Runtime Verification - Monitor-oriented Programming - Monitor-based Runtime Reflection

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  - theoretical background

Part I

Runtime Verification

Runtime Verification's Rationale

Never trust a running system

Definition

Verification

Verification comprises all techniques for showing that a system satisfies its specification.

Runtime Verification

Runtime verification deals with those techniques that allow checking whether a system under scrutiny satisfies or violates a given safety property.

Characterization

- It aims to be *lightweight* verification technique
- complementing verification techniques such as
  - model checking
  - testing

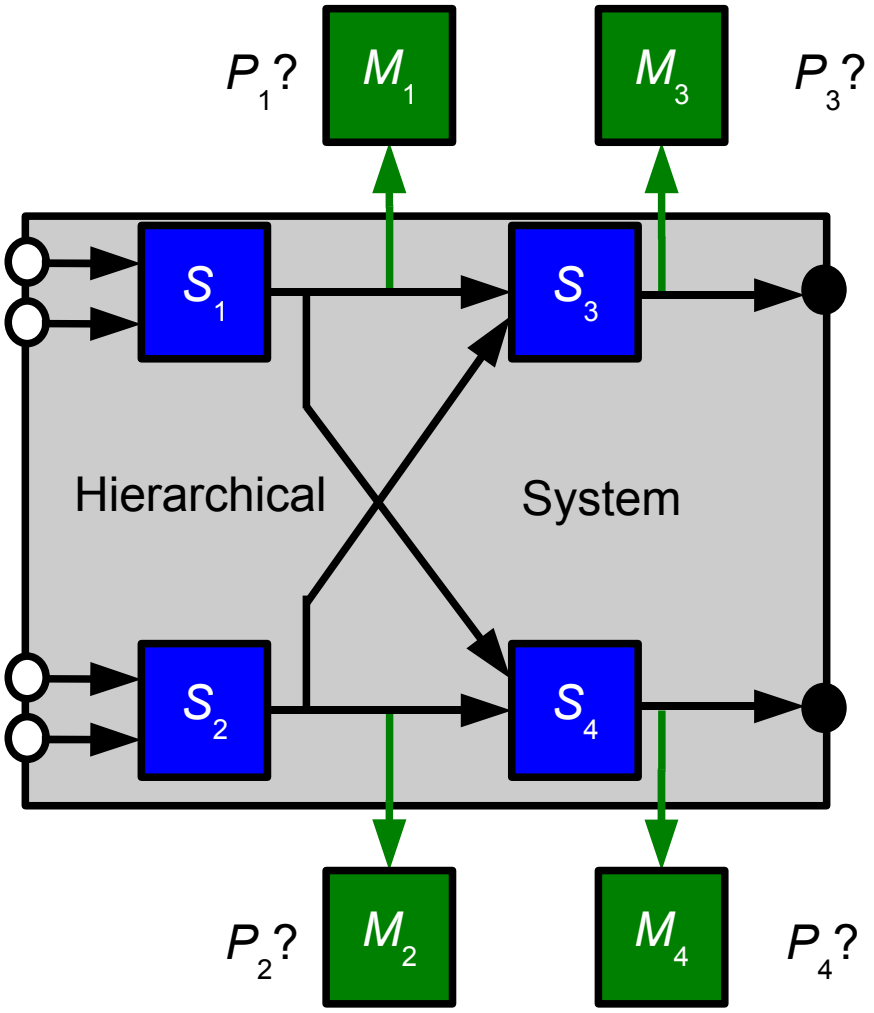
Formally

- Let φ be a correctness property
- Let $[\![\varphi]\!]$ denote the set of words conforming to
- Let w be an execution – a word
- In its mathematical essence, runtime verification is answering whether

$$w \stackrel{?}{\in} [\![\varphi]\!]$$

thus the word problem.

How it works – Online Monitoring

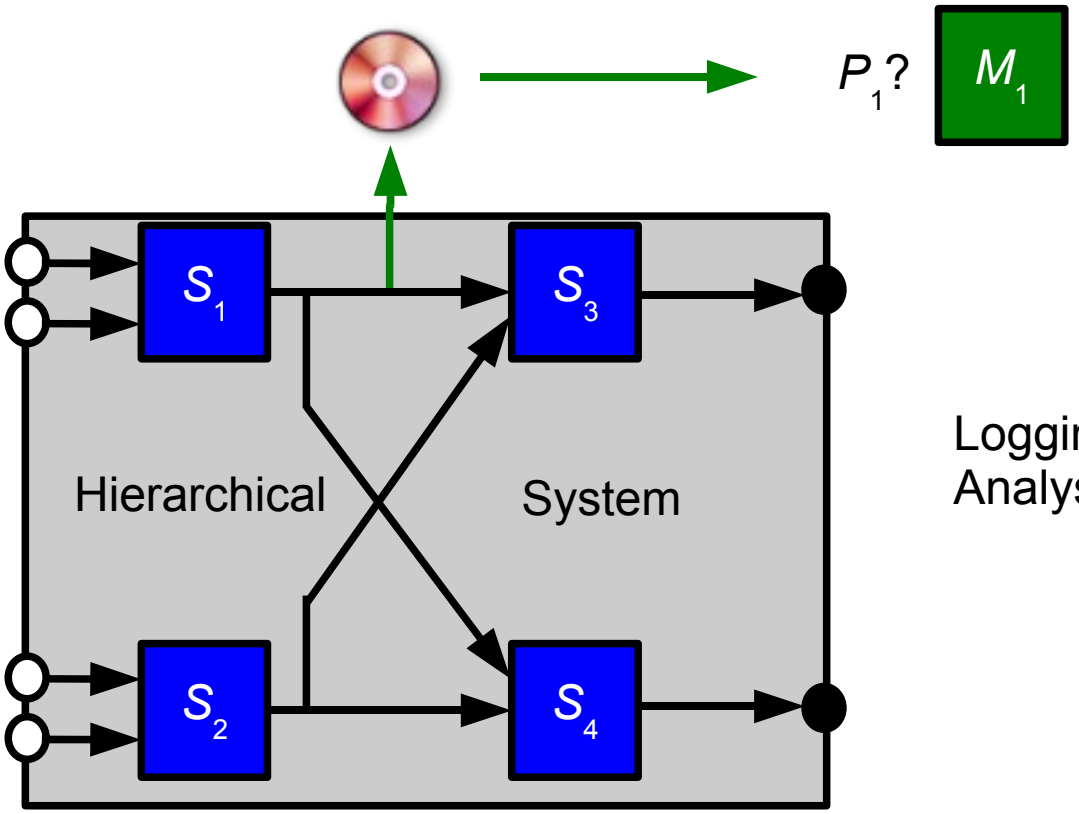


Four monitors,
M_1, M_2, M_3, M_4,
checking independently,
properties
P_1, P_2, P_3, P_4

S – Components,
Procedures, ...

Properties typically given in some variant of Lineartime Temporal Logic (LTL)

How it works – Offline Monitoring



Logging on Disk
Analysis by Monitor offline

Model Checking

- Formally, model checking asks

$$[\![S]\!] \stackrel{?}{\subseteq} [\![\varphi]\!]$$

  which is the language *inclusion problem* and often of much higher complexity
- Model checking consider (usually) *infinite traces*, runtime verification necessarily *finite traces*
- finite but *continuously longer* traces, asks for monitors working in an incremental fashion

Model Checking II

- LTL *semantics for finite traces* needed
- Complexity of monitor (automata) generation not important, but *complexity of monitor*
- Model checking only applicable to white-box systems
  Runtime verification *ideal* also *for black-box systems*

Testing (I)

- Testing is usually *incomplete* – like runtime verification
- Test case: finite sequence of input/output actions
- Test suite: finite collection of test cases
- Test execution: check whether output is as expected when input sequence is given to the system

Testing II

- Test case: only (finite) sequence of input actions
- Test suite: finite collection of test cases
- Test oracle: monitor checking behavior of the system
- Test execution: give test cases (input sequences) to system, check whether monitor complains

- sounds like runtime verification!

Testing II (cont.)

- Oracle defined manual

  Monitor derived from formal specification (LTL formula)
- Research issue in testing:

  How to find *good* test suites?
- Research issue in runtime verification:

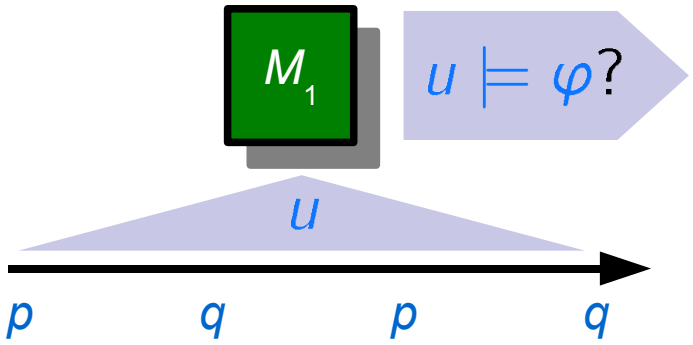
  How to derive *good* monitors?

