Introduction to Model Checking

https://clegra.github.io/mc.html

Lecture 1

Clemens Grabmayer
https://clegra.github.io

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Department of Computer Science

GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

January 26, 2026

Organization

Lectures (Clemens 4 / Emilio 3)

- this week:
  - Monday, 10.30−12.30, room B, Aurora
  - Tuesday, 14.30−16.30, P-2.6, Zenith
  - Thursday and Friday, 14.30−16.30, conference room -1, Zenith

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Exam (more later)

- options:
  - small verification project (of an algorithm, e.g. in Maude)
  - presentation about a paper
  - written exam?

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- (partial model checking)
  - (partially known systems (state properties/states/transitions))

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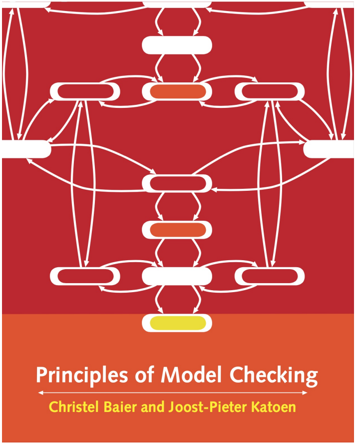
Course Goals are introduction to:

- Theory:
  - modeling systems by labeled transition systems,
  - expressing properties by temporal-logic formulas
  - model-checking algorithms
- Practice related: see Maude examples

Book



- pdf online available (see [1])
- we study chapters 1–3, 5, 6

Lectures

1. Introduction (preview extended, LTSs)
2. Modeling by labeled transition systems
   - executions; traces; non-determinism; examples
3. Linear-Time Behaviour and Properties
   - invariant, safety, and liveness (and fairness) properties
4. Linear Temporal Logic (LTL)
   - syntax and semantics; interpretation of LTSs; examples
5. LTL (continued)
   - model checking of LTL formulas, and fairness in LTL
   - Maude examples
6. Computation Tree Logic (CTL)
   - syntax and semantics, examples
7. Extensions of CTL, and Outlook
   - expressibility differences with LTL
   - model checking formulas in CTL
   - (μ-calculus | partial model-checking | Maude examples)

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  - \+ also possible for infinite-state system

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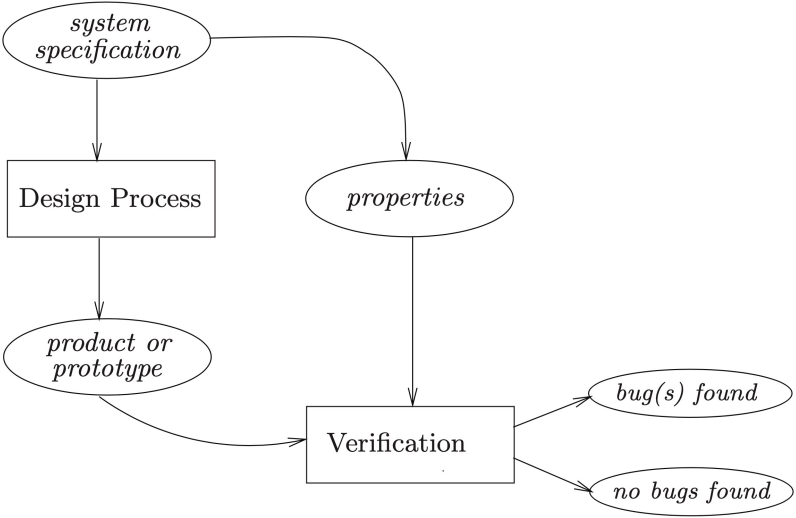
Hard-/Software Verification (traditionally)



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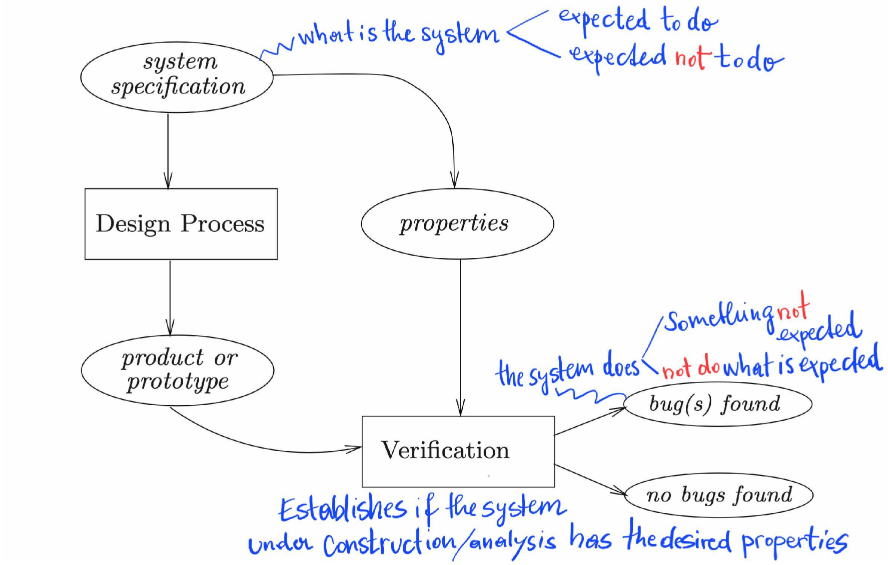

