Prosa: A Case for Readable Mechanized Schedulability Analysis

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Prosa

Open-source foundation for formally **pro**ven **s**chedulability **a**nalysis

Jobs

Multiprocessor

Response time

…

Readable Formal Specification

Schedulability Tests

Response-time Bounds

…

Mechanized Proofs

This Talk

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Mechanized proofs provide an opportunity to avoid the **correctness pitfalls in real-time scheduling**.

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By focusing on **readability** and by **maintaining the established proof culture,** mechanized proofs **can reach the community at large.**

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Mechanized proofs provide an opportunity to avoid the **correctness pitfalls in real-time scheduling**.

By focusing on **readability** and by **maintaining the established proof culture,** mechanized proofs **can reach the community at large.**

Thanks to **mature proof assistants and libraries**, Prosa allows mechanizing **recent and complex** schedulability analyses in **reasonable time.**

Outline of the Talk

Why mechanized proofs?

Challenges & Principles

A Taste of Prosa

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What do we mean by **mechanized?**

RTS theory has been built with pen-and-paper proofs

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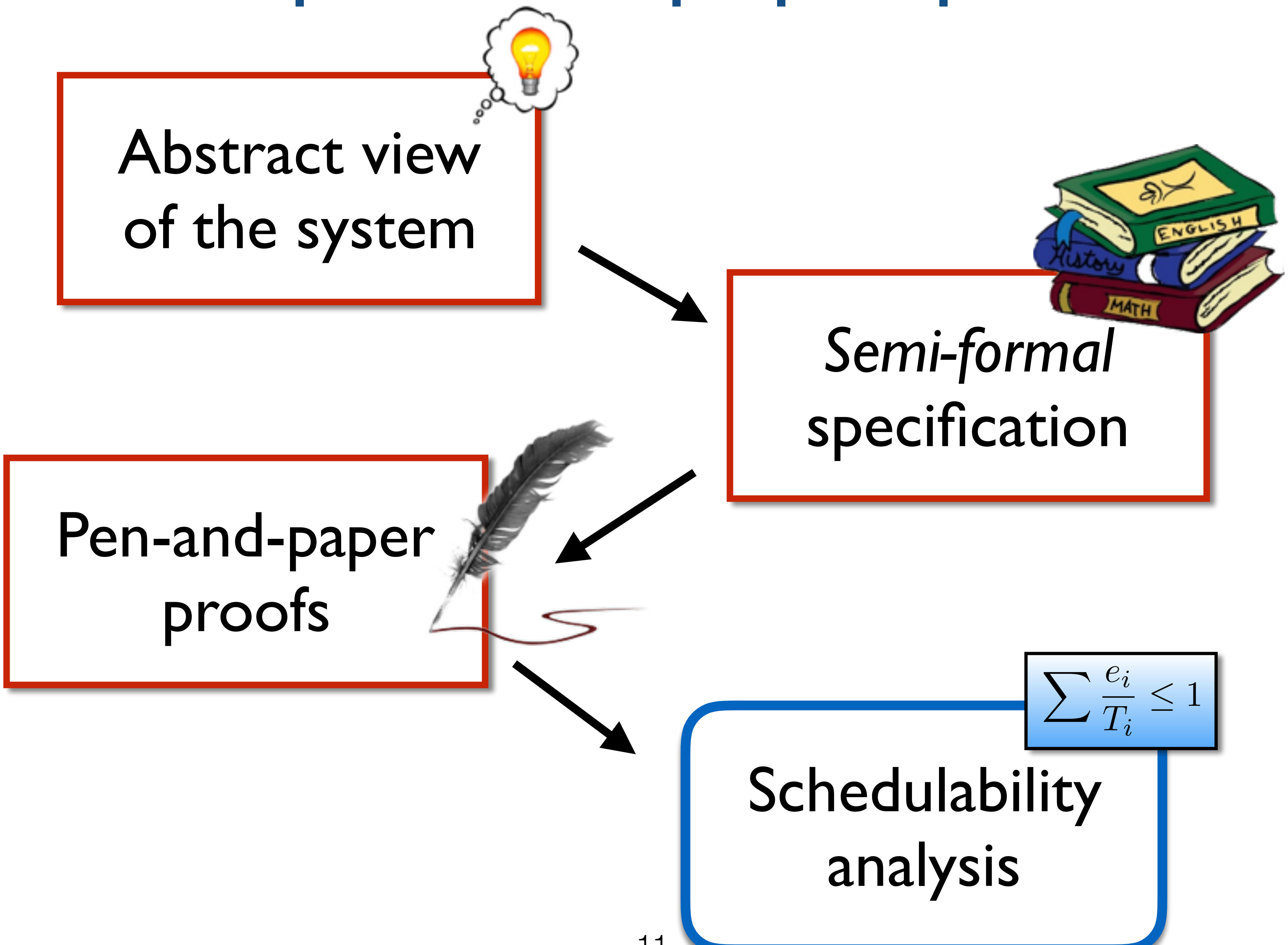
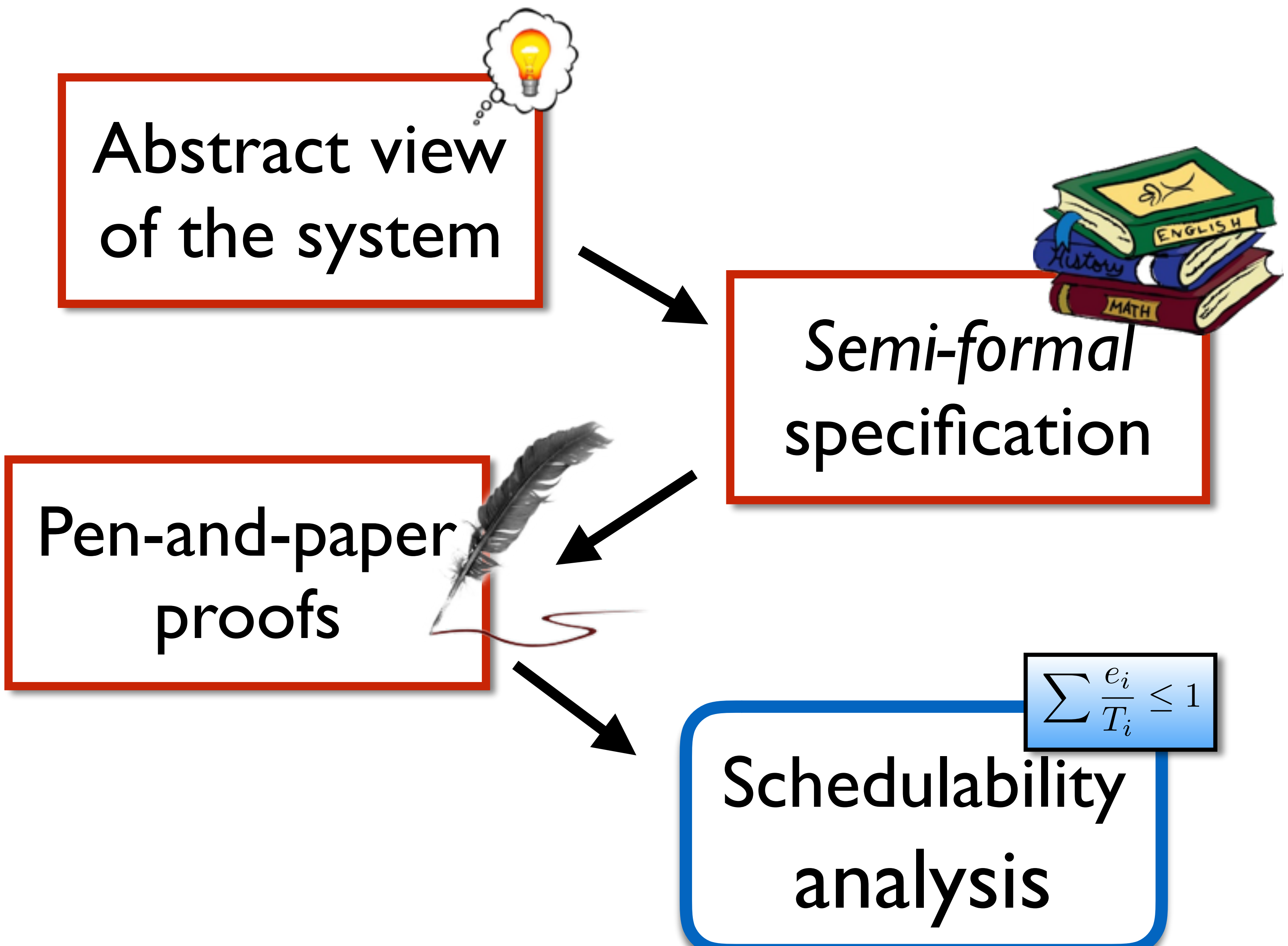
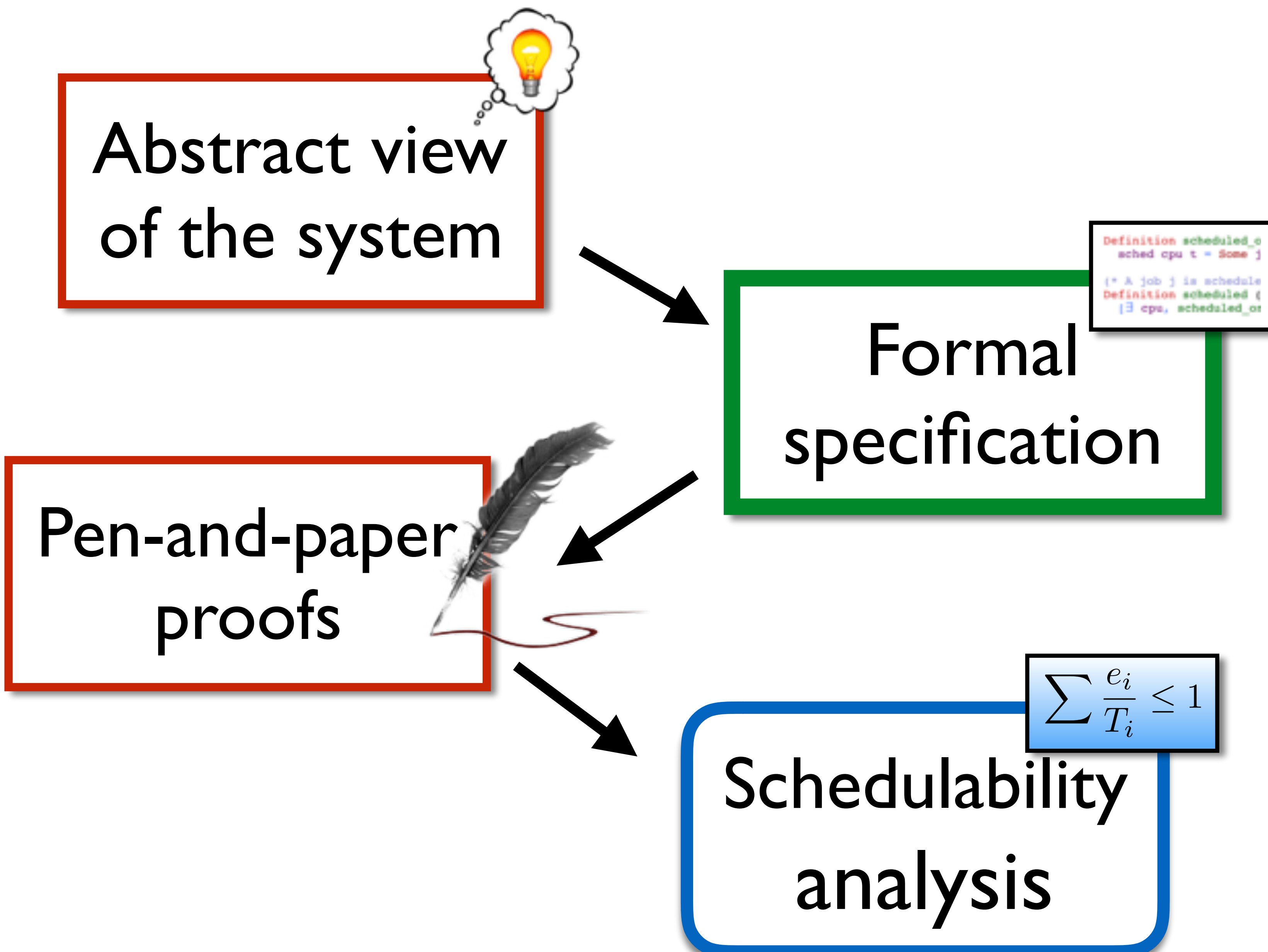