Runtime verification for LTL

- Syntax of LTL

$$\varphi ::= true \mid p \mid \neg\varphi \mid \varphi\ op\ \varphi \mid \varphi \mathbf{U} \varphi \mid \mathbf{X}\varphi \quad (p \in AP)$$

- Abbreviations: $F\varphi \equiv true U \varphi \quad G\varphi \equiv \neg F \neg \varphi$
- Some examples: $\mathbf{G}p, \mathbf{G}(\neg p \rightarrow \mathbf{X}p), \mathbf{G}\neg(p \wedge q)$
- Interpretation of φ over sequence of system events (behaviours), $u \in (2^{AP})^*$
- Automatic monitor generation: "Inspired" by translation of LTL to Büchi-automata



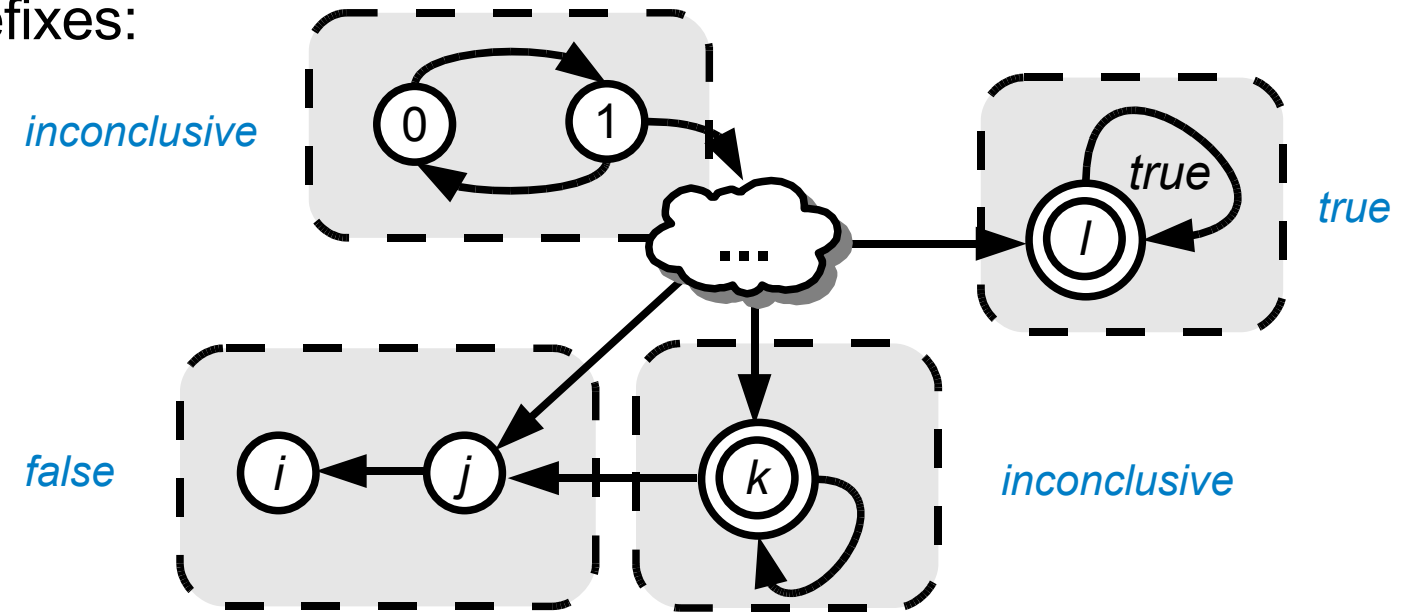
$$\varphi \rightarrow BA_\varphi \ s.t.\ L(BA_\varphi) = L(\varphi)$$

LTL over finite traces

- Introduce 3-valued semantics for LTL (resembling the 2-valued one):

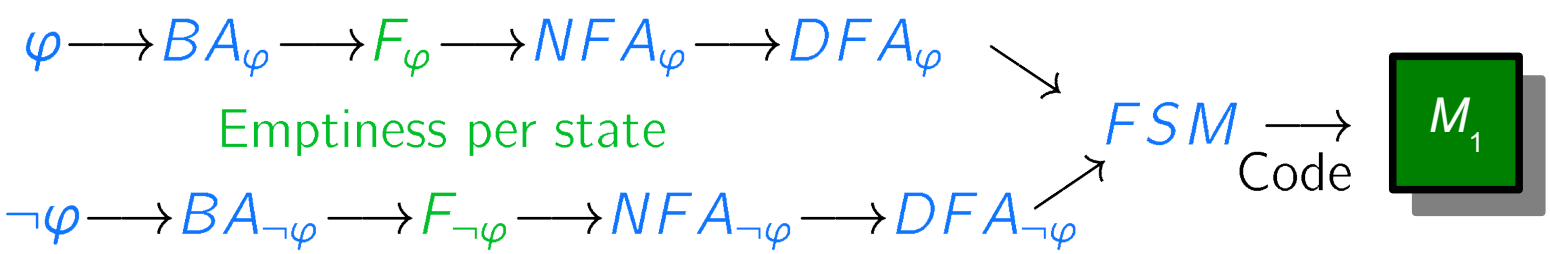
$$[u \models \varphi] = \begin{cases} \top & \text{if } \forall \sigma \in \Sigma^\omega : u\sigma \models \varphi \\ \bot & \text{if } \forall \sigma \in \Sigma^\omega : u\sigma \not\models \varphi \\ ? & \text{otherwise} \end{cases}$$

- The goal – finite-state machines for detecting *minimal* bad prefixes:



How it actually works

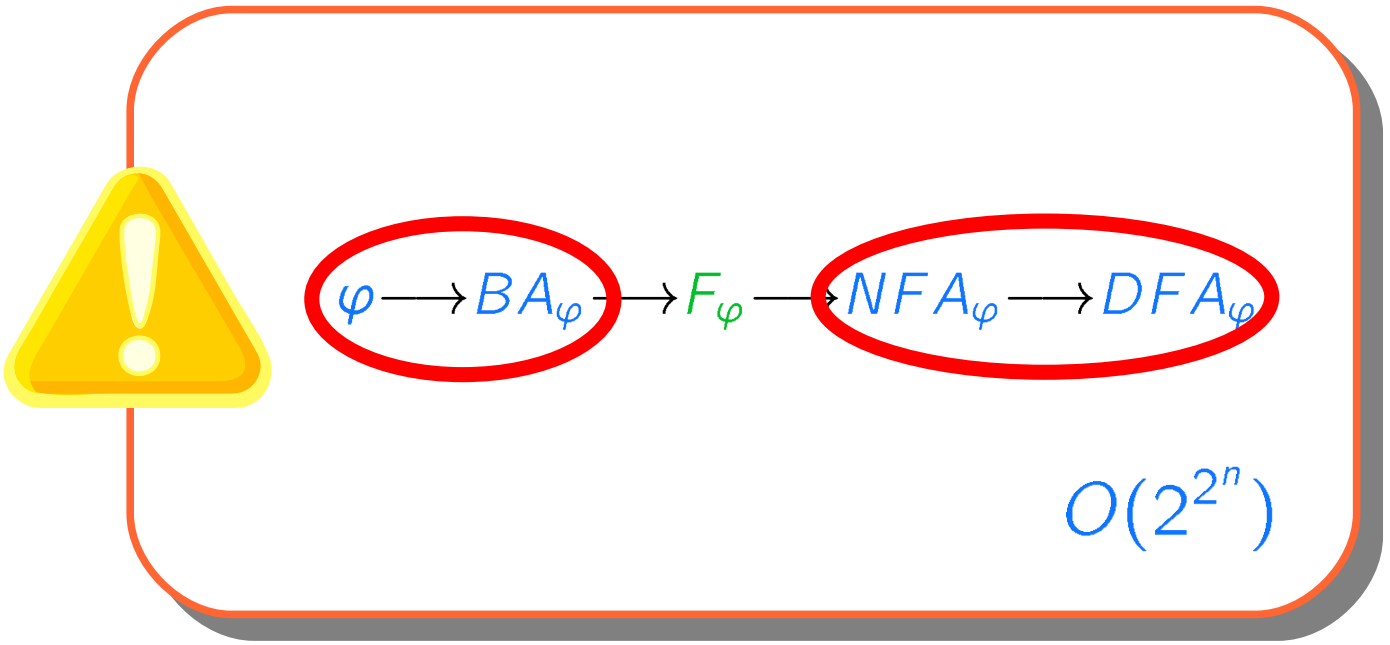
- Use emptiness-per-state as alternative acceptance condition:



- Emptiness only says whether language is non-empty, not whether <u>all future traces</u> are accepting or not!
- Now we have a formal decision procedure:

$$[u \models \varphi] = \begin{cases} \top & \text{if } u \notin L(NFA_{\neg\varphi}) \\ \bot & \text{if } u \notin L(NFA_{\varphi}) \\ ? & \text{if } u \in L(NFA_{\varphi}) \text{ and } u \in L(NFA_{\neg\varphi}) \end{cases}$$

Complexity

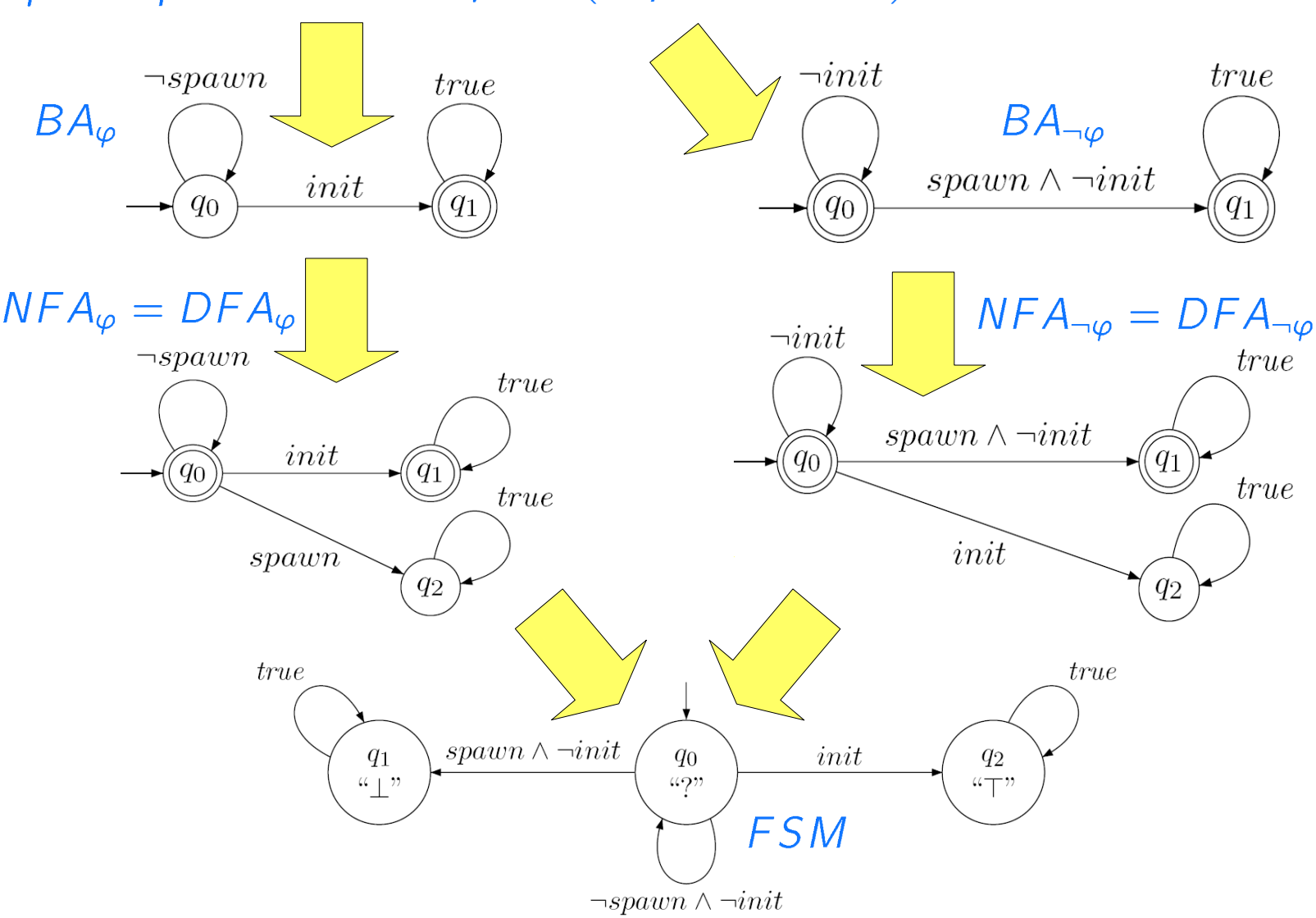

$\varphi \longrightarrow BA_\varphi \longrightarrow F_\varphi \longrightarrow NFA_\varphi \longrightarrow DFA_\varphi$
$O(2^{2^n})$

But optimal solution...

- Consider this:
  - FSMs can be minimised (Myhill-Nerode equivalence)
  - As such, any smaller automaton does not accept the same language **=>** Monitor generation optimal
- Moreover, procedure detects *all minimal* bad prefixes by defintion of 3-valued semantics:

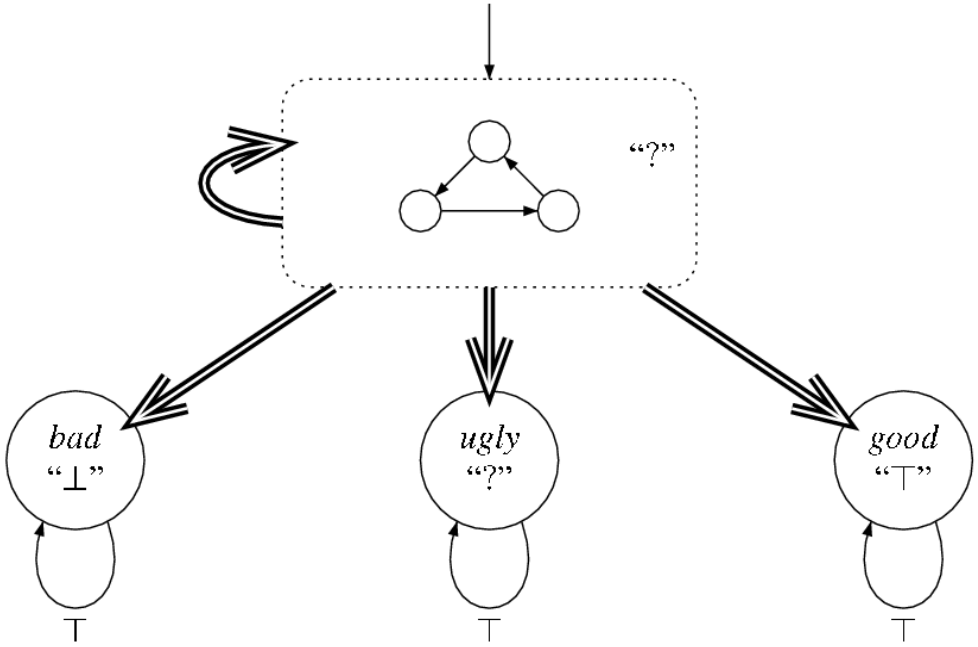
$$[u \models \varphi] = \begin{cases} \top & \text{if } \forall \sigma \in \Sigma^\omega : u\sigma \models \varphi \\ \bot & \text{if } \forall \sigma \in \Sigma^\omega : u\sigma \not\models \varphi \\ ? & \text{otherwise} \end{cases}$$

Static initialisation order fiasco



Monitors revisited

- The general structure



- Bad prefixes/Good prefixes/Ugly prefixes
- Monitorable (after u)
- Safety/co-safety properties

Works also for timed systems!

- Principle stays the same, but we use
  - Timed words $(a_0, t_0)(a_1, t_1)\ldots \quad (t \in \mathbb{R})$
  - TLTL aka state-clock logic for LTL
    (FO fragment of MSO interpreted over timed words)
    $\varphi ::= true \mid a \mid \lhd_a \in I \mid \rhd_a \in I \mid \neg\varphi \mid \varphi \text{ op } \varphi \mid \varphi \mathbf{U} \varphi \mid \mathbf{X}\varphi$
    for each symbol we have two clock variables:

Useful for time-bounded response properties!

    - a *predicting* clock
  - for translation timed (event-clock) automata with runs of the form: $\theta : (q_0, \gamma_0) \xrightarrow{d_1}\xrightarrow{a_1} (q_1, \gamma_1) \xrightarrow{d_2}\xrightarrow{a_2} (q_2, \gamma_2) \xrightarrow{d_3}\xrightarrow{a_3} \ldots$
  - Obviously, this execution scheme poses a problem!

Observing – Not Acting!

- Runtime verification does not influence/modify the running system
- at least tries to – it might consume resources of the monitored system

Part II

Monitor-oriented Programming
(Grigore Rosu et. al. - thanks for Slides)

But first

A commercial...

