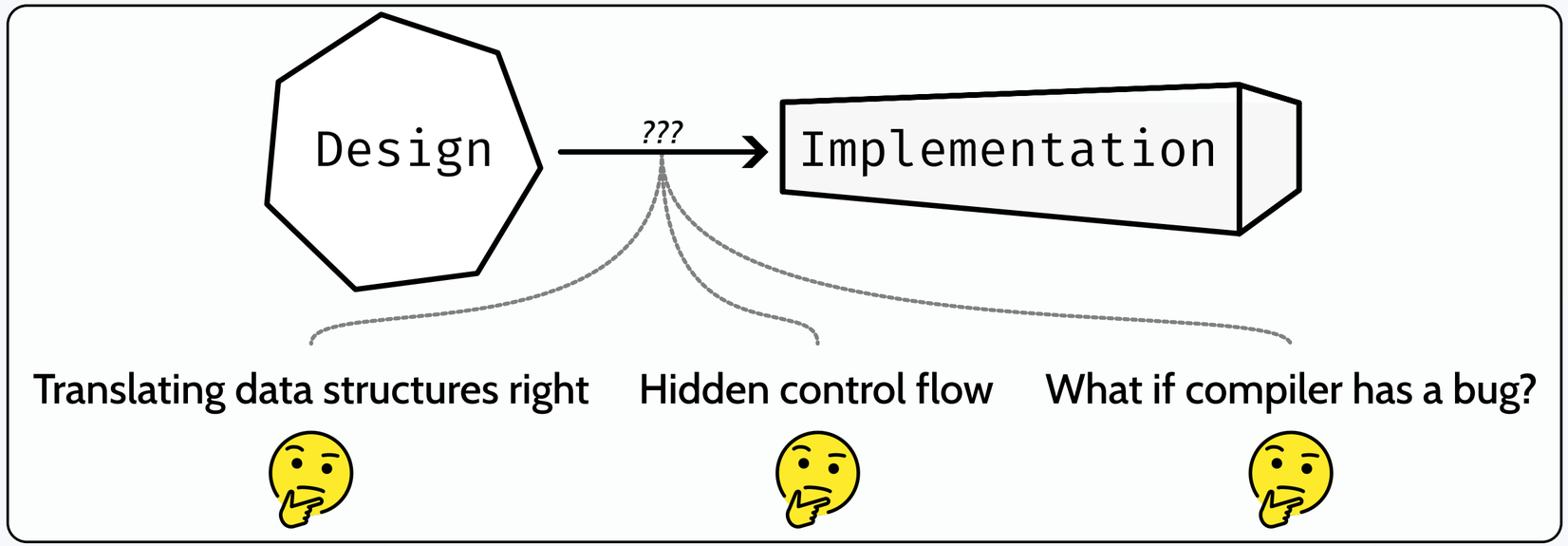
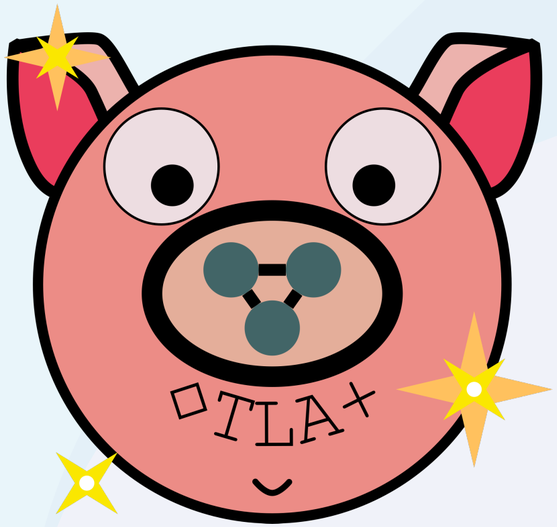
👉 **How to find problems in the compiled system?**