What is **mechanized** schedulability analysis?



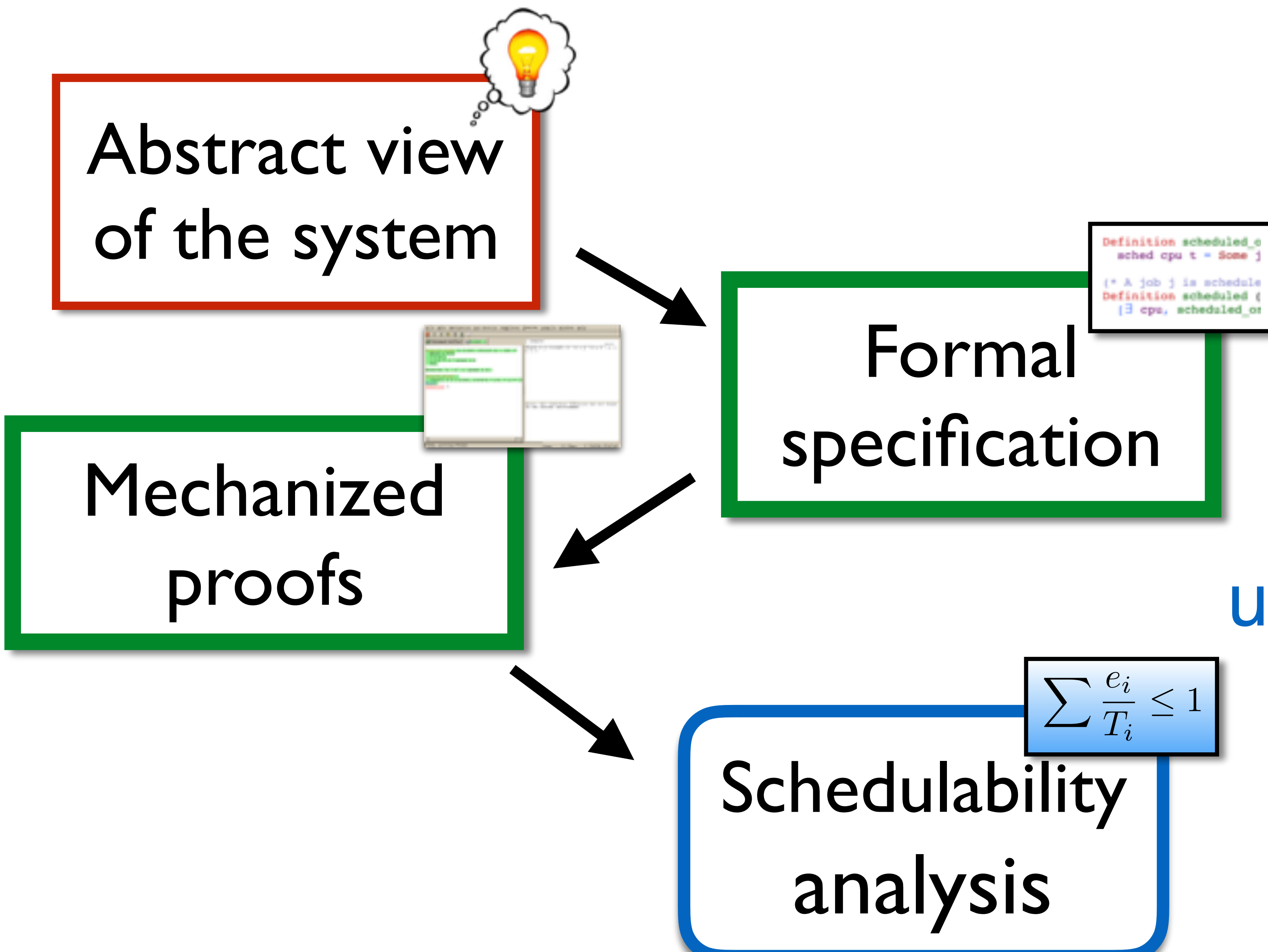
What is the difference?

What is **mechanized** schedulability analysis?



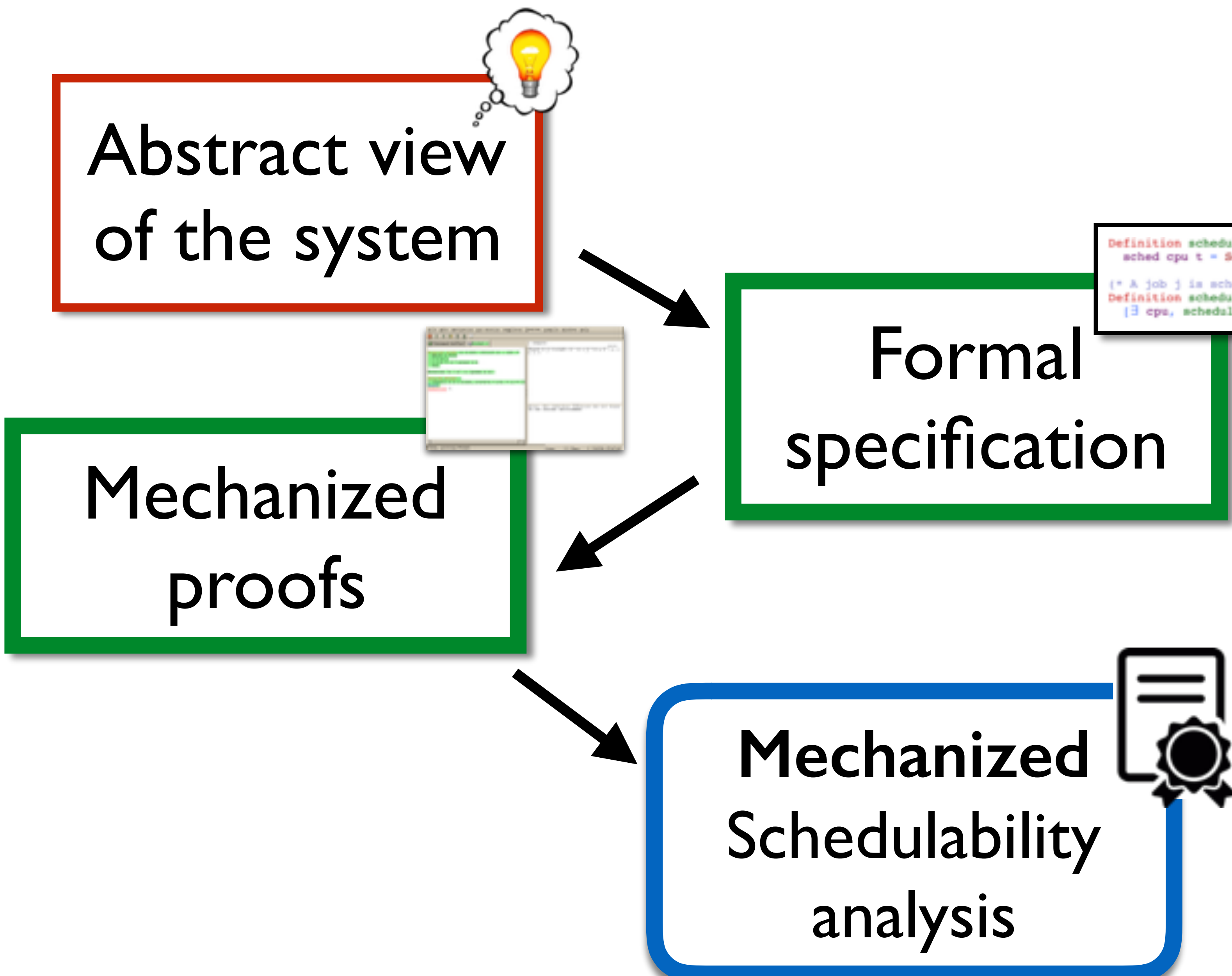
We switch to a **formal specification**

What is **mechanized** schedulability analysis?



We prove theorems using a **proof assistant**

What is **mechanized** schedulability analysis?



The resulting schedulability analysis is **formally verified**

Why mechanized proofs?

