

# Introduction to Model Checking

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

## Lecture 1

Clemens Grabmayer

<https://clegra.github.io>

Emilio Tuosto

<https://cs.gssi.it/emilio.tuosto/>

Department of Computer Science



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
- ▶ next week:
  - ▶ Monday, Tuesday, Thursday, 14.30–16.30, conference room -1, Zenith
- ▶ presentations (mainly) on blackboard
- ▶ notes after the lecture (notes 2024/25 already available)

## Webpage

- ▶ <https://clegra.github.io/mc.html>  
stable for later: <https://clegra.github.io/mc/25-26/mc.html>

## Exam (more later)

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

# Topics of the course

- ▶ modeling systems by **labeled transition systems (LTSs)**
- ▶ **safety**, **liveness**, and **fairness** properties
- ▶ **Linear Temporal Logic (LTL)**
  - ▶ model checking formulas
    - ▶ express properties by **Büchi automata**
    - ▶ model check LTSs and properties via **product automata**
- ▶ **Computation Tree Logic (CTL)**
- ▶ **Maude** examples **model-checker**
- ▶ **(partial** model checking)
  - ▶ (partially known systems (state properties/states/transitions))

# Model Checking

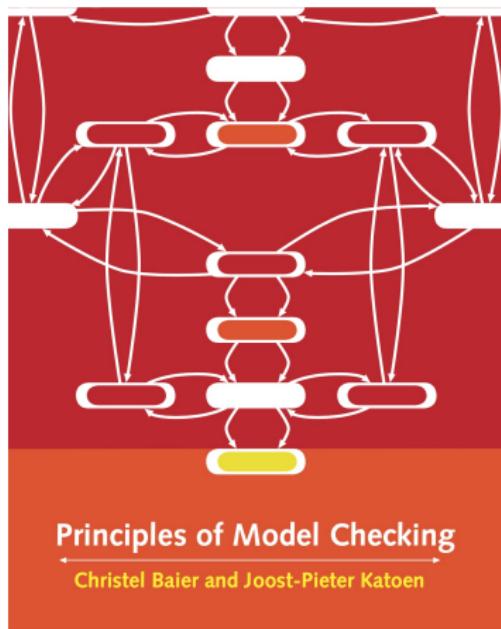
... is an effective automatable technique:

- ▶ *to expose potential software design errors;*
- ▶ *that, given a finite-state model of a system and a formal property, systematically checks whether this property holds for that model.*
- ▶ widely applied in industry
  - ▶ embedded systems, software engin., hardware design, **explainable AI**
- ▶ supports **partial verification** (of system parts)
- ▶ provides **diagnostic information** for debugging
- ▶ has sound **mathematical underpinning** (**logic** and **process theory**)

**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
  - ▶ ( $\mu$ -calculus | partial model-checking | Maude examples)

