FOUNDATIONAL RESPONSE-TIME ANALYSIS AS EXPLAINABLE EVIDENCE OF TIMELINESS

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MAX-PLANCK-GESELLSCHAFT

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Foundational Response-Time Analysis,

a new way of implementing response-time analysis tools

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3. produces **explainable evidence** of timeliness, which can be assessed independently of the tool itself.

+ a **proof of concept** that scales to large workloads (parameter magnitudes & task counts)

…IN A NUTSHELL

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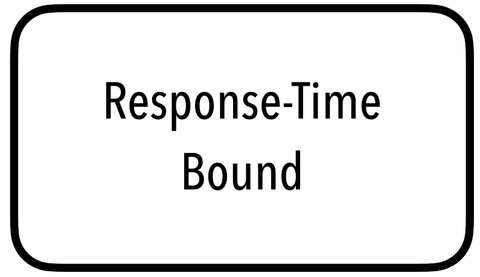
MOTIVATION

What is the issue with conventional response-time analysis?

RESPONSE-TIME ANALYSIS (RTA)

The goal of an **RTA** is to obtain **safe response-time bounds**



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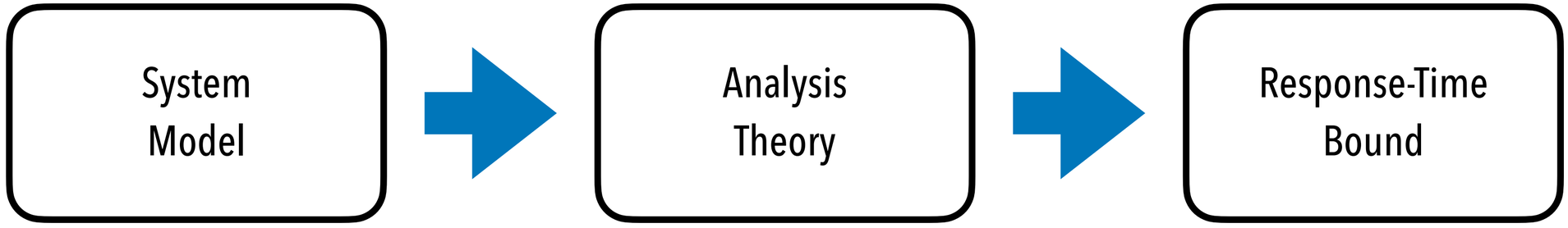

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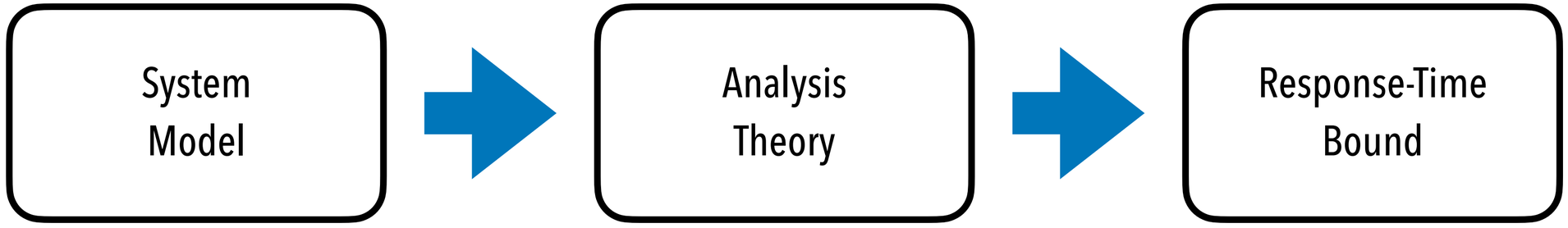

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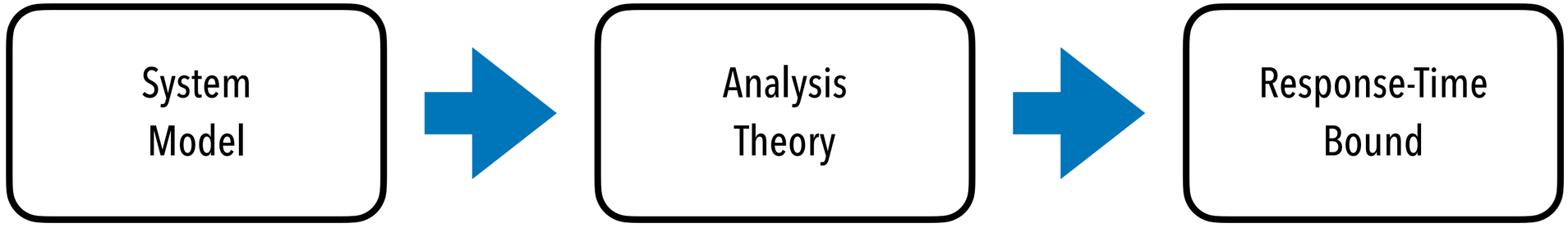
➔ *the ability for a human evaluator to **inspect** and **understand** the result of a computation*



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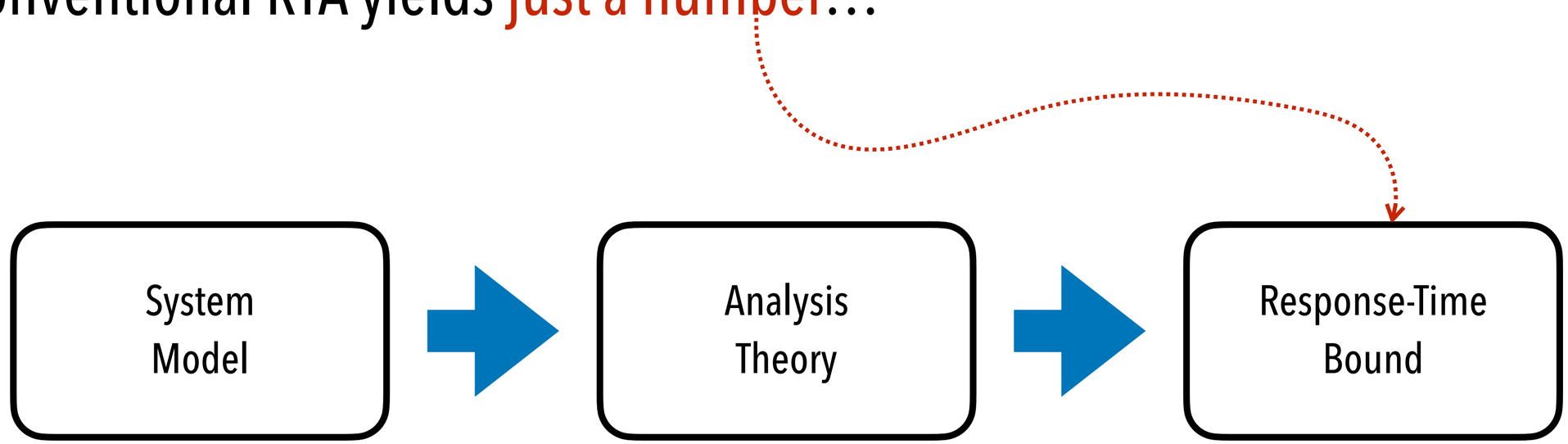

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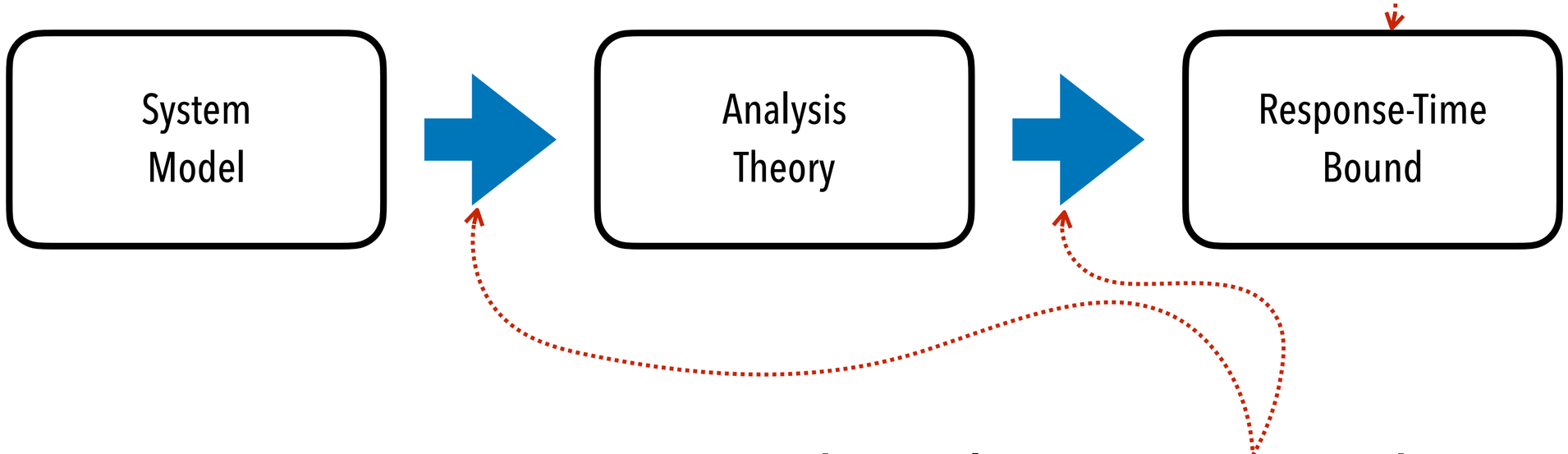
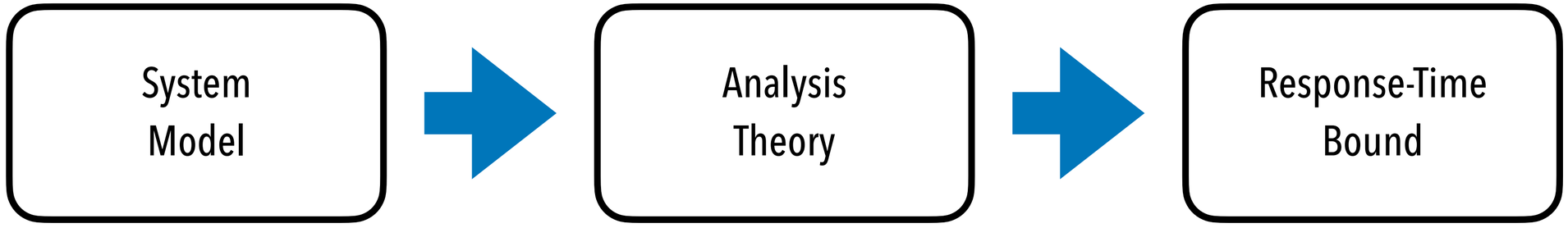


…so the evaluator must **trust** the process by which the result was obtained.

Should we?

ISSUE 2: RTA IS ERROR PRONE



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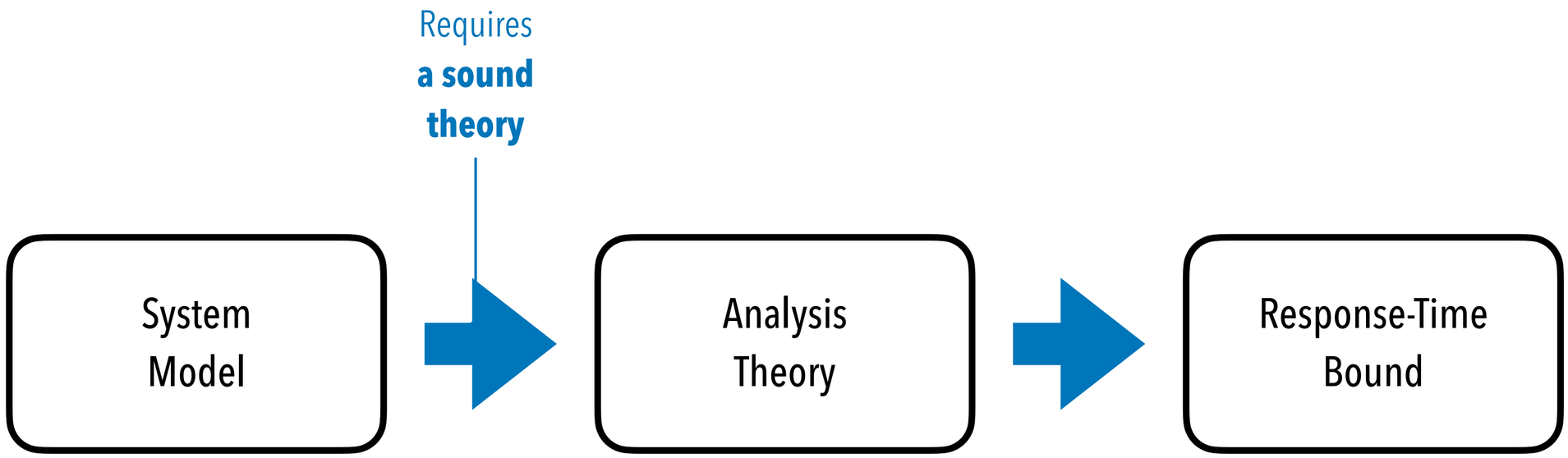

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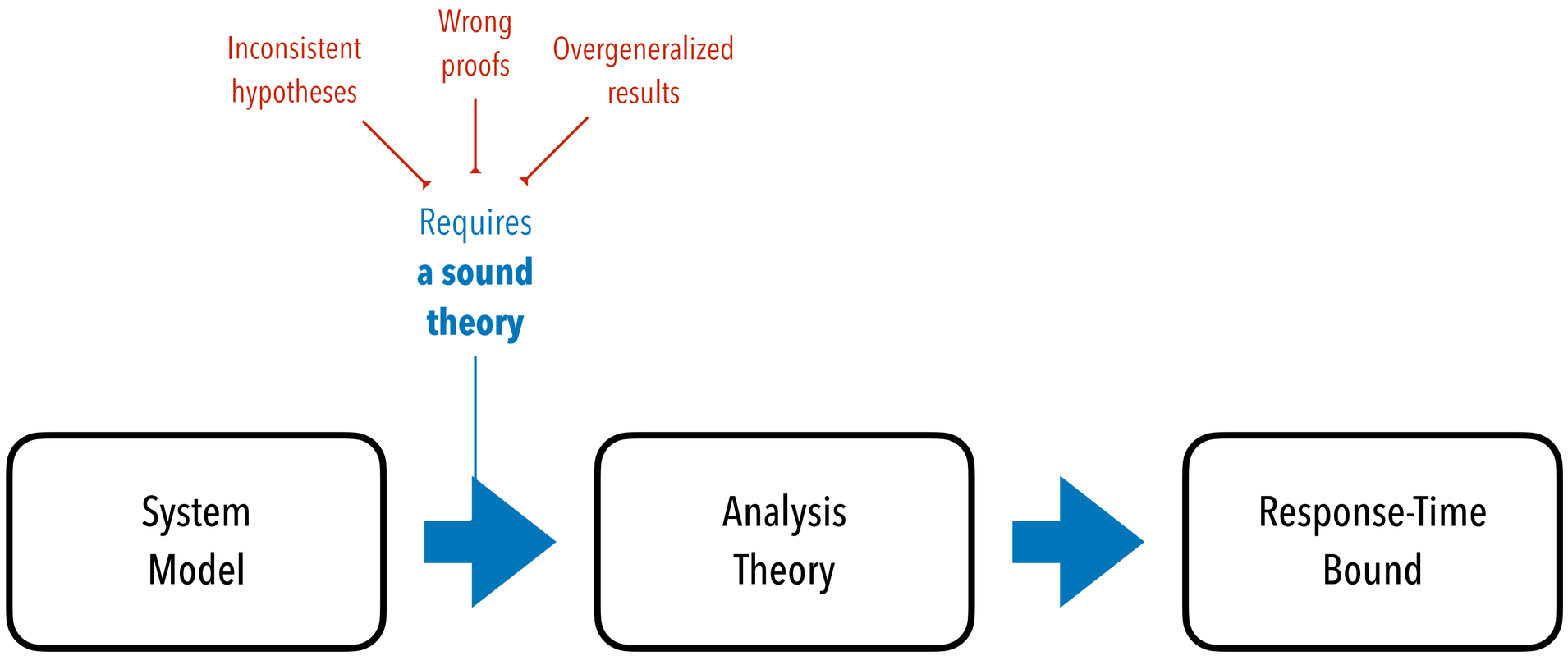

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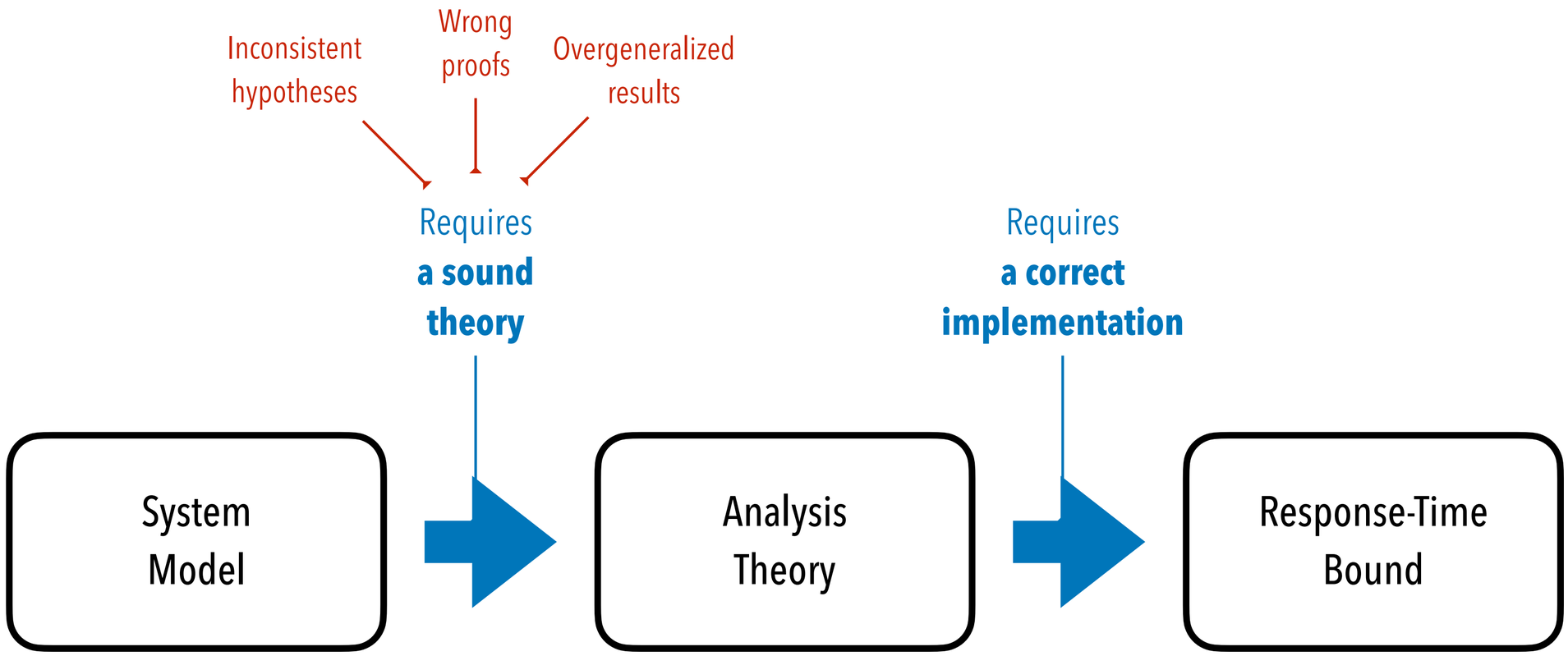