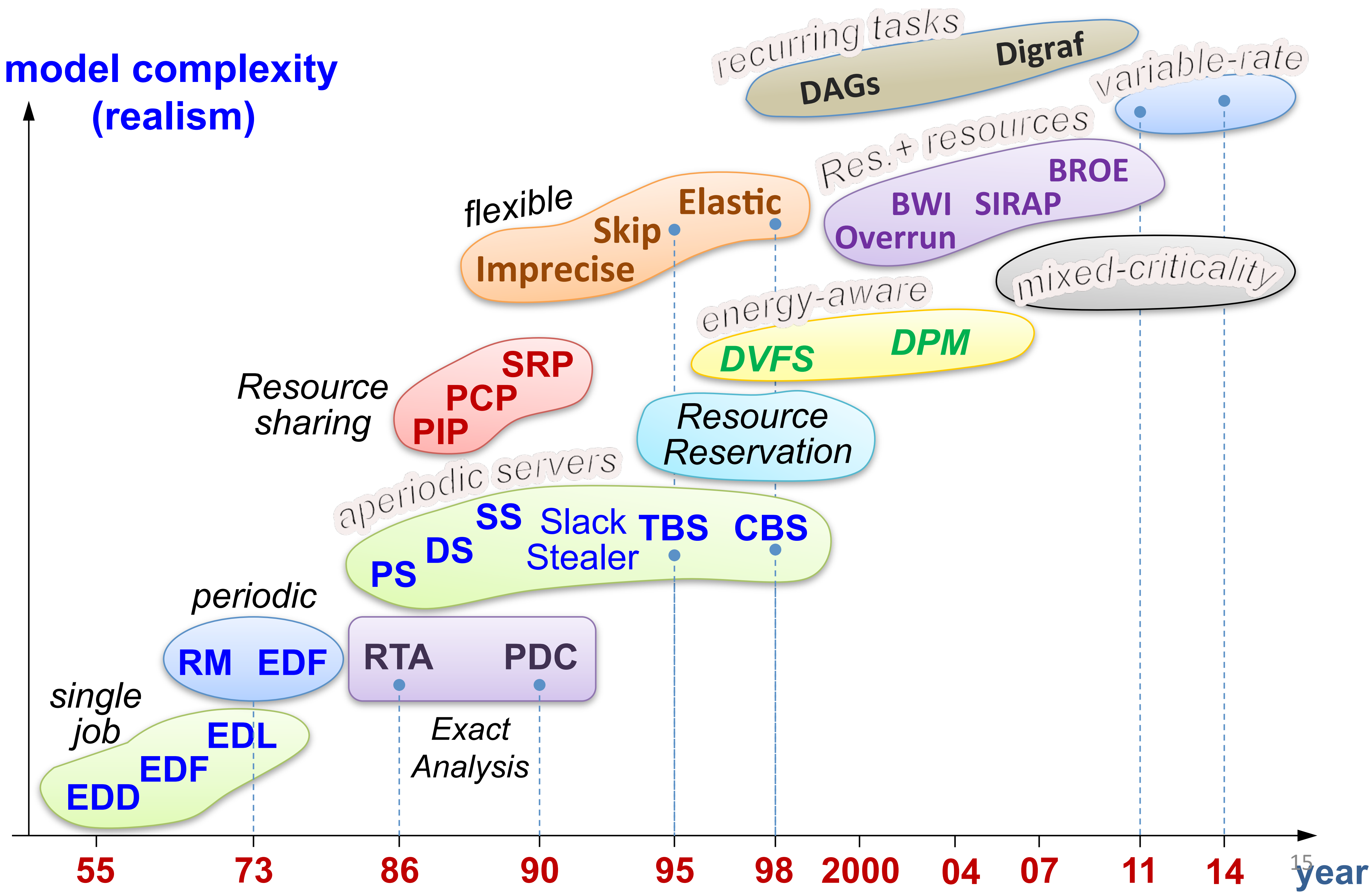
Why mechanized proofs?

Guaranteed Correctness

Trustworthy Extensions

Safe Composition

RTS have become more complex



Source: G. Buttazzo (Keynote @ RTSS'14)

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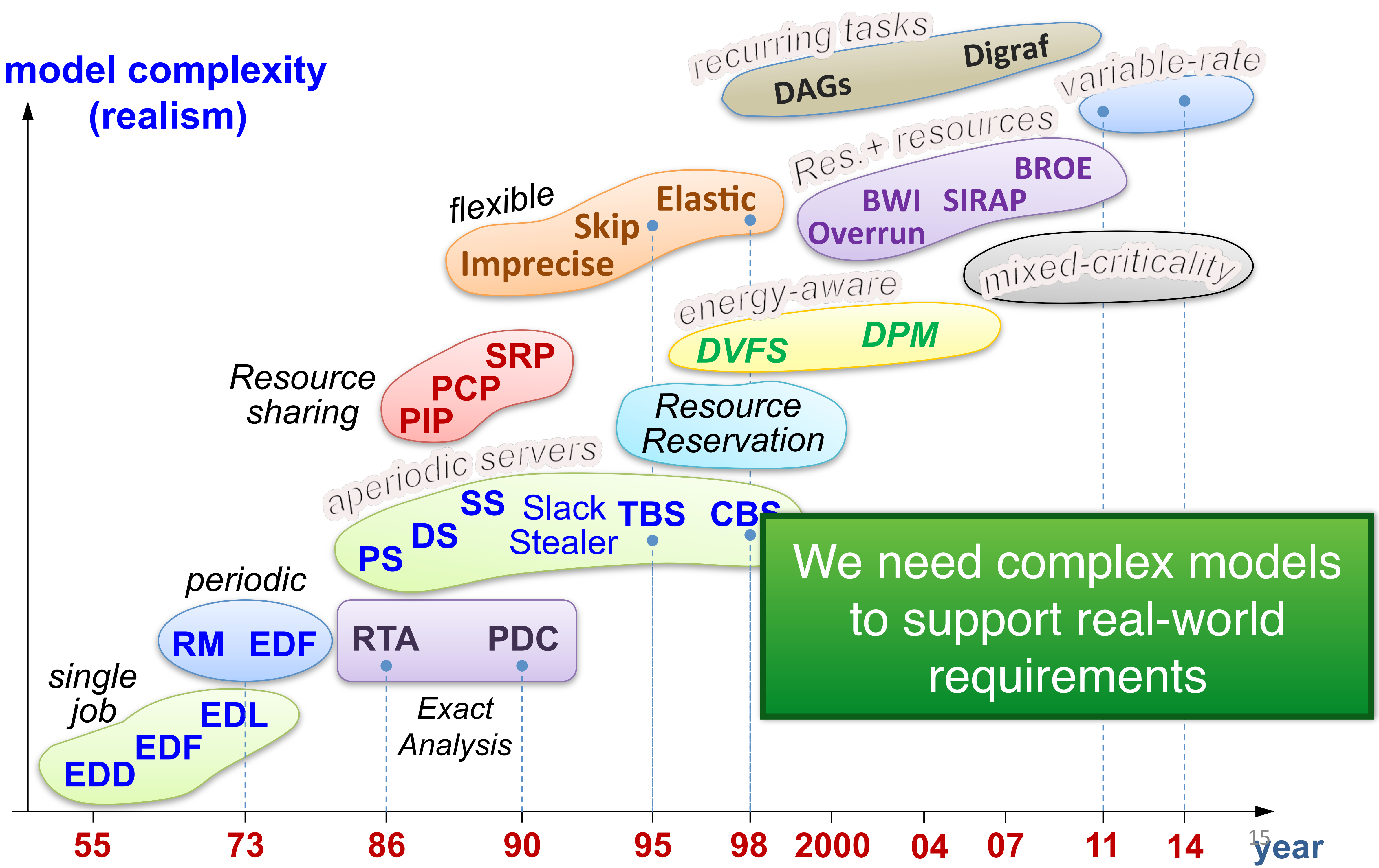