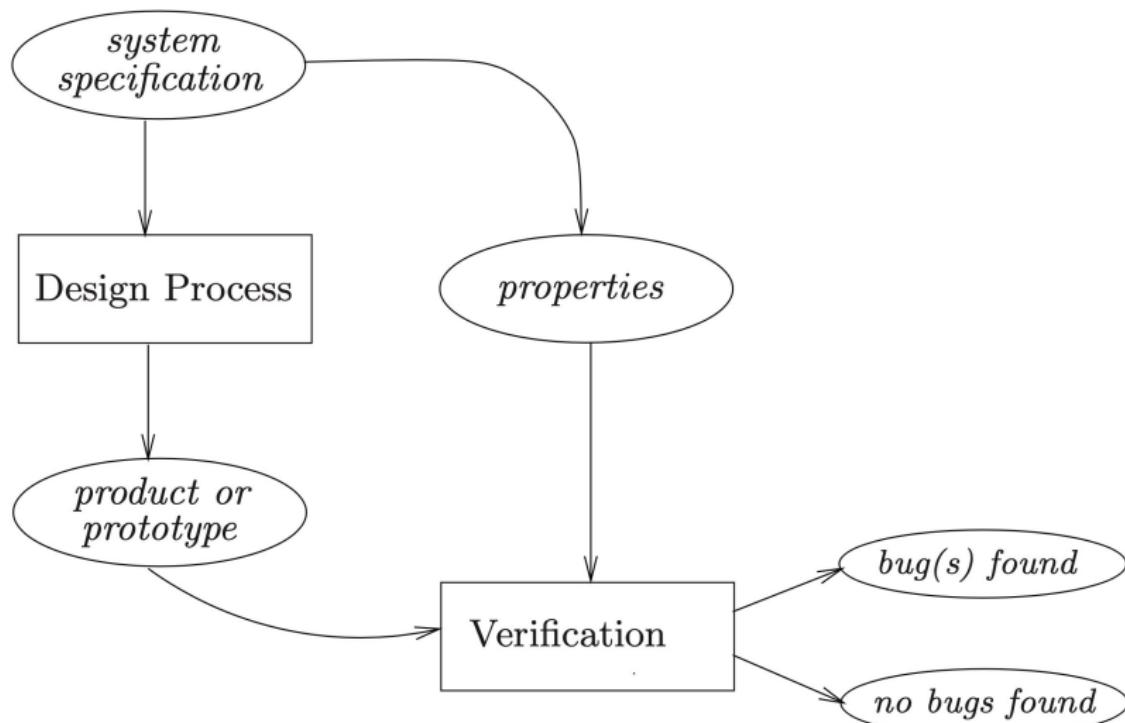
# Software correctness

- ▶ Software is ubiquitous  $\implies$  software is valuable

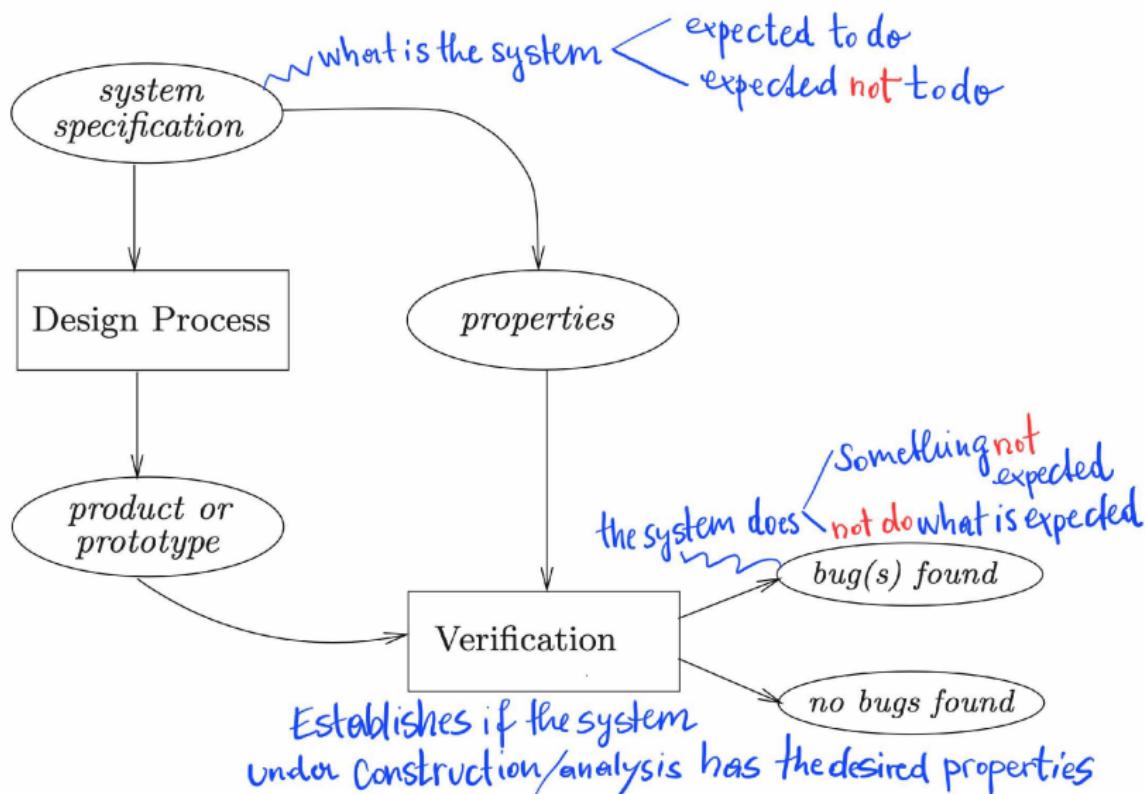
*"It is fair to state that in this digital era correct systems for information processing are more valuable than gold." (H.P. Barendregt, 'The quest for correctness', in *Images of SMC Research*, 1996).*

- ▶ Software bugs = loss of  $\begin{cases} \text{lives} \\ \text{money} \\ \text{reputation} \end{cases}$
- ▶ Simulation / testing
  - + concrete implemented systems are checked
  - + "simple"
  - partial (when do we stop?)
- ▶ Deductive reasoning
  - + also possible for infinite-state system
  - hard and time-consuming
  - interactive

# Hard-/Software Verification (traditionally)



# Hard-/Software Verification (traditionally)



# Software verification methods

## ► Peer review

-  rather useful: between 31% and 93% (median 60%)
-  hard to catch subtle errors (concurrency and algorithmic defects)

