An *Informal* Introduction to

Formal Methods for Software Engineering

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Luigi Libero Lucio Starace

Università degli Studi di Napoli Federico II

Agenda

Software Verification

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Formal Methods
- Formal Specification
- Formal Verification

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- Formal Methods in Software Engineering

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- Practice time!

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- Practice time!
- Take Home Messages

Software Verification

Software Verification
What it's all about

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Why should we care?

- Computer systems are everywhere and we depend more and more on them;
- Malfunctions may cause financial losses **or worse!**

Software Verification
Classic techniques

- Software Testing

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- Software Testing
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- Code inspection
  - static analysis (no software execution involved);
  - careful scrutiny of the source code carried on by software engineers.

Software Verification
When classic techniques fall short

Testing and code inspection are **very** effective at detecting bugs.

Software Verification
When classic techniques fall short

Testing and code inspection are **very** effective at detecting bugs, but...

- cannot prove their absence;

> [...] *program testing can be a very effective way to show the presence of bugs, but it is hopelessly inadequate for showing their absence.*
>
> – *The humble programmer*, E. W. Dijkstra [Dij72]

Software Verification
When classic techniques fall short

Testing and code inspection are **very** effective at detecting bugs, but...

- cannot prove their absence;
- ineffective with concurrent systems;

> [...] *a concurrent program can withstand very careful scrutiny without revealing its errors. The only way we can be sure that a concurrent program does what we think it does is to prove rigorously that it does it.*
>
> – *Proving liveness properties of concurrent programs*, L. Lamport [LO82]

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Testing and code inspection are **very** effective at detecting bugs, but...

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Testing and code inspection are **very** effective at detecting bugs, but...

- cannot prove their absence;
- ineffective with concurrent systems;
- expensive and time-consuming.
- only feasible in later stages of the software lifecycle;

Software Verification
When classic techniques fall short

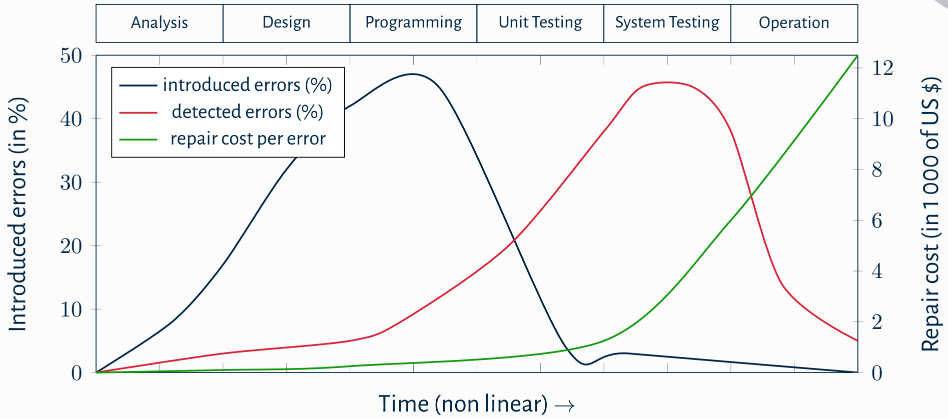

Figure: Error introduction, detection, and repair costs [BK08]

Formal Methods

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  - deductive verification (theorem proving);

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  - deductive verification (theorem proving);
  - automatic verification (model checking).

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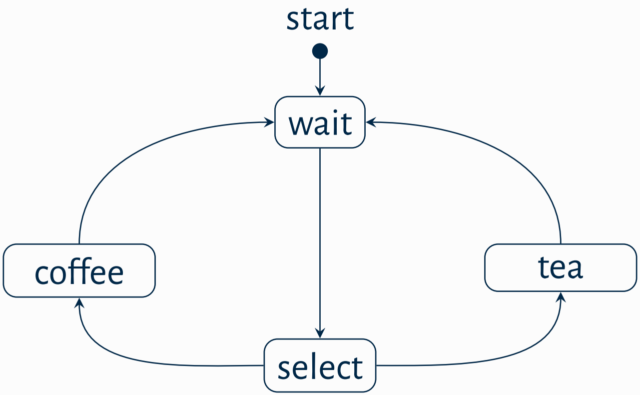
Formal methods can be considered as the applied mathematics for modelling and analyzing ICT systems.