Source: G. Buttazzo (Keynote @ RTSS'14)

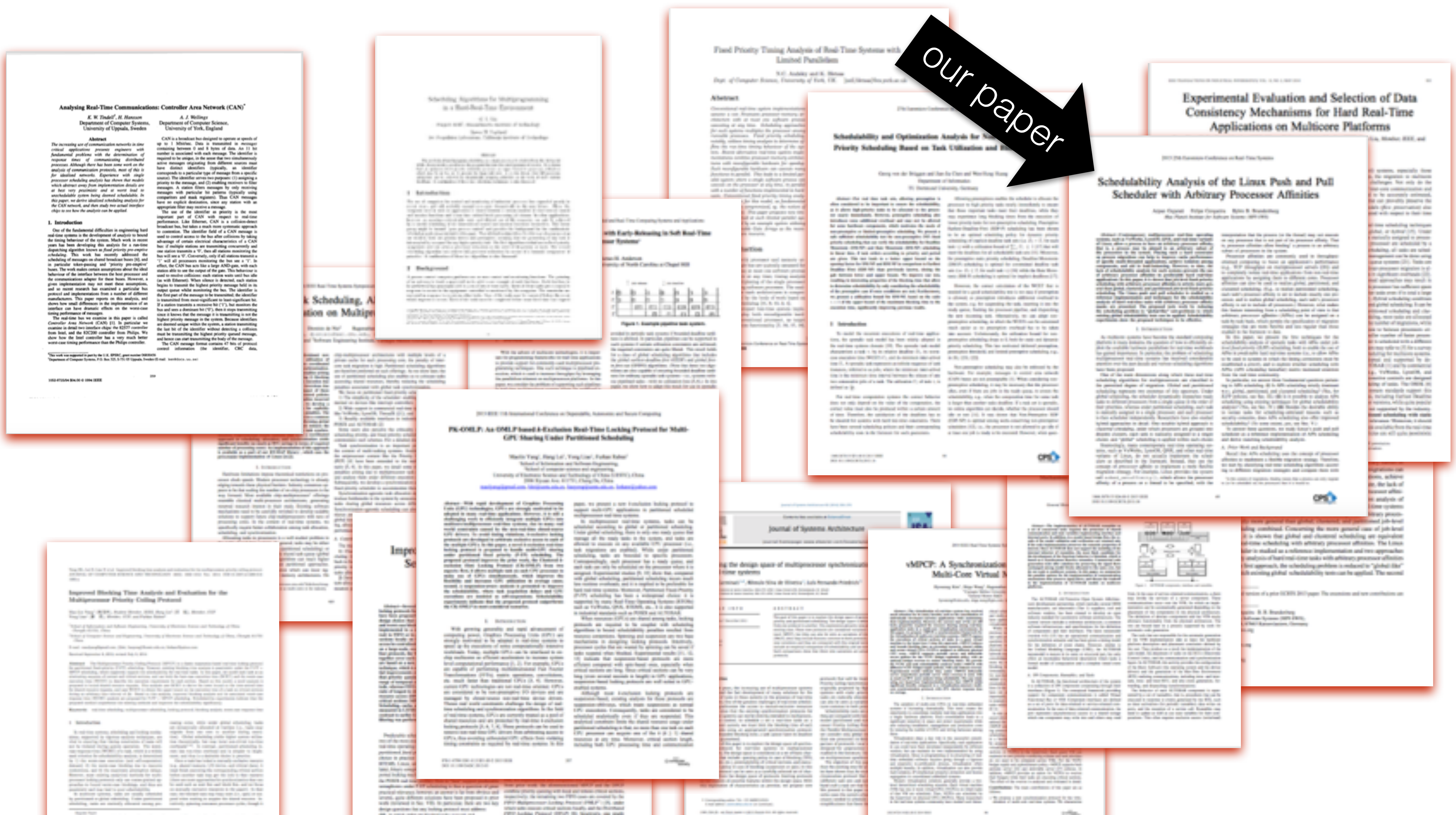
This complexity comes with a price

The original analysis for CAN **had a bug** that remained undetected from 1994 to 2006 [1].

[1] Davis, R. I., Burns, A., Bril, R. J., & Lukkien, J. J. “Controller Area Network (CAN) schedulability analysis: Refuted, revisited and revised.” Real-Time Systems, 35(3), 239-272, 2007.

Bugs are no longer an exception

Proofs have become so complicated
that they often contain bugs.



Analysis for safety-critical systems?

How to ensure that schedulability analysis is actually correct?

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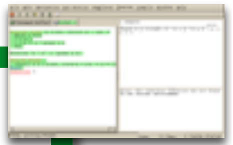
Mechanized proofs



Opportunity: correctness is **inherently guaranteed.**

Why mechanized proofs?

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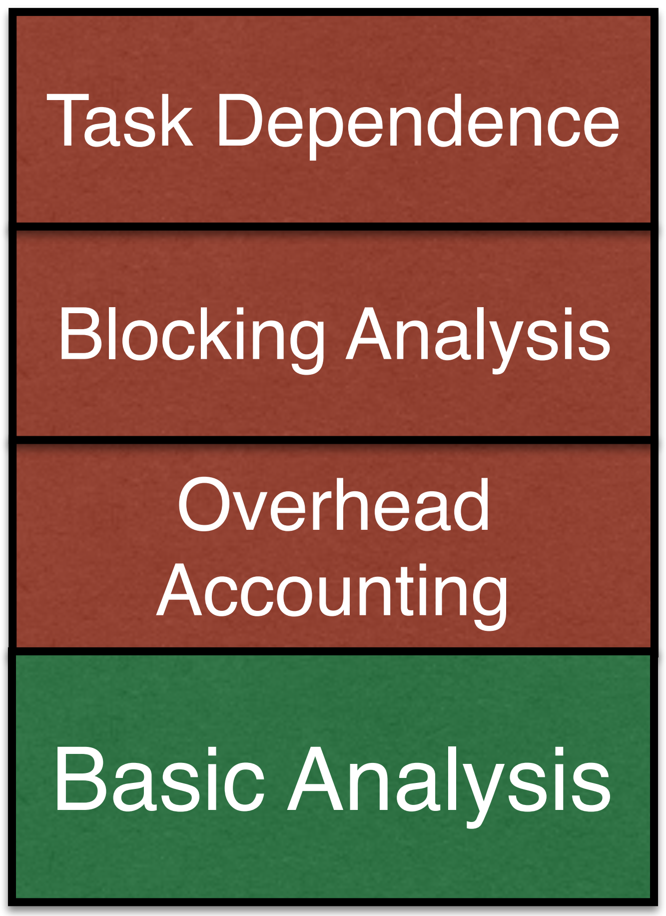
Analyses sometimes need refining

