Verification of Hybrid Controlled Processing Systems based on Decomposition and Deduction

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Introduction and Motivation

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Basic idea: **"divide and conquer"**

The Approach

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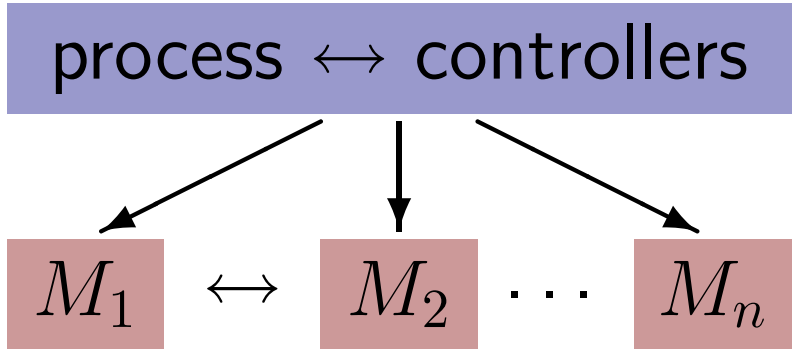
process $\leftrightarrow$ controllers

System

The Approach

Decomposition
(physical, functional)



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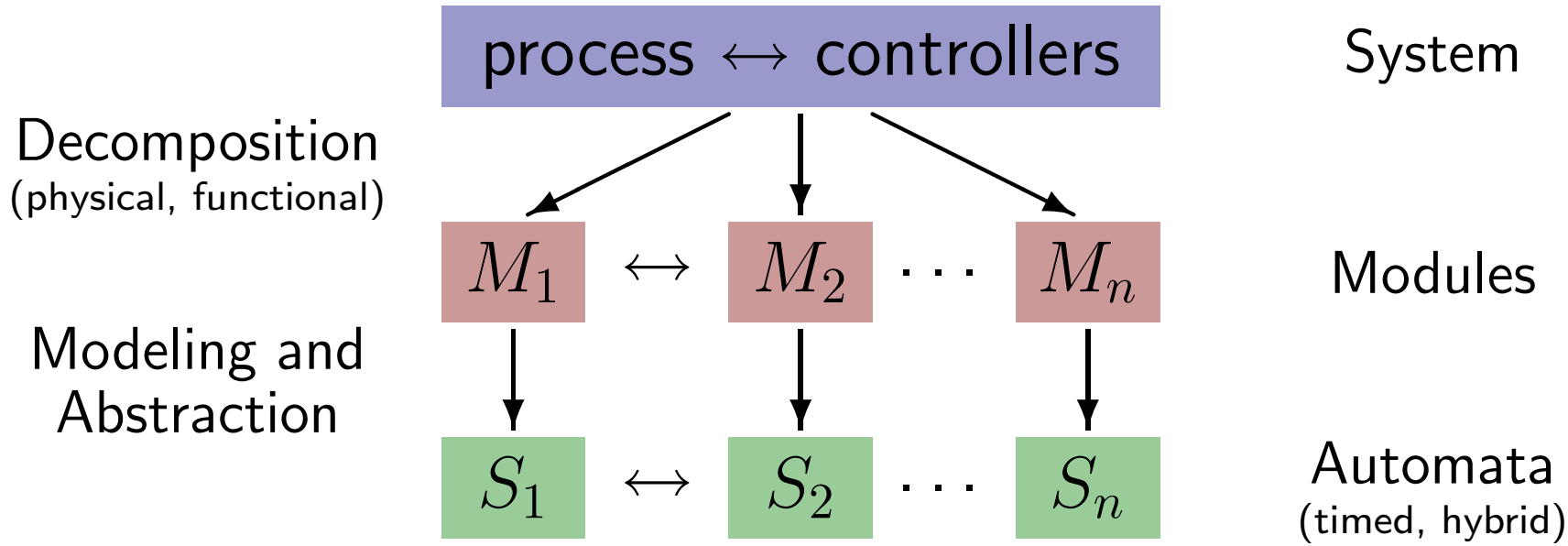

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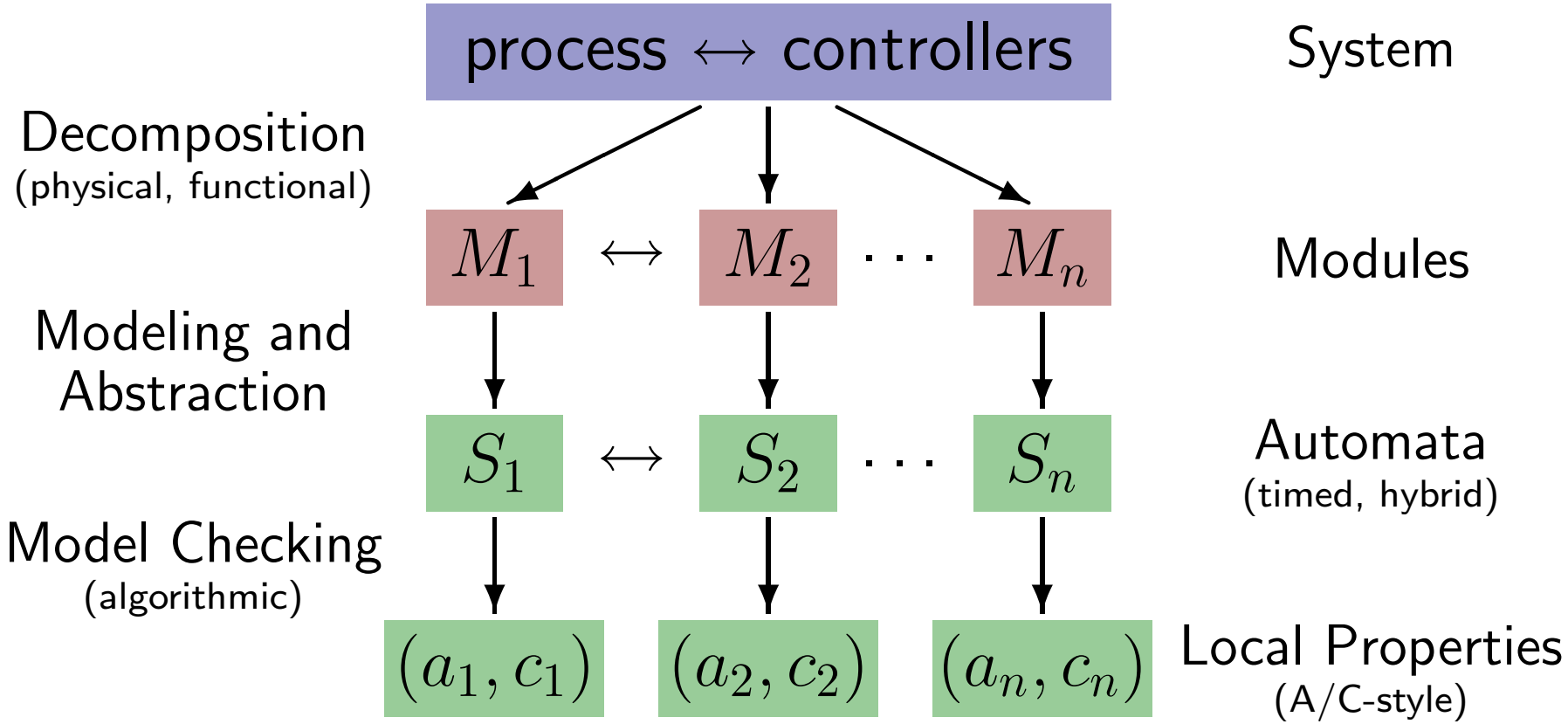