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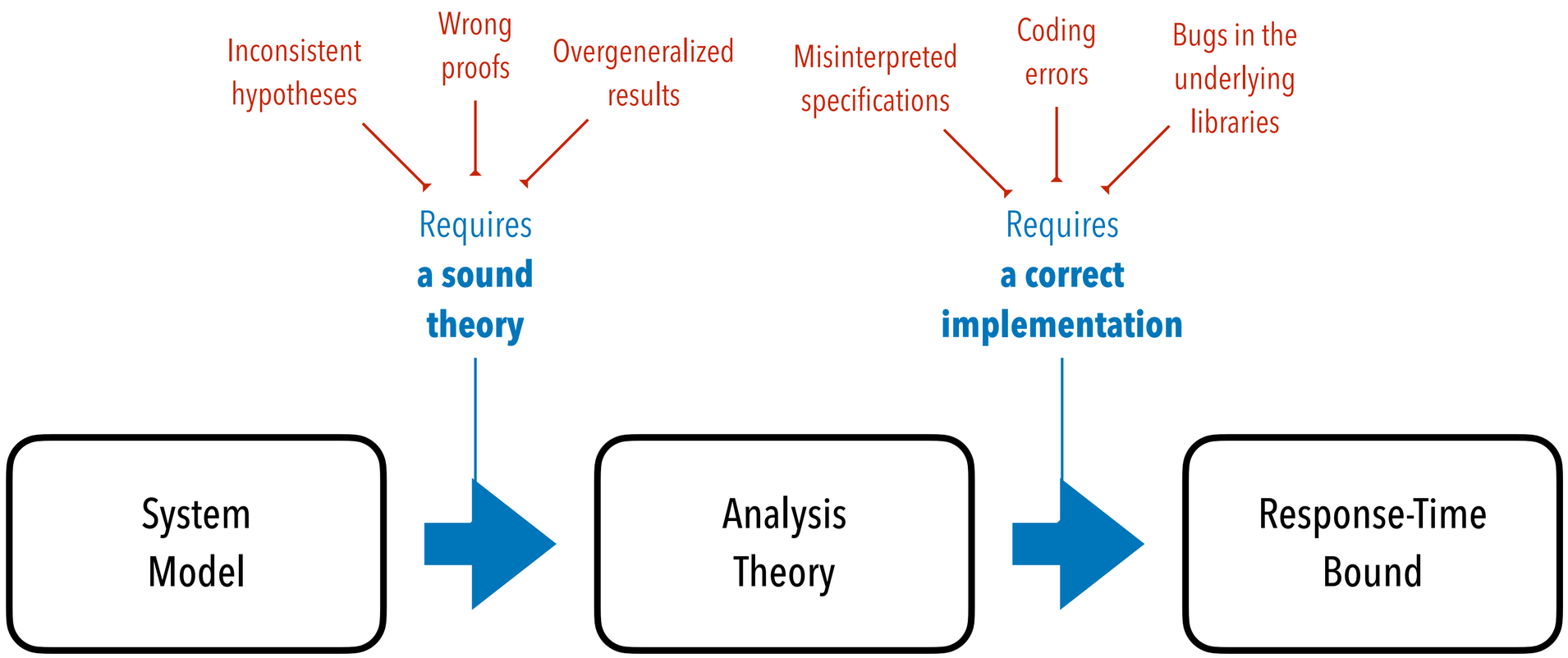

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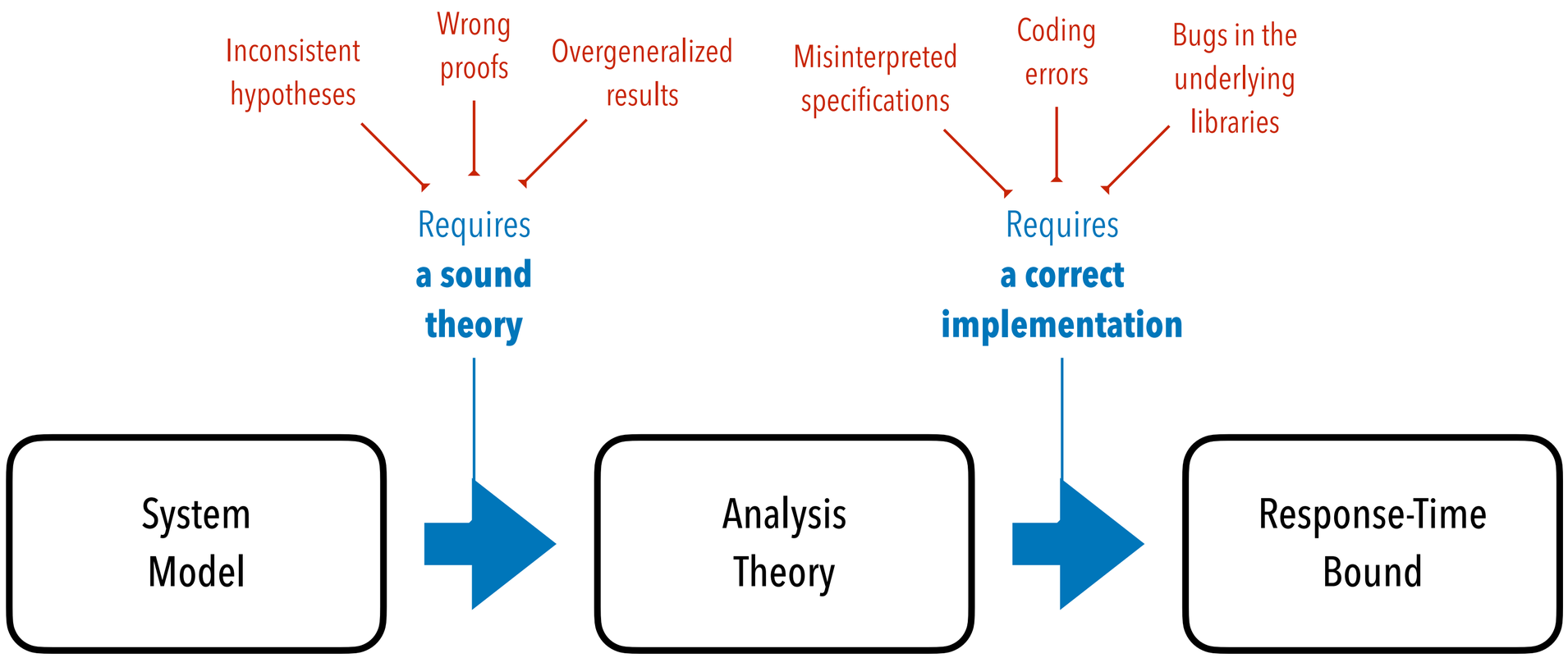


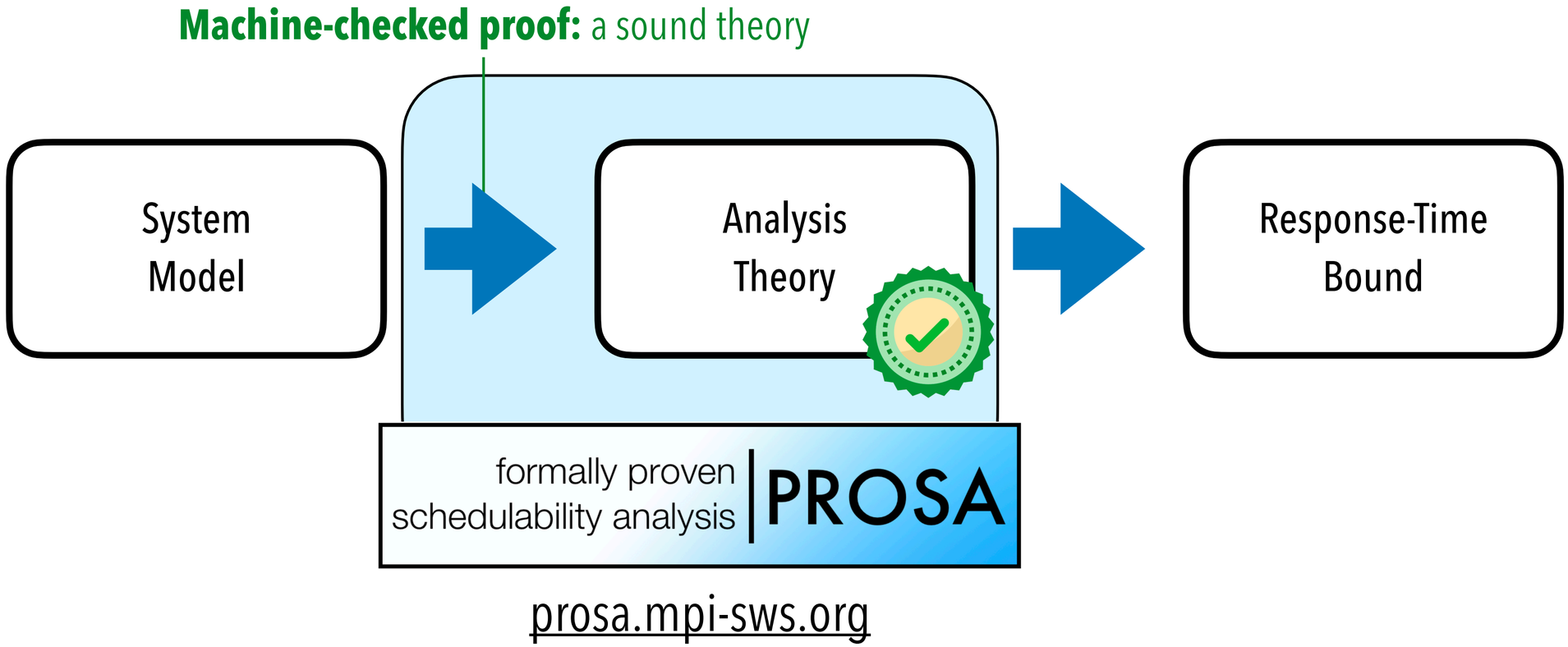
Can we make use of formal verification?

DESIGN SPACE

How to formally verify an RTA?

PRIOR WORK: VERIFY ONLY THE THEORY

[Cerqueira et al., ECRTS 2016]



prosa.mpi-sws.org

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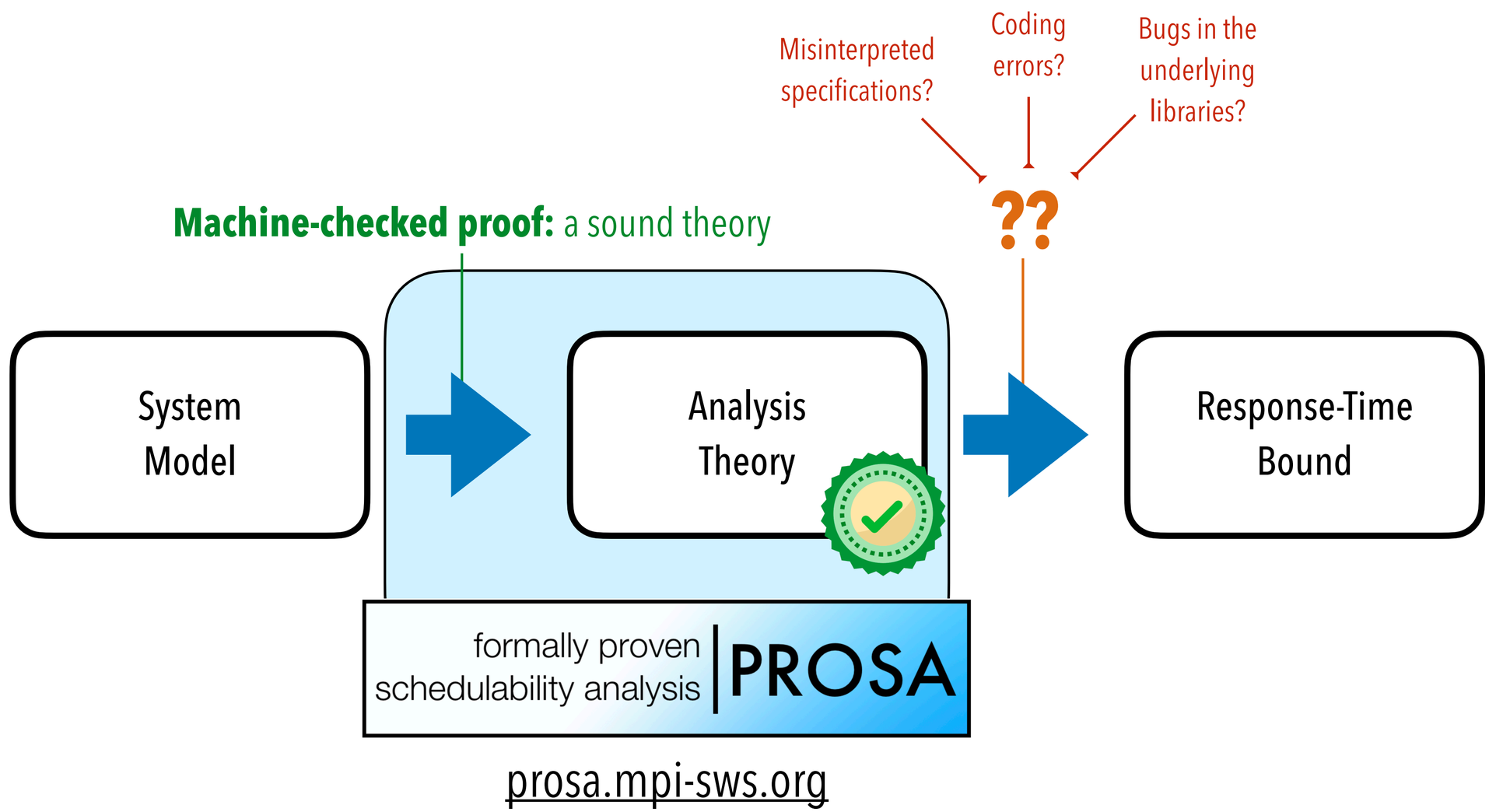

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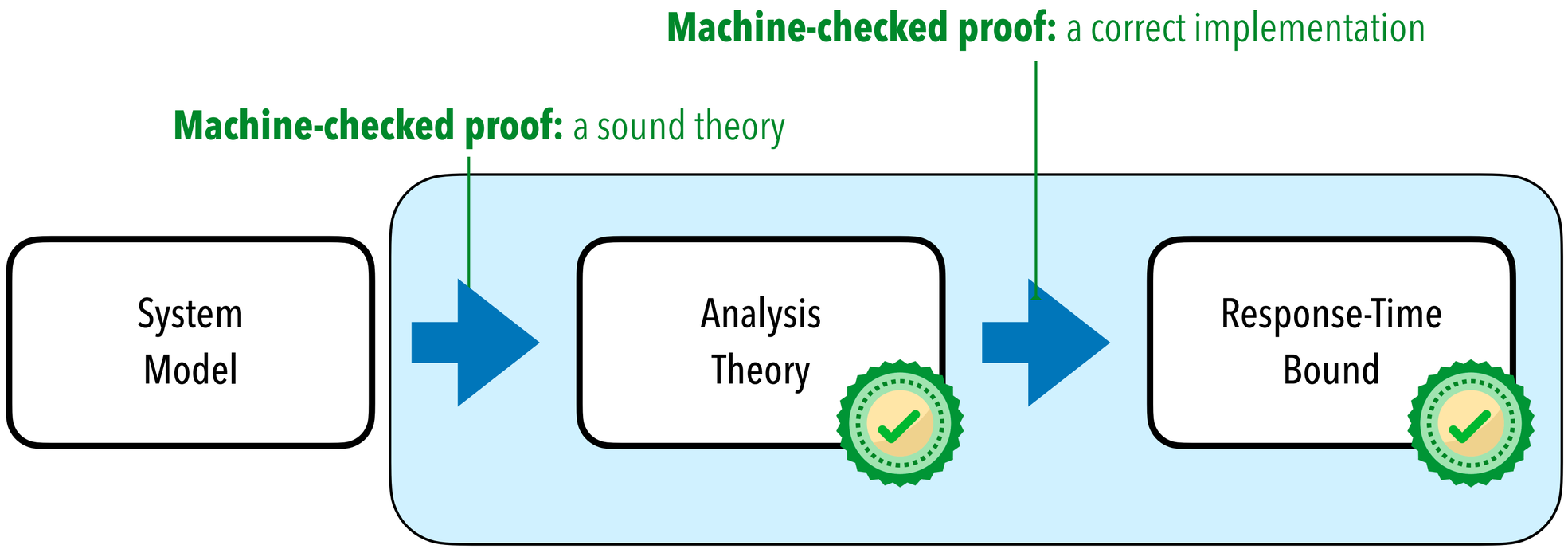

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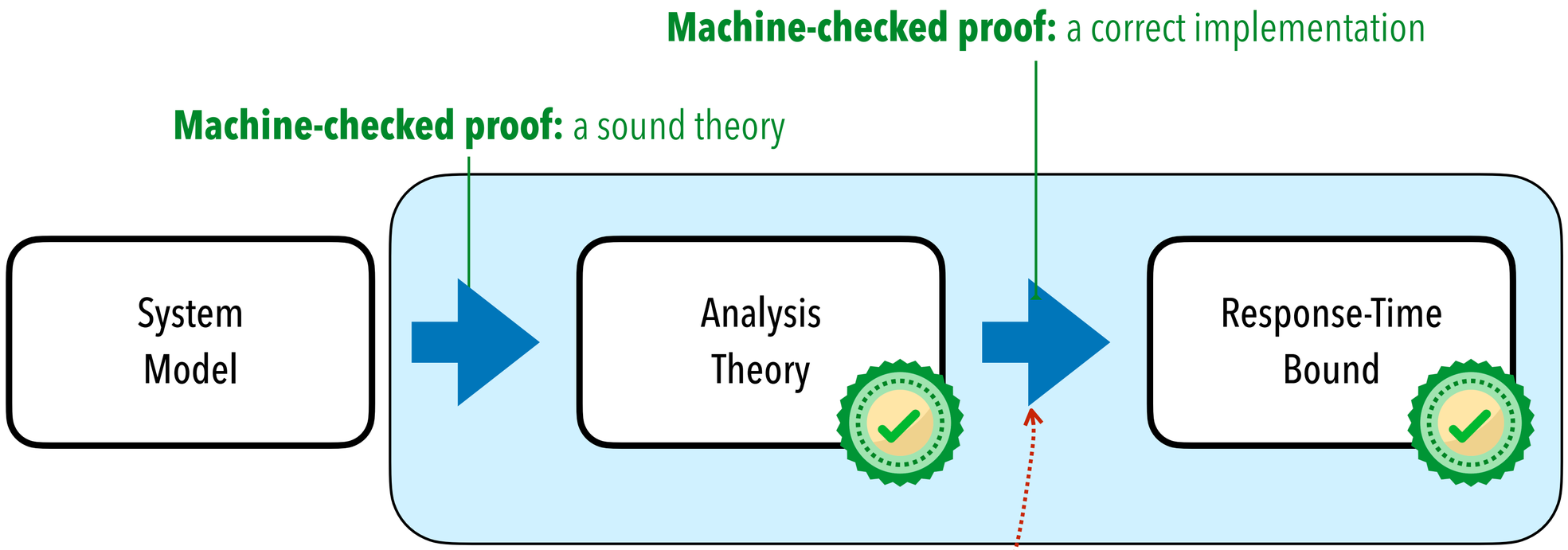


A "**heroic effort**" needed:

- massive amount of work to verify *everything* (e.g., input parser, I/O, etc.)
- not easily updated once verified