- Formal Specification
  - system modelling languages;
  - property specification languages.
- Formal Verification
  - deductive verification (theorem proving);
  - automatic verification (model checking).
- Others (formal synthesis)

Formal Specification: Models

Transition Systems (TS)



- the set of states is called *state space*.

Formal Specification: Models

Modelling Languages: features

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Formal Specification: Models

Modelling Languages: features

- Precise and Unambiguous;
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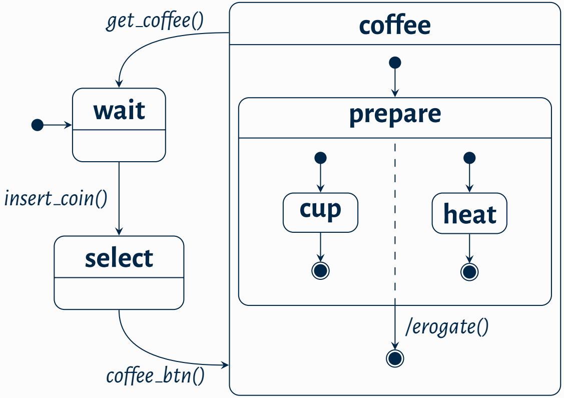
- "As simple as possible, as rich as needed" [Gli]
  - describe relevant aspects in a "natural" way;
  - trade-off between expressivity and analysis complexity;
  - using TS to model complex systems may be a bad idea: often higher-level languages are used instead.

Formal Specification: Models

Higher-level Modelling Languages: examples

- Statecharts;



Formal Specification: Models

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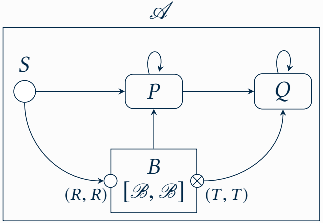

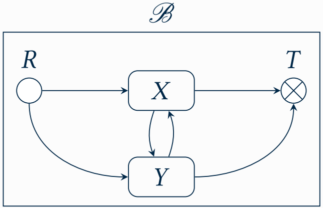

Formal Specification: Models

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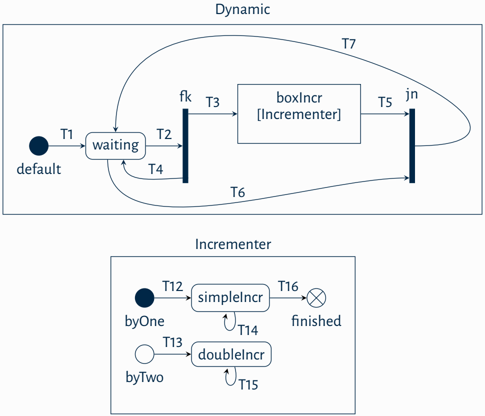

Formal Specification: Models

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Semantics can be defined in terms of transition systems.

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- Statecharts[1];
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[1]see Harel et al., [Har87; HN96]
[2]see Alur et al., [AKY99]
[3]see Benerecetti et al., [Ben+17]
[4]see [PRO]

Formal Specification: Models

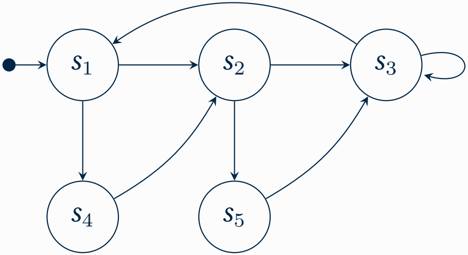
Beware of model reification!