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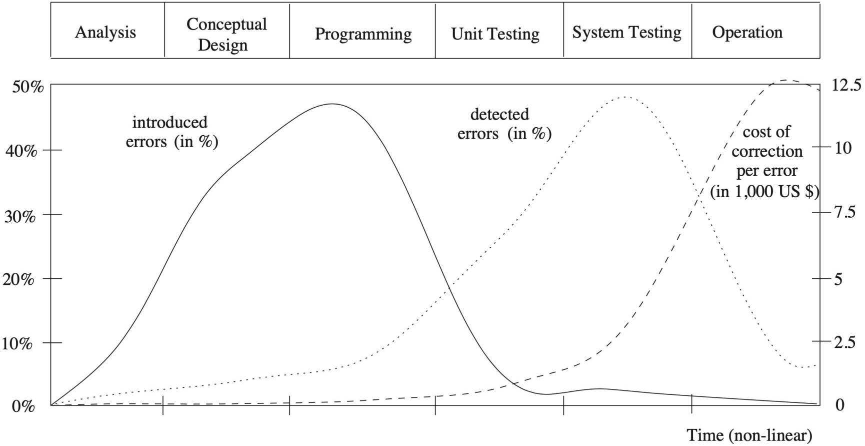
- Catching software errors: the sooner the better.

Software lifecycle, error introduction/detection, repair costs



Liggesmeyer et al: “Qualitätssicherung technischer Systeme . . .” [4, 1998]

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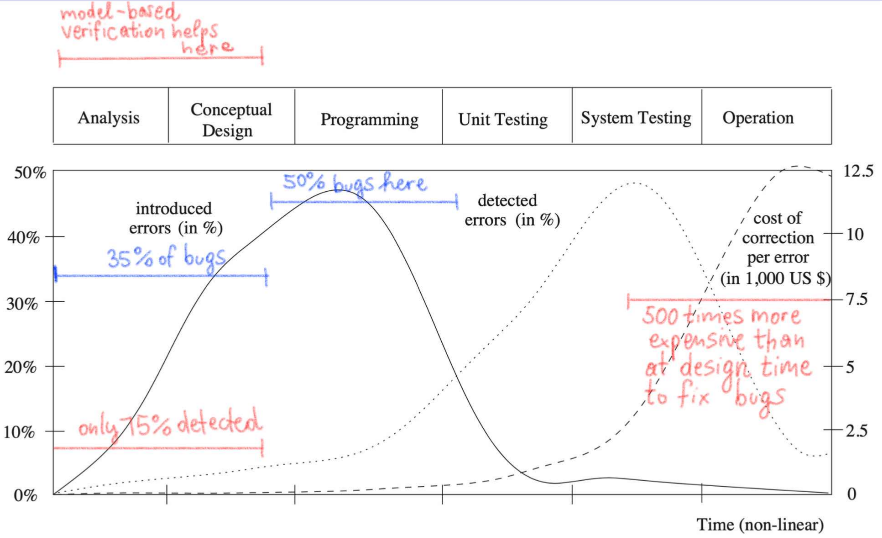