TOUR DE FORCE: VERIFY THE ENTIRE TOOL

hypothetical

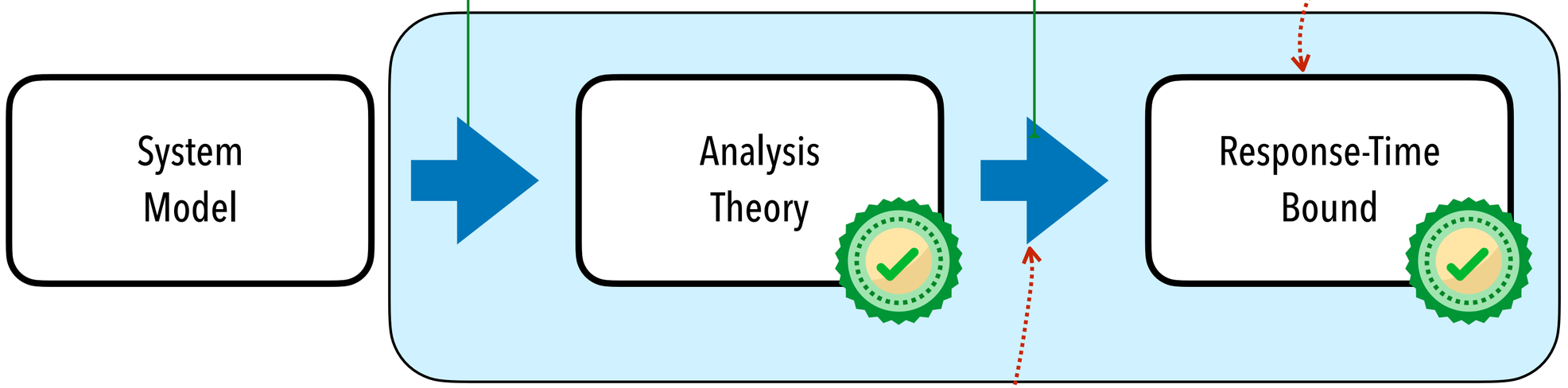
(never done in prior work)

no explainable evidence

(still just a number)

Machine-checked proof: a correct implementation

Machine-checked proof: a sound theory



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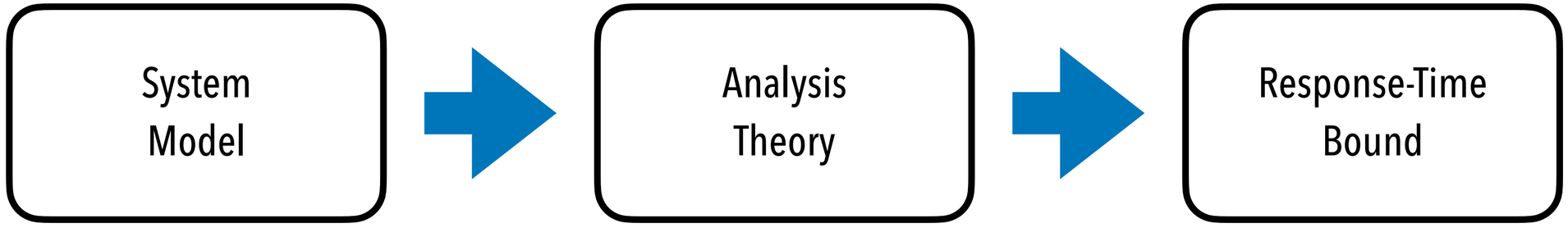

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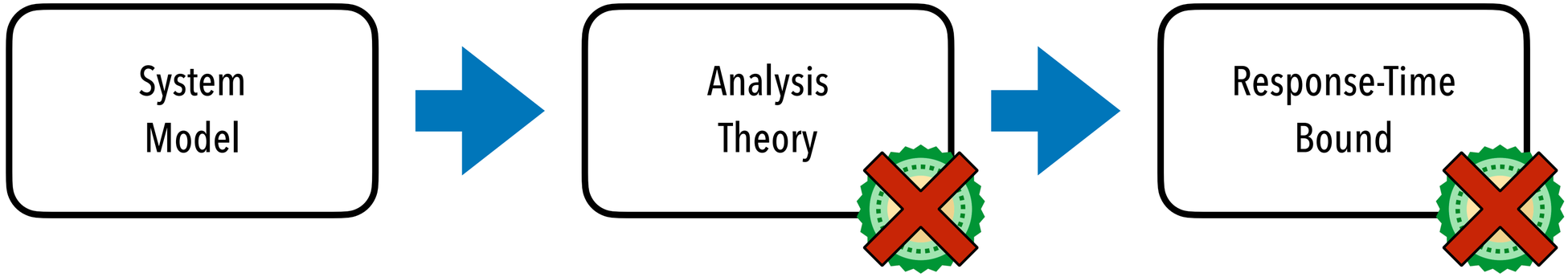

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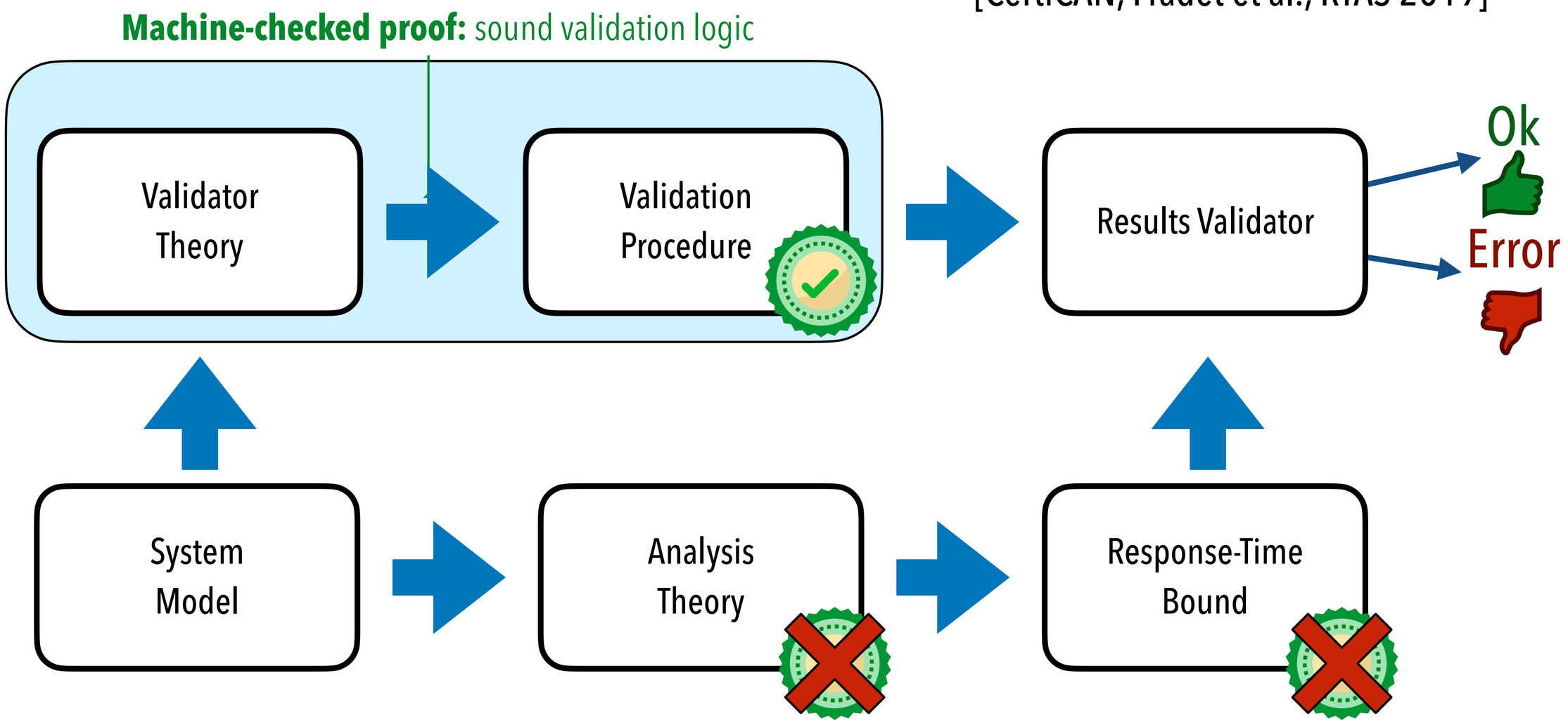

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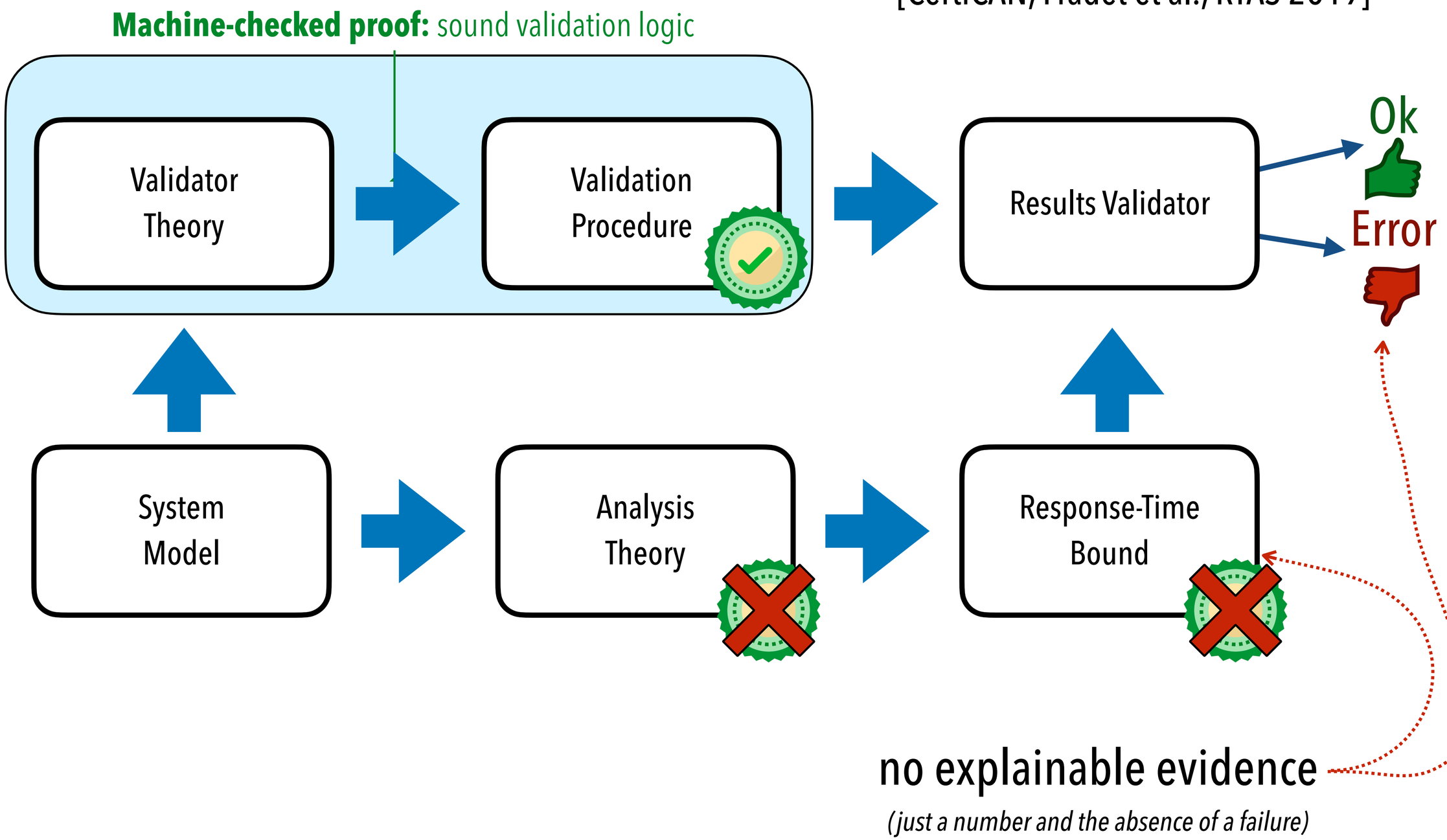

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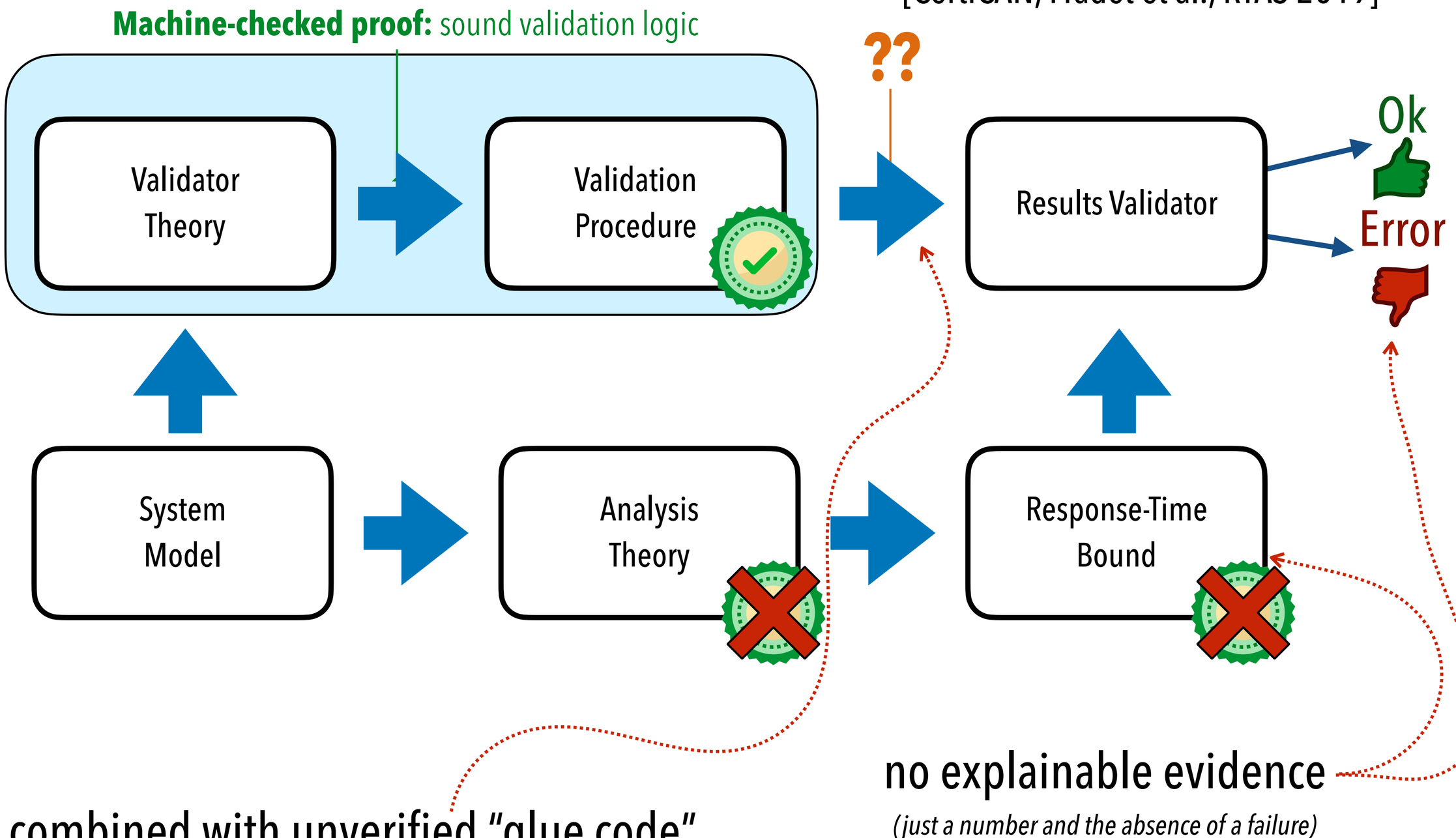
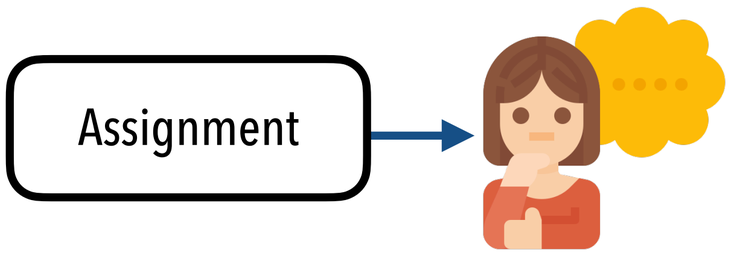


A NEW APPROACH:

FOUNDATIONAL RTA

DISTANT ANALOGY: SHOW YOUR WORK



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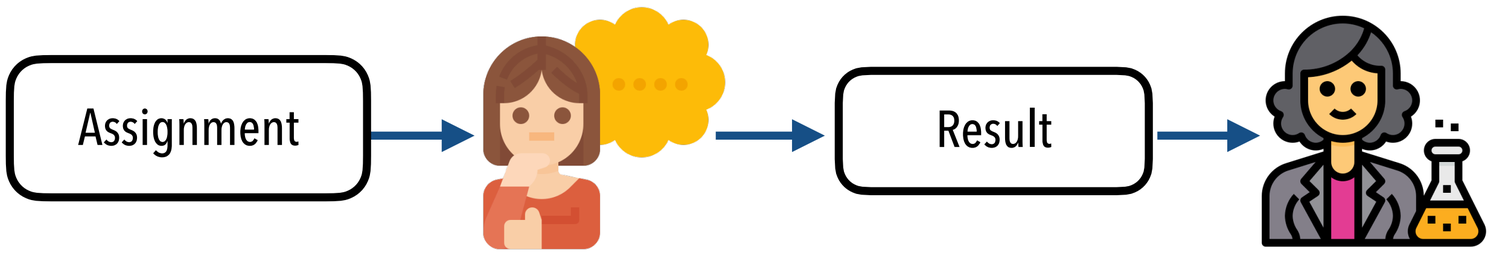

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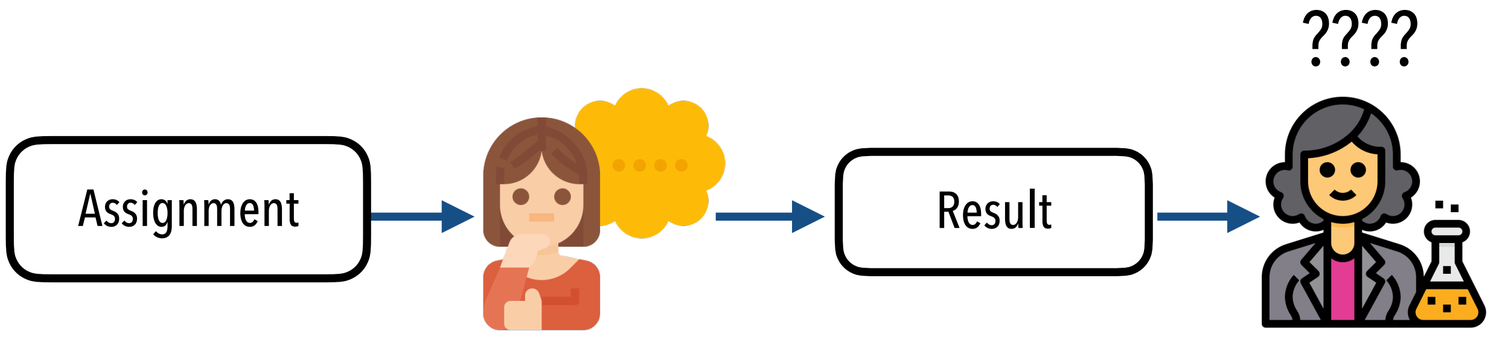

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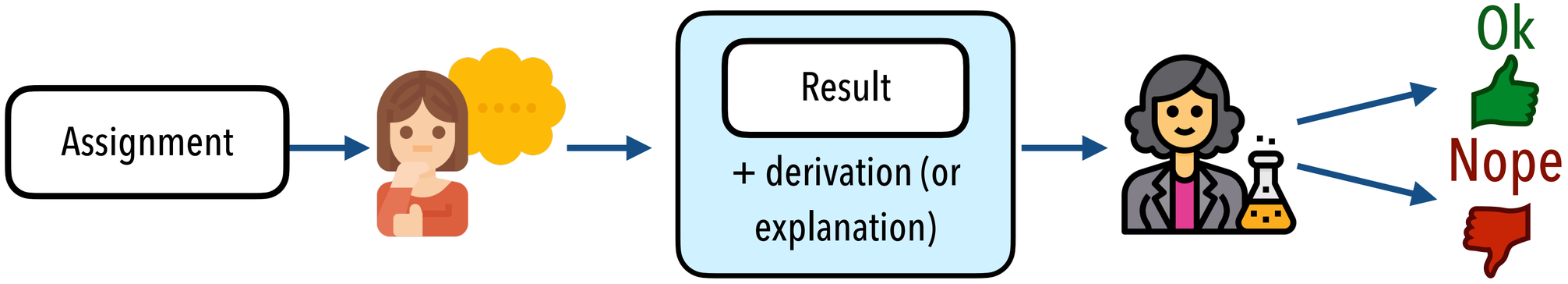