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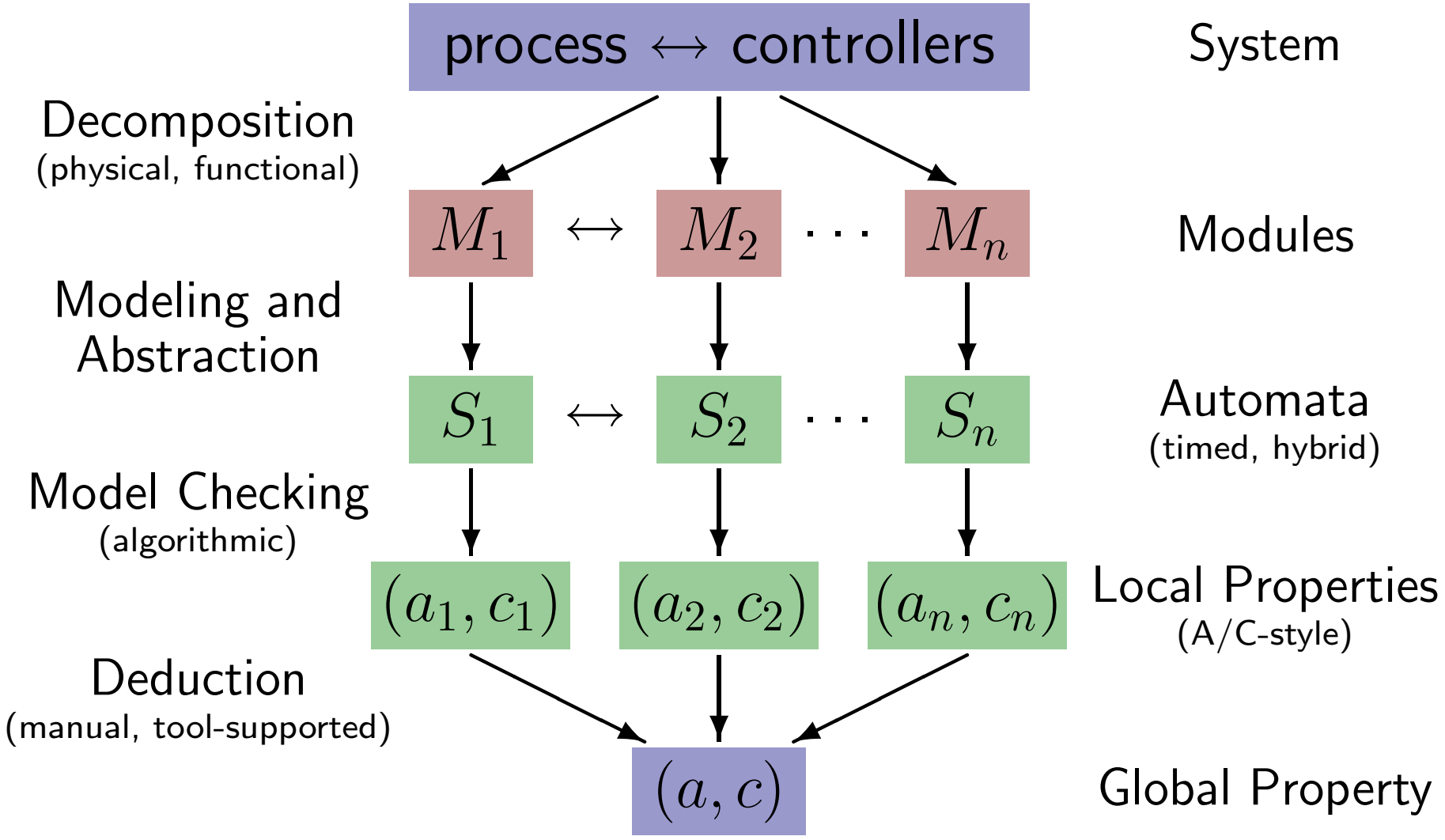
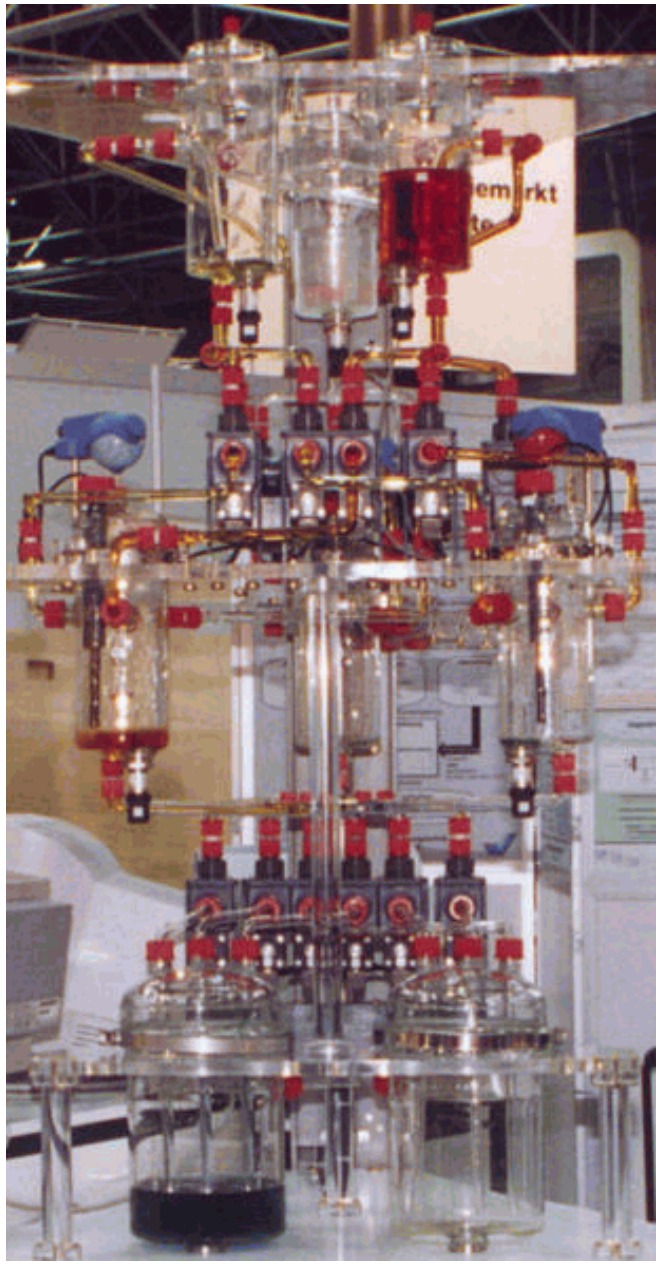


Example: A Multi-Product Batch Plant

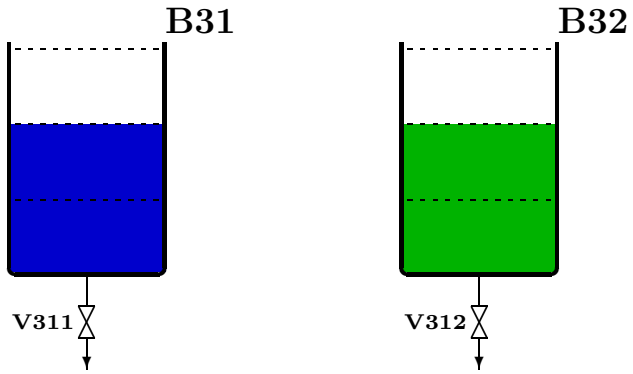
- located at: Process Control Lab, University of Dortmund (Germany)
- chemical batch production process
- used for teaching:
  - process control
  - PLC programming
- case study in research projects:
  - modeling
  - formal verification
  - scheduling



Example: A Multi-Product Batch Plant

- 2 products:

  blue, green



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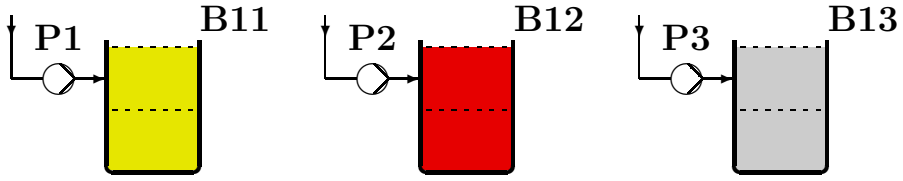

- 2 products:

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- 3 basic substances:

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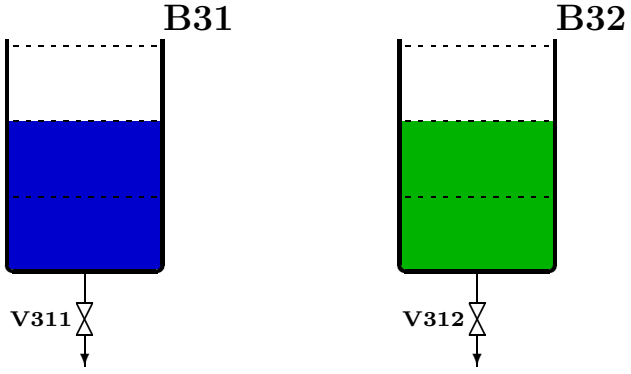

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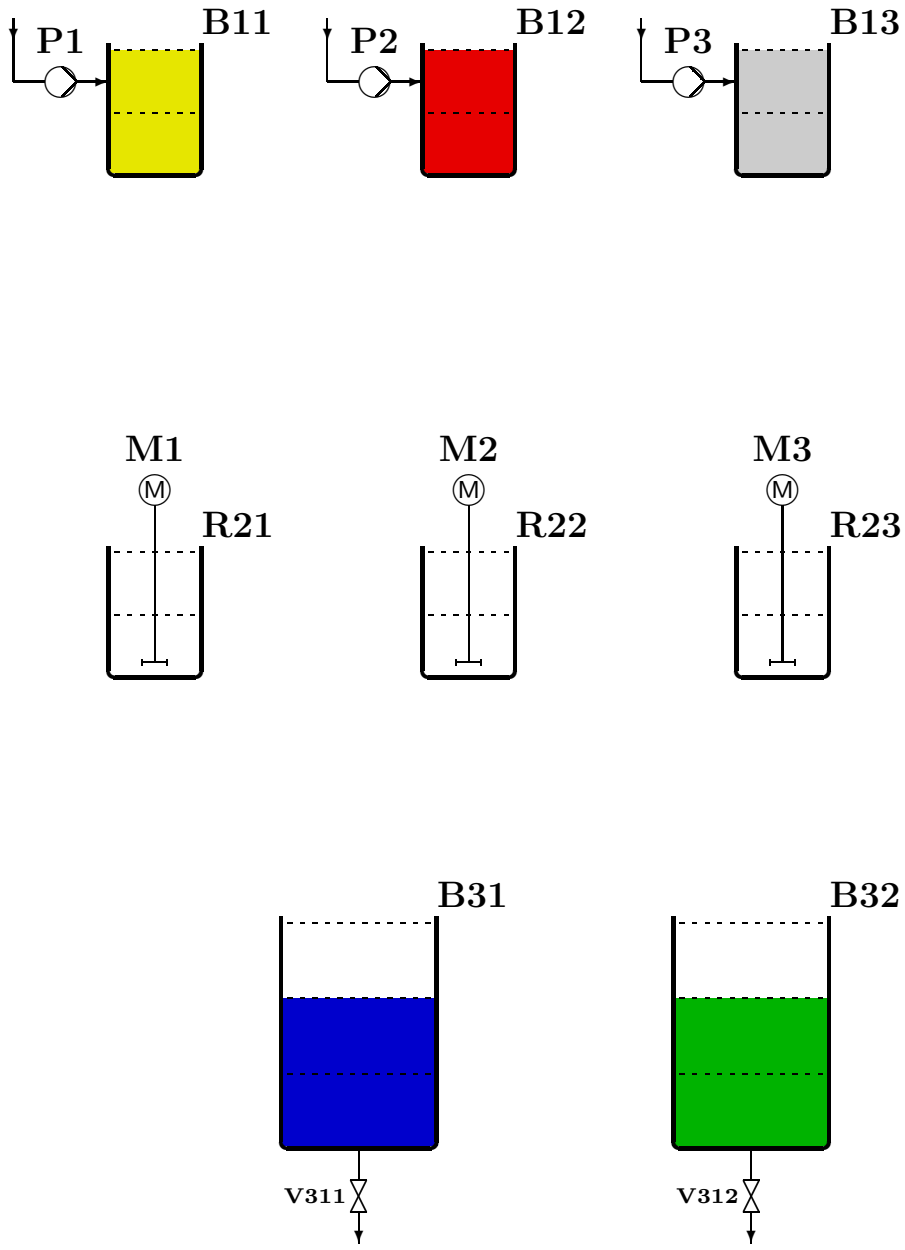