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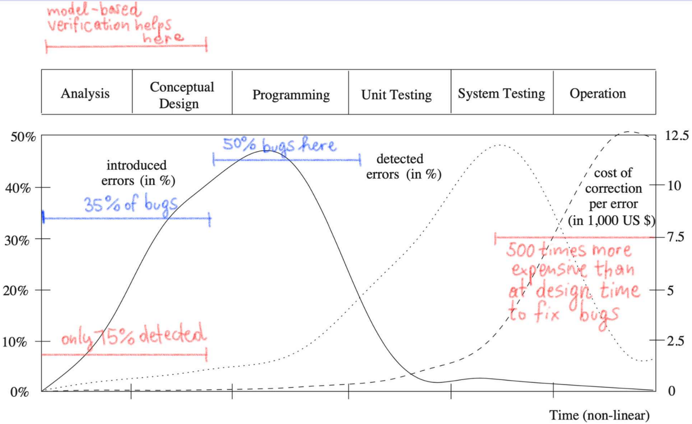
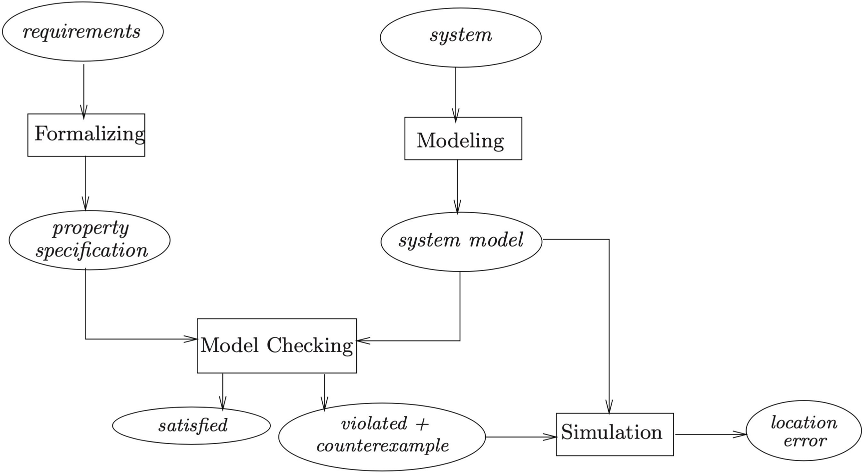


"In software and hardware design of complex systems, more time and effort are spent on verification than on construction. Techniques are sought to reduce and ease the verification efforts while increasing their coverage. Formal methods offer a large potential to obtain an early integration of verification in the design process, to provide more effective verification techniques, and to reduce the verification time."

Model checking



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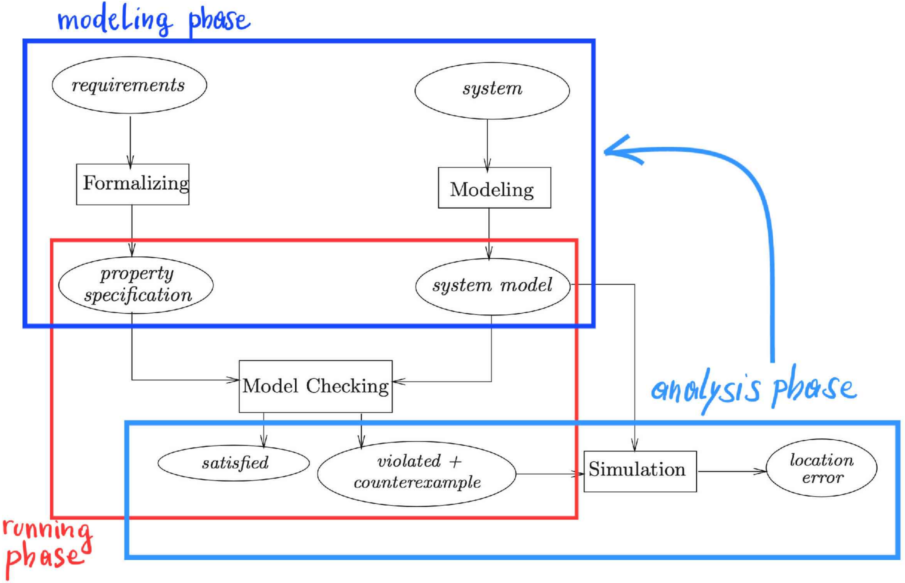

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Modality $\Box\phi \quad \hat{=} \quad$ for all time moments, ϕ holds.