Basic Analysis

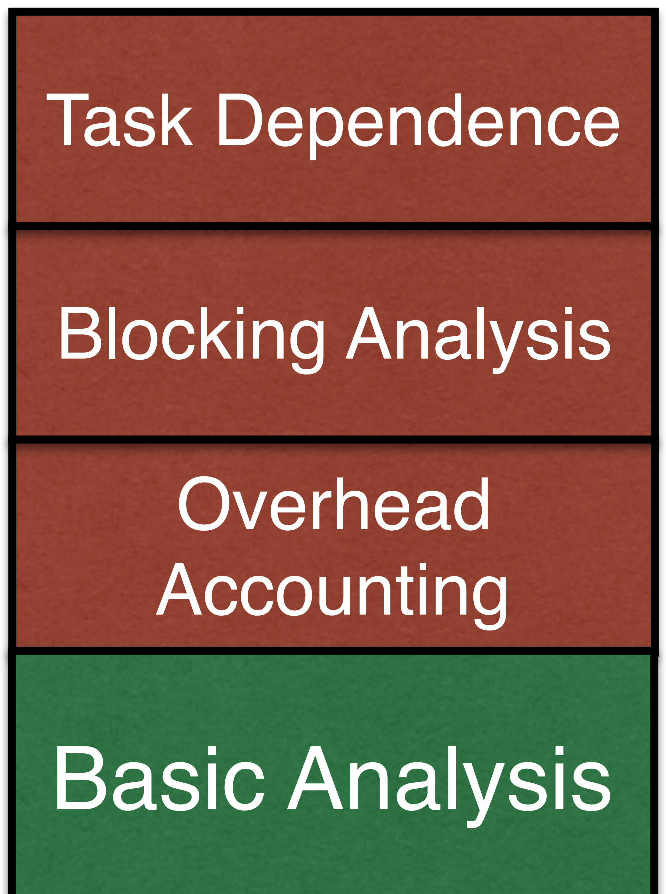
In most analyses, practical details
are assumed to be negligible.

Analyses sometimes need refining



But when deploying actual systems,
we might need to **refine the analysis**.

Analyses sometimes need refining



We call these extensions
(i.e., same results + tweaks)
neighboring proofs.

But when deploying actual systems,
we might need to **refine the analysis**.

Example: incorporating release jitter

	Basic RTA	RTA with Jitter
Uniprocessor	$R_i \leftarrow e_i + \sum_{\tau_j \in hp_i} \left\lceil \frac{R_i}{T_j} \right\rceil e_j$	$r_i \leftarrow e_i + \sum_{\tau_j \in hp_i} \left\lceil \frac{r_i + J_j}{T_j} \right\rceil e_j$ $R_i = J_i + e_i + r_i$

It has been known for more than 20 years how to incorporate release jitter into uniprocessor RTA [3].

[3] Audsley, N., Burns A., Richardson, M., Tindell, K., and Wellings, A. “Applying new scheduling theory to static priority pre-emptive scheduling,” Software Engineering Journal, vol. 8, no. 5, pp. 284-292, 1993.

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Multiprocessor	$R_i \leftarrow e_i + \frac{1}{m} \cdot \sum_{\tau_j \in hp_i} \left\lfloor \frac{I_j(R_i)}{T_j} \right\rfloor r_j$	**???**

But this result has not been proven for multiprocessor RTA.

Can we do the same for multiprocessors?

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Uniprocessor	$R_i \leftarrow e_i + \sum_{\tau_j \in hp_i} \left\lceil \frac{R_i}{T_j} \right\rceil e_j$	$r_i \leftarrow e_i + \sum_{\tau_j \in hp_i} \left\lceil \frac{r_i + J_j}{T_j} \right\rceil e_j$ $R_i = J_i + e_i + r_i$
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Just sum up
the max jitter?

The answer is that we don’t know

Different system models have **different** assumptions.

What if changing the model **breaks some existing proof?**

Recent case: self-suspending tasks

Misuse of release jitter in the analysis caused bugs in 12 papers related to self-suspensions!

Excerpt from [1]:

– Incorrect quantification of jitter for dynamic self-suspending task systems, which was used in [3,4,37,58]. This misconception was unfortunately adopted in [12, 14, 28, 36, 40, 73, 74, 76] to analyze the worst-case response time for partitioned multiprocessor real-time locking protocols.

[1] J.-J. Chen, G. Nelissen, W.-H. Huang, M. Yang, B. Brandenburg, K. Bletsas, C. Liu, P. Richard, F. Ridouard, N. Audsley, R. Rajkumar, and D. de Niz, "Many suspensions, many problems: A review of self-suspending tasks in real-time systems," Department of Computer Science, TU Dortmund, Tech. Rep. 854, 2016

How to derive safe extensions?

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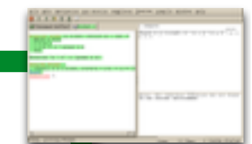
Mechanized proofs



Opportunity: neighboring proofs are conducted **systematically**.

We just need to refine the analysis and
let the proof assistant recheck the proofs.

If there is a bug, $\begin{cases} \text{it will always be detected.} \\ \text{we know exactly what to fix.} \end{cases}$

Why mechanized proofs?