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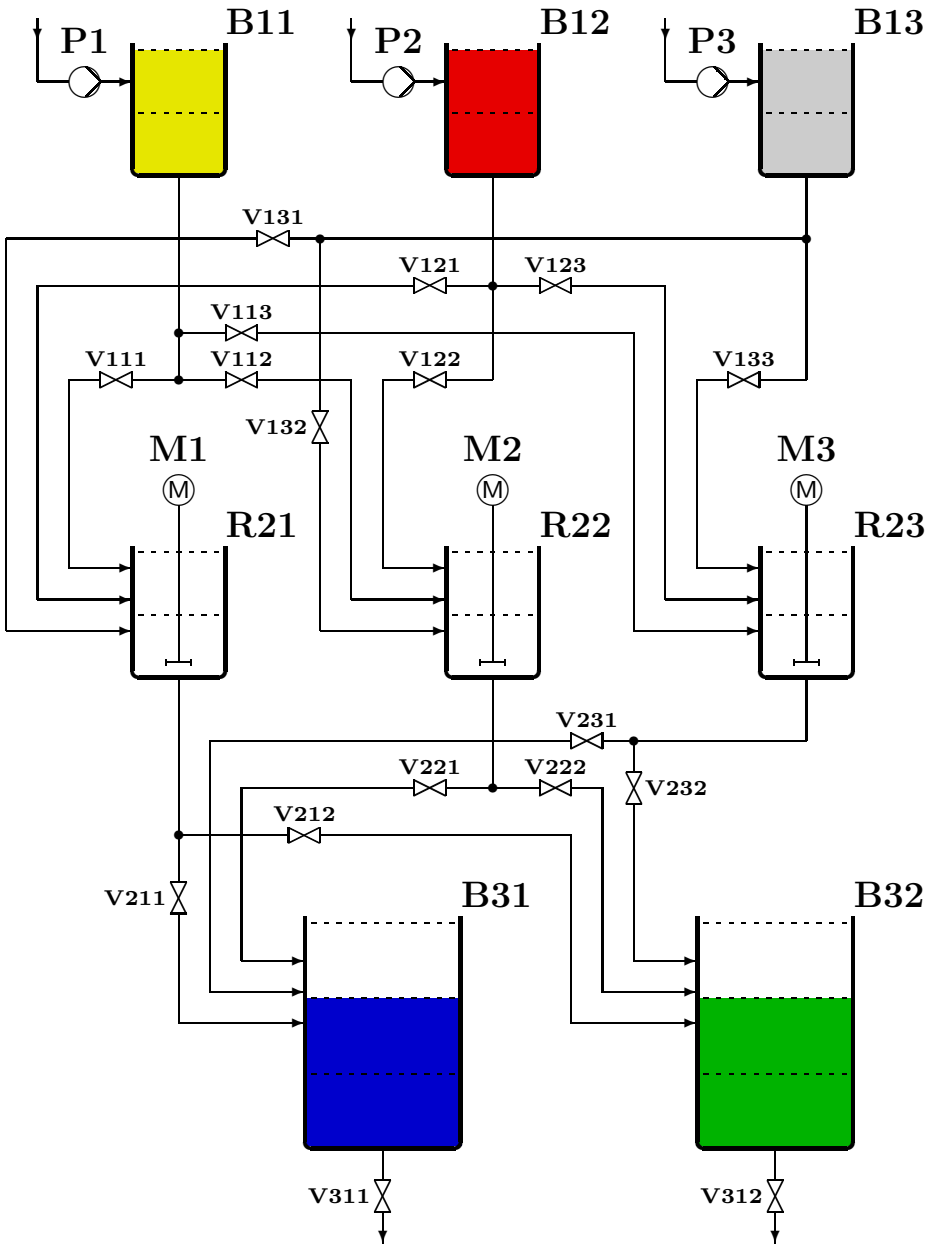

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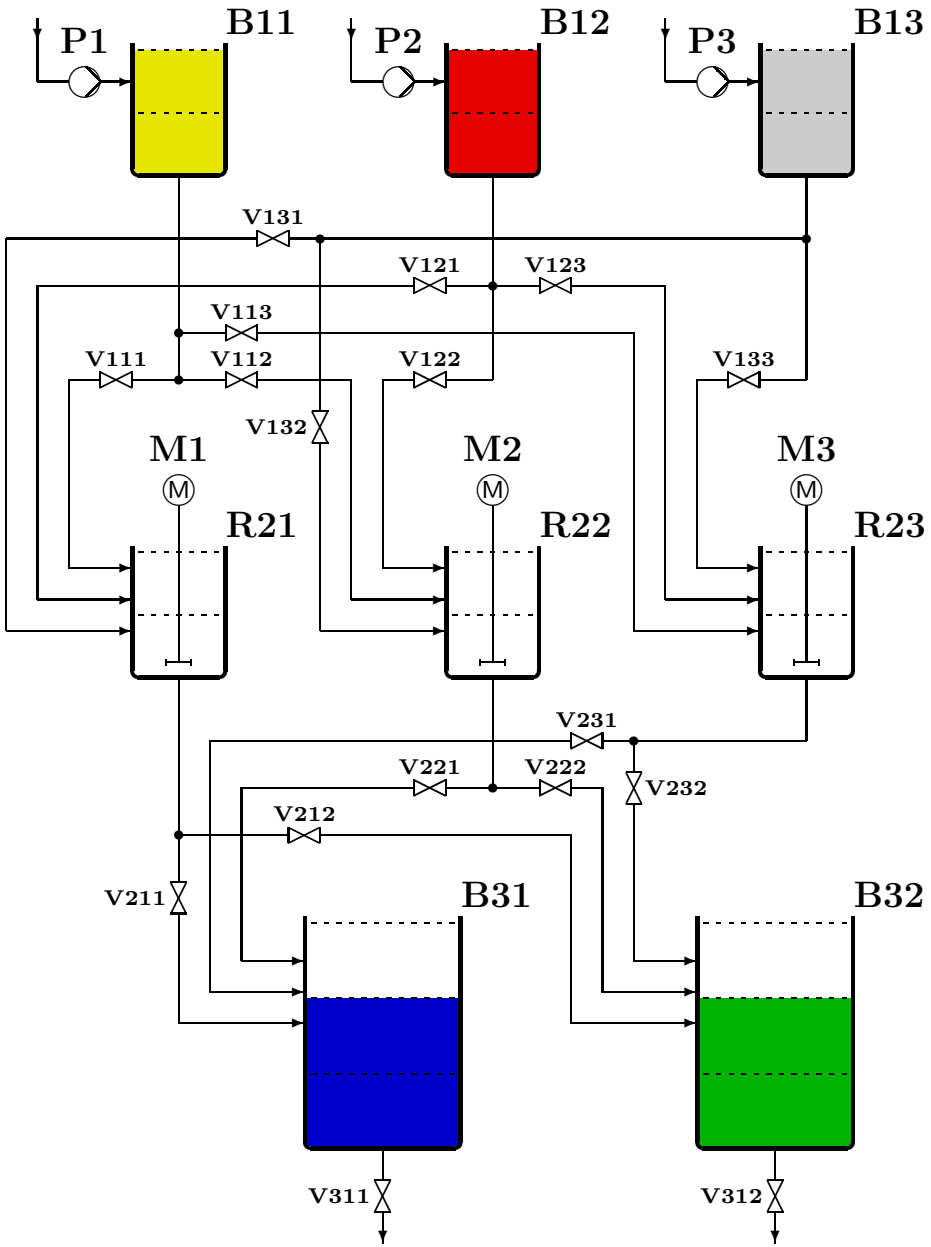