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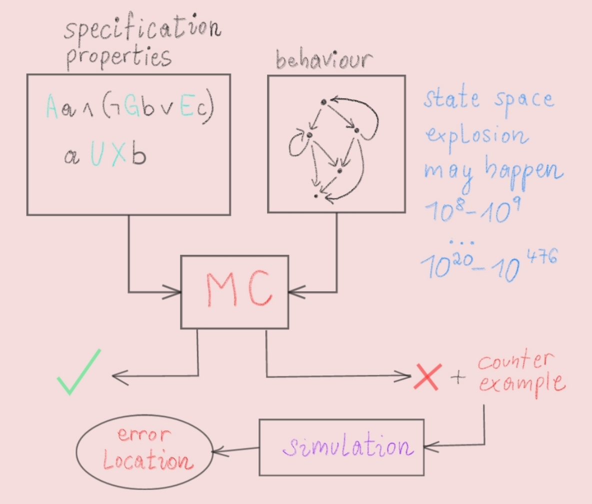
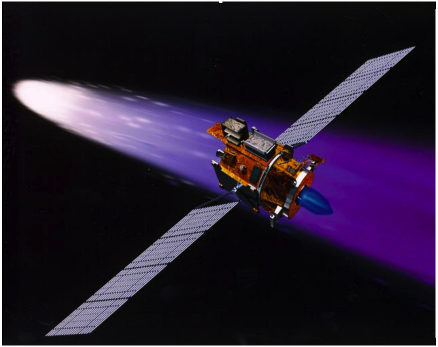
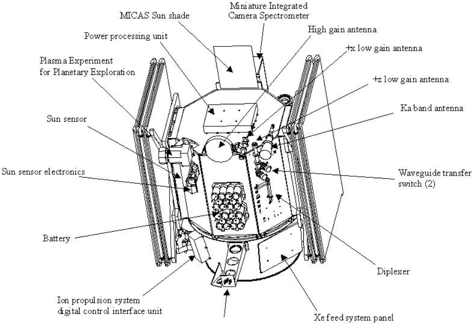
$=$ it will never happen that
events a and b occur at the same time.

Glancing at temporal logic (its use for model checking)



Deep Space 1 (NASA)





- Flyby of asteroid 9969 Braille (1999)
- Entered the coma of Comet Borrelly (2001)
- Model checking discovered 5 concurrency errors

Example (program concurrency/non-determinism)