Main Ideas

- Use monitors to check behavior of program
- *Influence behavior* of program when monitor either confirms that a correctness property is satisfied or falsified
- annotate code (e.g. Java code) by
  - monitor description, and
  - code to be triggered by monitor

JavaMOP example

Enforce authentication before use

```
class Resource {
/*@
        scope = class
        logic = PTLTL
        {
         Event authenticate: end(exec(* authenticate()));
         Event use: begin(exec(* access()));
         Formula : use -> <*> authenticate
        }
        violation Handler {
          @this.authenticate();
        }
@*/
void authenticate() {...}
void access() {...}
...
}
```

Where → scope = class

How → logic = PTLTL

what → Event authenticate: end(exec(* authenticate())); Event use: begin(exec(* access())); Formula : use -> <*> authenticate

What if → violation Handler { @this.authenticate(); }

Example

```
... (Java code A) ...

/*@ FTLTL
   Predicate red : tlc.state.getColor() == 1;
   Predicate green : tlc.state.getColor() == 2;
   Predicate yellow : tlc.state.getColor() == 3;
   // yellow after green
   Formula : [](green -> (! red U yellow));
   Violation handler : ... (Java "recovery" code) ...
@*/

... (Java code B) ...
```

- Programming methodology
- some ideas similar as in aspect-oriented programming

MOP key features

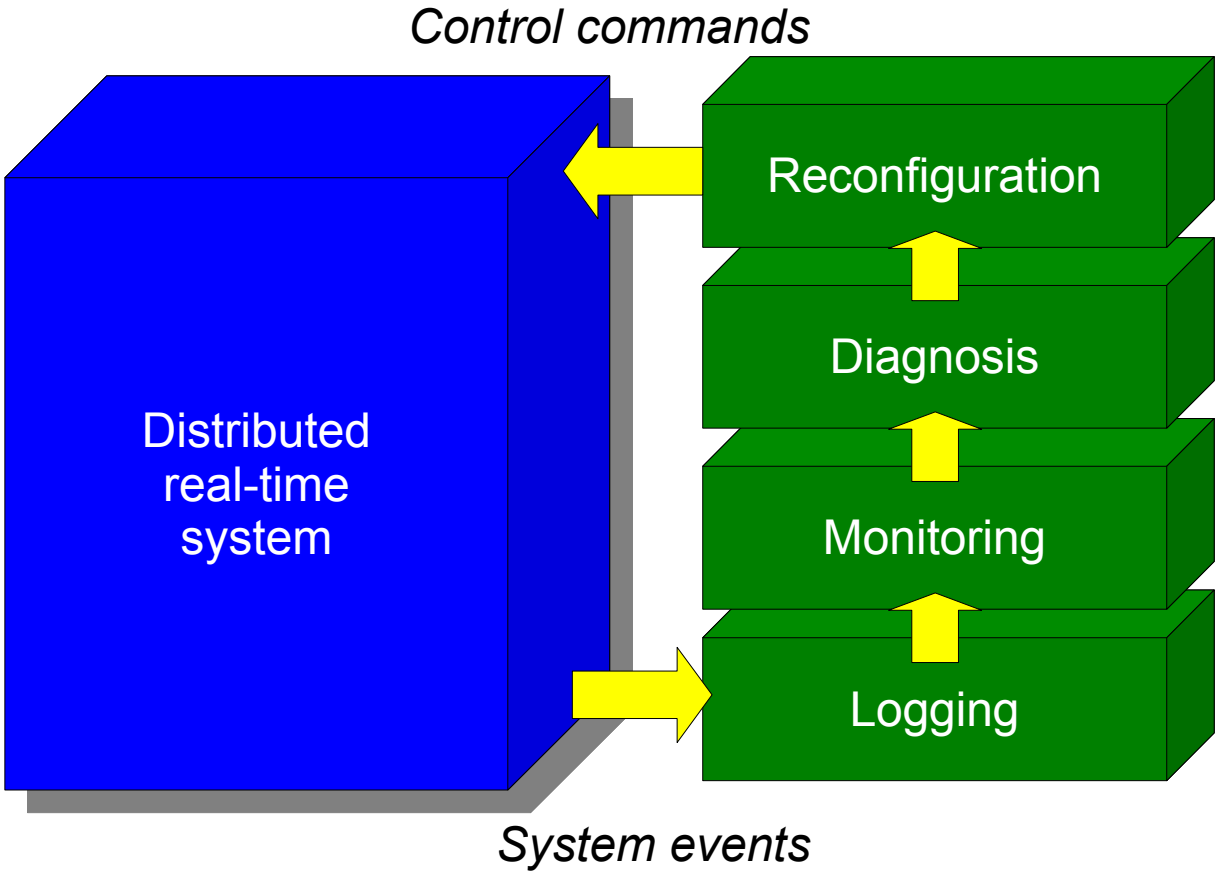
- Extensible logic framework
  - "Plug and use" user-defined logics using logic plugins
  - Supported logics: ERE (Extended Regular Expression), PtLTL (Past Time Linear Temporal Logic), FtLTL (Future Time Linear Temporal Logic), ATL (Allen Temporal Logic)
- Generic and efficient support for universal parameters
  - Allow monitor instances per groups of objects
  - Faster than logic-specific monitoring techniques, e.g., Tracematches and PQL. [OOPSLA'07]
- Configurable monitors
  - Running mode: inline/outline, online/offline
  - Working scope: method, class, global, …
  - User-provided actions for violations and validations