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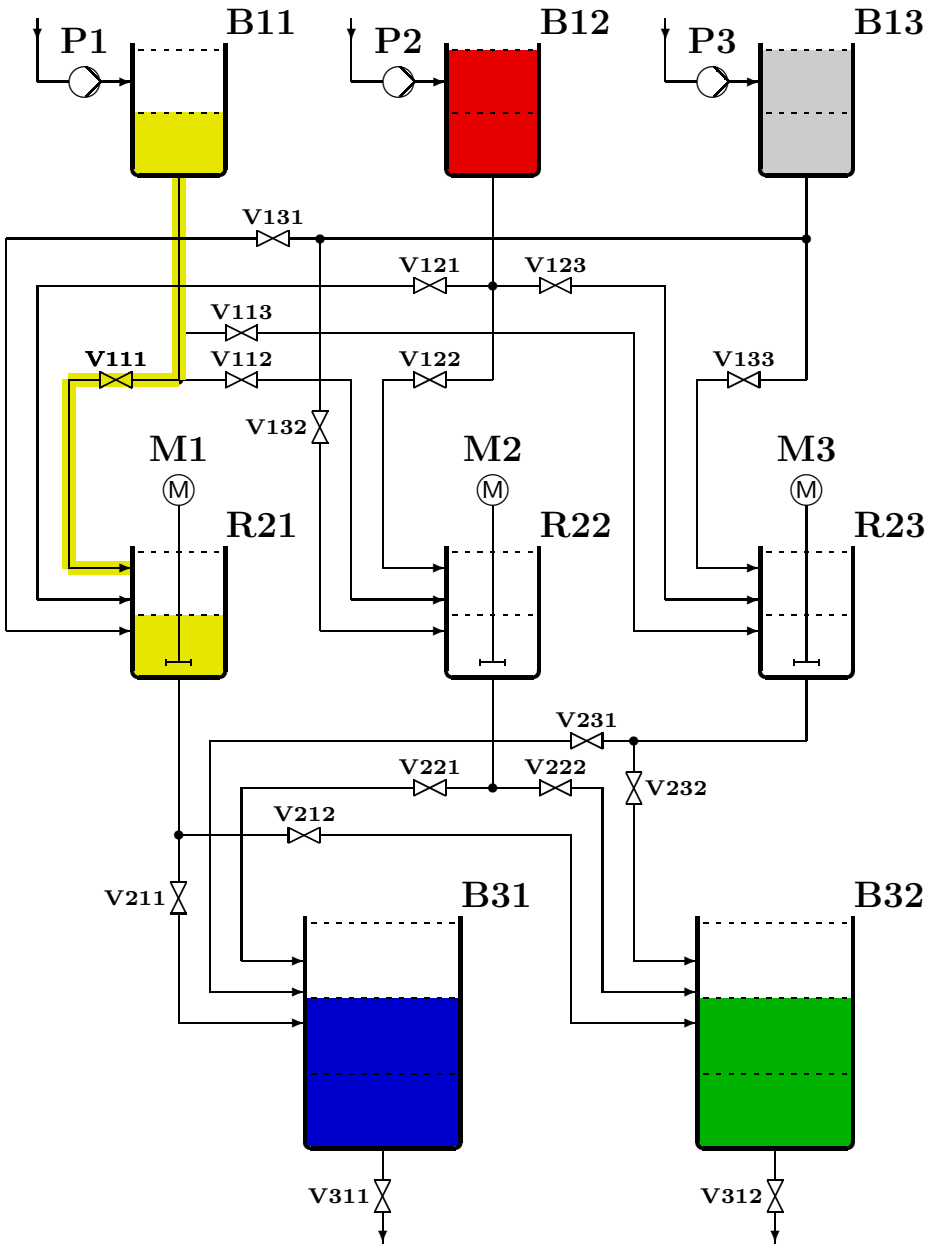

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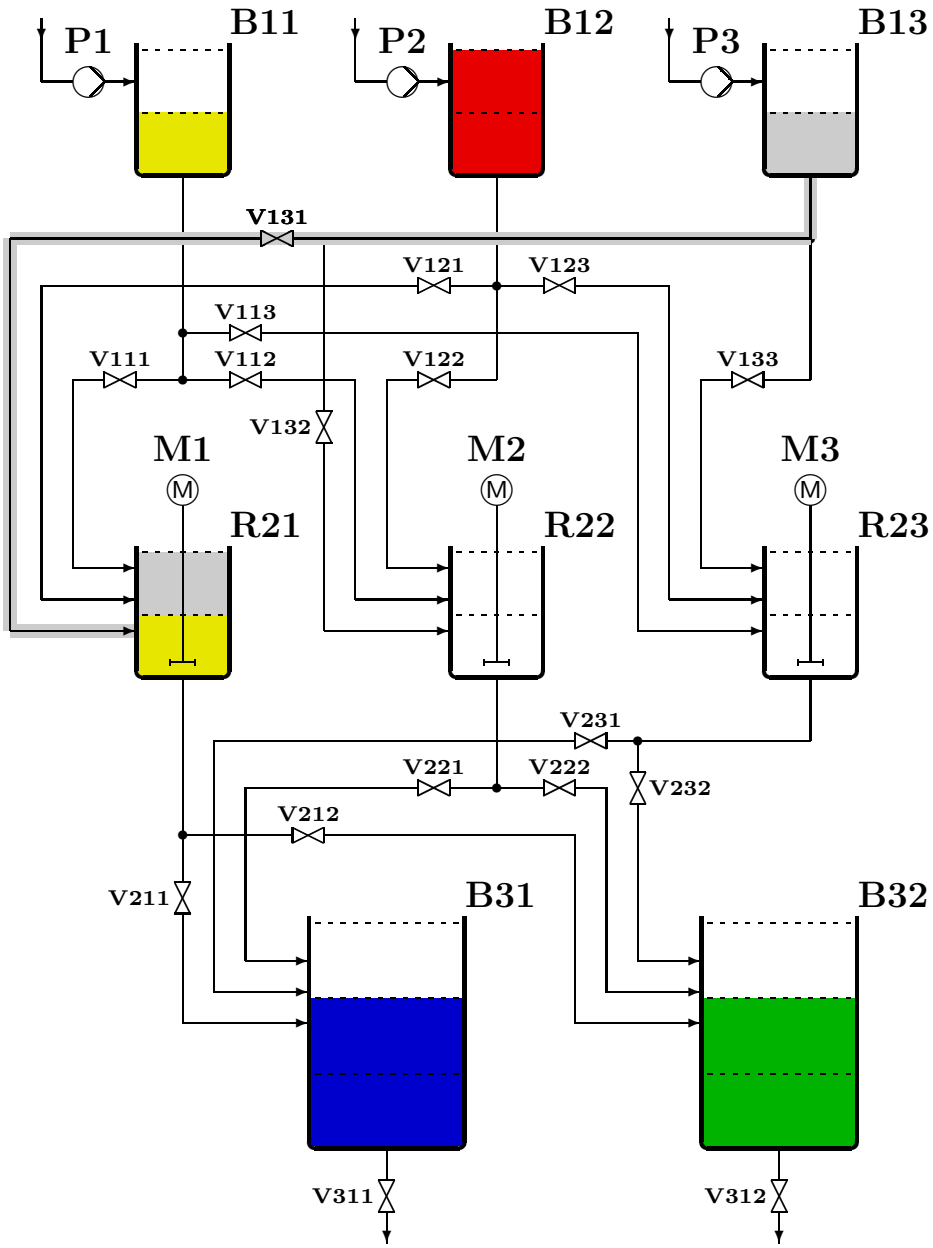

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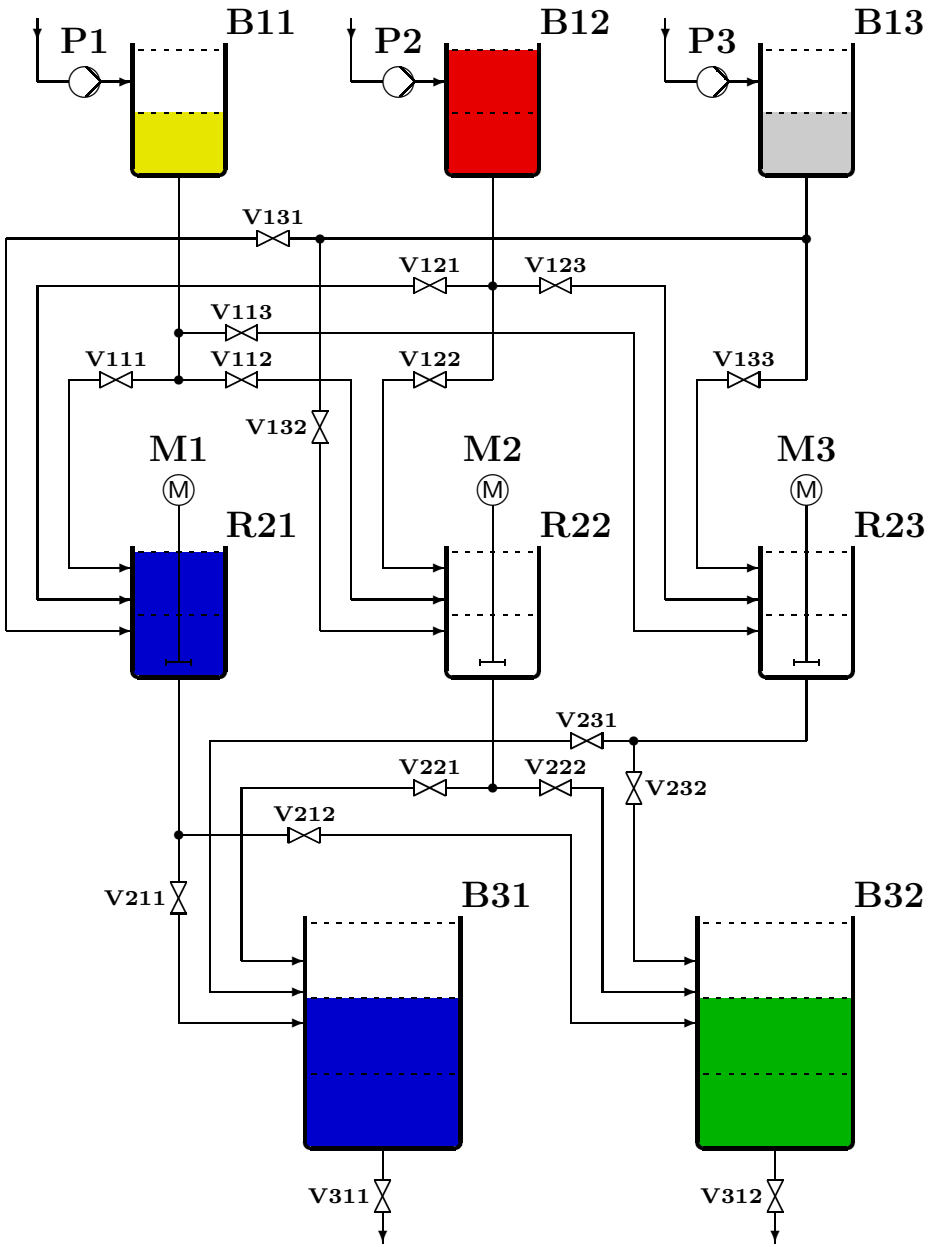