> *All models are wrong, but some are useful.*
>
> – G. Box [Box76]

> *All models are right, most are useless.*
>
> – T. Tarpey [Tar09]

Formal Specification: Properties

System Behaviours



Formal Specification: Properties
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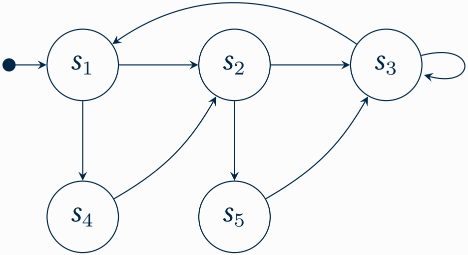

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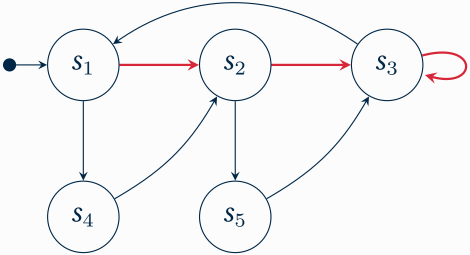

Possible behaviours:

- $\pi_1 = s_1 \rightarrow s_2 \rightarrow s_3 \rightarrow s_3 \rightarrow s_3 \rightarrow s_3 \rightarrow \ldots$ $s_1\, s_2\, (s_3)^\omega$

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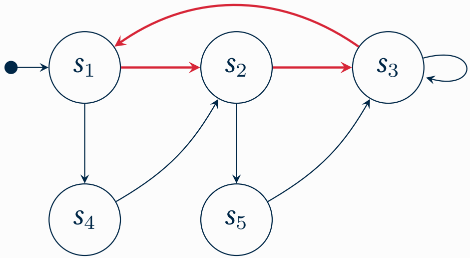

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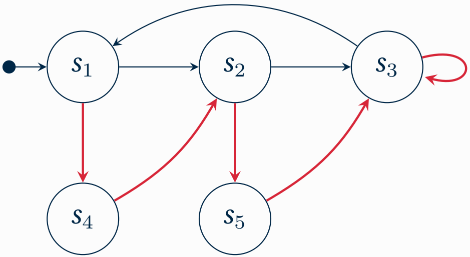

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- $\pi_3 = s_1 \rightarrow s_4 \rightarrow s_2 \rightarrow s_5 \rightarrow s_3 \rightarrow s_3 \rightarrow \dots$ $\quad s_1\, s_4\, s_2\, s_5\, (s_3)^\omega$

Formal Specification

Temporal logics: timeline

One way of formally specifying properties of behaviours is using **temporal logics**.

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- **LTL** (Linear-time Temporal Logic) was introduced by Pnueli in 1977 [Pnu77];

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- **CTL**, **CTL*** (Computation Tree Logic), a branching-time temporal logic;
- others (**CaRet** [AEM04], **HLTL**$^{\lightning}$, ...).

Formal Specification
LTL Syntax

LTL extends propositional logic with temporal modalities.

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LTL syntax

LTL formulae over the set $\mathcal{AP}$ of atomic proposition are formed according to the following grammar:

$$\phi ::= \top \mid a \mid \neg\phi \mid \phi_1 \wedge \phi_2 \mid \mathsf{X}\phi \mid \phi_1 \,\mathsf{U}\, \phi_2 \mid \mathsf{F}\phi \mid \mathsf{G}\phi$$

with $a \in \mathcal{AP}$.

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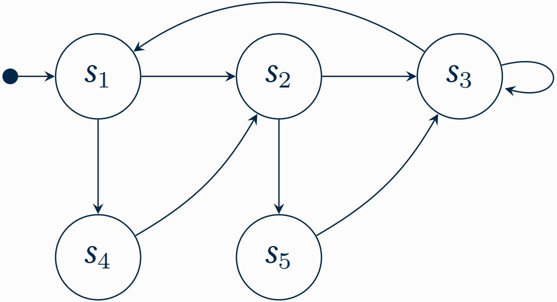
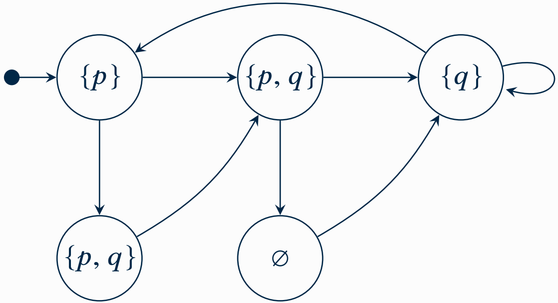
LTL formulae are interpreted over system behaviours.