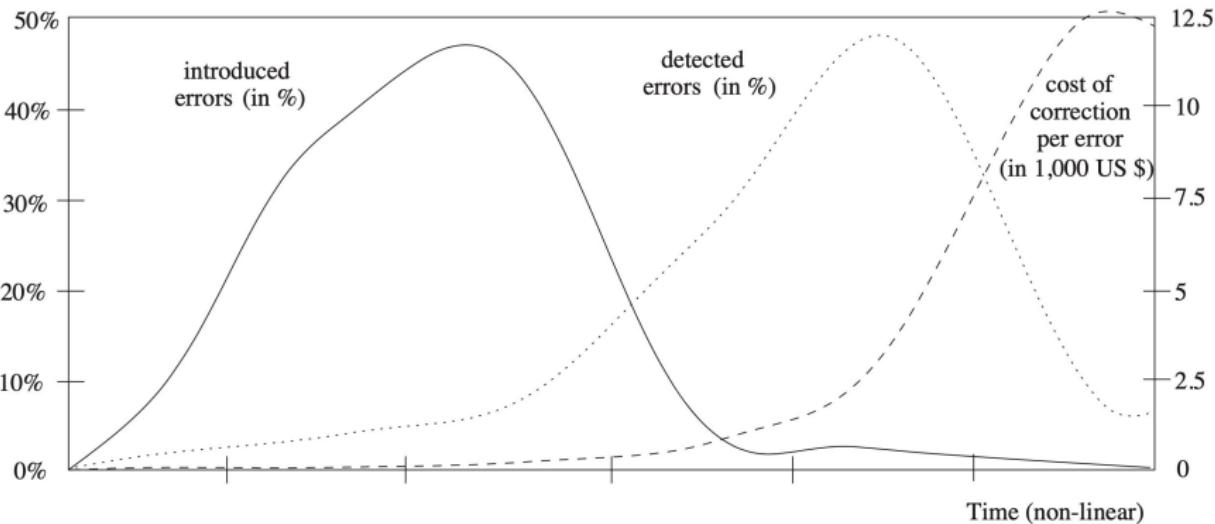
## ► Software testing

-  applicable to all sorts of software
-  test generation can (partly) be automated
-  exhaustive testing of all execution paths is infeasible
-  When do we stop?

## ► Catching software errors: **the sooner the better**.

# Software lifecycle, error introduction/detection, repair costs

Analysis	Conceptual Design	Programming	Unit Testing	System Testing	Operation
----------	-------------------	-------------	--------------	----------------	-----------

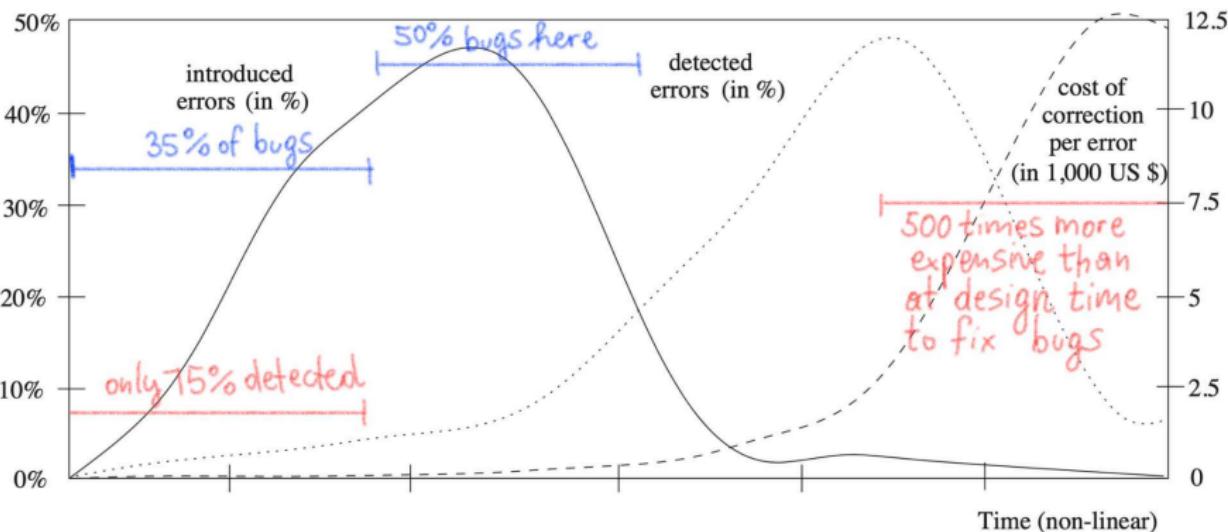


Liggesmeyer et al: "Qualitätssicherung technischer Systeme . . ." [4, 1998]