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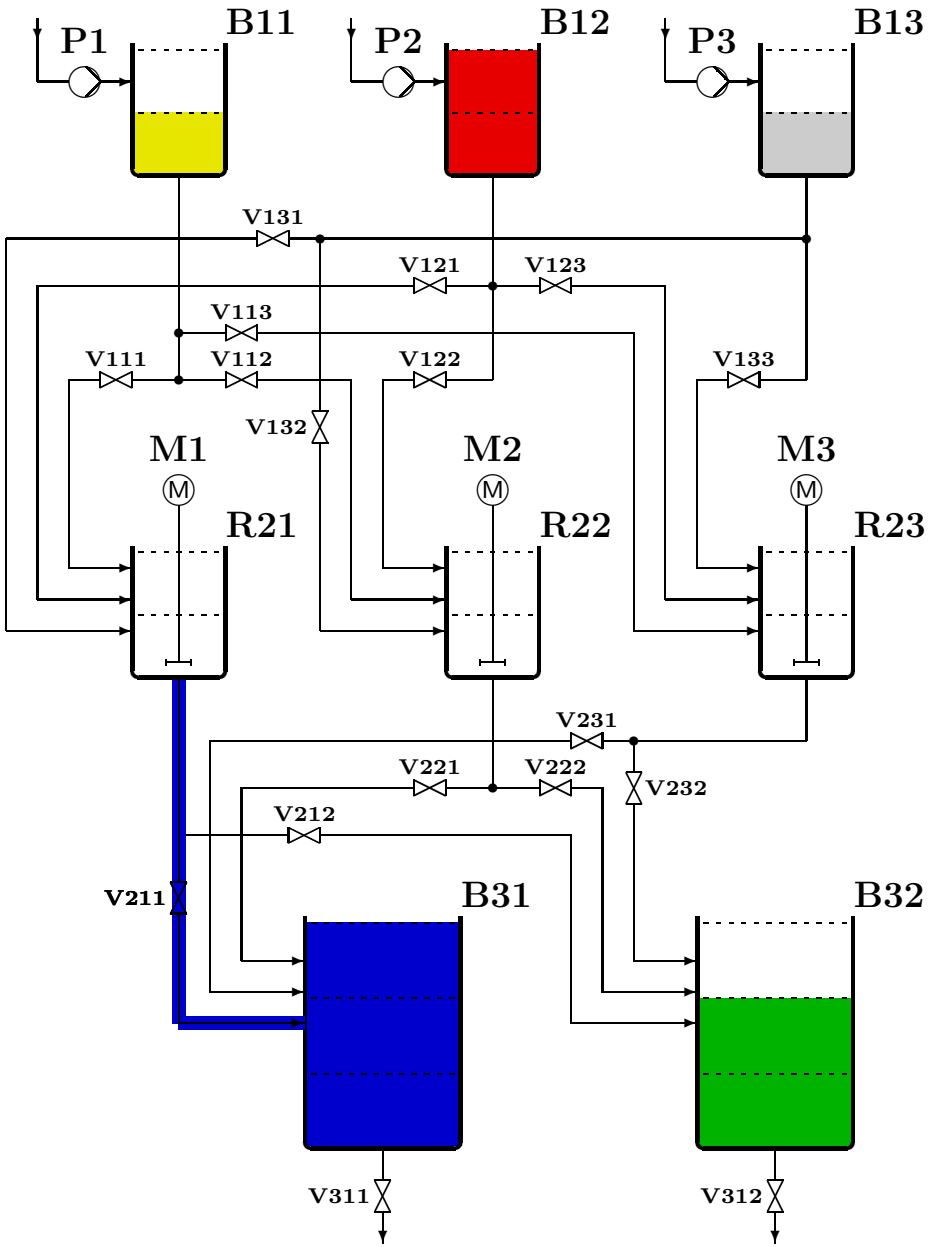

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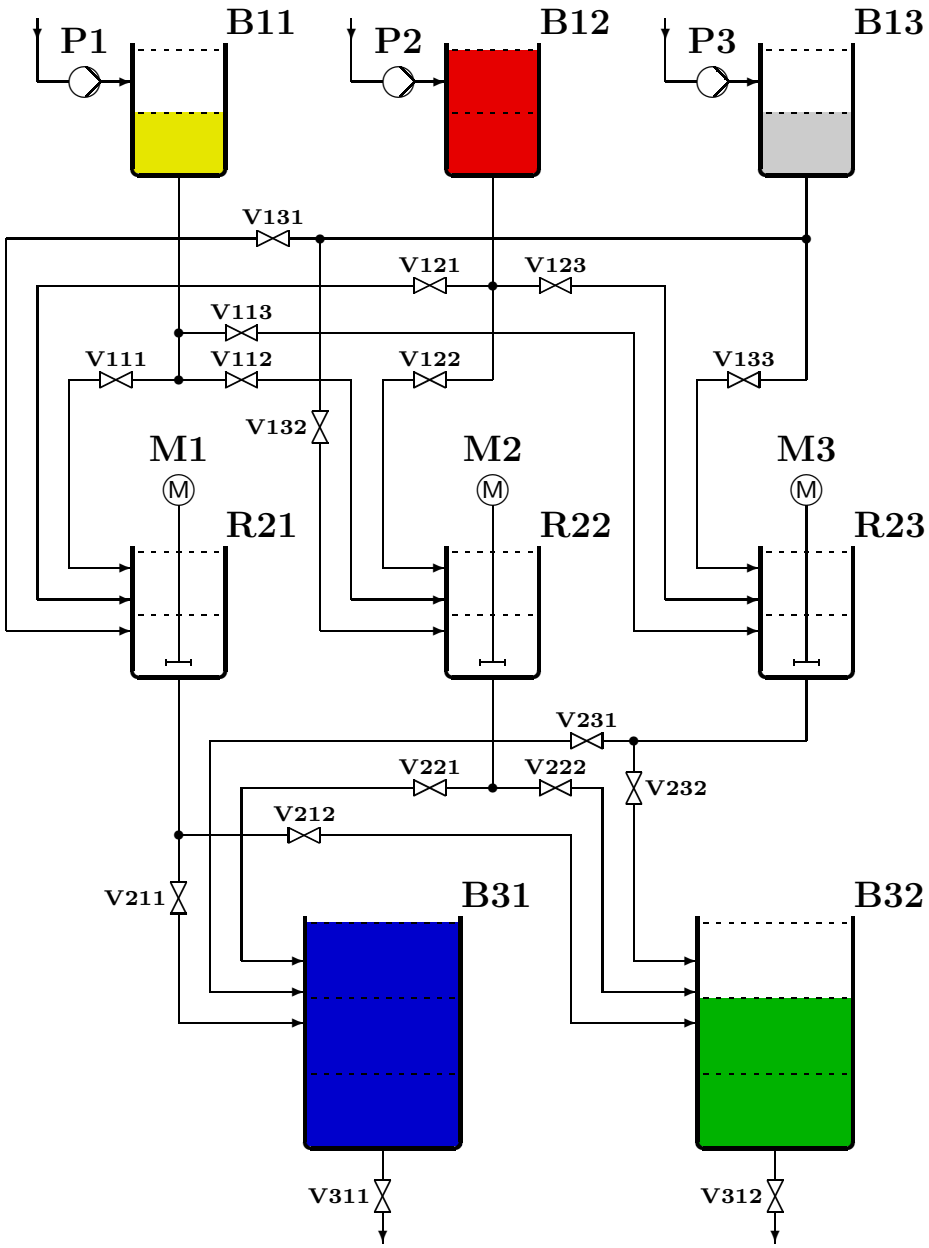

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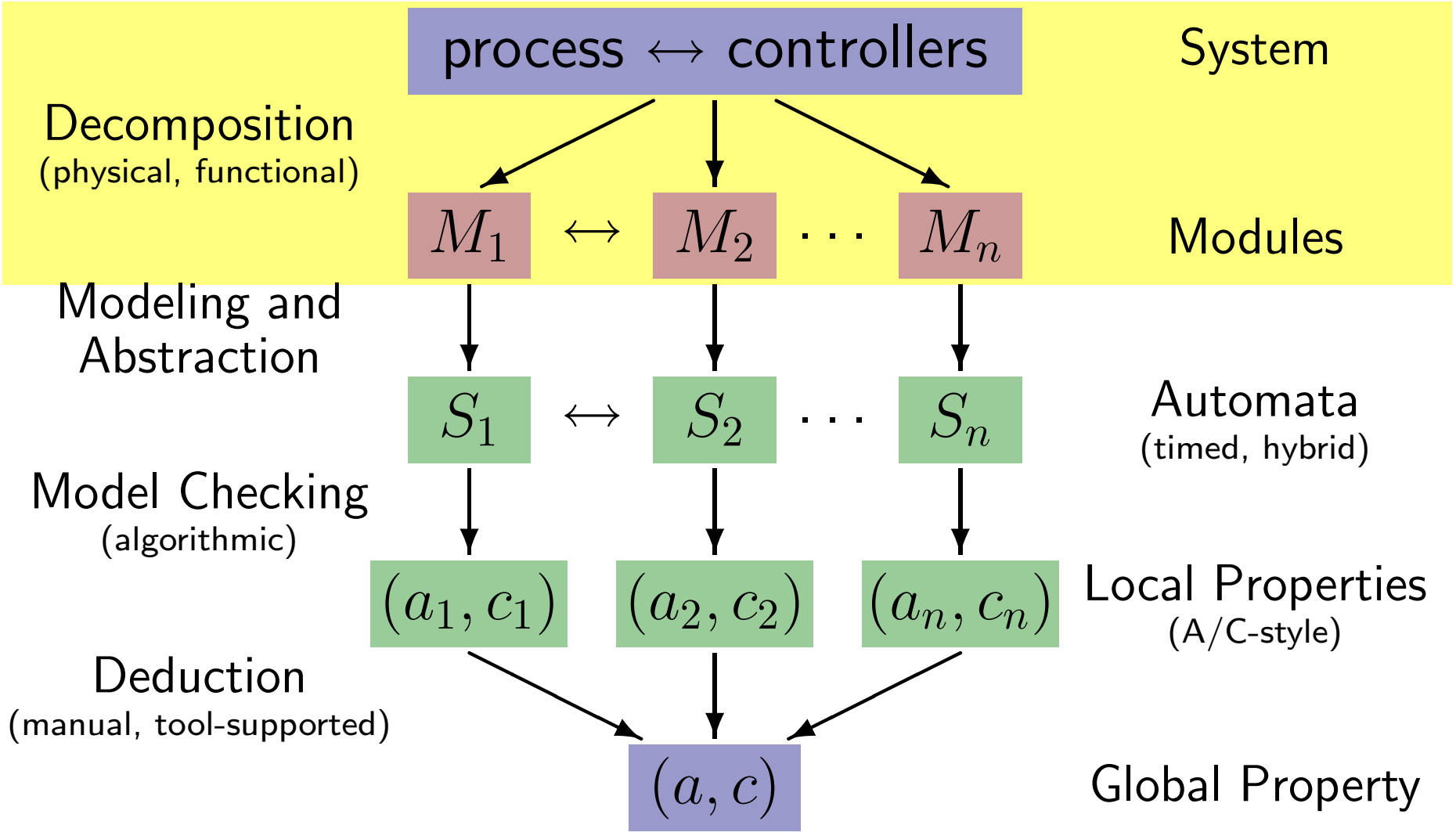