Programs Inc, Dec, and Reset cooperate, and use a shared variable x:

```
proc Inc
  while 0 ≤ x ≤ 200
    do
      if x < 200
        then x := x + 1
      fi
    od
```

```
proc Dec
  while 0 ≤ x ≤ 200
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then $x := x + 1$	**then** $x := x - 1$	**then** $x := 0$
fi	**fi**	**fi**
od	**od**	**od**

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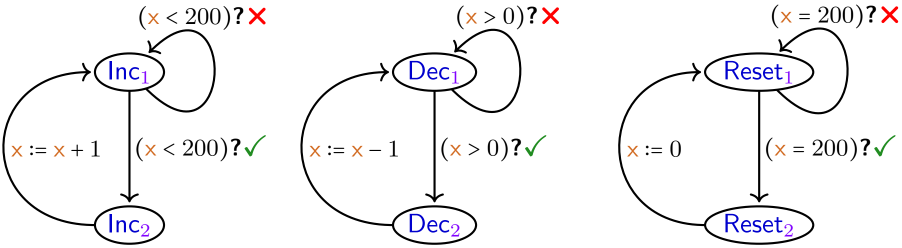
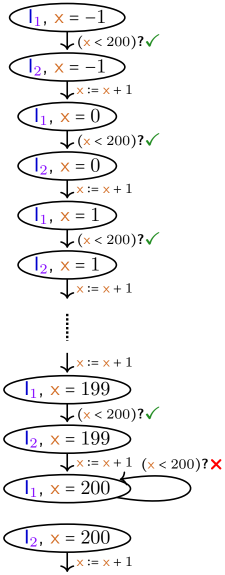


Program graphs (PG)

Modeling (by labeled transition systems, with state space explosion)



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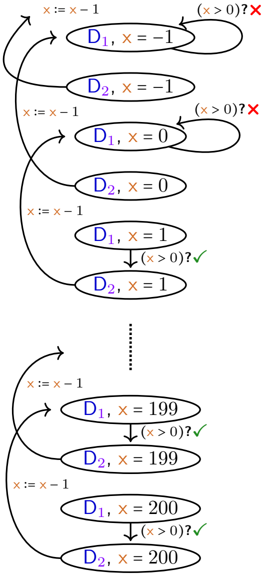

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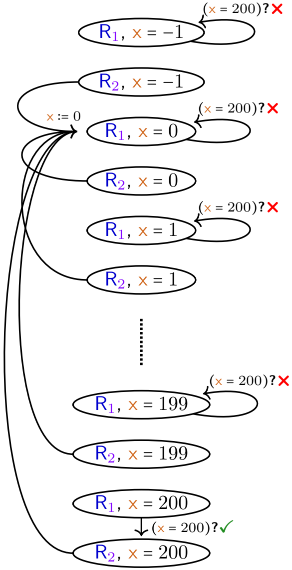

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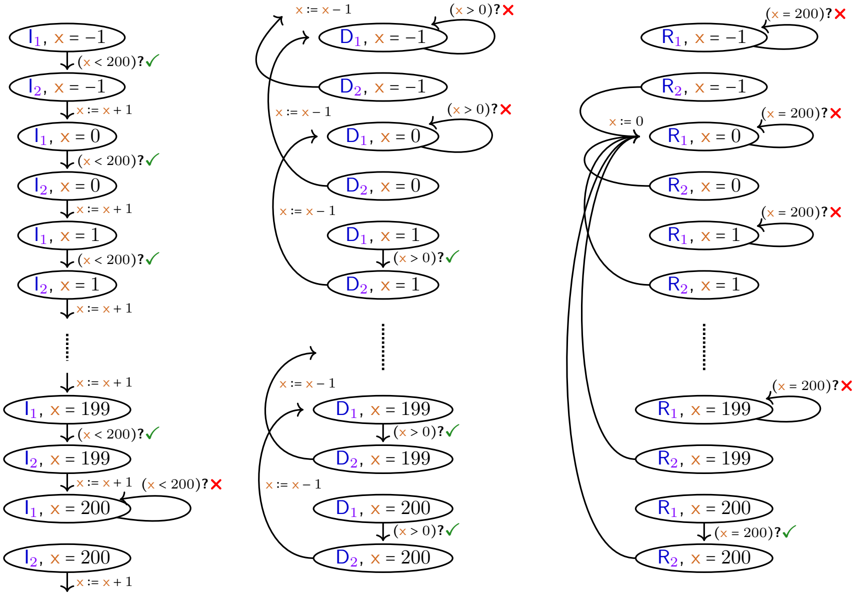
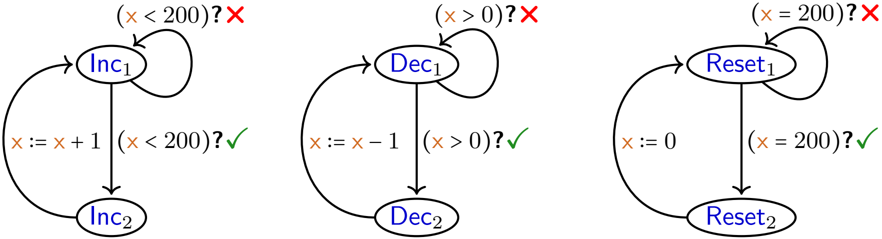


Formalizing properties (in temporal logic)



We assume x : = 0 initially.

$\mathsf{Inc}_1 \parallel \mathsf{Dec}_1 \parallel \mathsf{Reset}_1 \overset{?}{\models} \Box(0 \leq x \wedge x \leq 200)$ (Linear-TL formula)

Counterexample (offending execution trace)

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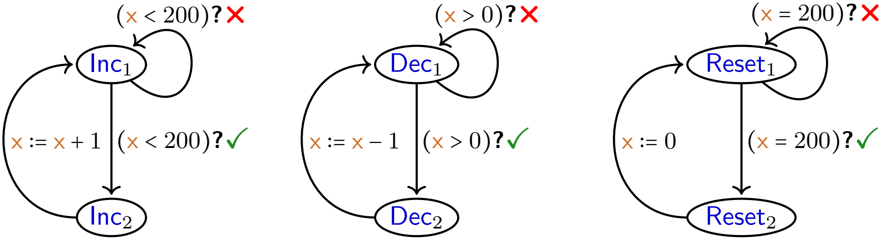
$$\langle x = -1\,;\ \mathsf{Inc}_1 \parallel \mathsf{Dec}_1 \parallel \mathsf{Reset}_1 \rangle$$

Formalizing properties (in temporal logic)



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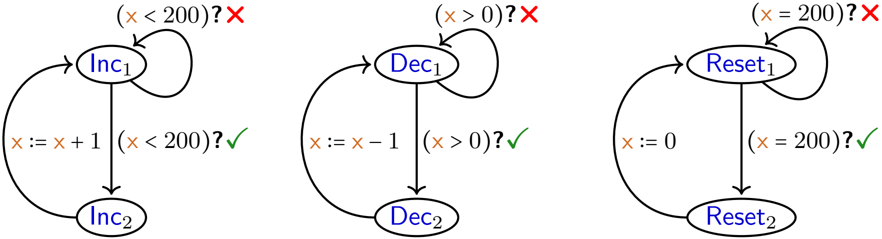