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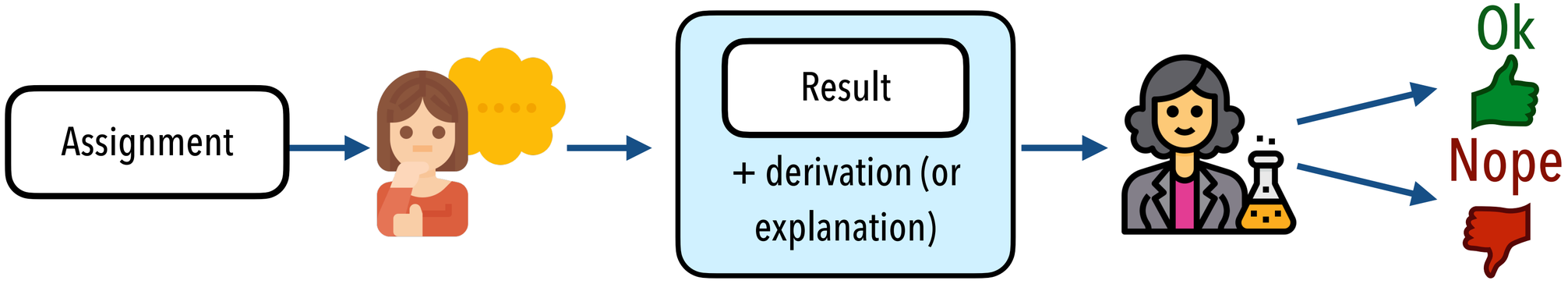
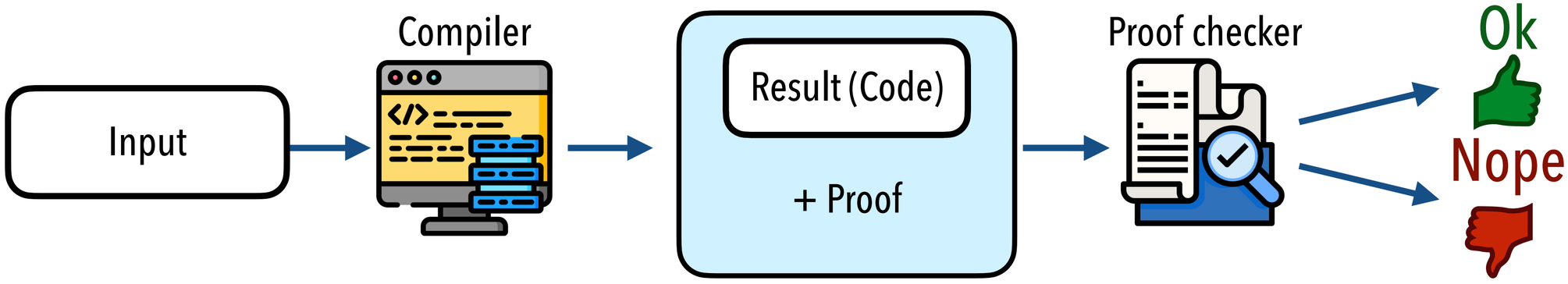


Idea: report both results and an argument for why the results are correct

PROOF-CARRYING CODE

[Necula, POPL 1997]



Idea: tool must produce both *results* and *proofs* that the results are correct

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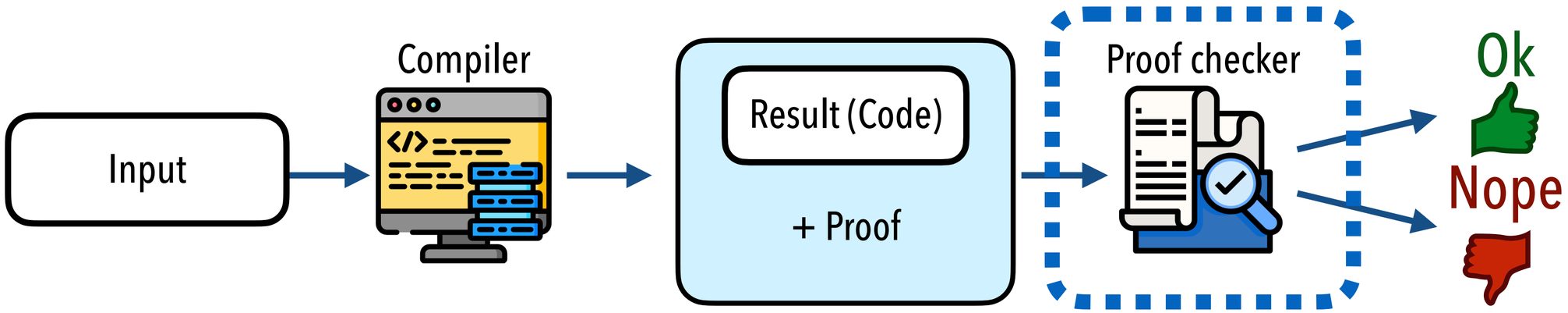

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Trusted Computing Base (TCB)

does not include the compiler

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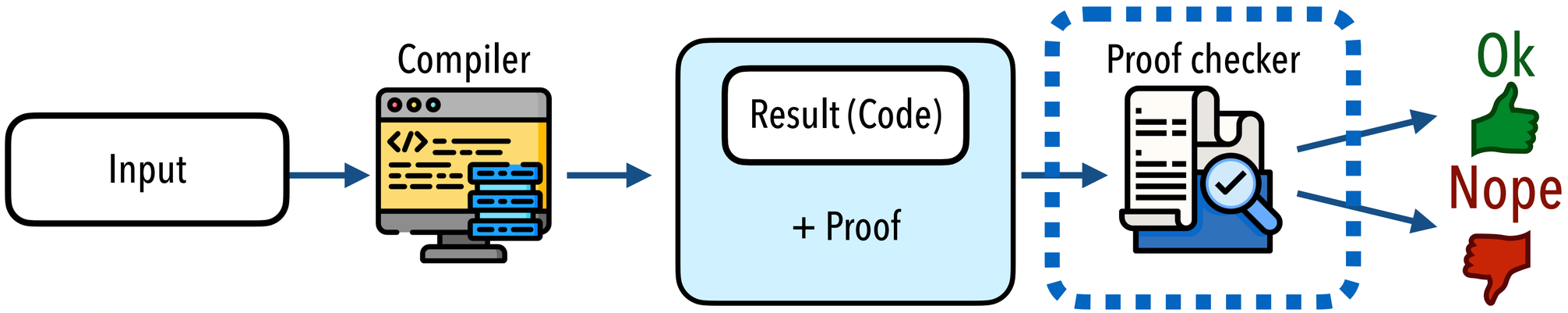

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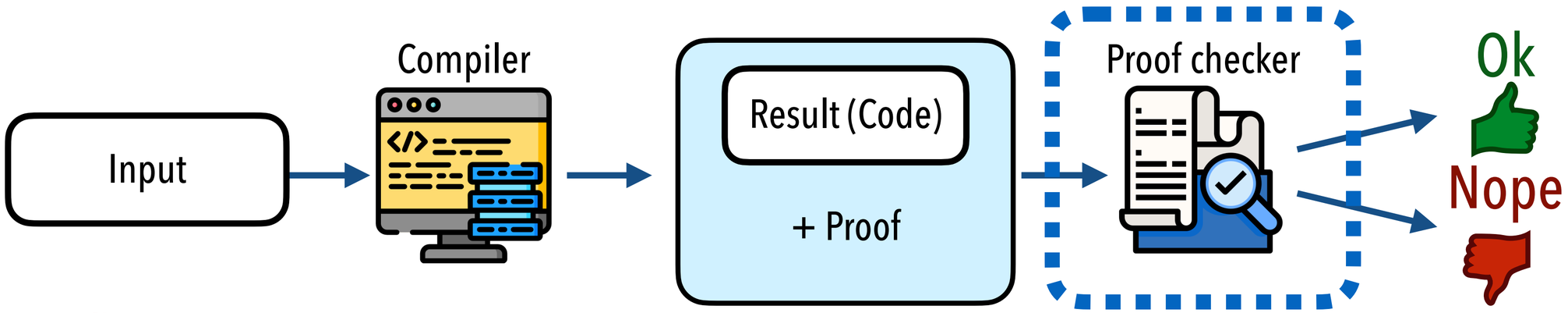

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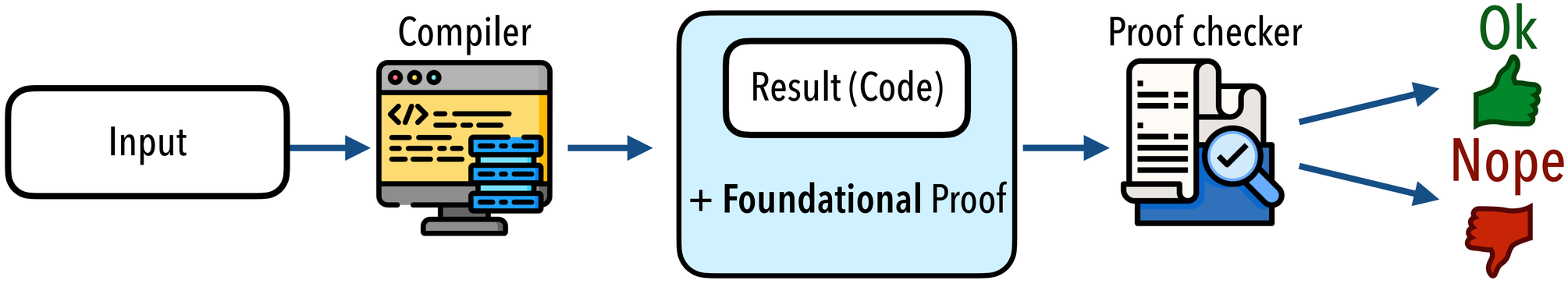
But who is checking the checker?

➔ Keep the checker as **simple** as possible!

FOUNDATIONAL PROOF-CARRYING CODE

[Appel, LICS 2001]



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Foundational proof

= proof relies only the foundations of mathematical logic

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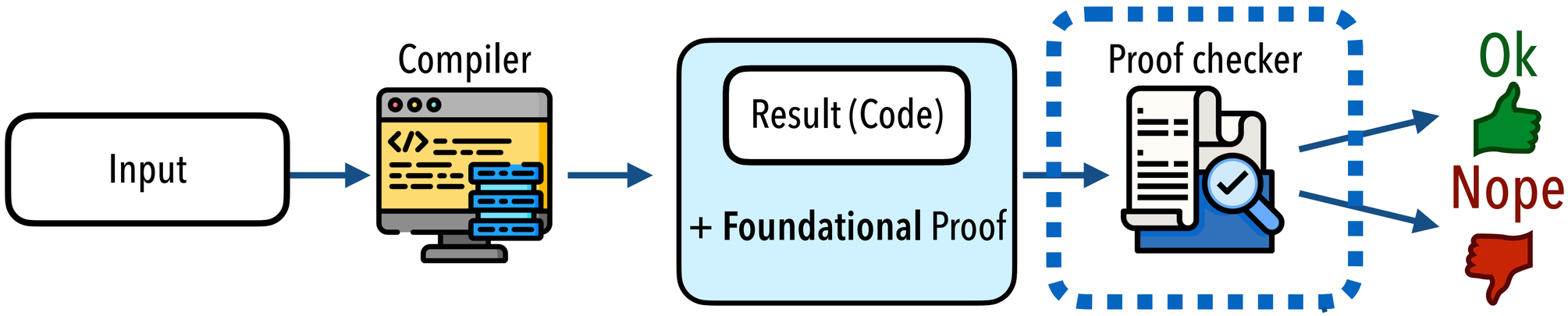

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Goal: minimal TCB

Foundational proof

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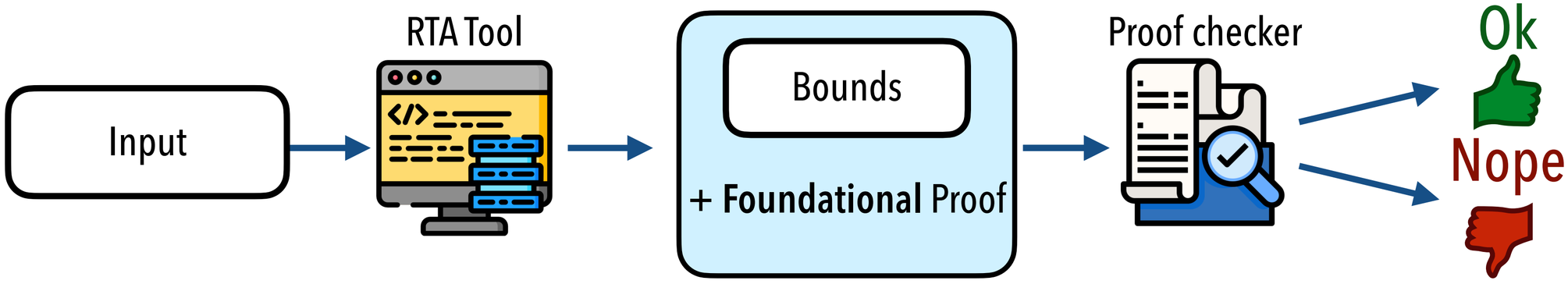

Idea: RTA must produce both *results* and a *foundational proof* of correctness

➔ Provably **safe** results

➔ **Small TCB**, not including RTA tool or theory

➔ Independently checkable **evidence** of timeliness

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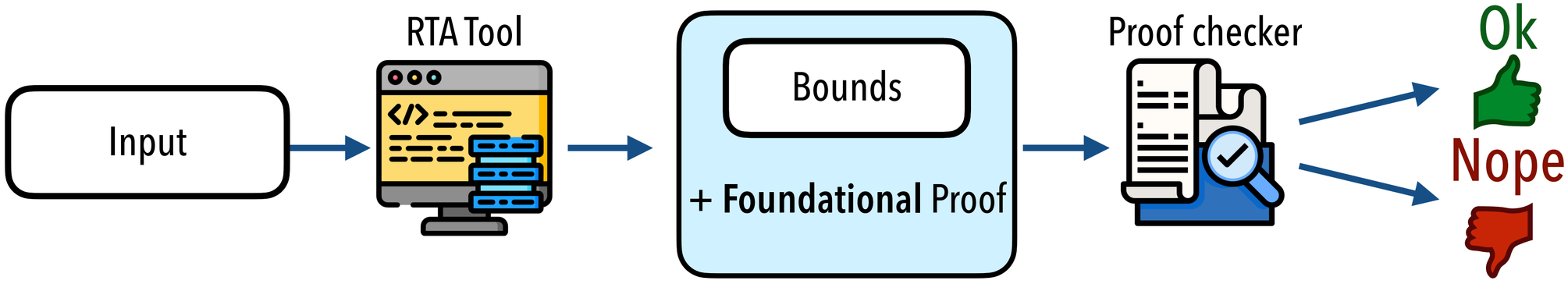

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…but does it scale?

What logic to use as a foundation?

How to automatically generate proofs?

How to keep proofs explainable?

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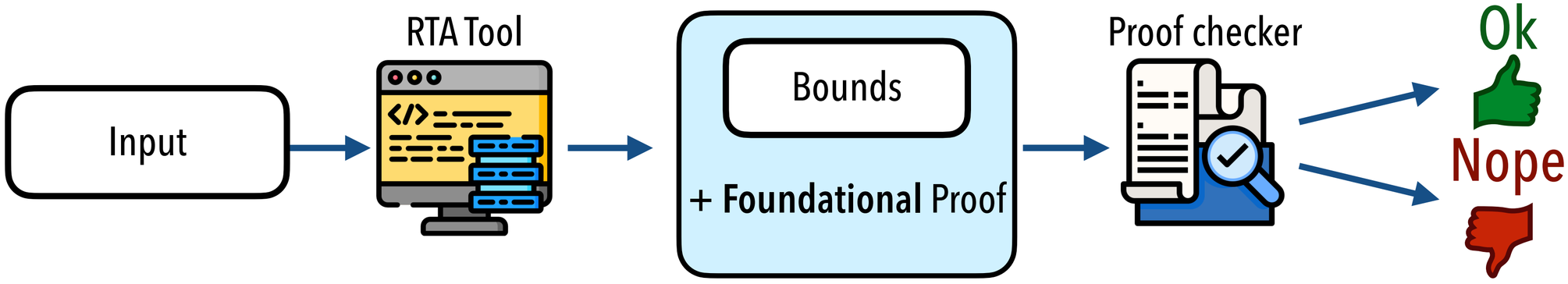

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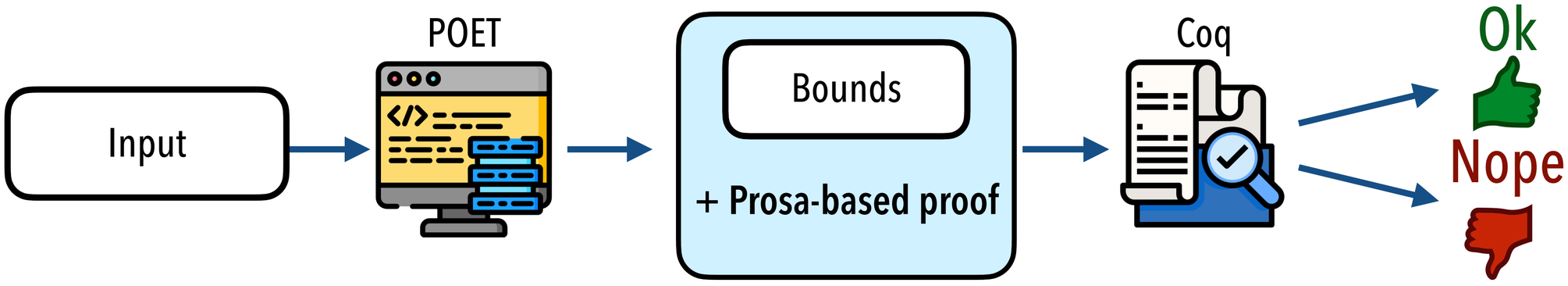
Nice concept… but does it actually work?

POET

Prosa Obsigned Evidence of Timeliness

POET: FOUNDATIONAL RTA BASED ON PROSA

Generate proof-carrying response-time bounds based on Prosa and Coq



…let's have a quick look at Coq and Prosa.

BACKGROUND: COQ

- Coq is a **proof assistant**
- It is used to write **programs**/**definitions** and to **prove theorems**
- The **proof engine** is **not** fully automatic!

```
Theorem a_simple_theorem:
  ∀ x y,
  x + y = y + x.
Proof.
  move⇒ x y.
  induction x.
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Qed.
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Coq **checks** that proofs are correct

BACKGROUND:PROSA

Prosa is the to-date largest

machine-checked **framework** for **Real Time Systems Theory**

```
Variables (j : Job) (t1 : instant) (δ : duration).