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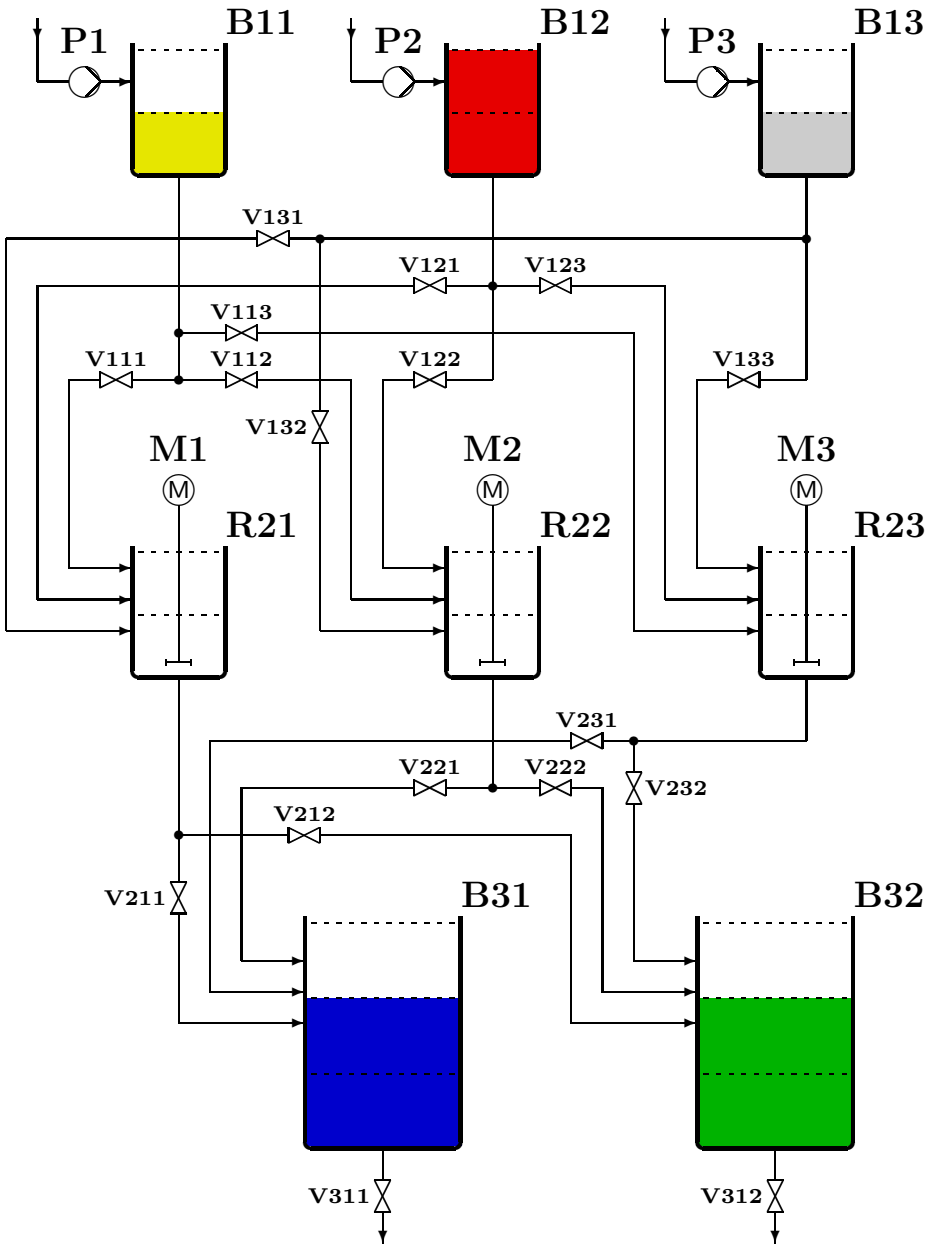
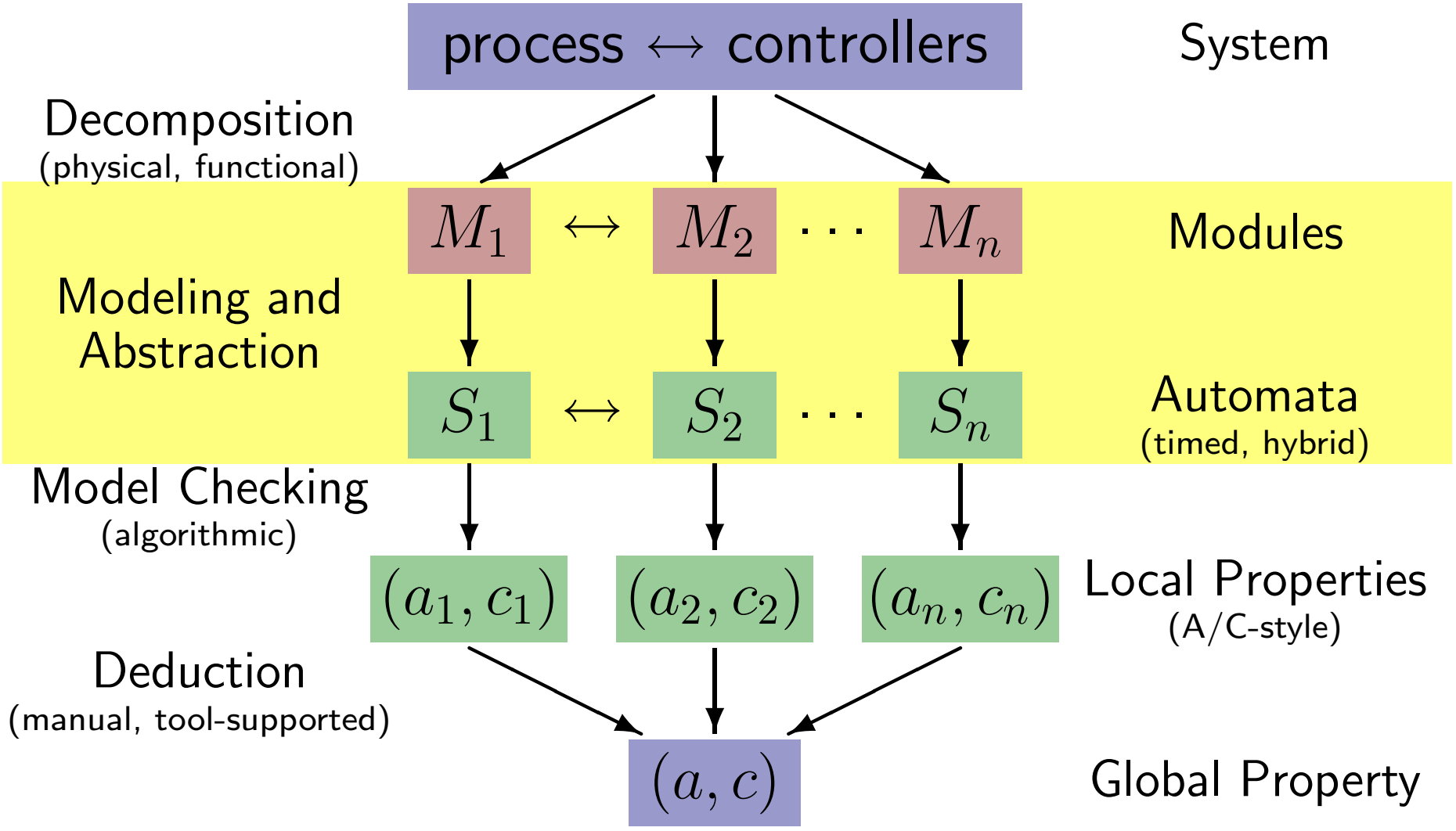


- Plant Hardware
  - tanks, pumps
  - reactors, mixers
  - valves, pipes
  - sensors
- Control Software
  - raw material delivery
  - production
  - resource management
  - emergency shutdown, maintenance, . . .