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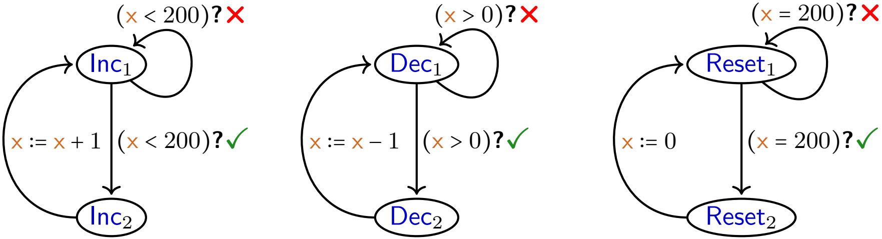

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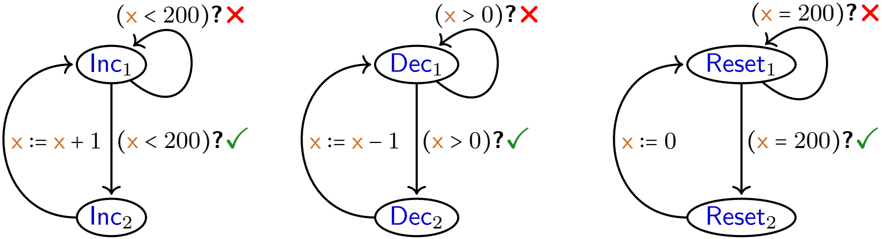

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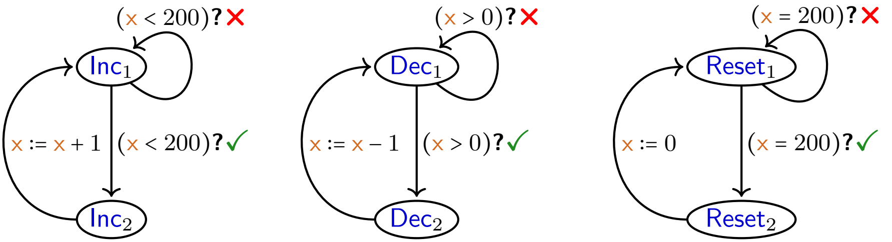

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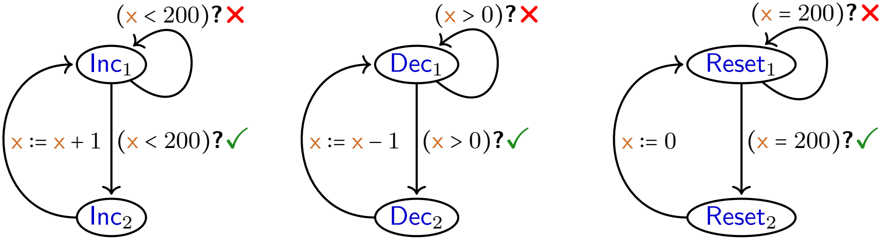

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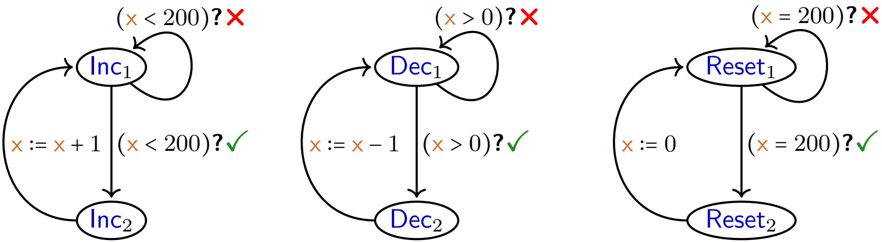

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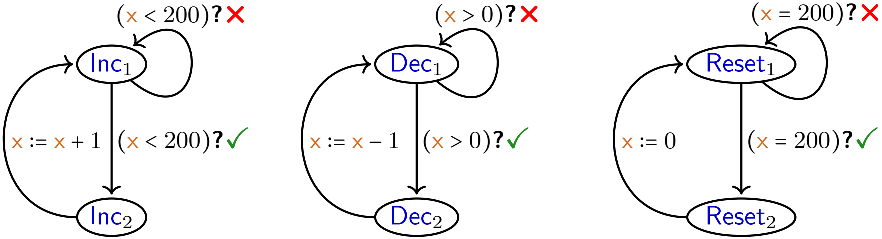

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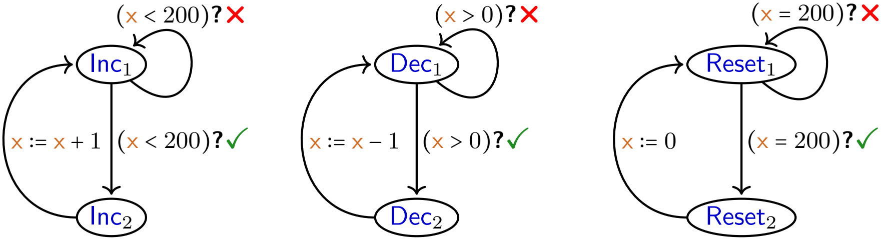

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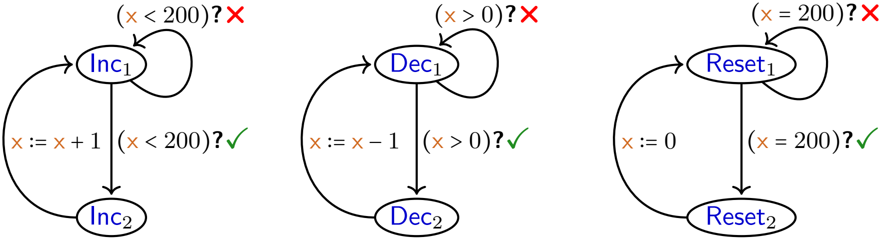

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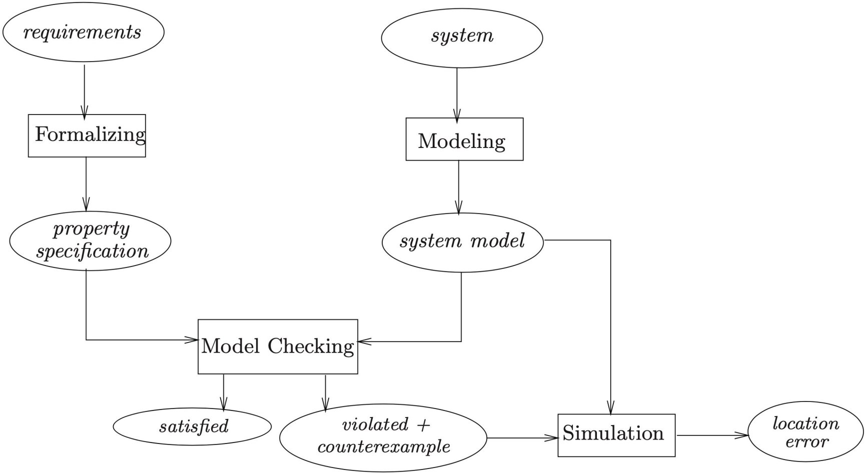
Model checking: validation



Any [such] verification is only as good as the model of the system.

Modeling: Verification versus Validation

VERIFICATION	VALIDATION
Are we building the thing right?	Are we building the right thing?
$\Updownarrow$	$\Updownarrow$
Does the design satisfy the expected properties?	Is the design faithfully capturing the requirements?

Model-checking: strengths and weaknesses

Strengths:

- it is a general technique
- supports partial verification, checking properties individually

Weaknesses:

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- does not permit to directly check generalizations (infinitely many components, parameterized systems)