Part III

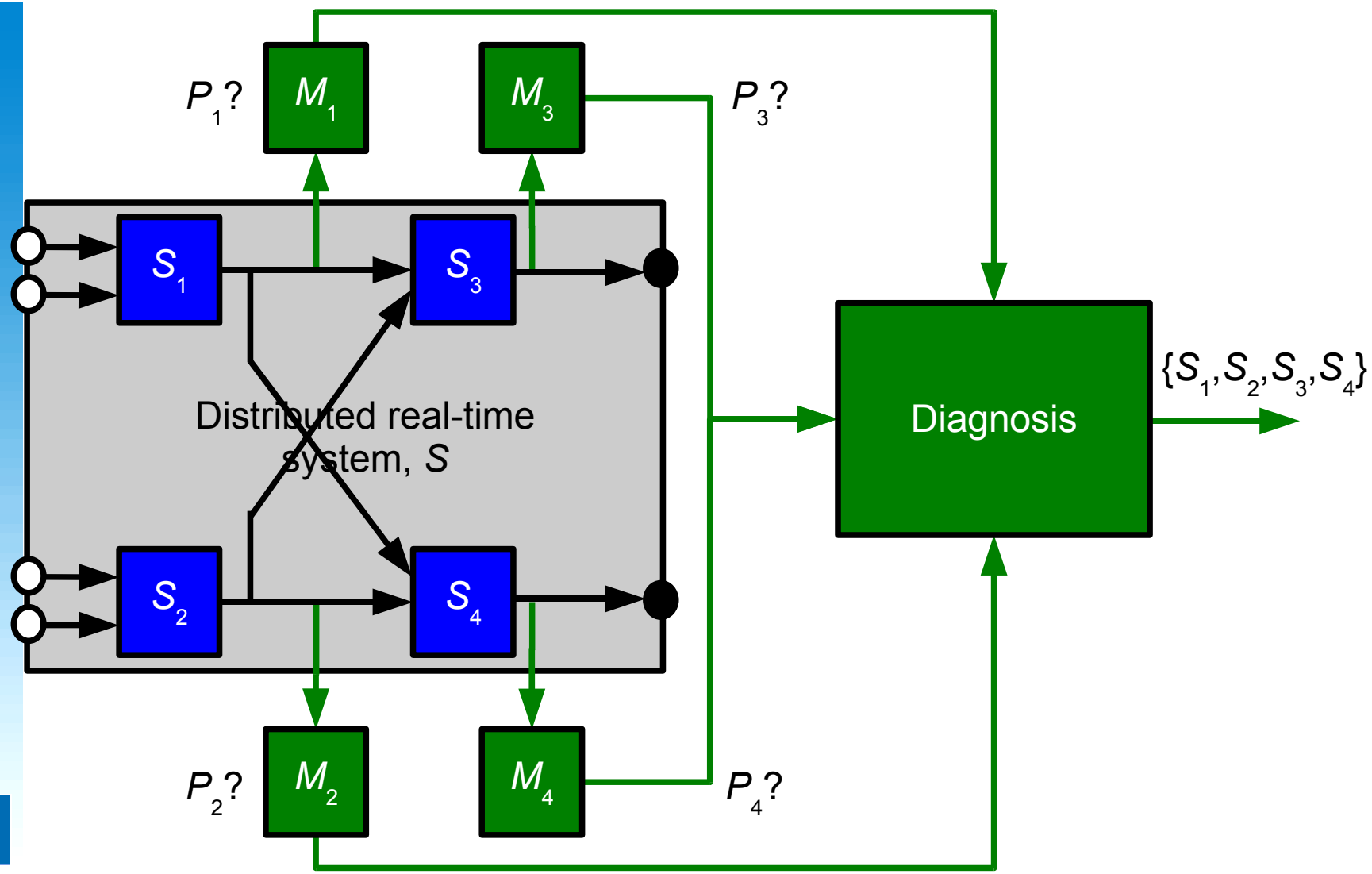
Monitor-oriented Runtime Reflection

Runtime reflection

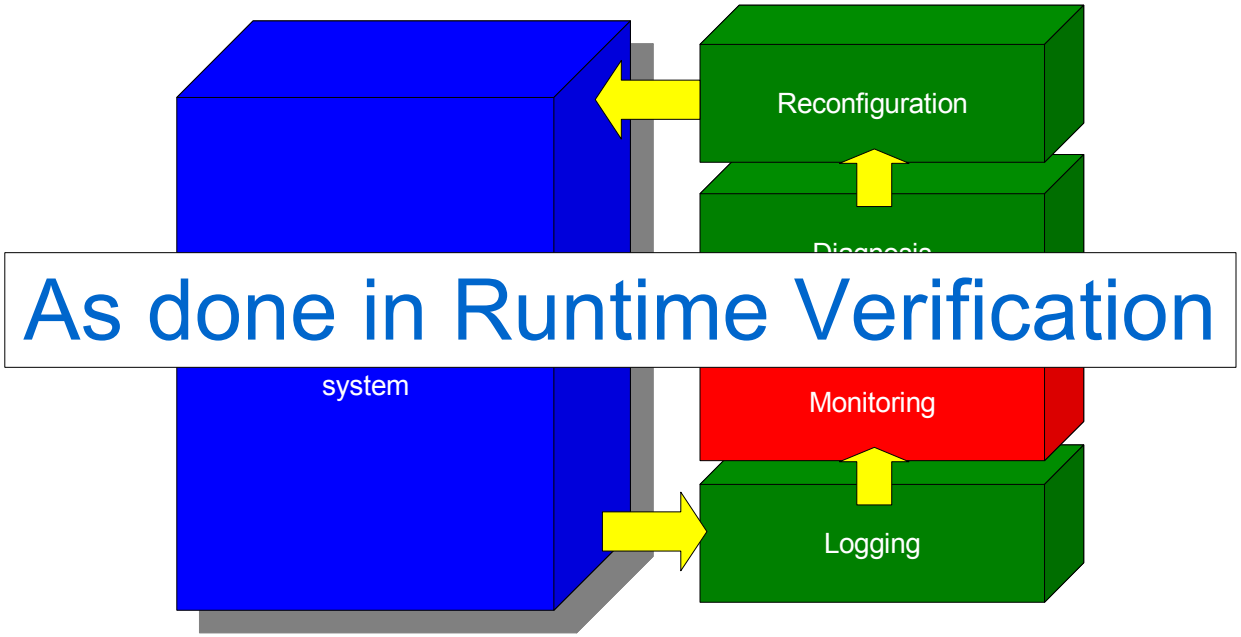
- An architecture for model-based runtime analysis:



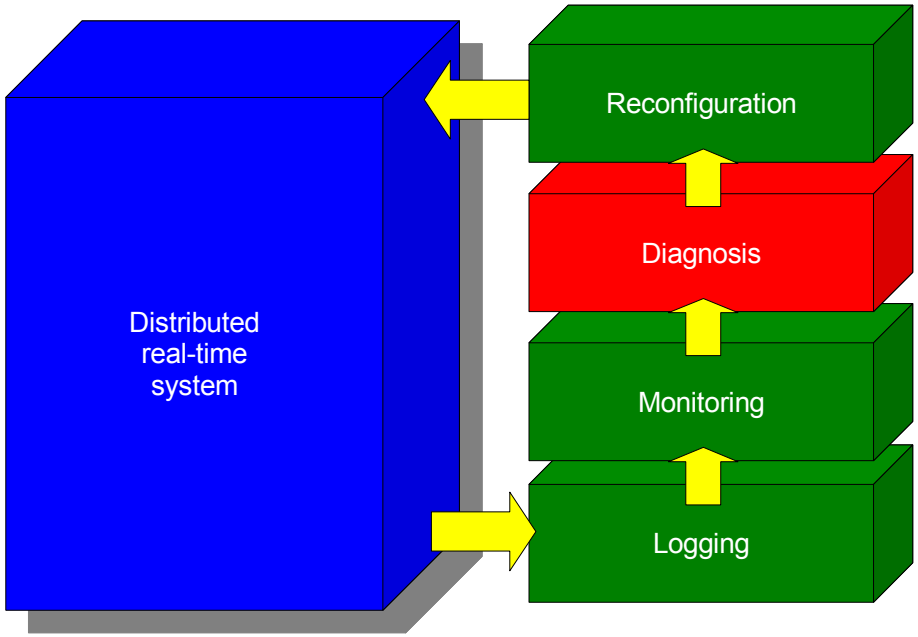
How it works – A functional overview



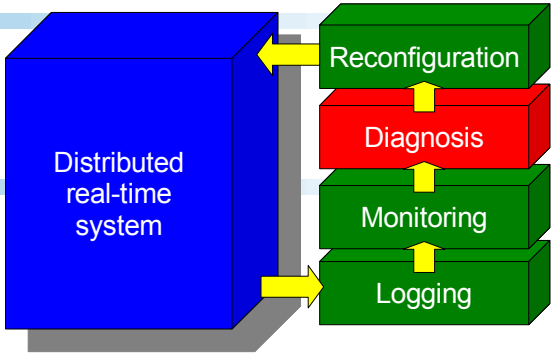
Part - Monitoring



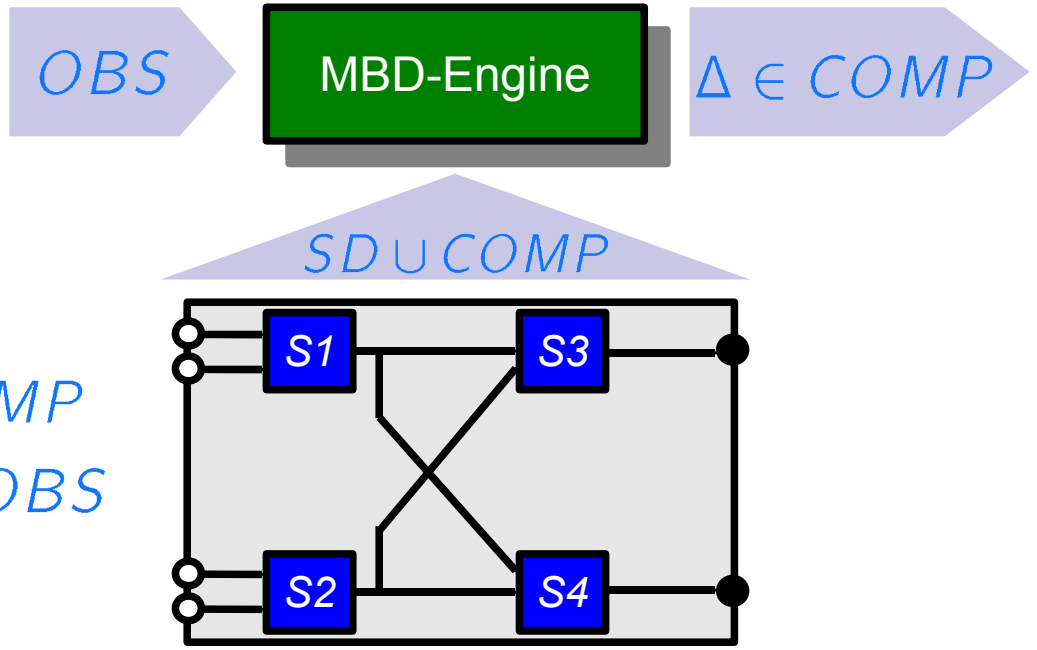
Part - Diagnosis



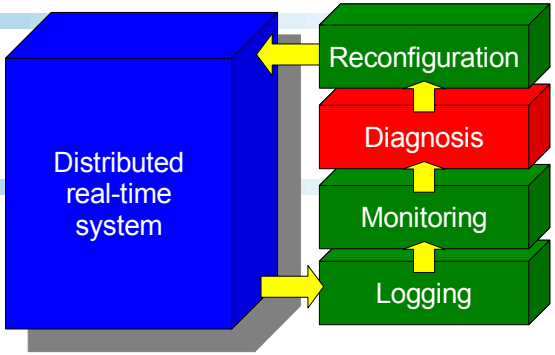
Part – Diagnosis



- **System model:** set of components, $COMP$, system description, SD, specified in terms of first-order sentences, e.g.,
  $SD = \{mult(X) \wedge \neg AB(X) \rightarrow (out(X) = in1(X) * in2(X)),$
  $mult(S1), \ldots\}$
- **Diagnostic task:** given a set of observations, OBS, find *all minimal diagnoses* $\Delta \in COMP$ s.t. $SD \cup COMP \cup OBS$ is explicable, i.e., is consistent

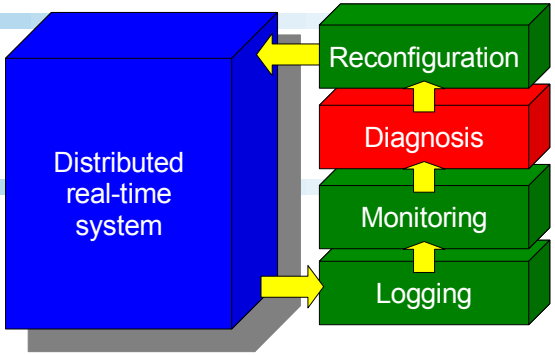


But what about...