💡 *Do trace validation on on the compiled system.*

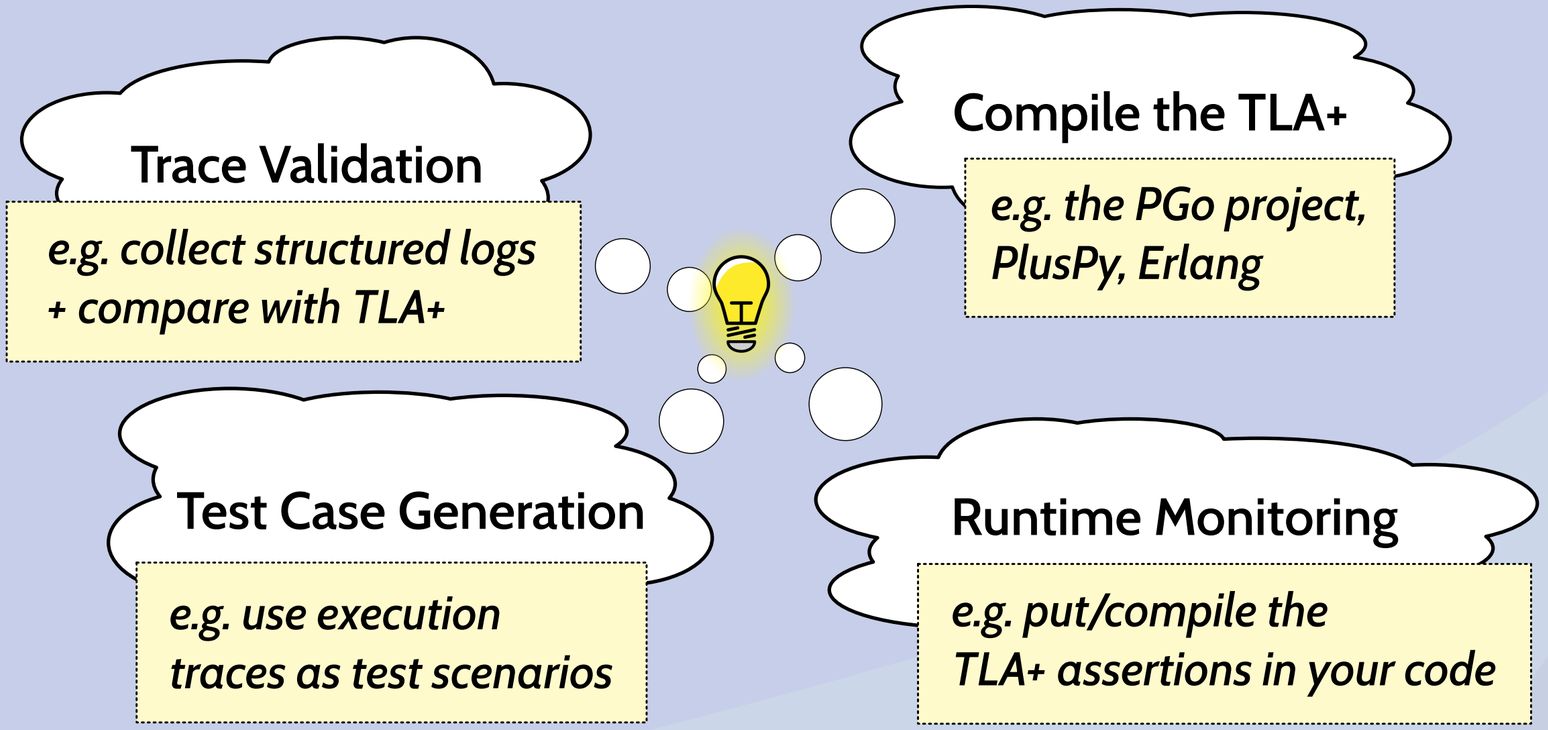
💡 *Use the compiler to automate trace validation workflow.*





distcompiler.github.io

Promises and Challenges in Bridging TLA+ Designs with Implementations



Any Questions?