(* ... *)

Lemma busy_interval_is_bounded:
  ∃ (t2 : instant),
    t2 ≤ t1 + δ ∧
    busy_interval j t1 t2.
```

formally proven schedulability analysis | PROSA

prosa.mpi-sws.org

[Cerqueira et al., ECRTS 2016]

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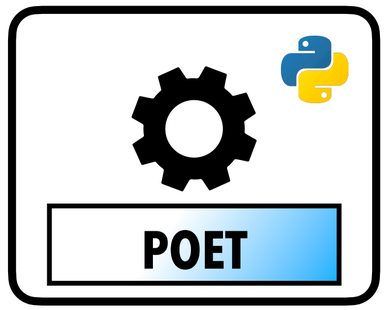
Generate proof-carrying response-time bounds based on Prosa and Coq

(a) Certificate generation



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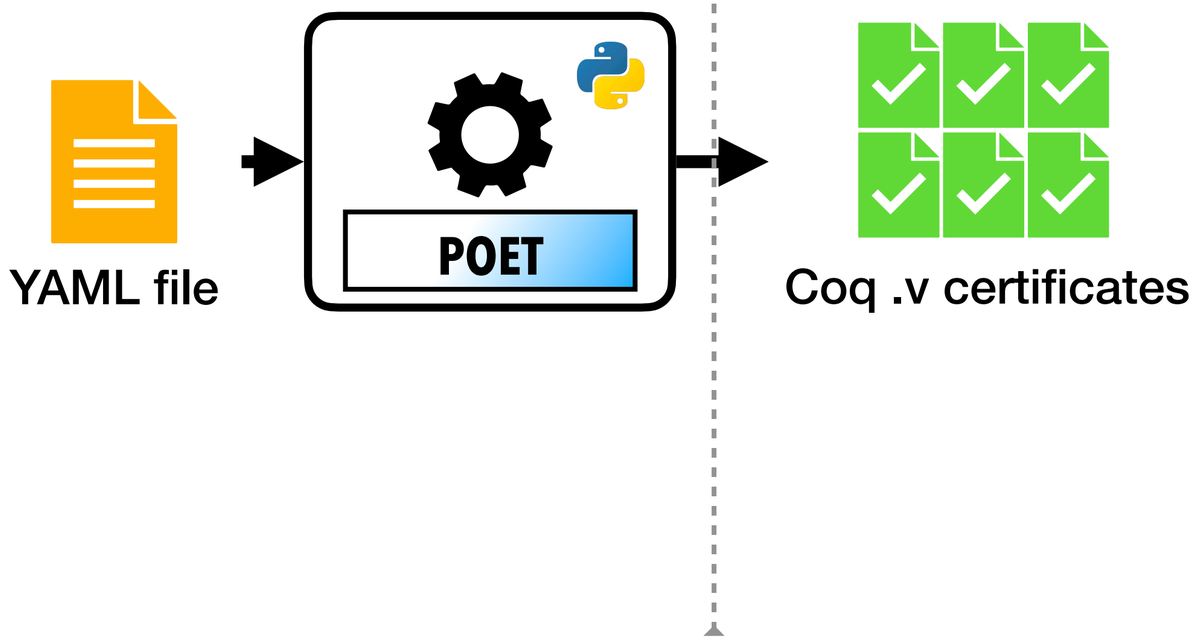

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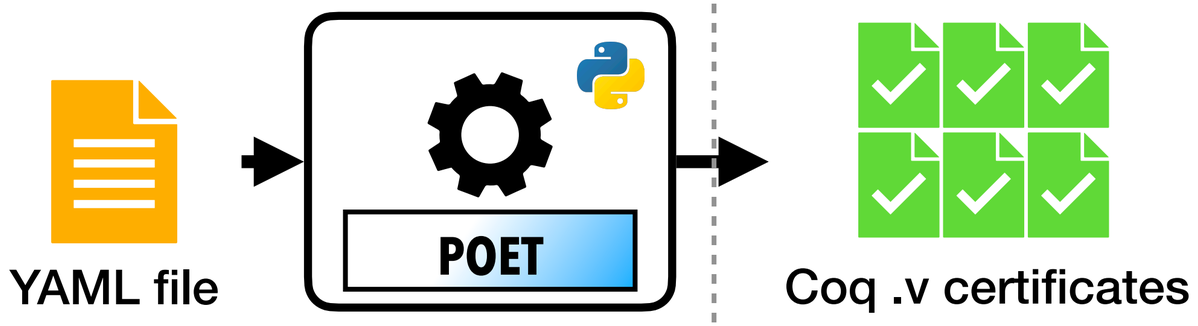
Generate proof-carrying response-time bounds based on Prosa and Coq

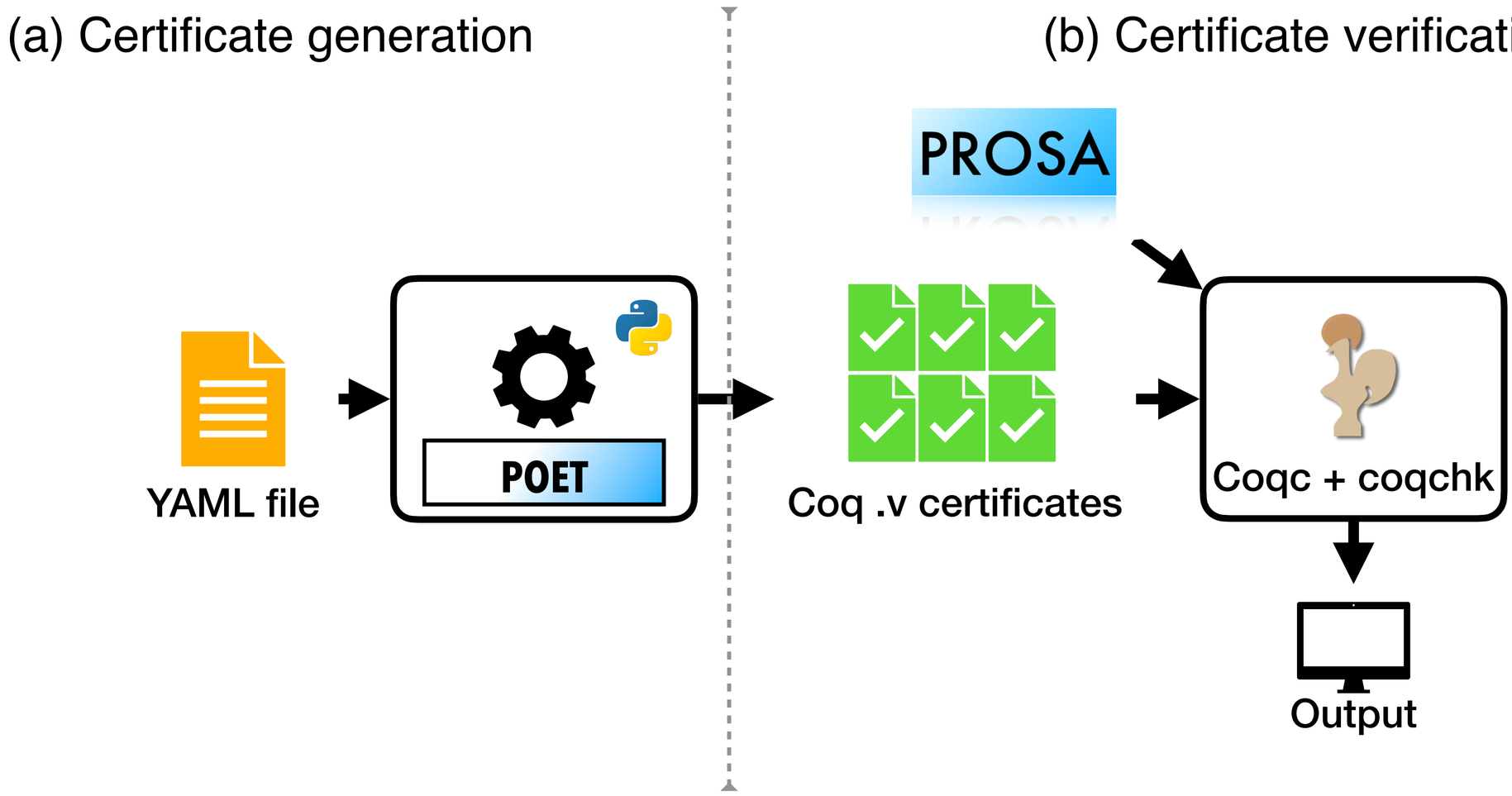
(a) Certificate generation

(b) Certificate verification



POET: FOUNDATIONAL RTA BASED ON PROSA

Generate proof-carrying response-time bounds based on Prosa and Coq



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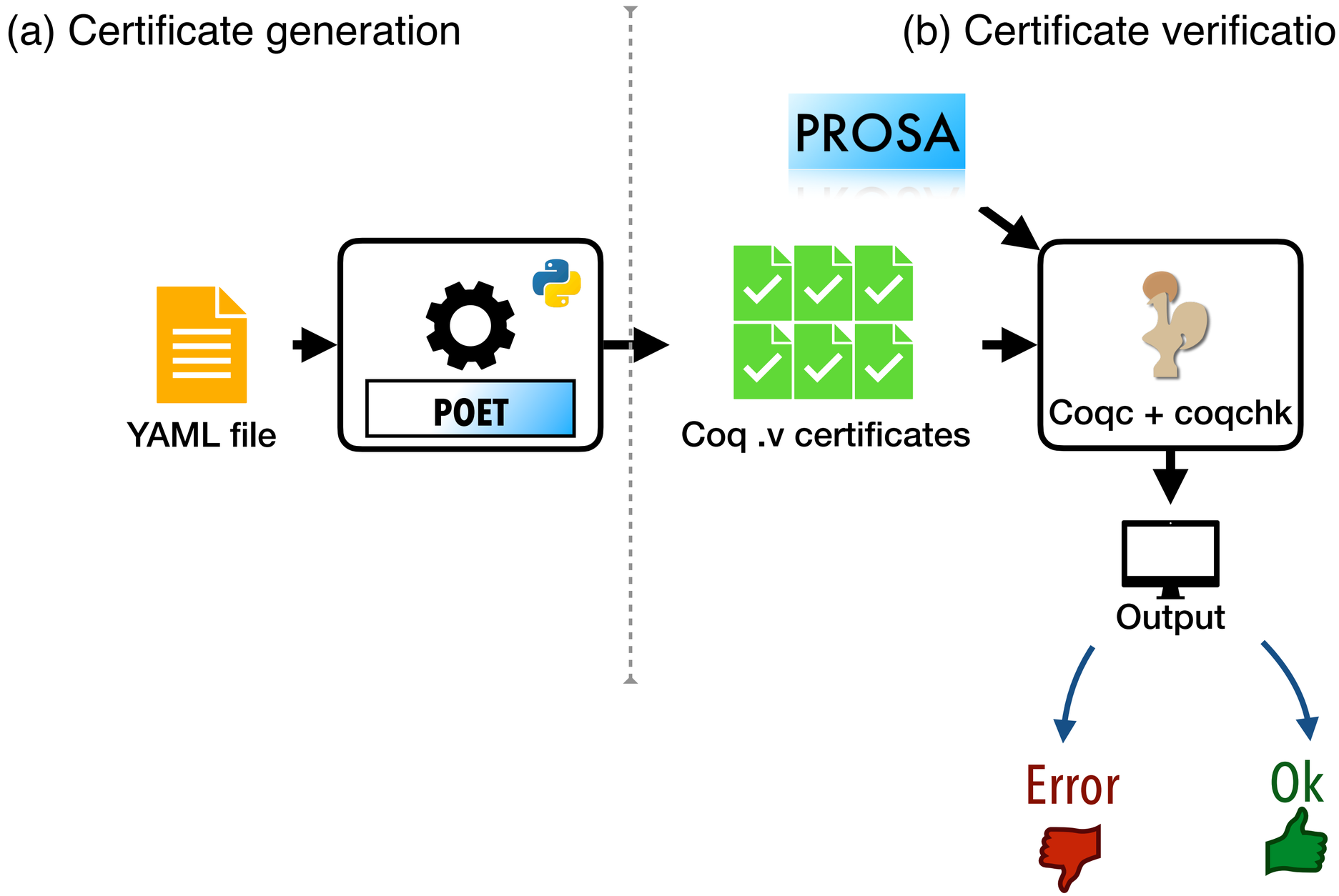

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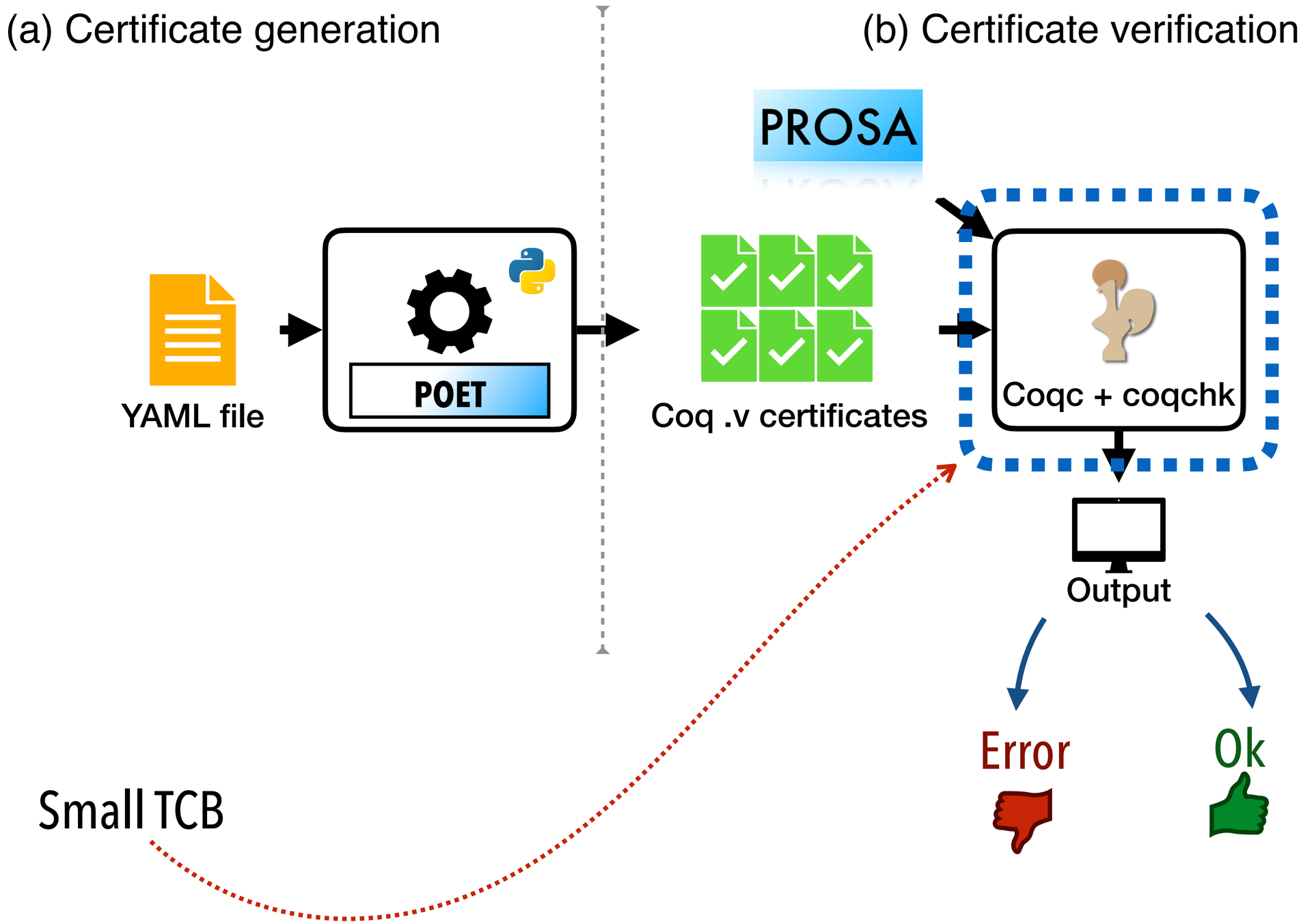

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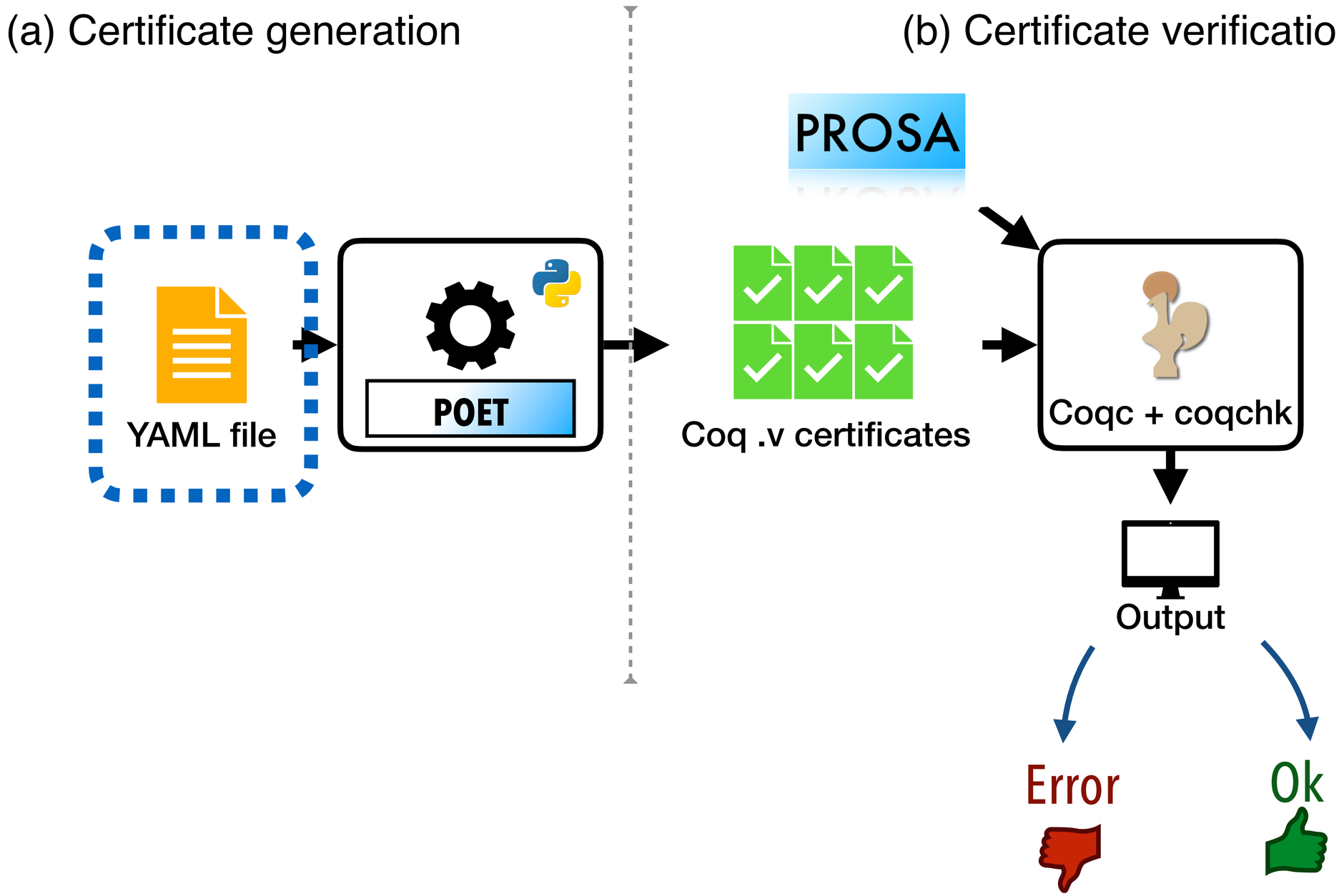


INPUT FILE

YAML File

≅

Policy {

```
scheduling policy: fixed-priority
preemption policy: fully-preemptive
```

INPUT FILE

YAML File

≃

Policy

Task 1

```
scheduling policy: fixed-priority
preemption policy: fully-preemptive

- id: 1
  worst-case execution time: 50
  period: 30
  deadline: 100
  priority: 2
```

INPUT FILE

YAML File

≃

Policy

Task 1

Task 2

```
scheduling policy: fixed-priority
preemption policy: fully-preemptive

- id: 1
  worst-case execution time: 50
  period: 30
  deadline: 100
  priority: 2

- id: 2
  worst-case execution time: 10
  arrival curve: [220,[[1,1],[105,2]]]
  deadline: 100
  priority: 1
```

INPUT FILE

YAML File

≃

Policy

Task 1

Task 2