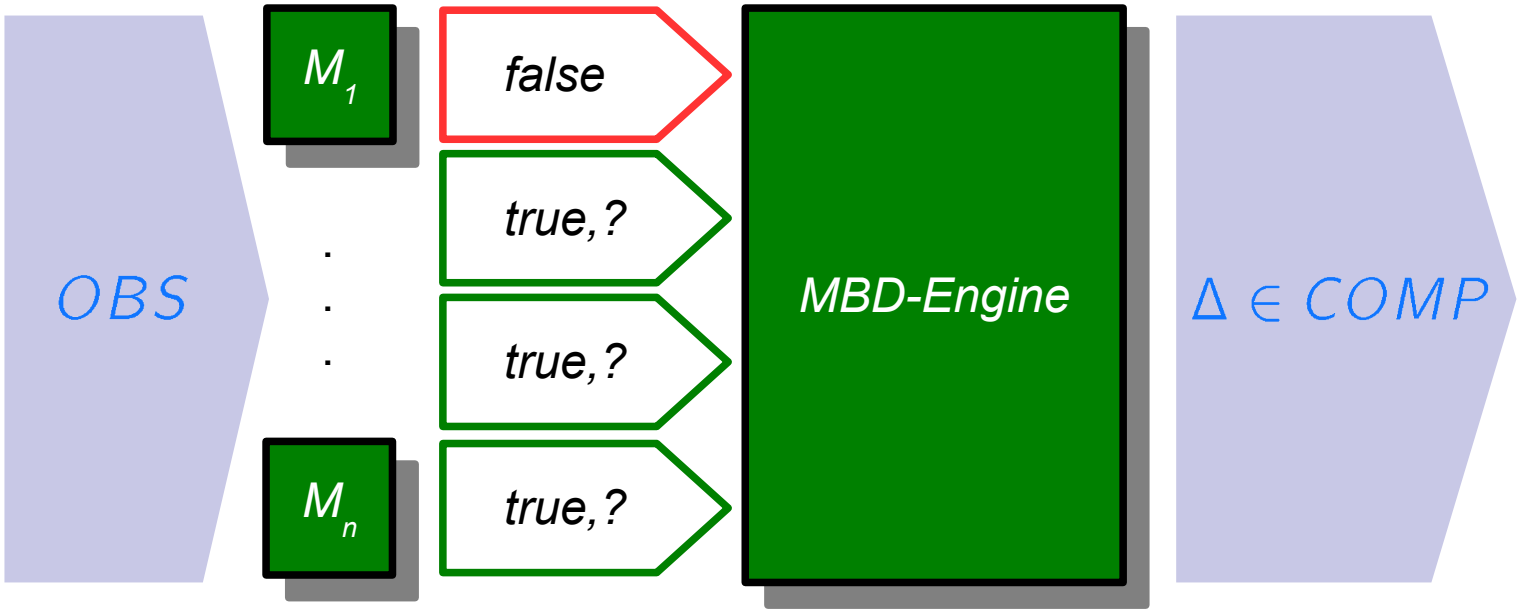


- But, first-order diagnosis is hard!
  - Automatic conflict set determination may not always be possible (e.g., non-termination, HS-problem is NP-hard)
  - Although tailored for it, introduction of "*unknowns*" may result in exponential blowup of conflict search space
- Not laid out for real-time / event-triggered systems
- Ultimately, hard to think of doing all this *continuously* at *runtime*!

Combined analysis



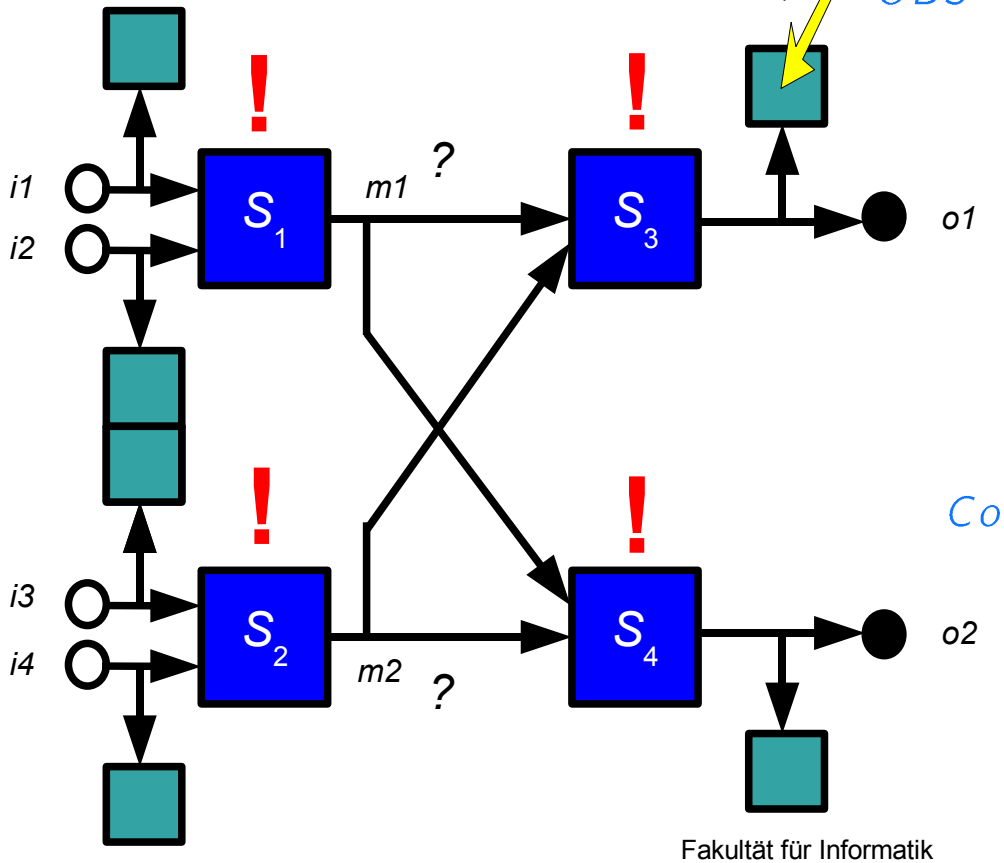
- Diagnosis-on-demand, using the automatically generated monitors as inputs



- Propositional system model, *SD*: *ok*(*M1*), *ok*(*M2*), ...
- Problem still in NP, but powerful algorithms for computing conflicts

Example: where is the fault?

$$SD \in NF(SD) = \left\{ \begin{array}{l} ok(i_1) \wedge ok(i_2) \wedge \neg AB(S_1) \Rightarrow ok(m_1), \\ ok(i_3) \wedge ok(i_4) \wedge \neg AB(S_2) \Rightarrow ok(m_2), \\ ok(m_1) \wedge ok(m_2) \wedge \neg AB(S_3) \Rightarrow ok(o_1) \\ ok(m_1) \wedge ok(m_2) \wedge \neg AB(S_4) \Rightarrow ok(o_2) \end{array} \right\}$$