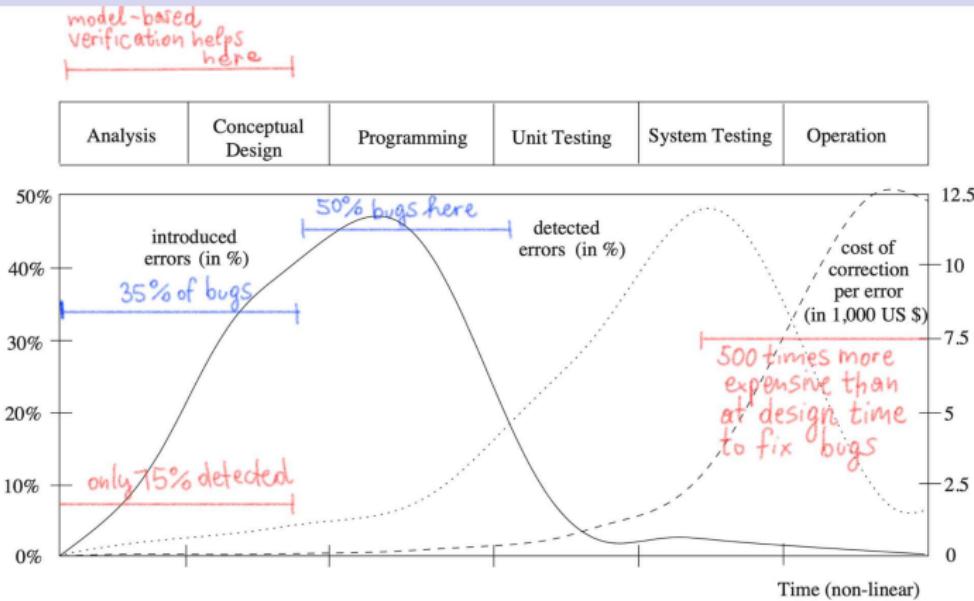
# Software lifecycle, error introduction/detection, repair costs

model-based verification helps here

Analysis	Conceptual Design	Programming	Unit Testing	System Testing	Operation
----------	-------------------	-------------	--------------	----------------	-----------

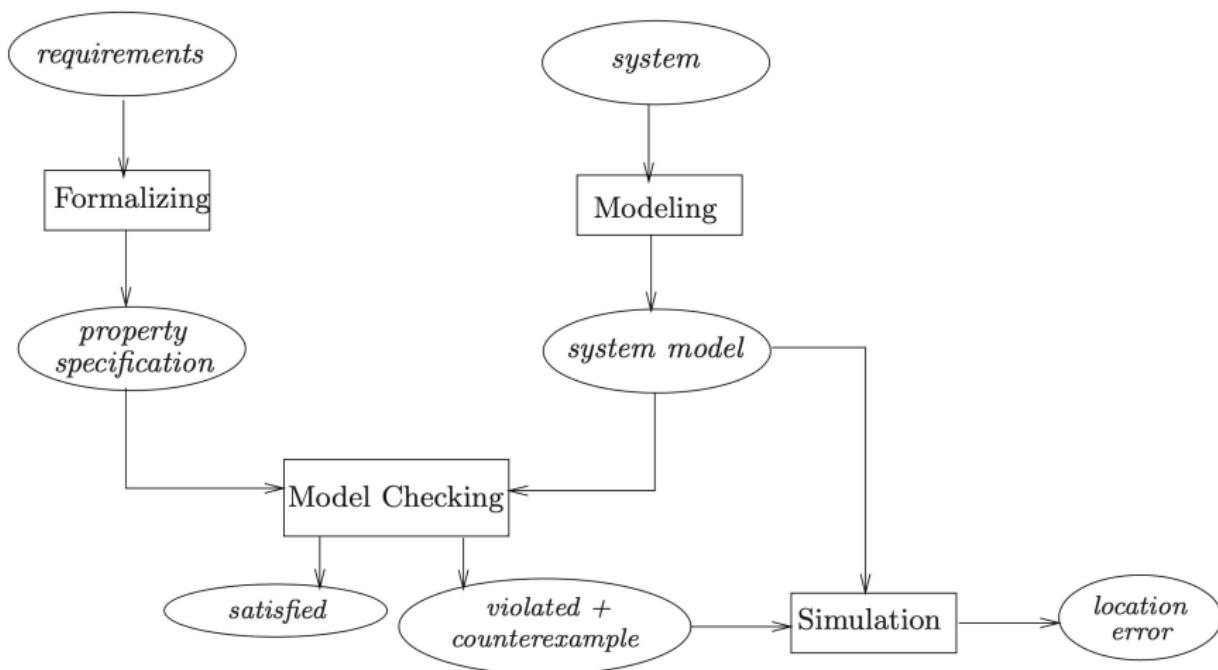


# Software lifecycle, error introduction/detection, repair costs



"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



# Glancing at temporal logic

## Temporal logic

- ▶ stems from philosophy: modal logic to reason about time (in an idealized natural language)
- ▶ makes it possible to reason about concurrent events
- ▶ events are ordered in time
- ▶ time is considered to be discrete
- ▶ but moments of time are only referred to relatively