```
scheduling policy: fixed-priority
preemption policy: fully-preemptive

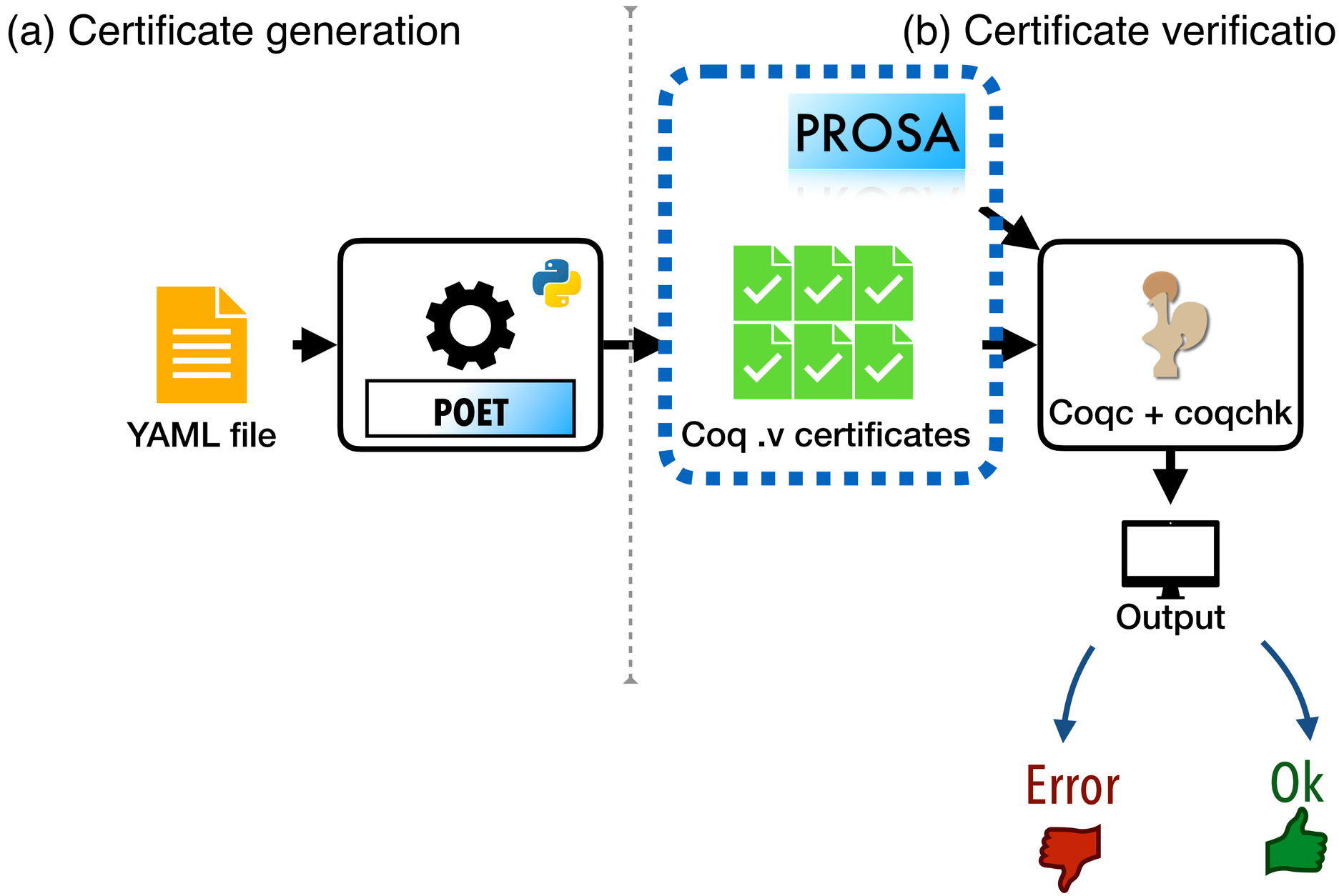
- id: 1
  worst-case execution time: 50
  period: 30
  deadline: 100
  priority: 2

- id: 2
  worst-case execution time: 10
  arrival curve: [220,[[1,1],[105,2]]]
  deadline: 100
  priority: 1
```

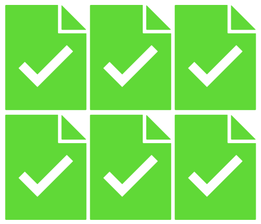
POET supports arbitrary arrival curves

POET: FOUNDATIONAL RTA BASED ON PROSA

Generate proof-carrying response-time bounds based on Prosa and Coq



CERTIFICATES



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Coq Certificates

```
- id: 1
  worst-case execution time: 10
  period: 30
  deadline: 100
  priority: 2
```

CERTIFICATES

$\simeq$

Coq Certificates

Task set

```
Let tsk1 := {|
  task_id := 1;
  task_cost := 10;
  task_period := Period 30;
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Let tsk2 := ...
Let ts := [::tsk01,tsk02].
```

```
- id: 1
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CERTIFICATES

≃

Coq Certificates

Task set

Task under analysis

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Let tsk := tsk1.
```

```
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```

CERTIFICATES

≃

Coq Certificates

Task set

Task under analysis

Response time

```
Let tsk1 := {|
  task_id := 1;
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  task_deadline := 100;
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Let tsk2 := ...
Let ts := [::tsk01,tsk02].

Let tsk := tsk1.

...
Let R := 10%N.
...
```

```
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Task set

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Response time

Fix-point equation

Auto-generated proof

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Let tsk1 := {|
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```
- id: 1
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```

```
Lemma R_is_maximum:
  ∀ A, is_in_search_space tsk L A →
    ∃ F, rbf tsk (A + ε) + rbf ts tsk (A + F) ≤ A + F
         ∧ F ≤ R.
Proof.
  move ⇒ A SS.
  ...
```

CERTIFICATES

≅

Coq Certificates

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- id: 1
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```

Prosa: this equation implies the RTA theorem

POET: given task set satisfies this equation

CERTIFICATES

≅

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Task under analysis

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Auto-generated proof

```
Proof.
  move ⇒ A SS.
  ...
```

Final conclusion

```
Theorem R_respects_deadlines :
   task_response_time_bound arr_seq sched tsk R
   ∧ R ≤ task_deadline tsk.
```

Auto-generated proof, again