Guaranteed Correctness

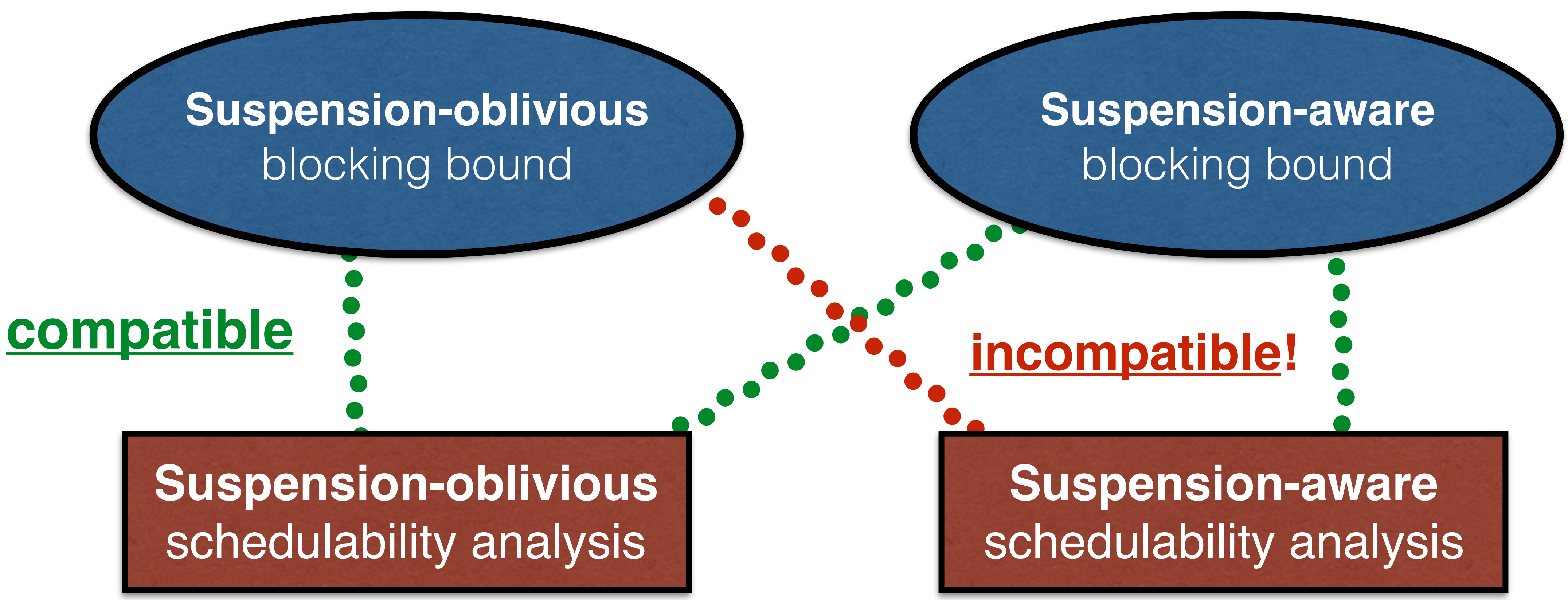
Trustworthy Extensions

Safe Composition

Sometimes we have to combine different analyses

Even if each analysis is **individually correct,**
they should not be combined if assumptions mismatch.

Example:



How to avoid mismatching assumptions?

How to avoid mismatching assumptions?

Mechanized proofs

Opportunity: mismatching assumptions are **automatically caught by the proof assistant.**

We just need to **avoid stating contradictory assumptions.**

But this can also be mechanically verified!

No more correctness pitfalls

Guaranteed Correctness

Trustworthy Extensions

Safe Composition

Mechanized proofs provide an opportunity to avoid the **correctness pitfalls in real-time scheduling**.

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Challenges & Principles

A Taste of Prosa

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Verification has many challenges

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"Knowledge about formal methods tends to be restricted to few research groups."

But there's an opportunity to change…

Principles & Goals of Prosa

1. **Readability** is crucial
2. Some proofs are **more important than others**
3. We should **maintain the proof culture**
4. **Community involvement**

Principle 1: Readability is crucial

The specification should be accessible to researchers with no previous experience with formal methods.

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The specification should be accessible to researchers with no previous experience with formal methods.

We favor:

Many lemmas, short proofs (few dozen lines)

Long, verbose names and few cryptic symbols

Heavy use of documentation

Complex notation harms readability

Duration Calculus [Yuhua and Chaochen, 1994]

Furthermore, if there exists a ready task which is not running, then no processor should be idle. So let,

$$SCH_m \mathrel{\widehat{=}} \begin{pmatrix} \neg\Diamond \begin{pmatrix} true; Run(S) \\ \wedge(\bigvee_{i\in S}\bigvee_{j\in\alpha-S}(Urgt(j,i)\ ;\ \lceil p_j.rdy\rceil \wedge Run(S))) \end{pmatrix} \\ \wedge\Box(Run(S)\wedge\lceil\bigvee_{i\in\alpha-S} p_i.rdy\rceil \ \Rightarrow\ \sharp S = m) \end{pmatrix}$$

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Prosa

```
(* A scheduler is work-conserving iff all processors
   are busy (non-idle) whenever a job is backlogged. *)
Definition work_conserving :=
  ∀ j ∀ t,
    backlogged job_cost sched j t →
    ∀ cpu, ∃ j_other,
      scheduled_on sched j_other cpu t.
```

Long names and few symbols

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...if job j is backlogged at time t, ...

...then every processor cpu has a job j_other...

...that is scheduled on cpu at time t.

Principle 2: Some proofs are more important than others

To make progress, we should focus on practical results.

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To make progress, we should focus on practical results.

We should formalize **recent analyses** and move towards **multiprocessor scheduling.**

Critical results should be proven first.
E.g., proving **analysis safety** is more important than termination, time complexity or optimality.

Principle 3: Maintain the proof culture

To ensure accessibility, we should reuse the established proof style of the real-time systems community.

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To ensure accessibility, we should reuse the established proof style of the real-time systems community.

We avoid **complex logics** (e.g., temporal operators) and **advanced constructs** from the proof assistant (e.g., records, canonical structures, etc.).

We favor instead **first-order logic, lists, functions, basic arithmetic**.

Unusual notation discourages adoption

EDF Optimality in PPTL [Zhang, 2014]

Lemma 6. *If P_i overflows at $t = kT_i$, there is no idle time unit in $[(k-1)T_i, kT_i]$.*

That is,

$$Sch \supset \left(\bigcirc^{kT_i} (ac_i < C_i) \to \bigcirc^{t} \left(\bigvee_{j=1}^{m} r_j = 1 \right) \right) \quad (k-1)T_i < t < kT_i.$$

Prosa — Definition of Instantaneous Service

```
Definition service_at (t: time) :=
  \sum_(cpu < num_cpus | scheduled_on j cpu t) 1.
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LaTeX-like operators improve readability

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Sum over each processor...

...where job j is scheduled...

LaTeX-like operators improve readability

Instantaneous Service

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Sum over each processor...

...where job j is scheduled...

...of 1 (i.e., a count).

Principle 4: Community involvement

Vision: shared repository of real-time scheduling concepts and proofs.

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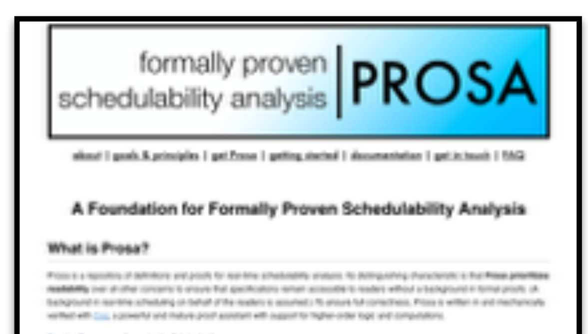
Vision: shared repository of real-time scheduling concepts and proofs.

We encourage **participation by the community**:

Specification accepted by the community + Mechanized Proofs = Non-disputable Results

Check out our website:
prosa.mpi-sws.org



Mechanized proofs can reach the community at large

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Prosa is a collection of definitions, assumptions and theorems

Definitions

Assumptions

Theorems

Prosa covers **many concepts** from real-time scheduling

Definitions

```
Library schedule:  instantaneous service,
                   cumulative service,
                   job is pending, job is complete…

Library interference:  total interference,
                       per-task interference…

Library platform:  work conservation,
                   priority enforcement…
```

Assumptions

Theorems

Assumptions can be **easily checked** (~10–15 in each analysis)

Definitions

Assumptions

```
Hypothesis H_completed_jobs_dont_execute:
  completed_jobs_dont_execute job_cost sched.

Hypothesis H_enforces_FP_policy:
  enforces_FP_policy job_cost job_task sched higher_priority.

Hypothesis H_work_conserving: work_conserving job_cost sched.