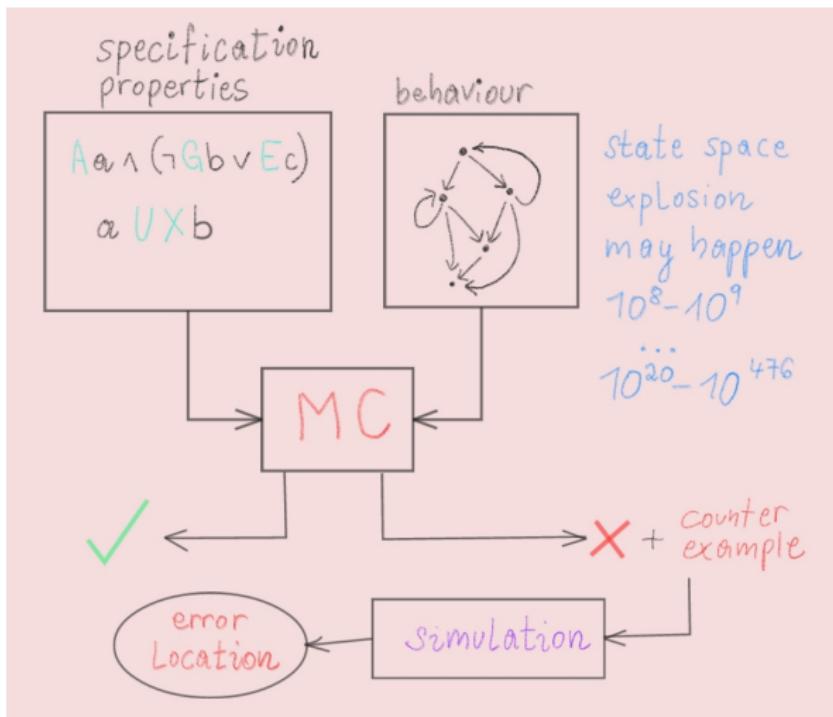
### Example

Modality  $\Box\phi$   $\stackrel{\wedge}{=}$  for all time moments,  $\phi$  holds.

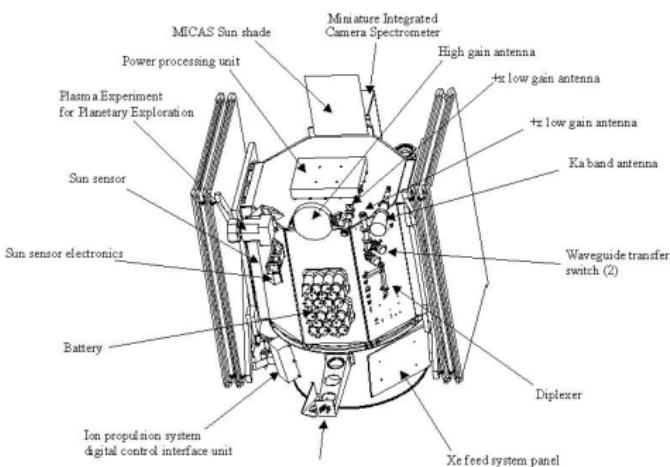
Then we have:

$\Box(\neg(a \wedge b))$   $\stackrel{\wedge}{=}$  for all time moments,  
events  $a$  and  $b$  do not occur at the same time,  
= 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
  do
    if x > 0
    then x := x - 1
    fi
  od
```