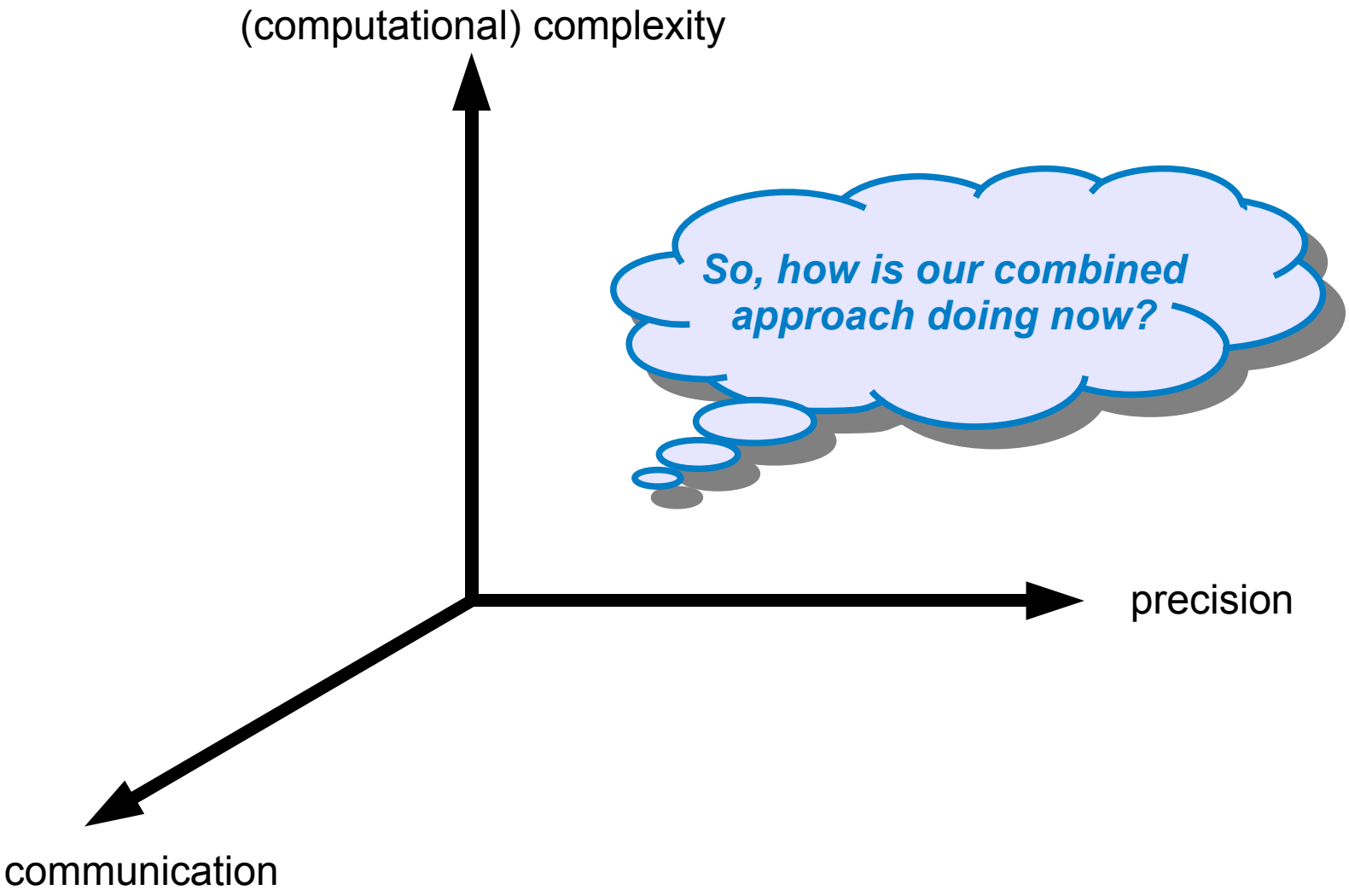


$$OBS = \{i1, i2, i3, i4, \neg o1, o2\}$$

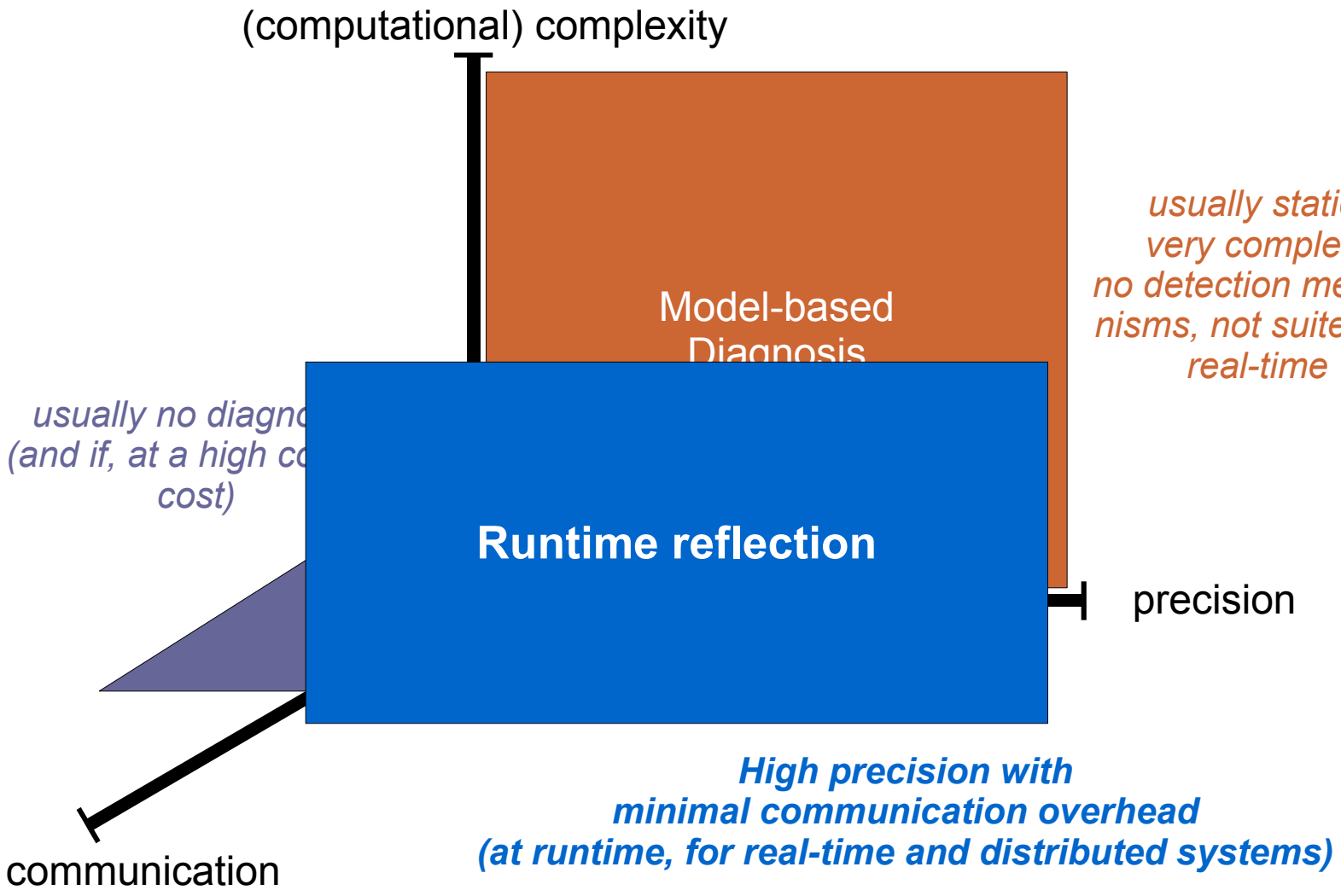
$$SD \cup COMP \cup OBS$$

$$Conf = \left\{ \begin{array}{l} \{S1, S2, S3, \neg S4\}, \\ \{S1, S2, \neg S3, \neg S4\}, \\ \{S1, \neg S2, S3, \neg S4\}, \\ \{S1, \neg S2, \neg S3, \neg S4\}, \\ \{\neg S1, S2, S3, \neg S4\}, \\ \{\neg S1, S2, \neg S3, \neg S4\}, \\ \{\neg S1, \neg S2, S3, \neg S4\} \end{array} \right\}$$