Modeling and Abstraction



Modeling and Abstraction

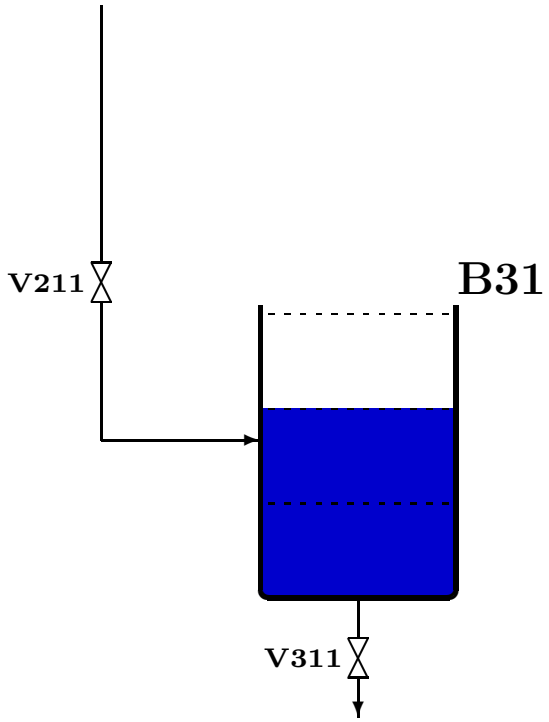
Modeling framework:

communicating linear hybrid automata (CLHA)

CLHA are LHA with

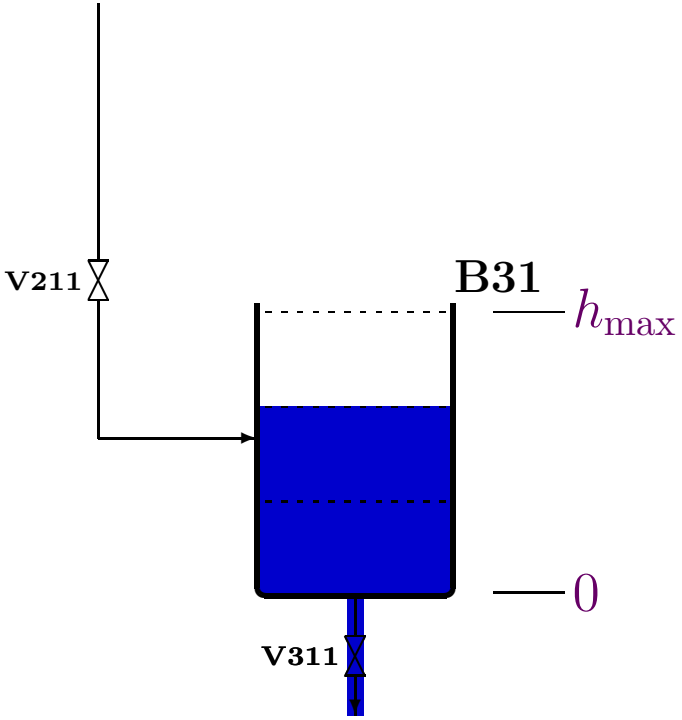
- continuous input/output variables
- labels for directed and undirected communication:
  - *send*
  - *receive*
  - *synchronization*

CLHA model of Tank B31



CLHA model of Tank $\mathrm{B31}$

- draining ($\mathrm{V211}$ closed): level sinks with rate $r_1 = 1\,\mathrm{cm\,s^{-1}}$
- filling ($\mathrm{V211}$ open): level rises with rate $r_2 = 2\,\mathrm{cm\,s^{-1}}$
- desired level: $0 < h < h_{\max}$



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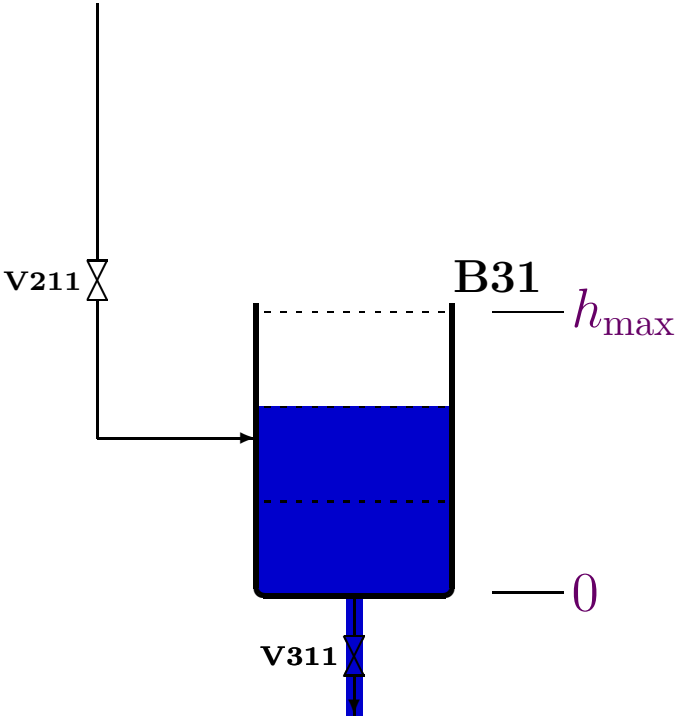
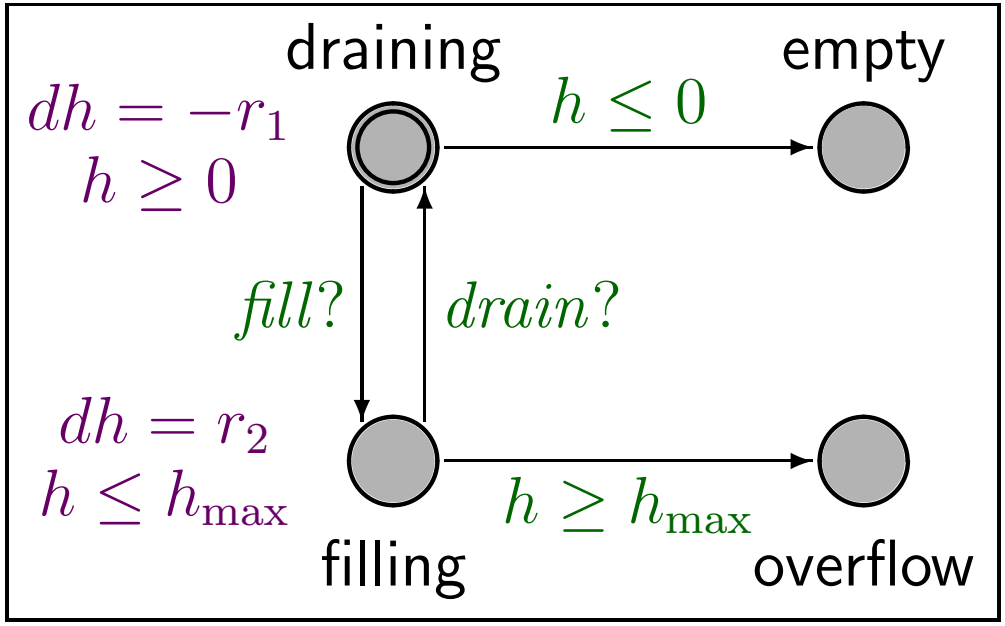
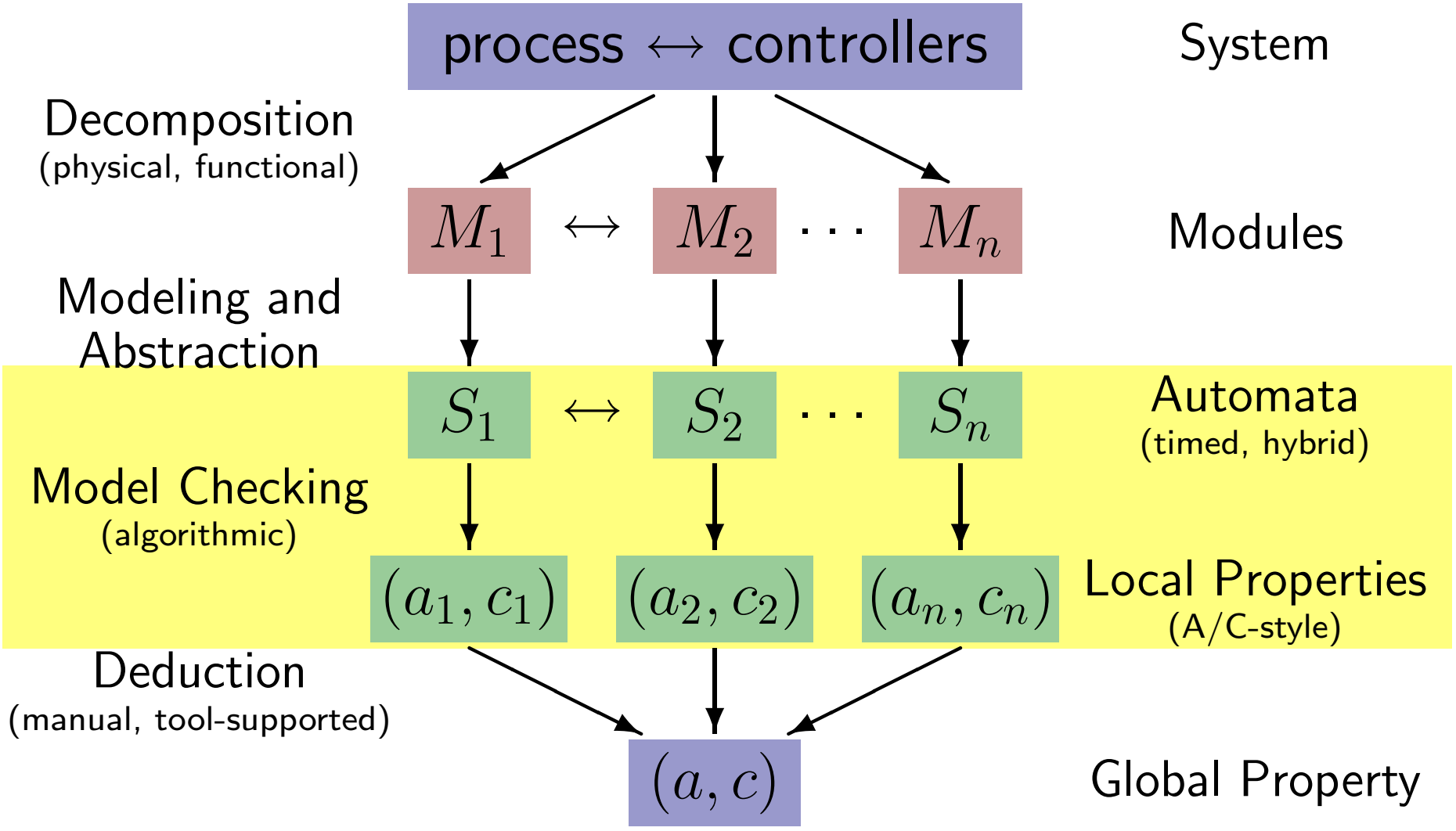