Origins of model checking

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See Baier and Katoen [1] for more references.

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   - executions; traces; non-determinism; examples
3. Linear-Time Behaviour and Properties
   - invariant, safety, and liveness (and fairness) properties
4. Linear Temporal Logic (LTL)
   - syntax and semantics; interpretation of LTSs; examples
5. LTL (continued)
   - model checking of LTL formulas, and fairness in LTL
   - Maude examples
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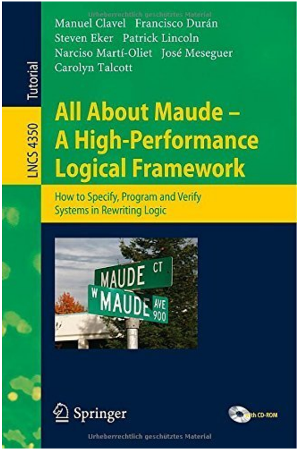
Book Maude



- Maude documentation page:
  https://maude.cs.illinois.edu/documentation

Maude code (idea)

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crl [Inc1a]   :  Inc1 x => Inc2 x  if x < 200
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crl [Inc1b]   :  Inc1 x => Inc1 x  if not(x < 200)

crl [Dec1a]   :  Dec1 x => Dec2 x  if 0 < x
rl  [Dec2]    :  Dec2 x => Dec1 (x - 1)
crl [Dec1b]   :  Dec1 x => Dec1 x  if not(0 < x)

crl [Reset1a] :  Reset1 x => Reset2 x  if x = 200
rl  [Reset2]  :  Reset2 x => Reset1 0
crl [Reset1b] :  Reset1 x => Reset1 x  if not(x = 200)

eq initial = { Inc1 Dec1 Reset1 0 }

ceq (S1 S2 S3 x |= counterge0) = true  if (0 = x \/ 0 < x)
ceq (S1 S2 S3 x |= counterlt0) = true  if (x < 0)
ceq (S1 S2 S3 x |= counterle200) = true  if (x < 200 \/ x = 200)
```