```
proc Reset
  while 0 ≤ x ≤ 200
  do
    if x = 200
    then x := 0
    fi
  od
```

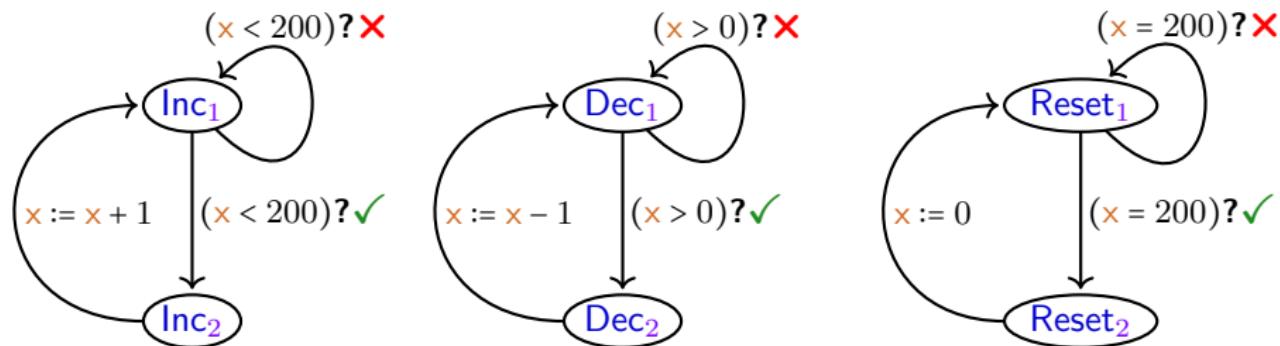
**Question:** When started on  $x = 0$ , do the counter programs run forever?  
Is  $0 \leq x \leq 200$  always guaranteed?

# Modeling (by program graphs)

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

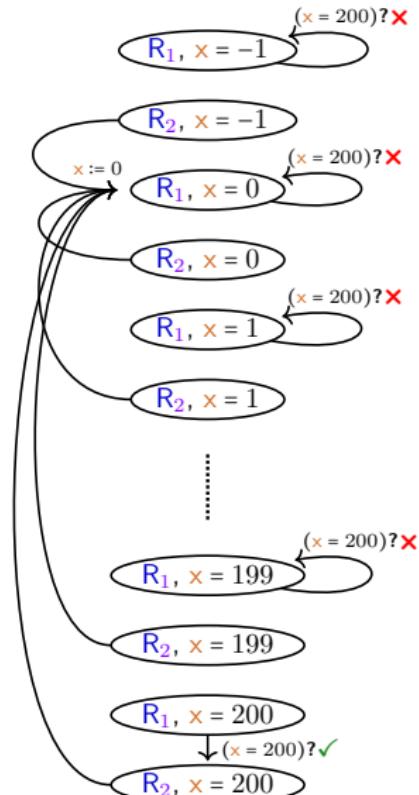
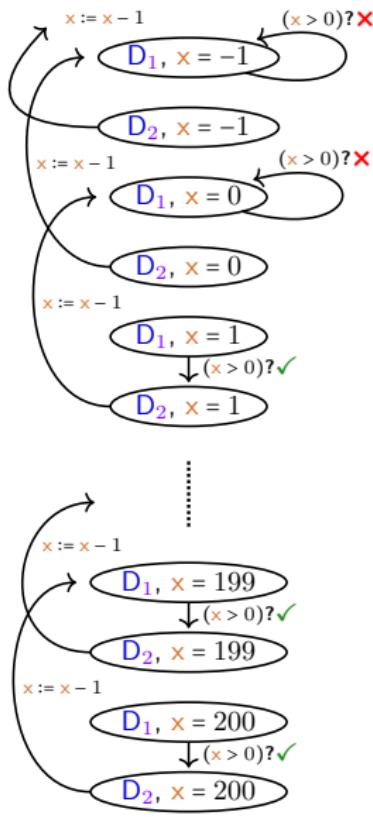
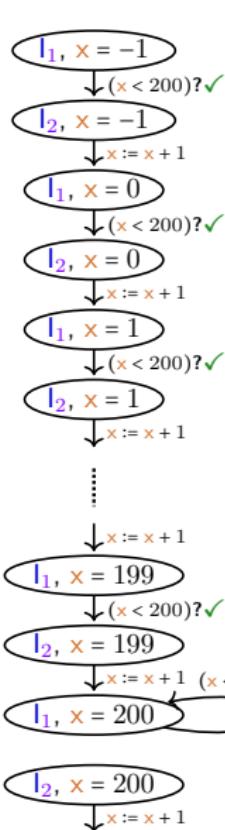
```
proc Dec
  while true
    do
1:   if x > 0
2:   then x := x - 1
    fi
  od
```