Model Checking



Model Checking

The Assumption/Commitment (A/C) paradigm

assumption a expected behavior of the environment

commitment c guaranteed behavior of the module

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The Semantics of an A/C Formula (a, c)

$S \models (a, c) \iff$ "if the environment of module S fulfills a, then module S fulfills c"

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Example: A/C Property of Tank $\mathrm{B31}$

a "*fill*" happens before $h \leq 0$ and "*drain*" before $h \geq h_{\max}$

c Tank $\mathrm{B31}$ does not run empty and does not overflow

Model Checking

Verifying $\mathrm{B31} \models (a, c)$

Model checkers usually do not support A/C directly, but:

- a can be expressed as another automaton A
  (sending "$fill$" and "$drain$" at the right time)
- c can be expressed as the reachability property
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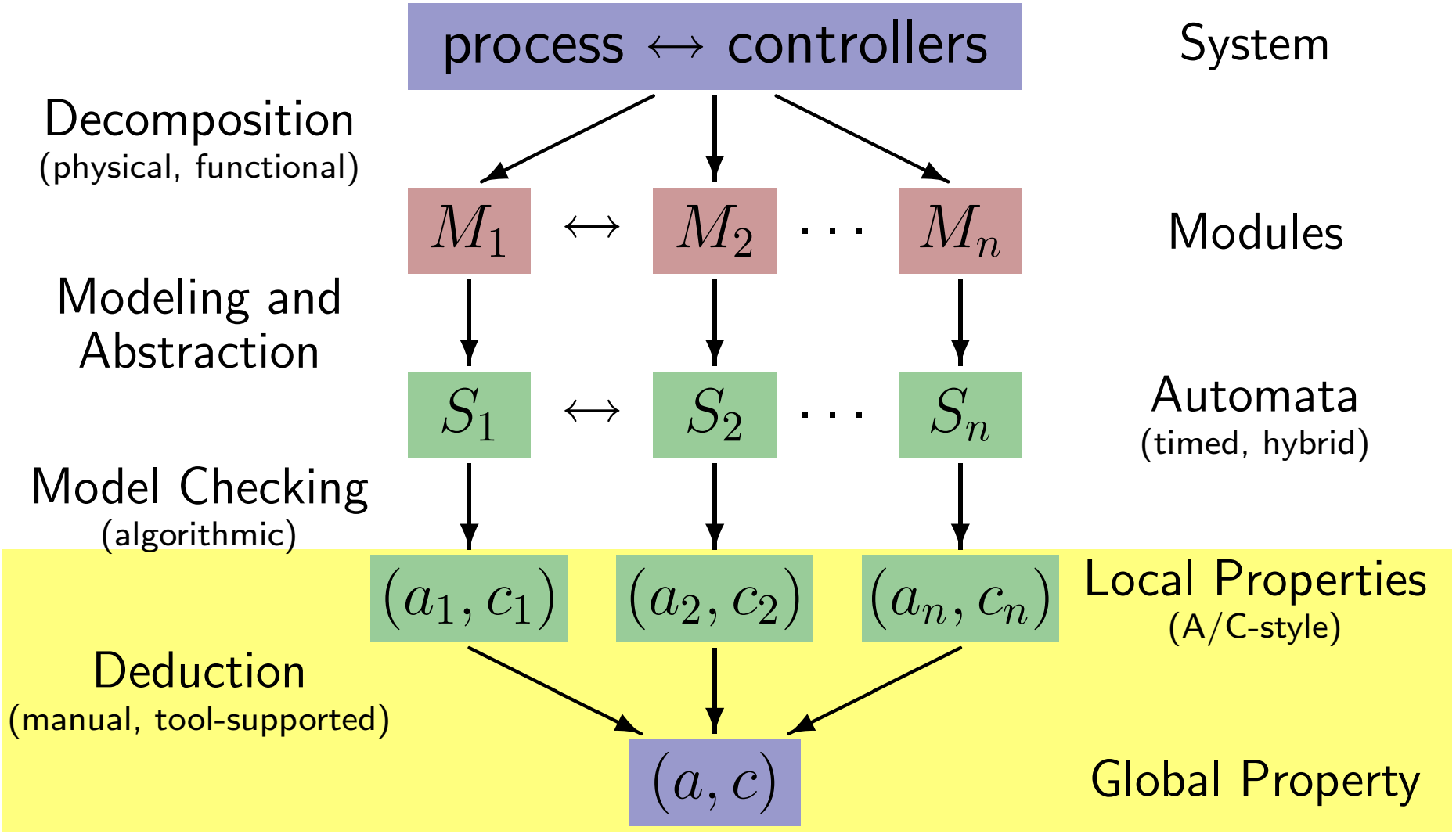
Now use a hybrid model checker to show

$$\mathrm{B31} || A \models \neg reach(\mathsf{empty}) \wedge \neg reach(\mathsf{overflow})$$

A is much smaller than the full environment of $\mathrm{B31}$

$\Rightarrow$ **model checking becomes feasible**

Deduction


process ↔ controllers
System
Decomposition
(physical, functional)
M_1 ↔ M_2 ⋯ M_n
Modules
Modeling and
Abstraction
S_1 ↔ S_2 ⋯ S_n
Automata
(timed, hybrid)
Model Checking
(algorithmic)
(a_1, c_1) (a_2, c_2) (a_n, c_n)
Local Properties
(A/C-style)
Deduction
(manual, tool-supported)
(a, c)
Global Property

Deduction

Given

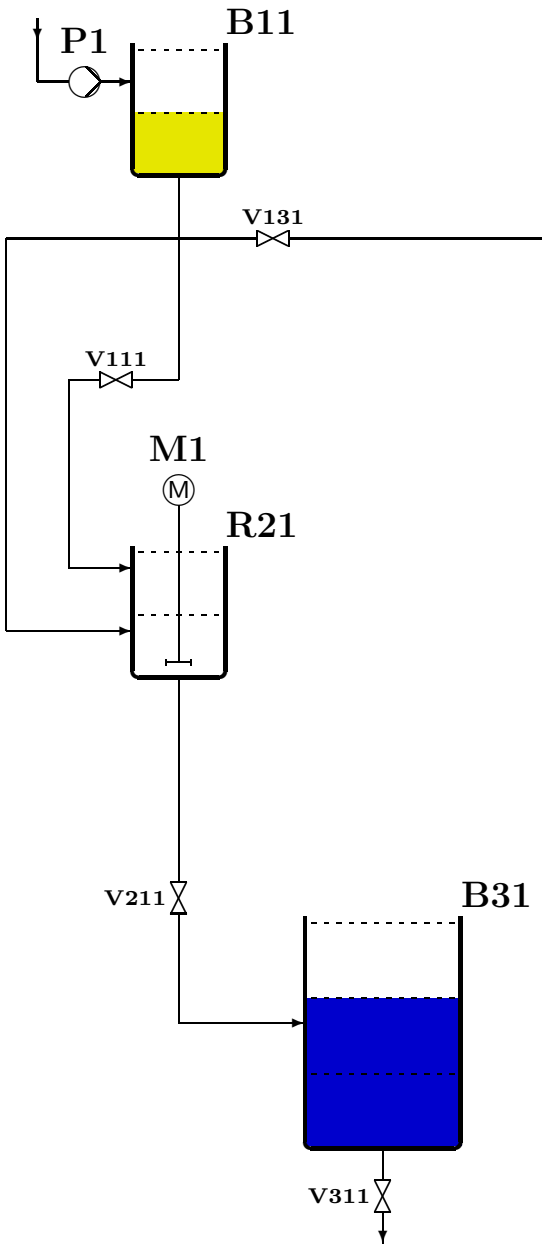
- the **local properties** $S_1 \models (a_1, c_1)$, ..., $S_n \models (a_n, c_n)$
- additional conditions B

we use **deductive analysis** to derive

- a **global property** (a, c) of the system.

A theorem prover (e.g., PVS) can be used to support the analysis.

Deduction



a_{B11} P1 can deliver yellow to B11

c_{B11} yellow is available for R21

a_{B13} P3 can deliver white to B13

c_{B13} white is available for R21

a_{R21} yellow and white are available for R21

c_{R21} R21 contains blue in time

a_{Ctrl} R21 contains blue in time

c_{Ctrl} "*fill*" happens before $h \leq 0$

...

a P1 and P3 can deliver raw materials

c B31 does not run empty

Computation Results

Verifying a part of the multi-product batch plant

Method	Memory	Time
conventional	70 MB	600 sec.
A/C (17 specs)	17× $<$1 MB	17× $<$10 sec.

Related Work

- Hungar (1993)
  A/C and data abstraction for CSP programs
- Dingel, Filkorn (1995)
  A/C and data abstraction for infinite state systems
- Xu, Swarup (1998)
  A/C in Hoare logic and duration calculus
- de Alfaro, Alur, Grosu, Henzinger, Kang (2000)
  A/G and refinement for reactive modules
- Henzinger, Minea, Prabhu (2001)
  A/G for hierarchical hybrid systems
- Amla, Emerson, Namjoshi, Trefler (2001)
  A/G for synchronous transition diagrams
- Shankar (2000) The SAL framework