Let's compare!
The three dimensions of runtime analysis



Problems and strengths of methods

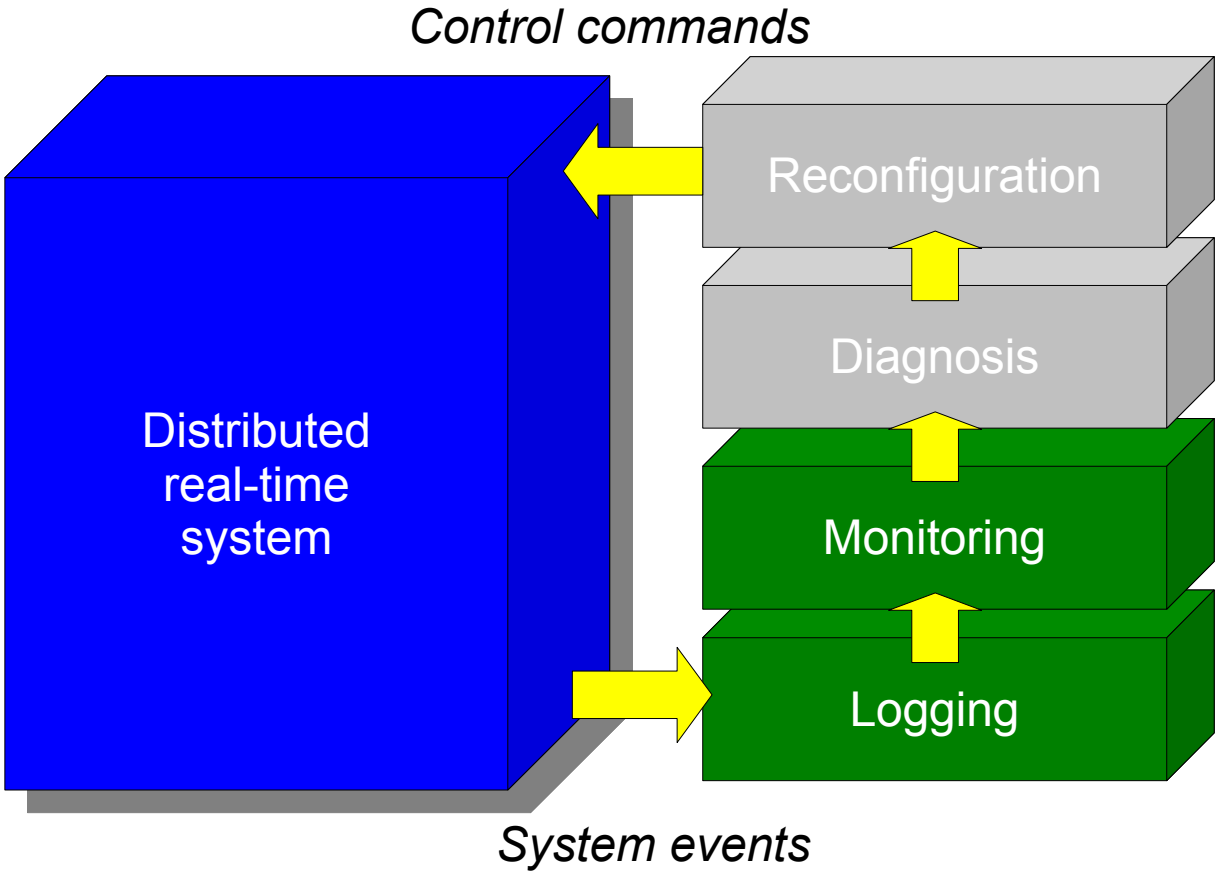


High precision with
minimal communication overhead
(at runtime, for real-time and distributed systems)

Towards conclusion

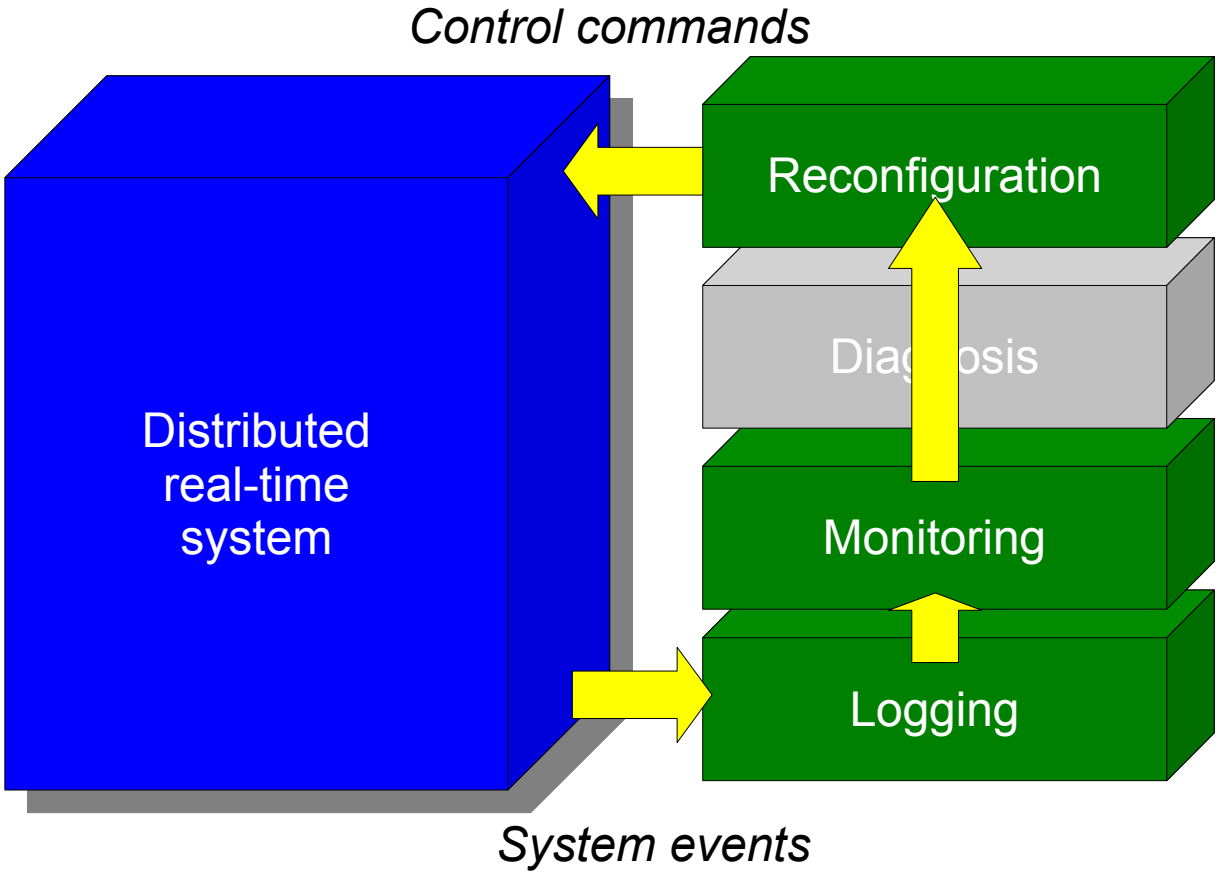
Let's wrap up!

Runtime verification



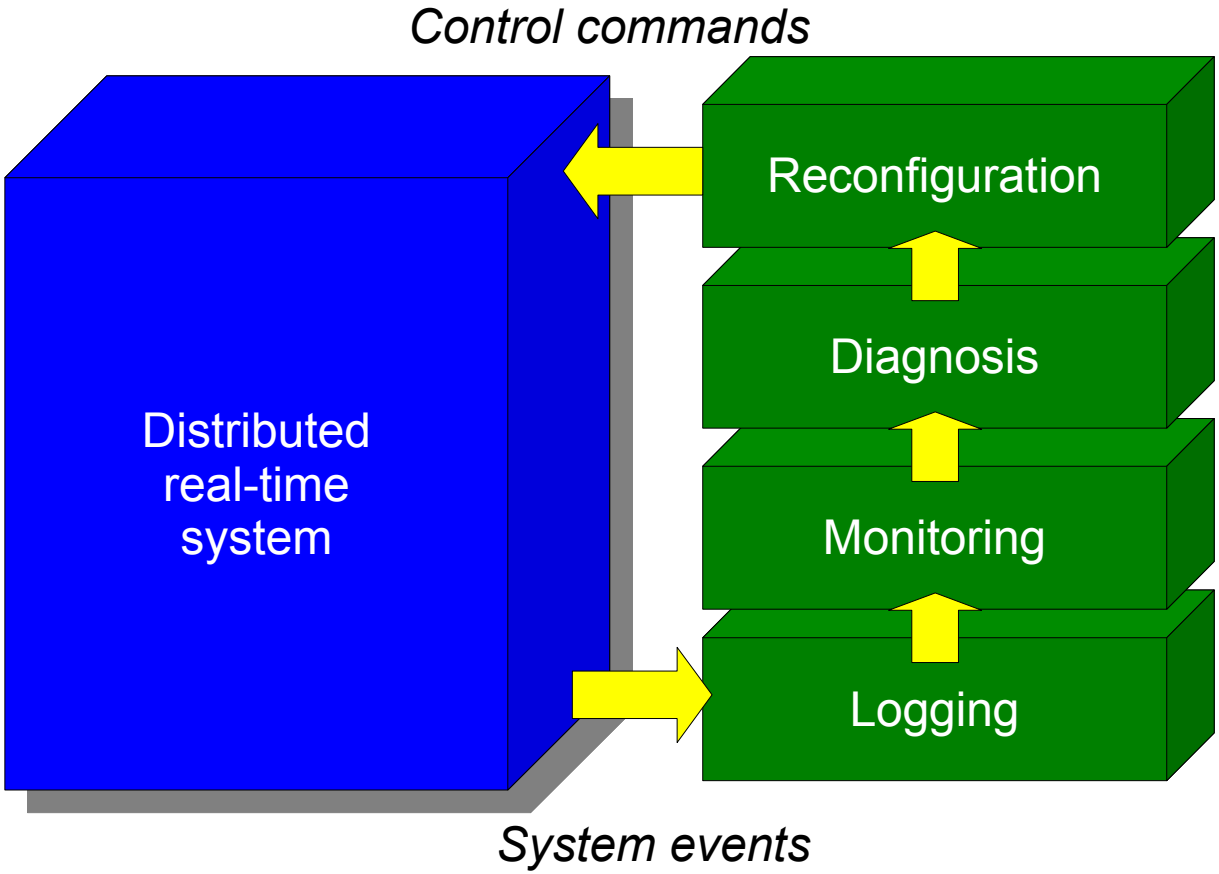
Monitor-oriented programming

- Combination of Runtime Verification with Diagnosis



Runtime reflection

- Combination of Runtime Verification with Diagnosis



Thank you!

- http://runtime.in.tum.de/

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