Maude output (simplified)

```
Maude> red modelCheck(initial, <> counterlt0)
reduce in COUNTERS-CHECK : modelCheck(initial, <> counterlt0)
result ModelCheckResult:
result Bool :  true
```

Maude output (simplified)

```
Maude> red modelCheck(initial, <> counterlt0)
reduce in COUNTERS-CHECK : modelCheck(initial, <> counterlt0)
result ModelCheckResult:
result Bool :  true
```

```
Maude> red modelCheck(initial, [](counterge0 /\counterle200)
reduce in COUNTERS-CHECK :
               modelCheck(initial, [](counterge0 /\counterle200)
result ModelCheckResult:
counterexample({Inc1 Dec1 Reset1 199}
               {Inc2 Dec1 Reset1 199}
               {Inc1 Dec1 Reset1 200}
               {Inc1 Dec2 Reset1 200}
               {Inc1 Dec2 Reset2 200}
               {Inc1 Dec2 Reset1 0}
               {Inc1 Dec1 Reset1 -1})
```

Lectures (tentative)

1. Introduction (preview extended)
2. Modeling by labeled transition systems
   - executions; traces; non-determinism; examples
3. Linear-Time Behaviour and Properties
   - invariant, safety, and liveness (and fairness) properties
4. Linear Temporal Logic (LTL)
   - syntax and semantics; interpretation of LTSs; examples
5. LTL (continued)
   - fairness in LTL
   - model checking of LTL formulas
6. Computation Tree Logic (CTL)
   - syntax and semantics, examples
7. Extensions of CTL, and Outlook
   - expressibility differences with LTL
   - model checking formulas in CTL
   - Maude examples | partial model-checking | μ-calculus

Exam options

Together we decide on a topic.

Study an article, or a book chapter.

or

Dive deeper into a proof from the lecture.

or

Model a basic algorithm, and check basic properties.

or

Develop an idea that motivates you.

or

...

You give a 25-minute presentation about what you found.

Exam options

Together we decide on a topic.

Study an article, or a book chapter.
or
Dive deeper into a proof from the lecture.
or
Model a basic algorithm, and check basic properties.
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Develop an idea that motivates you.
or
. . .

You give a 25-minute presentation about what you found.

Exam examples

Presentations about articles:

- *Progress, Justness, and Fairness* (2019) by R. van Glabbeek, P. Höfner
- *Comparison of Model Checking Tools for Information Systems* (2010) by M. Frappier et al. (focusing on SPIN and NuSMV)

References I

Christl Baier and Joost-Pieter Katoen.
Principles of Model Checking.
MIT Press, 2008.
Available at:
https://is.ifmo.ru/books/_principles_of_model_checking.pdf.

Edmund M. Clarke and E. Allen Emerson.
Design and Synthesis of Synchronization Skeletons using Branching Time Temporal Logic.
In Dexter Kozen, editor, *Logics of Programs*, pages 52–71, Berlin, Heidelberg, 1982. Springer Berlin Heidelberg.

References II

M. Clavel, F. Durán, S. Eker, P. Lincoln, N. Martí-Oliet, J. Meseguer, and C. Talcott.
All About Maude - A High-Performance Logical Framework: How to Specify, Program, and Verify Systems in Rewriting Logic.
Lecture Notes in Computer Science. Springer Berlin Heidelberg, 2007.

Peter Liggesmeyer, Martin Rothfelder, Michael Rettelbach, and Thomas Ackermann.
Qualitätssicherung Software-Basierter Technischer Systeme – Problembereiche und Lösungsansätze.
Informatik-Spektrum, (21):249–258, 1998.

References III

J. P. Queille and J. Sifakis.
Specification and Verification of Concurrent Systems in CESAR.
In Mariangiola Dezani-Ciancaglini and Ugo Montanari, editors, *International Symposium on Programming*, pages 337–351, Berlin, Heidelberg, 1982. Springer Berlin Heidelberg.