```
Proof.
  ...
```

CERTIFICATES ARE EXPLAINABLE EVIDENCE OF TIMELINESS

Coq Certificates

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- Certificates are **short** and **readable** Coq files
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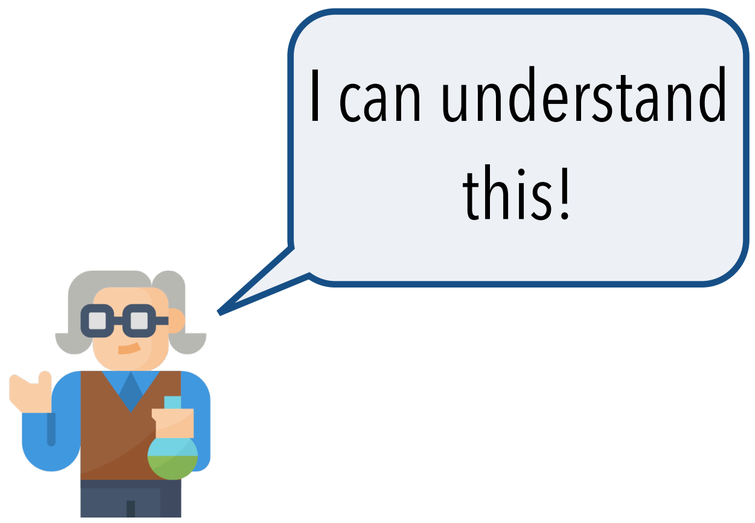

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- Certificates can be **studied** and **dissected** up until their fundamental axioms
  - → POET generates **explainable** evidence of timeliness

- Certificates **do not depend** on POET
  - → We do not need to verify or trust POET

CURRENT CAPABILITIES OF POET

POET currently supports:

- Scheduling policies: *Earliest-deadline first (EDF)*, *Fixed-priority (FP)*
- Preemption policies: *Fully preemptive*, *Fully non-preemptive*
- Workload: *Periodic* and *sporadic* with arbitrary *arrival curves*
- Tasks with *arbitrary deadlines*

…see paper for details!

EVALUATION

EVALUATION: SETUP

Goal: assess scalability of the proposed approach w.r.t. such as number of tasks and utilization

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- **Cardinality**: 2-40 with step 2 (50 tasks in the paper)
- **Utilization**: 50%, 60%, 70%, 80%, 90%

EVALUATION: SETUP

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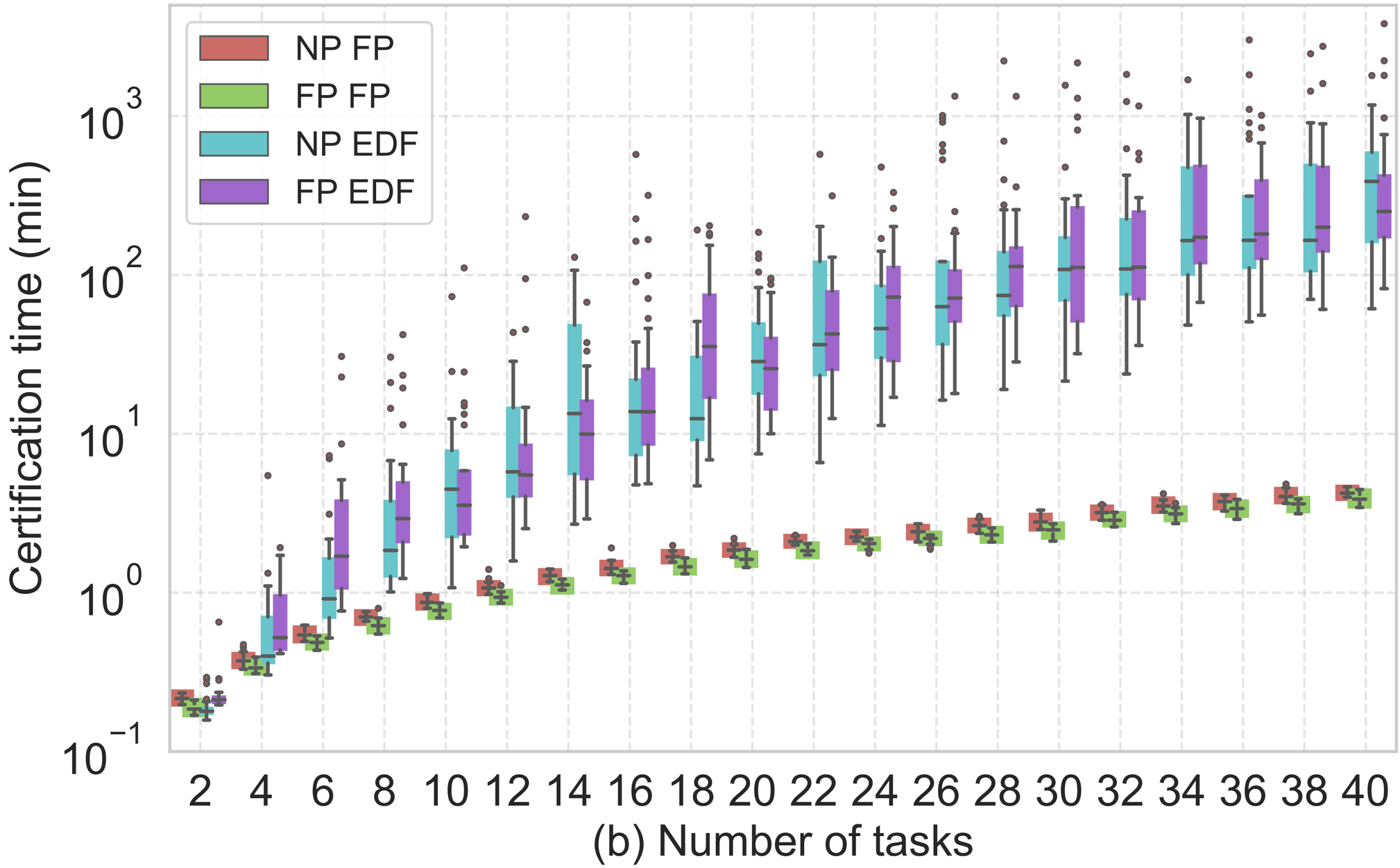
- **Utilization**: 50%, 60%, 70%, 80%, 90%
- **Workload**:
  - **This talk**: mixed workload
  - **Paper**: two move workload-types

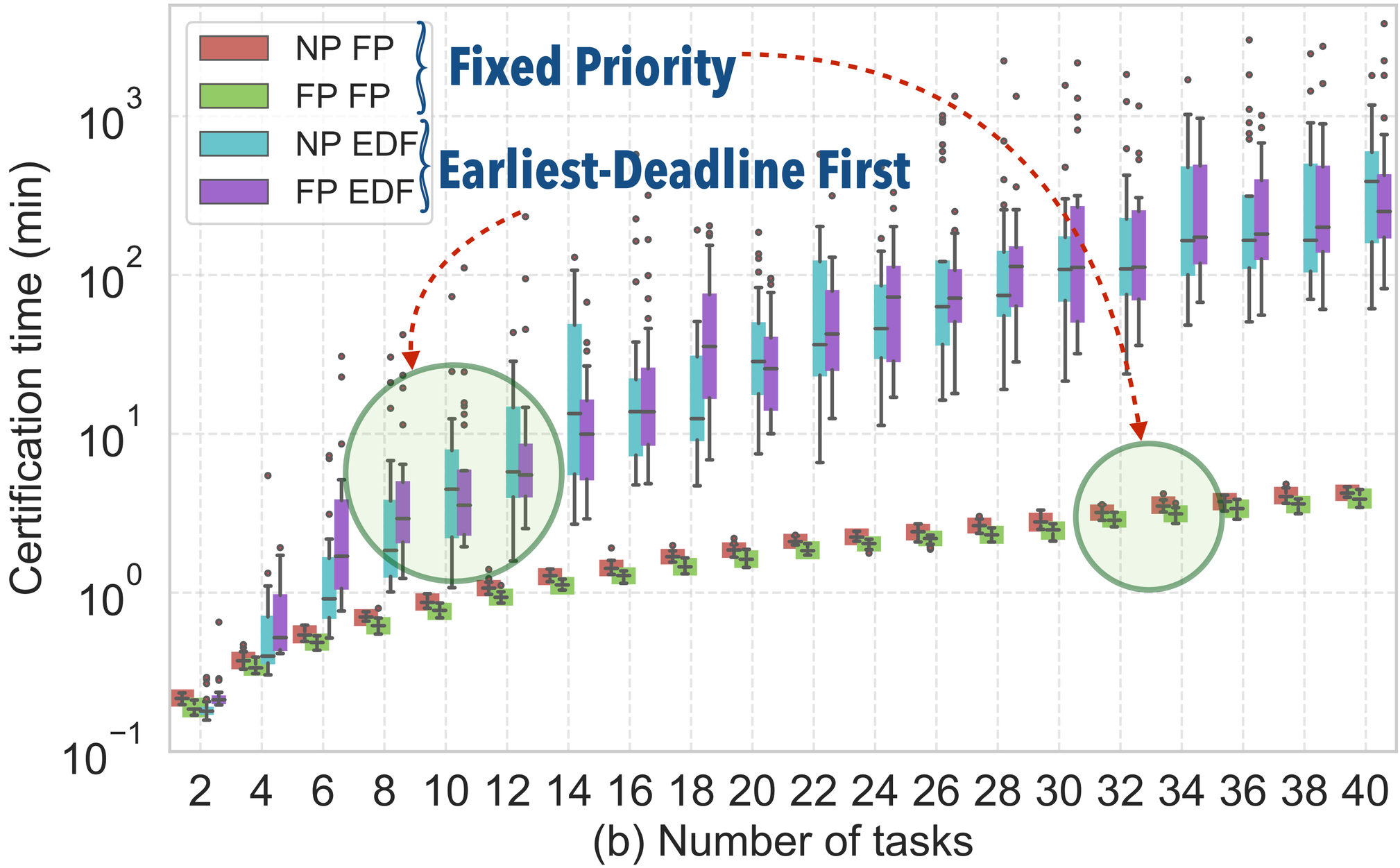
(defined by arrival curves)

BRIEF OVERVIEW



Workload: Mixed workload **# Task sets**: 2000 task sets

BRIEF OVERVIEW



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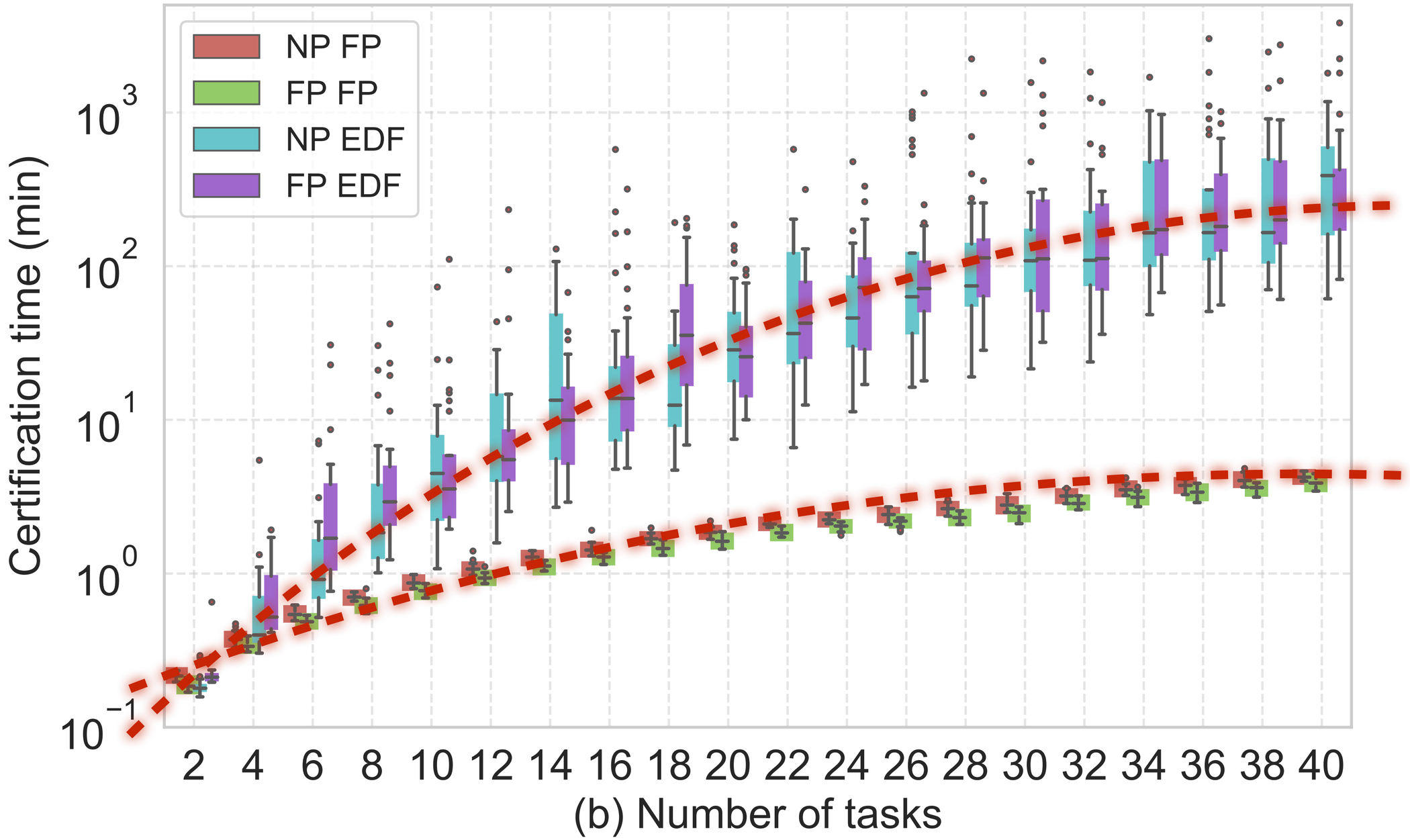
OVERALL TREND



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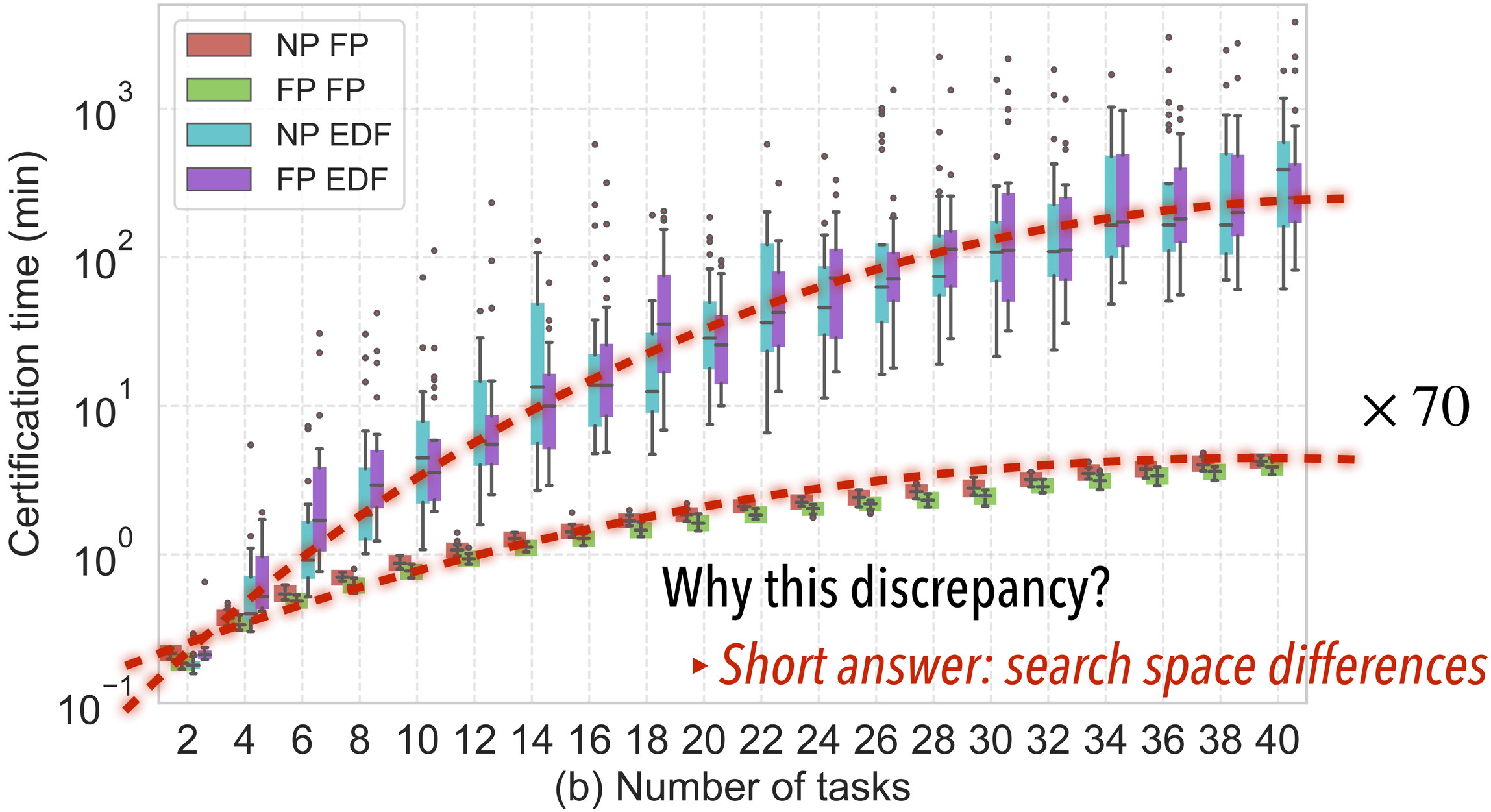

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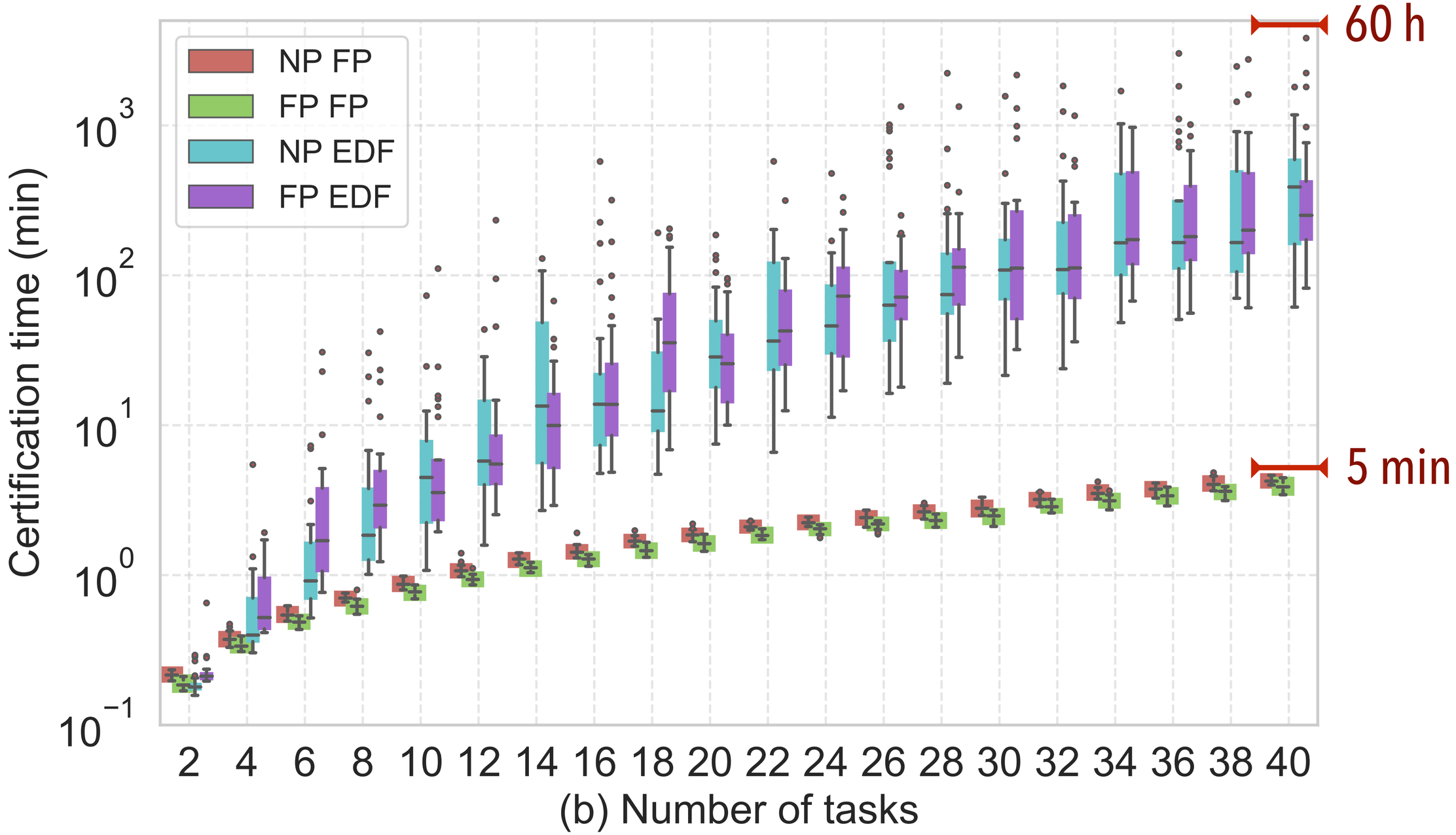
MAXIMUM RUNTIME



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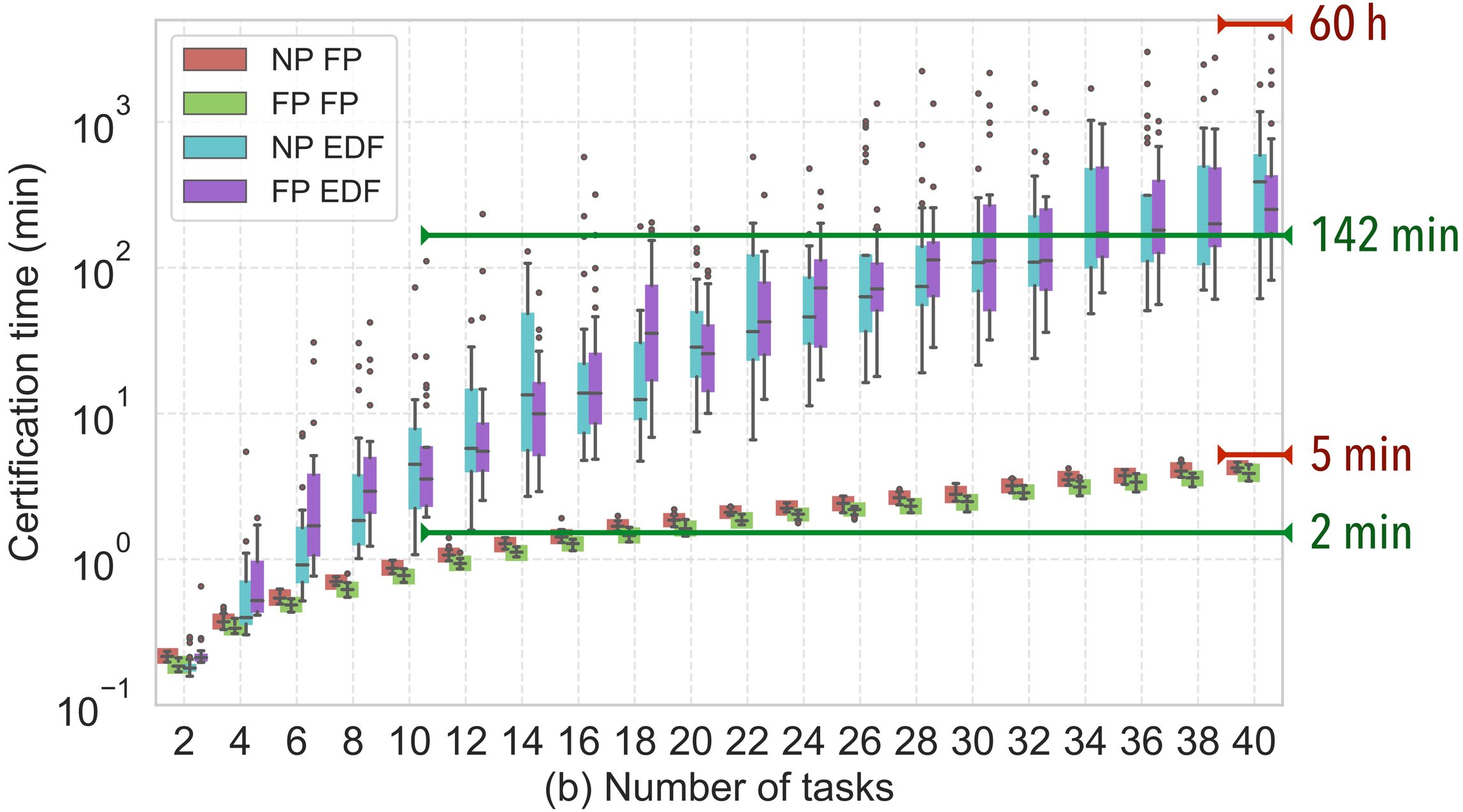
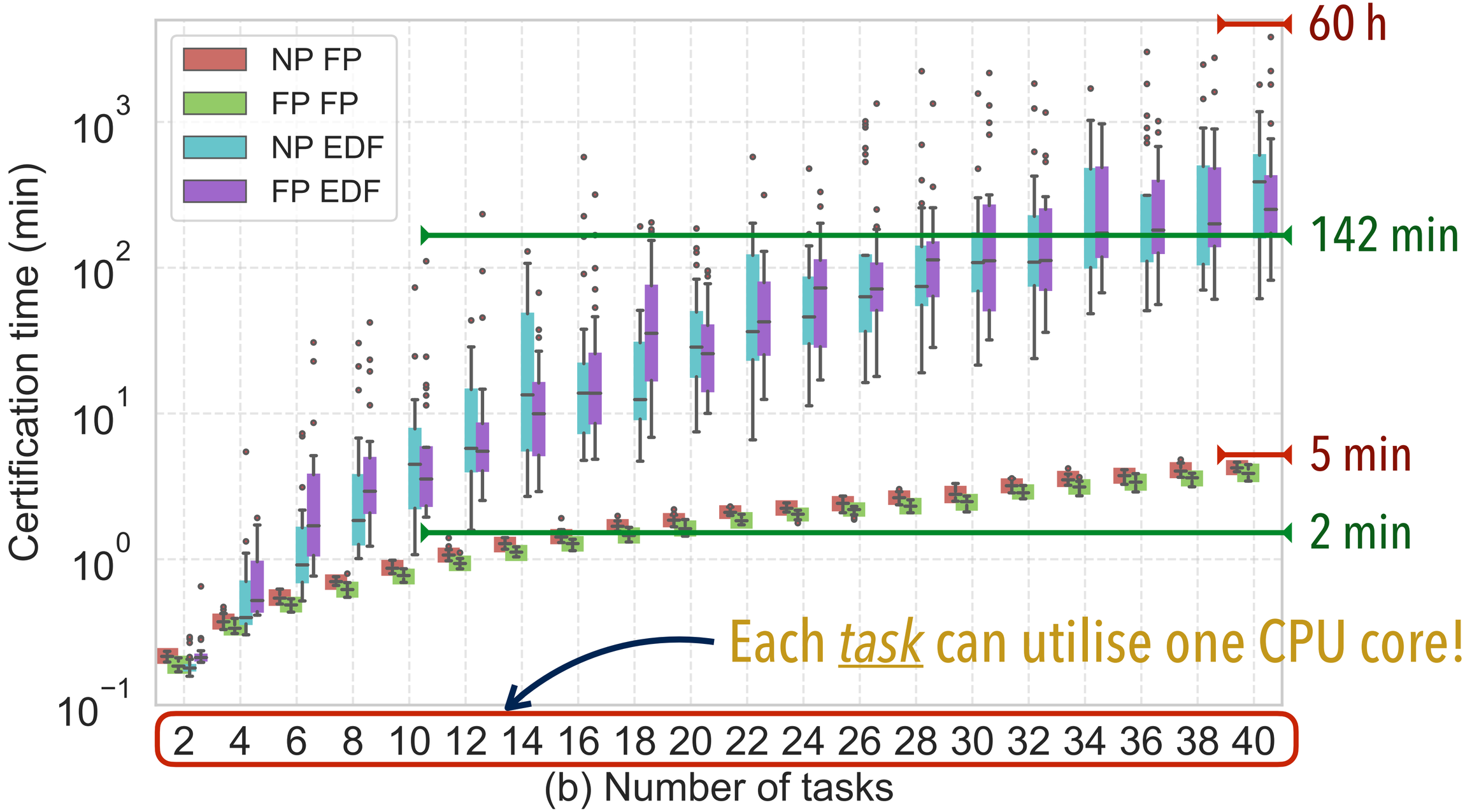
AVERAGE RUNTIME



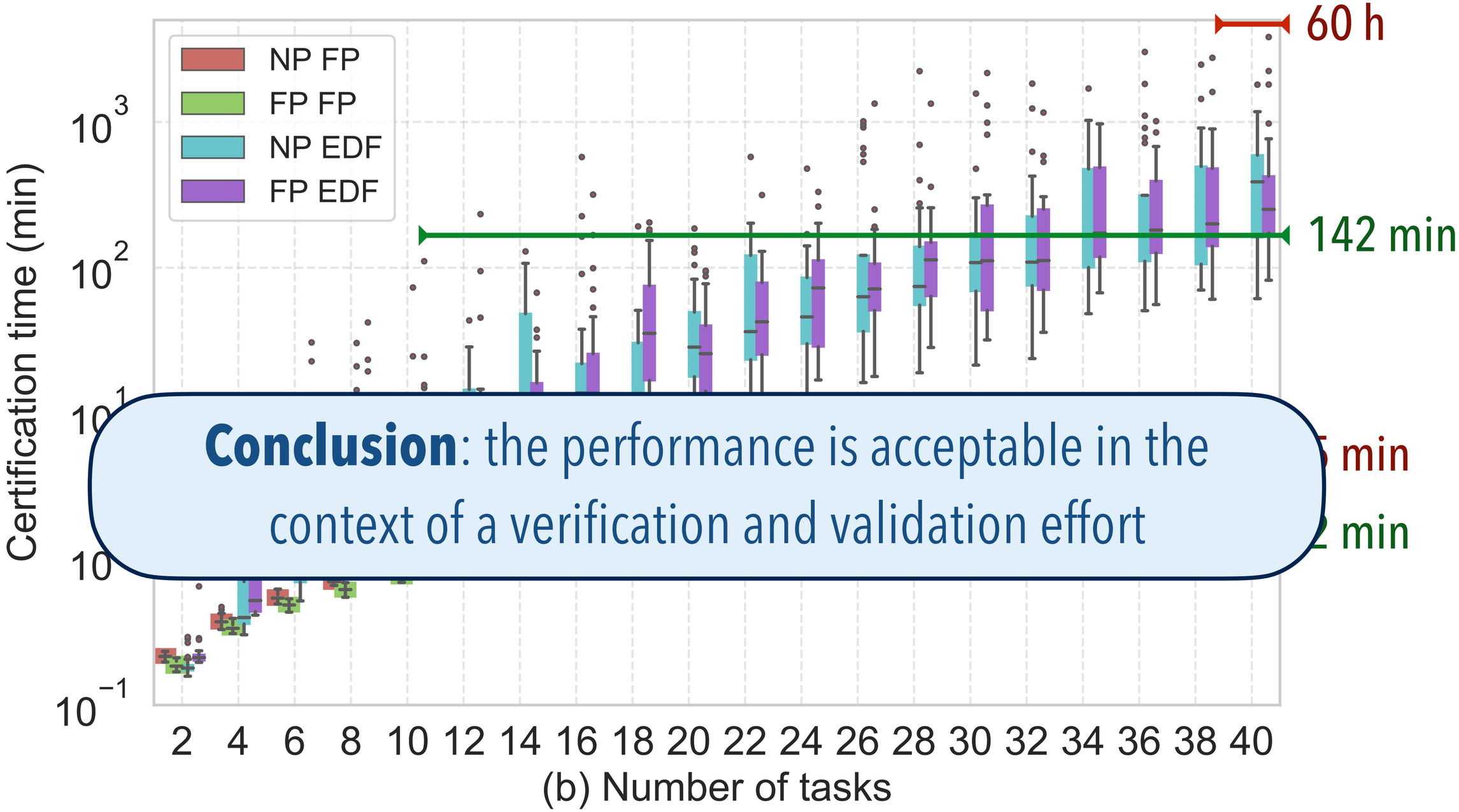
Workload: Mixed workload **# Task sets**: 2000 task sets

VERIFICATION IS EASILY PARALLELIZABLE



Workload: Mixed workload **# Task sets**: 2000 task sets

OVERALL CONCLUSION