```
proc Reset
  while true
    do
1:   if x = 200
2:   then x := 0
    fi
  od
```

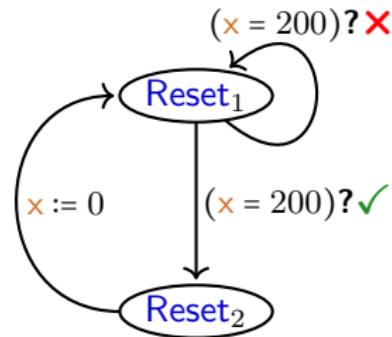
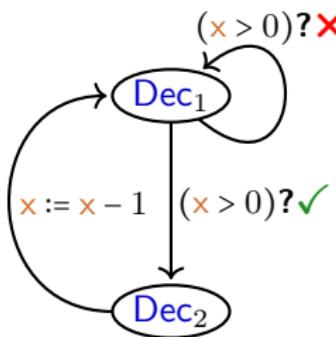
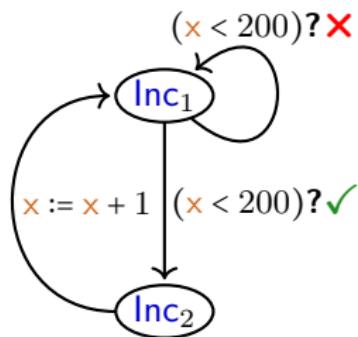


Program graphs (PG)

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



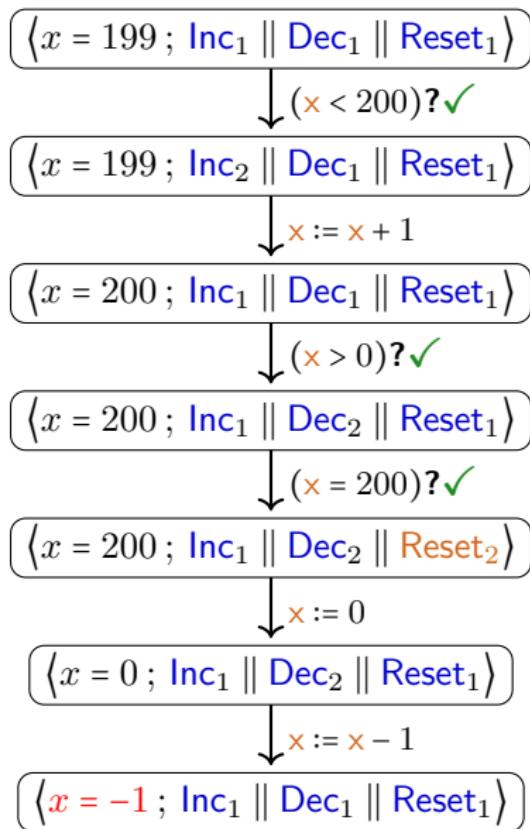
# Formalizing properties (in temporal logic)



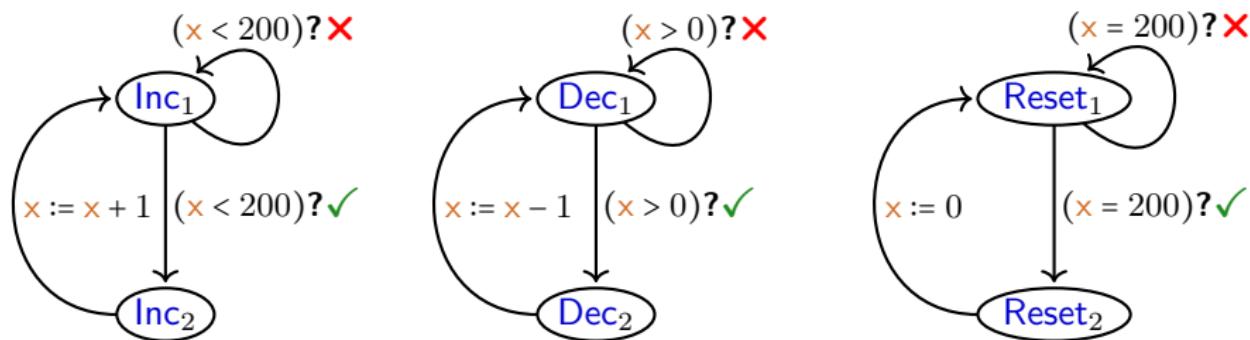
We assume  $x := 0$  initially.

$$Inc_1 \parallel Dec_1 \parallel Reset_1 \stackrel{?}{\models} \Box(0 \leq x \wedge x \leq 200) \quad (\text{Linear-TL formula})$$

# Counterexample (offending execution trace)



# Formalizing properties (in temporal logic)



We assume  $x := 0$  initially.

$$\text{Inc}_1 \parallel \text{Dec}_1 \parallel \text{Reset}_1 \not\models \Box(0 \leq x \wedge x \leq 200) \quad (\text{Linear-TL formula})$$

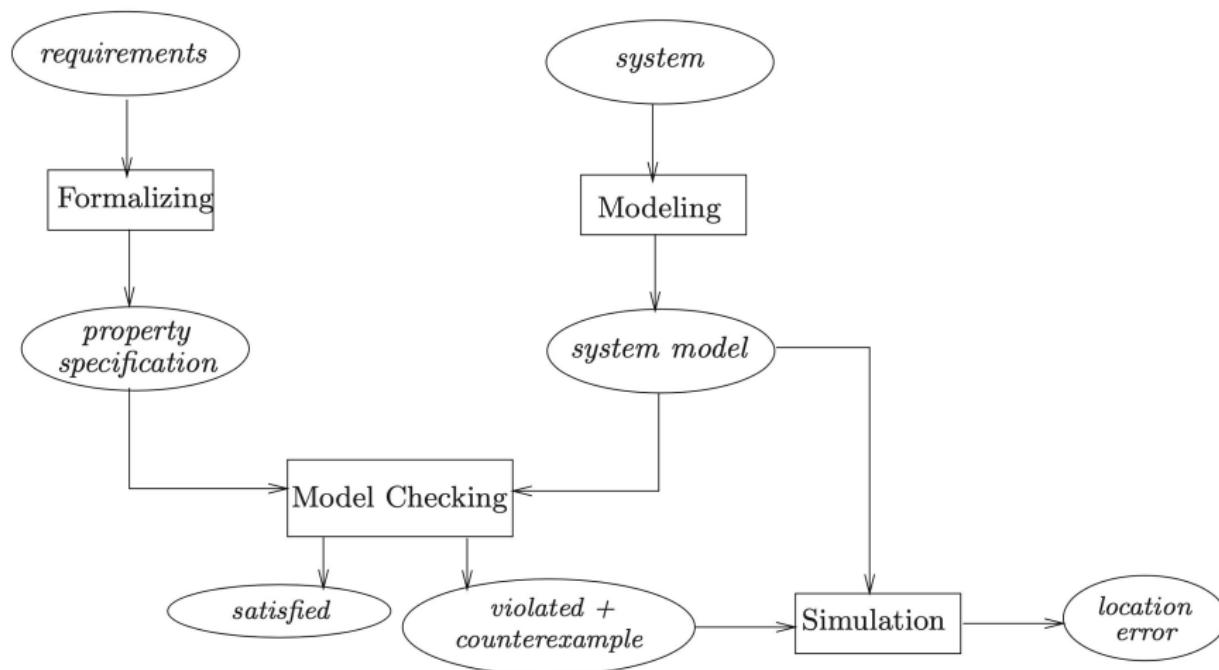
$$\text{Inc}_1 \parallel \text{Dec}_1 \parallel \text{Reset}_1 \models \Diamond(x < 0) \quad (\text{LTL formula})$$

$$\text{Inc}_1 \parallel \text{Dec}_1 \parallel \text{Reset}_1 \not\models \forall \Box(0 \leq x \wedge x \leq 200) \quad (\text{Computation-Tree-L formula})$$

$$\text{Inc}_1 \parallel \text{Dec}_1 \parallel \text{Reset}_1 \models \exists \Box(0 \leq x \wedge x \leq 200) \quad (\text{CTL formula})$$

$$\text{Inc}_1 \parallel \text{Dec}_1 \parallel \text{Reset}_1 \models \forall \Box \exists \Diamond(x < 0) \quad (\text{CTL formula})$$

# Model checking: validation



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

# Modeling: Verification versus Validation

## VERIFICATION

Are we building the **thing right**?



Does the **design** satisfy the  
expected properties?

## VALIDATION

Are we building the **right thing**?



Is the **design** faithfully capturing  
the requirements?

# Model-checking: strengths and weaknesses

## Strengths:

- ▶ it is a **general** technique
- ▶ supports **partial** verification, checking properties individually
- ▶ bug-detection is **not dependent on chance**
- ▶ provides **diagnostic information** for debugging
- ▶ potential push-button technology
- ▶ widely used in industry