Hypothesis H_sequential_jobs: sequential_jobs sched.
```

[…]

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In any given schedule and for any given actual job execution costs, ...

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Definitions

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Hypothesis H_completed_jobs_dont_execute:
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In any given schedule and for any given actual job execution costs, ...

...jobs do not execute after completion.

Theorems

Assumptions can be **easily checked** (~10–15 in each analysis)

Definitions

Assumptions

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Hypothesis H_completed_jobs_dont_execute:
  completed_jobs_dont_execute job_cost sched.

    Definition completed_jobs_dont_execute :=
      ∀ j ∀ t,
        service sched j t ≤ job_cost j.
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Theorems

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Hypothesis H_completed_jobs_dont_execute:
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For every job j at any time t,

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For every job j at any time t,

...the service received by j is no larger than its cost.

Theorems

Theorems are proven in small steps using **lemmas**

Definitions

Assumptions

Theorems

```
Theorem workload_bounded_by_W :
  workload_of tsk t1 (t1 + delta) ≤ workload_bound.
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Definitions

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We upper-bound the workload of a task...

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Definitions

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```
Lemma workload_bound_many_periods_in_between :
  job_arrival j_lst - job_arrival j_fst t ≥ num_mid_jobs.+1
                                              × (task_period tsk).
```

We upper-bound the workload of a task...

...based on the minimum distance between its first and last jobs in the interval.

```
Theorem workload_bounded_by_W :
  workload_of tsk t1 (t1 + delta) ≤ workload_bound.
```

Prosa covers many concepts and is well-documented

Sporadic Tasks

Job priorities

Job arrival constraints

Response time bounds

Interference

Deadline misses

Parallelism

	Definition/Let	Lemma/Theorem
Total	714	699

We use short, easy-to-understand definitions.

	Specification	Proofs	Comments
Lines	6661	17104	3442

1 comment for every 2 lines of spec!

What we have proven so far

(in ~8 person months)

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- **Sporadic Task Model**
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    - ➡ Same for Bertogna and Cirinei's RTA for EDF scheduling
  - Implementation of a work-conserving scheduler to test for contradictory assumptions
- **Extensions**
  - ➡ Same definitions and proofs for workloads with release jitter
  - ➡ Same definitions and proofs for workloads with parallel jobs

novel results

What we have proven so far

(in ~8 person months)

- **Sporadic Task Model**
  - Workload-based interference bounds for work-conserving and EDF schedulers
  - Definition and proofs of correctness and termination of Bertogna and Cirinei's

Thanks to **mature proof assistants and libraries**, Prosa allows mechanizing **recent and complex** schedulability analyses in **reasonable time.**

assumptions

- **Extensions**
  - ➡ Same definitions and proofs for workloads with release jitter
  - ➡ Same definitions and proofs for workloads with parallel jobs

Future Work

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1. Correct recently refuted proofs
   a) ~~APA scheduling~~ **(done! see prosa.mpi-sws.org/apa)**
   b) Self-suspending tasks

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2. Verify practical results

   a) Semi-partitioned scheduling (e.g. C=D)

   b) Blocking analysis

   c) Overhead accounting

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1. Correct recently refuted proofs
   a) ~~APA scheduling~~ **(done! see prosa.mpi-sws.org/apa)**
   b) Self-suspending tasks
2. Verify practical results
   a) Semi-partitioned scheduling (e.g. C=D)
   b) Blocking analysis
   c) Overhead accounting
3. Investigate how to integrate Prosa with analysis tools and scheduler implementations

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We aim for **readable specifications,** but writing formal proofs **remains non-trivial.**

formally proven schedulability analysis | PROSA

More info at prosa.mpi-sws.org

Mechanized proofs provide an opportunity to avoid the **correctness pitfalls in real-time scheduling**.

By focusing on **readability** and by **maintaining the established proof culture,** mechanized proofs **can reach the community at large.**

Thanks to **mature proof assistants and libraries**, Prosa allows mechanizing **recent and complex** schedulability analyses in **reasonable time.**

Backup slides

Generality of discrete time

Theorem 6 *A sporadic arbitrary-deadline task system $\mathcal{T}$ is feasible with respect to continuous schedules iff it is feasible with respect to discrete schedules.*

Results about dense time could still be formalized with Coq libraries for real numbers, e.g. Coquelicot.

[2] Bonifaci, V. and Marchetti-Spaccamela, A., "Feasibility analysis of sporadic real-time multiprocessor task systems," in Proc. of the 18th Annual European Symposium on Algorithms (ESA'10), 2010.

Working with Real Numbers

Coquelicot:

A User-Friendly Library of Real Analysis for Coq

Formalization of limits, continuity, differentiability, Riemann integrals, series, etc.

More info at coquelicot.saclay.inria.fr

Library: Probability Theory

Total/conditional probability, Bayes' theorem, random variables and finite distributions

```
Lemma prob_decomp: forall A B,
  \Pr_d[A] = \Pr_d[A :&: B] + \Pr_d[A :&: ~:B].
```

Moreira, D. *Finite Probability Distributions in Coq (2012).*

Related Work

Formalisms for schedulability analysis

Based on the Duration Calculus (DC) interval logic

- Proof of EDF optimality *[Yuhua and Chaochen 1994]*
  — improved version *[Zhan 2000]*
- Schedulability condition of RM *[Schuzhen et al. 1999]*
- Simplified proofs and review *[Xu and Zhan 2008]*

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+ Formalism reduces ambiguity

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+ Formalism reduces ambiguity

- Complex logics and manual proofs
- Only uniprocessor scheduling

Earlier mechanized proofs

- Proof of **EDF optimality** using *Nqthm* *[Wilding 1998]*
- Analysis of the **Priority Ceiling** and **Priority Inheritance** Protocols *[Zhang et al. 1999] [Dutertre 1999] [Dutertre and Stavridou 2000]*
- Schedulability conditions based on **task phase** using *Coq* *[De Rauglaudre 2012]*
- Certified Computations of **Network Calculus** in Isabelle/HOL *[Mabille et al. 2013]*
- Implementation and proof of **EDF optimality** with Propositional Projection Temporal Logic (PPTL) in Coq *[Zhang et al. 2014]*

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+ Mechanically-checked
- No results about multiprocessors
- Not widely adopted by our community

Model checking and timed automata

- Analysis of **uniprocessor** FP scheduling using UPPAAL
  [Fersman at al. 2006]
- Analysis of **multiprocessor** FP and EDF scheduling of **periodic tasks** using UPPAAL and NuSMV
  [Guan et al. 2007] [Guan et al. 2008] [Cordovilla et al. 2011]
- Analysis of **sporadic tasks** based on state exploration and automata reachability *[Baker and Cirinei 2007] [Geeraerts et al. 2012] [Burmyakov et al. 2015] [Sun and Lipari 2015]*

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+ Multiprocessor, exact schedulability analysis

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+ Multiprocessor, exact schedulability analysis
- State explosion (≤ 10 tasks or 4 processors)

Avoiding contradictory assumptions

1. **Implement a scheduler function S** using the proof assistant (take pending jobs, sort by priority, assign to CPUs, …).

2. **Prove that scheduler S satisfies every requirement** of the analysis (work-conserving, enforces priority, etc.) in an assumption-free context.

3. Since S is an actual algorithm, it is **impossible that two contradictory assumptions are satisfied by S.**