Conclusion: the performance is acceptable in the context of a verification and validation effort

Workload: Mixed workload **# Task sets**: 2000 task sets

CONCLUSION

SEE PAPER FOR IMPORTANT DETAILS

"Naive" proof-oriented computation in Coq is **very slow**

- *How to speed it up?*

SEE PAPER FOR IMPORTANT DETAILS

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Coq cannot automatically find potential **contradictions** in analysis assumptions

- *How to defend against conflicting hypotheses?*

SEE PAPER FOR IMPORTANT DETAILS

"Naive" proof-oriented computation in Coq is **very slow**

- *How to speed it up?*

Coq may accept **truncated certificates**

- *How to engineer POET in light of this?*

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Coq may accept **truncated certificates**

- *How to engineer POET in light of this?*

Coq cannot automatically find potential **contradictions** in analysis assumptions

- *How to defend against conflicting hypotheses?*

Support for **arbitrary arrival curves** was not trivial

- *How to compute the search space efficiently?*

POET, THE FIRST FOUNDATIONAL RTA TOOL

Summary:

- POET produces **formally-verified** response-time bounds
- Bounds are proven correct by **automatically generated Coq proofs**
- Users **do not need to know** formal verification

POET, THE FIRST FOUNDATIONAL RTA TOOL

Summary:

- POET produces **formally-verified** response-time bounds
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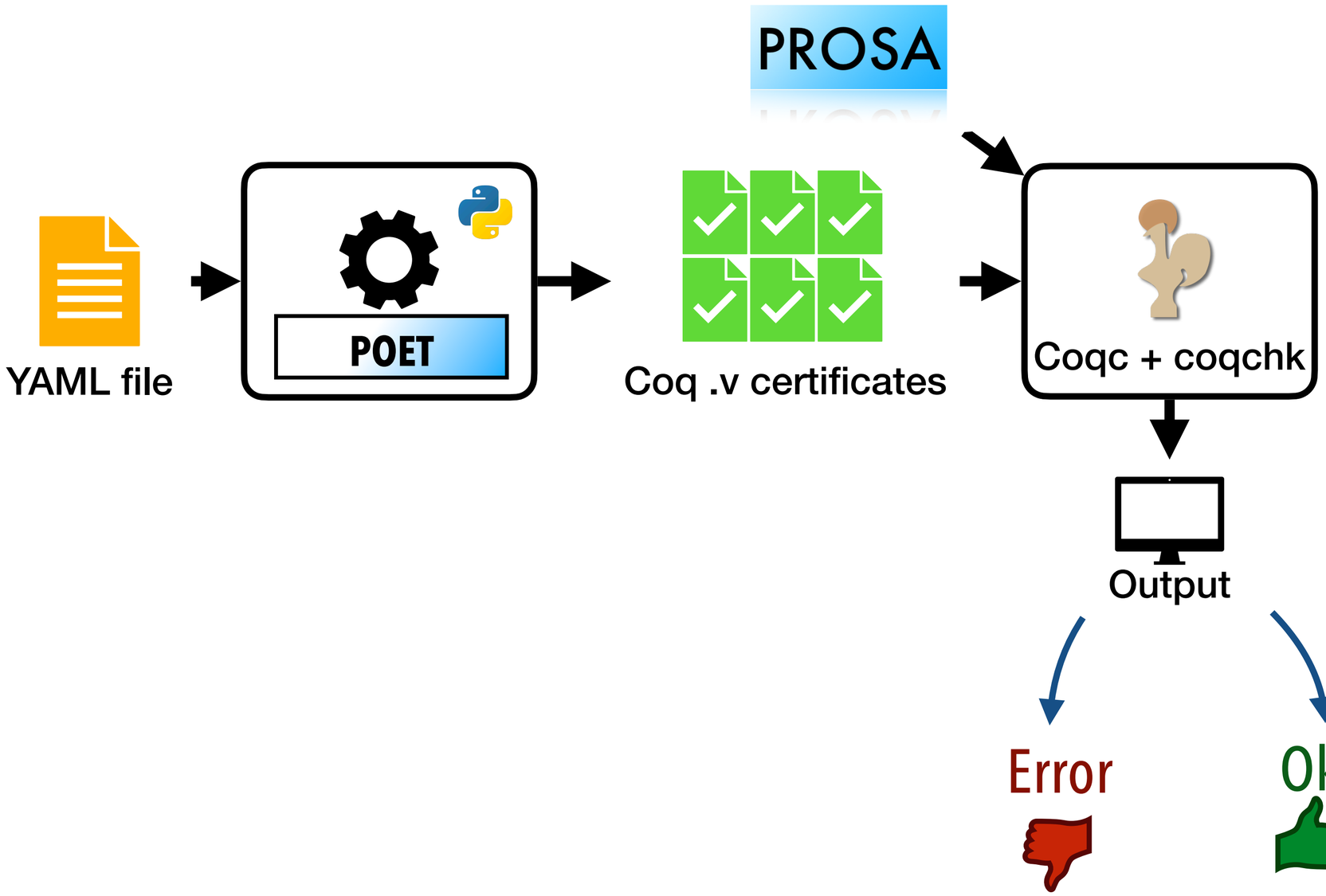
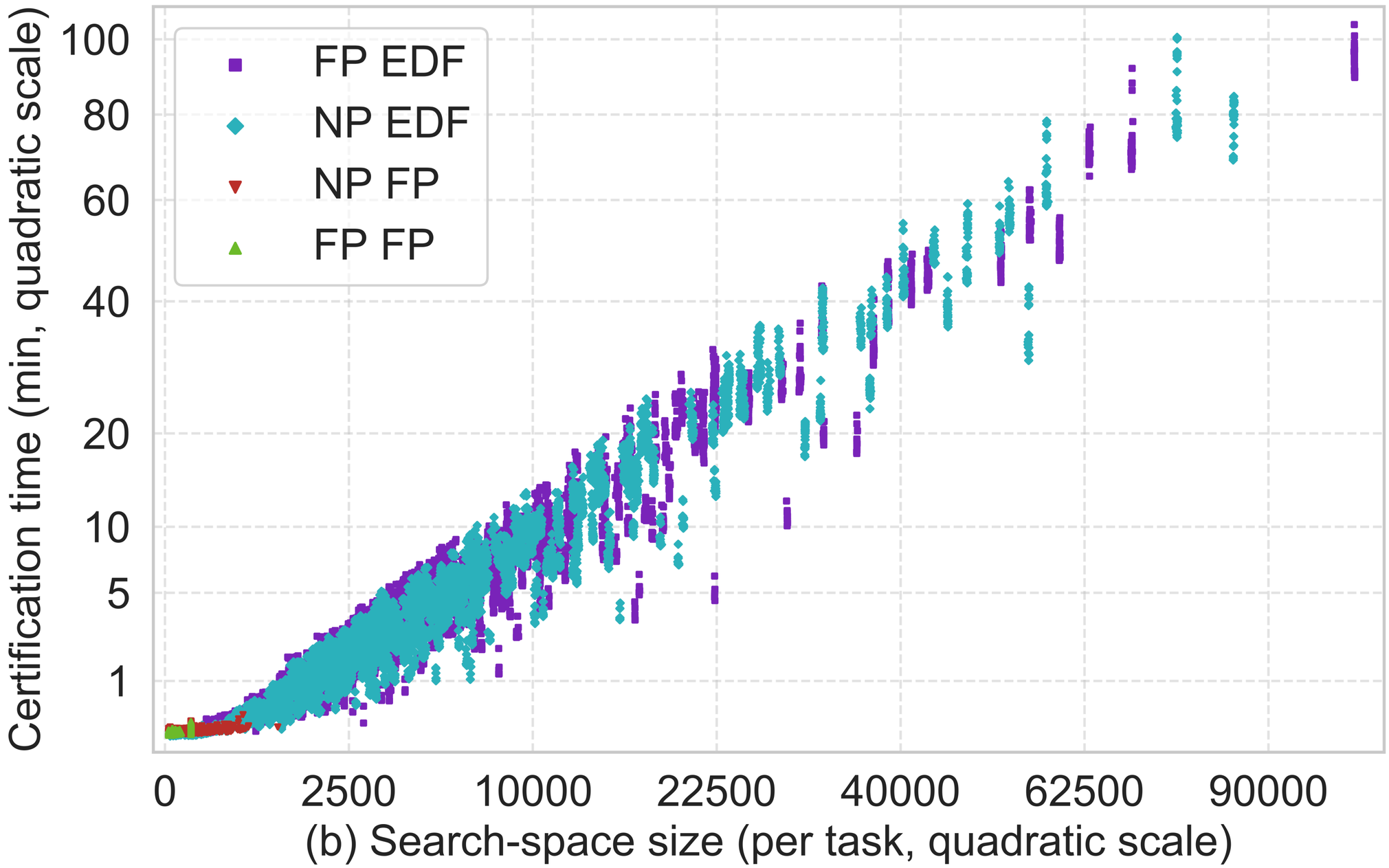
Future work:

- More **complex workloads**: synchronization and precedence constraints
- **Realistic system models**: scheduling overheads and multiprocessor platforms


PROSA
YAML file
POET
Coq .v certificates
Coqc + coqchk
Output
Error
Ok

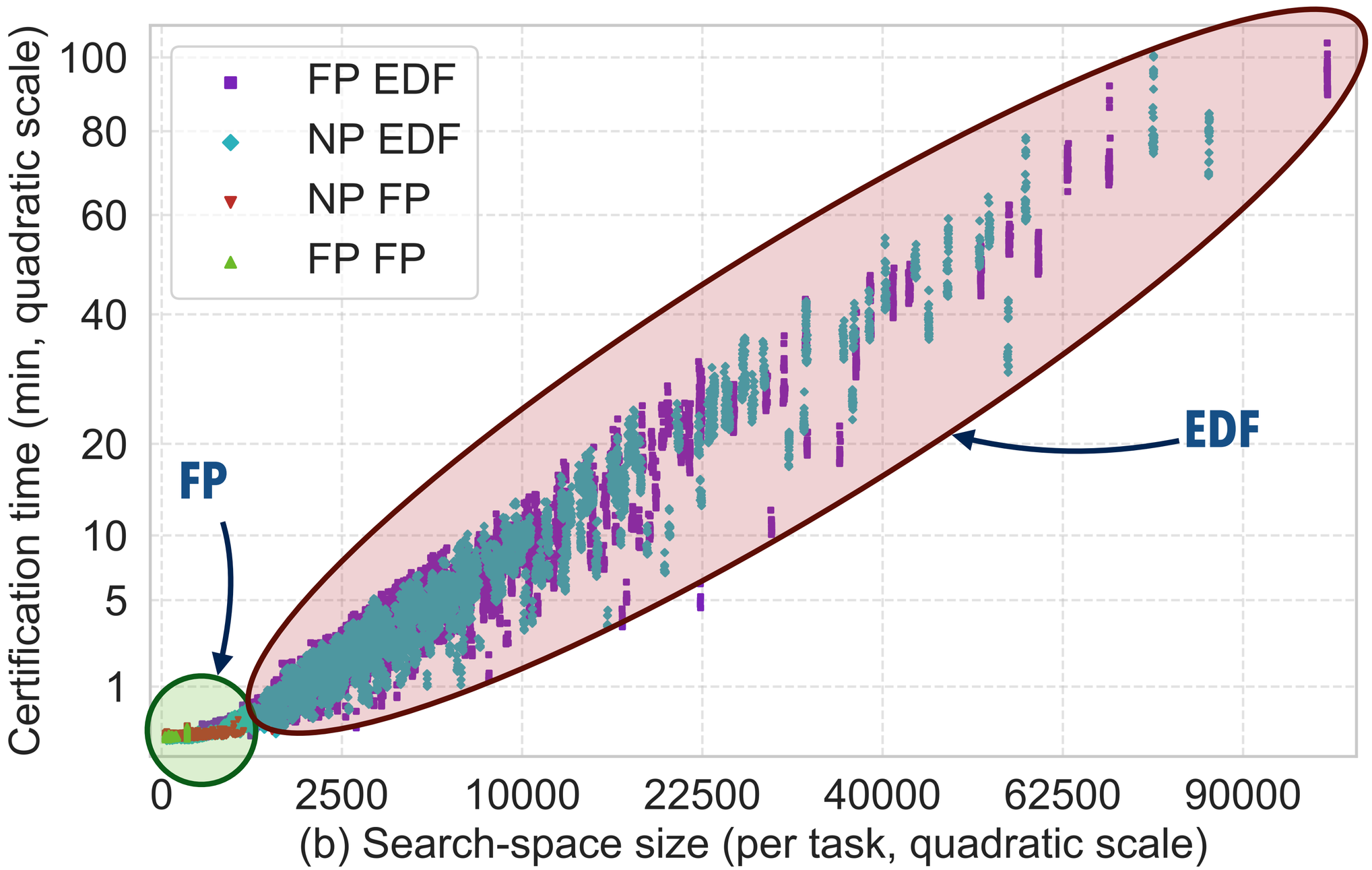
Back up slides

DIFFERENCE IN SEARCH SPACE SIZE



Workload: Mixed workload **# Task sets**: 2000 task sets

DIFFERENCE IN SEARCH SPACE SIZE



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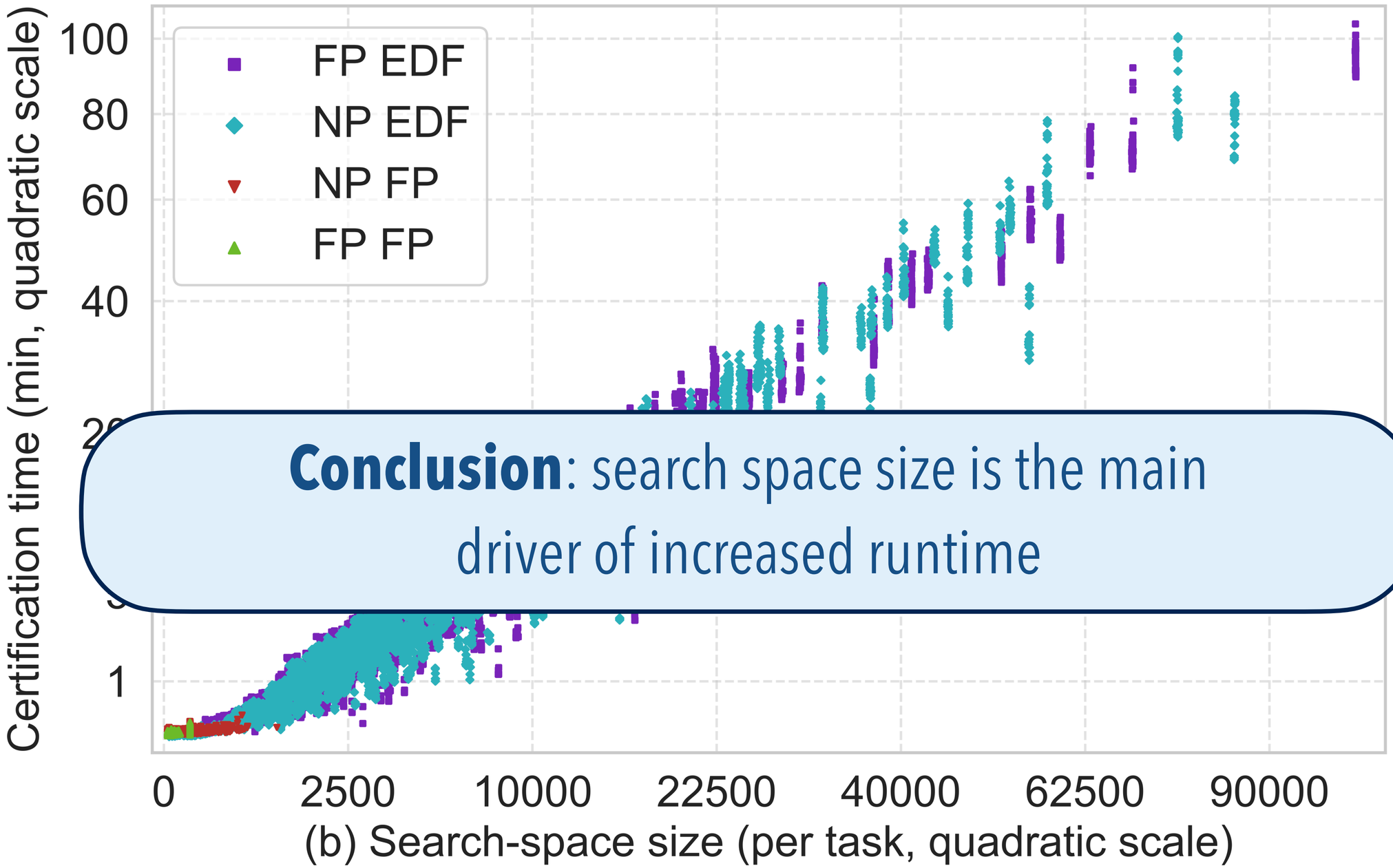
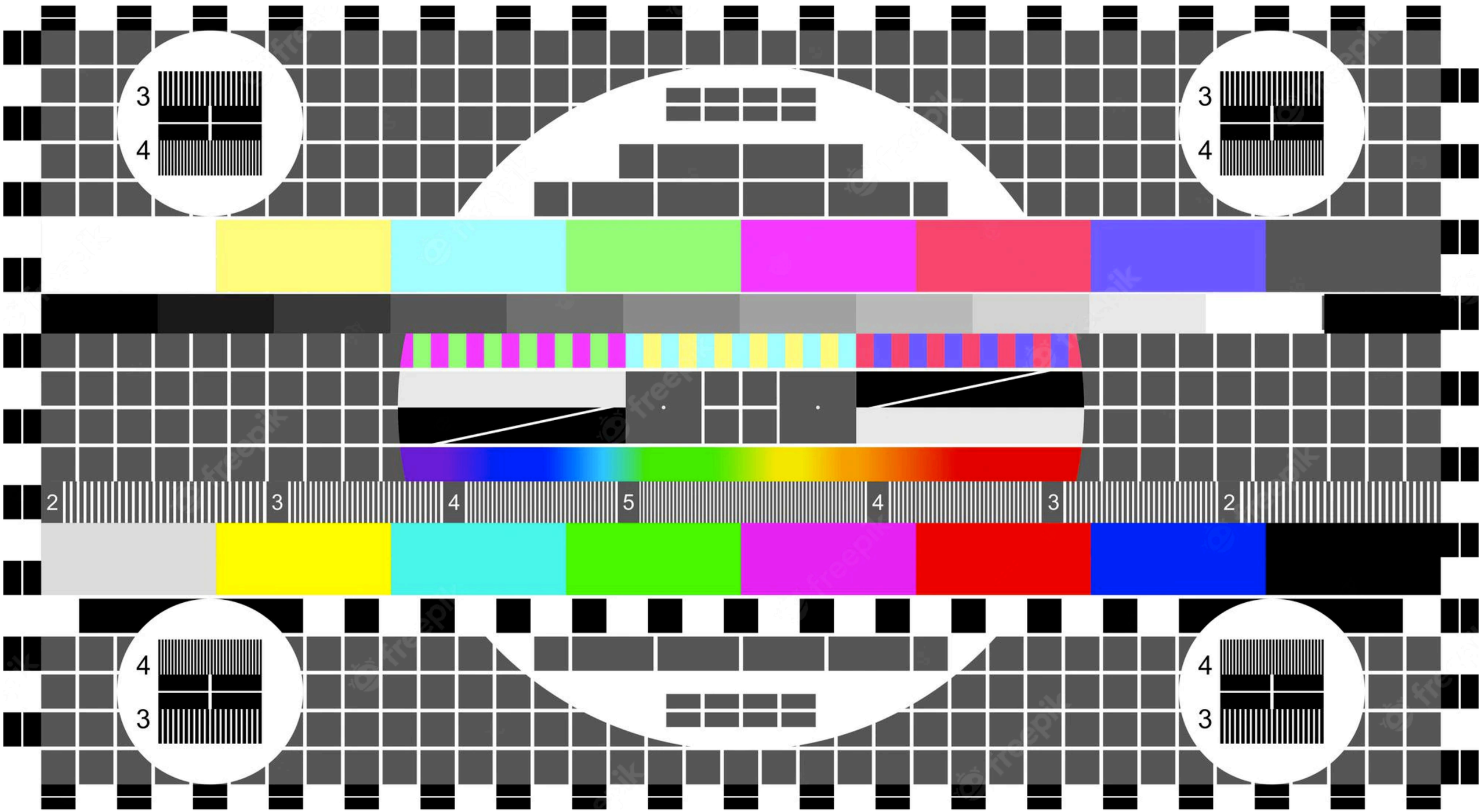
DIFFERENCE IN SEARCH SPACE SIZE



Conclusion: search space size is the main driver of increased runtime

Workload: Mixed workload

 # Task sets: 2000 task sets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