- ▶ can be **integrated** in existing development cycles
- ▶ **sound mathematical underpinning** (graph alg's, data structures, logic)

## Weaknesses:

- ▶ ideal for **control-intensive** applic., **less so** for **data-intensive** applic.
- ▶ verifies **system model**, not the actual system
- ▶ only checks stated requirements (no guarantee for completeness)
- ▶ suffers from **state-explosion** problem
- ▶ modeling requires expertise (finding smaller models, state properties as formulas)
- ▶ model-checker may have defects as well
- ▶ does not permit to directly check generalizations (infinitely many components, parameterized systems)

# Origins of model checking

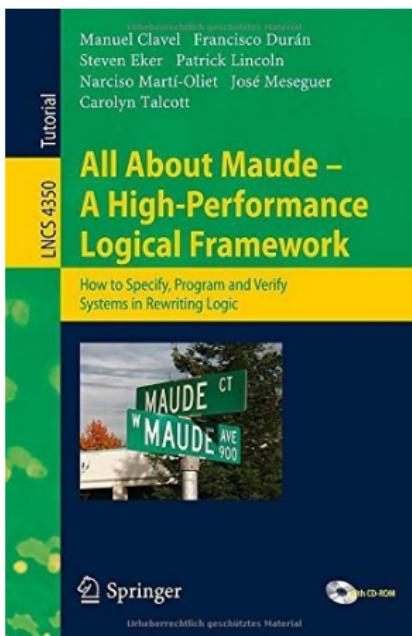
- I. Clarke and Emerson [2, 1986]: *Design and Synthesis of Synchronization Skeletons using Branching Time Temporal Logic*.  
They coined the term **model checking**.
- II. Queille and Sifakis [5, 1982]: *Specification and Verification of Concurrent Systems in CESAR*.
- III. Hajek (1978), and West (1978): introduced automated **protocol validation techniques** based on a **brute-force examination** of the entire **state space**, of which model checking can be viewed to be an extension.  
These earlier techniques were restricted to checking **absence of deadlocks or livelocks**, whereas model checking allows for the investigation of a broader class of properties.

See Baier and Katoen [1] for more references.

# 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
  - ▶ ( $\mu$ -calculus | partial model-checking | Maude examples)

# Book Maude



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

# Maude code (idea)

```

crl [Inc1a]    : Inc1 x => Inc2 x  if x < 200
rl  [Inc2]      : Inc2 x => Inc1 (x + 1)
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 \vee 0 < x)
ceq (S1 S2 S3 x |= counterlt0) = true  if (x < 0)
ceq (S1 S2 S3 x |= counterle200) = true  if (x < 200 \vee x = 200)

```

# 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 |  $\mu$ -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 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](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.