Formal Specification
From Transition Systems to Kripke Structures



Formal Specification
From Transition Systems to Kripke Structures



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Formal Specification

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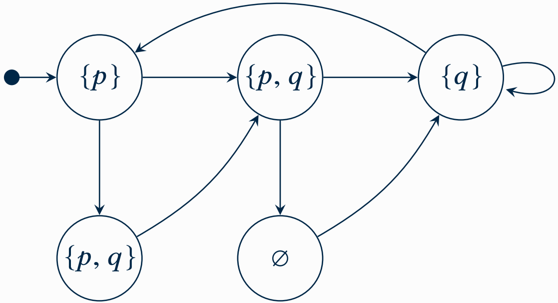

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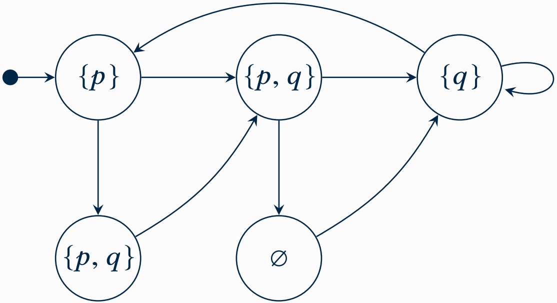

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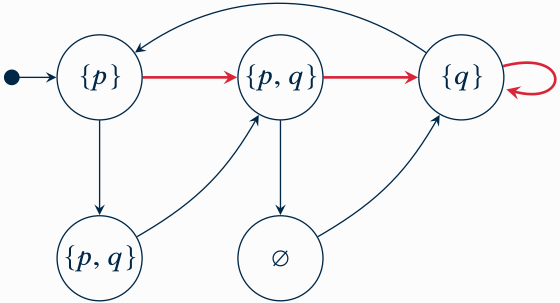

- we associate a set of atomic propositions to each TS state;
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- $\pi_1 = \{p\} \rightarrow \{p, q\} \rightarrow \{q\} \rightarrow \{q\} \rightarrow \{q\} \rightarrow \{q\} \rightarrow \{q\} \rightarrow \dots$

Formal Specification

LTL Semantics – Part 1

LTL syntax

$$\phi ::= \top \mid a \mid \neg\phi \mid \phi_1 \wedge \phi_2 \mid \mathsf{X}\phi \mid \phi_1 \,\mathsf{U}\, \phi_2 \mid \mathsf{F}\phi \mid \mathsf{G}\phi, \quad \text{with } a \in \mathcal{AP}.$$

Given a Kripke Structure behaviour $\pi = \pi_1 \to \pi_2 \to \ldots$, with $\pi_i \in \wp(\mathcal{AP})$, and LTL formula ϕ, the *satisfaction* relation $\pi \vDash \phi$ is defined inductively as follows:

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Formal Specification
LTL Semantics – Part 1

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- $\pi \models \phi_1 \wedge \phi_2$ iff $\pi \models \phi_1$ and $\pi \models \phi_2$;

Formal Specification

LTL Semantics – Part 2

LTL syntax

$$\phi ::= \top \mid a \mid \neg\phi \mid \phi_1 \wedge \phi_2 \mid \mathsf{X}\phi \mid \phi_1 \,\mathsf{U}\, \phi_2 \mid \mathsf{F}\phi \mid \mathsf{G}\phi, \quad \text{with } a \in \mathcal{AP}.$$

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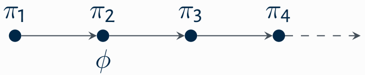

Formal Specification

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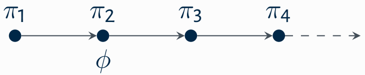
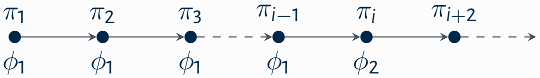


- $\pi \models \phi_1 \, U \, \phi_2$ iff ϕ_2 holds in a future moment, and ϕ_1 is true **until** ϕ_2 holds;



Formal Specification

LTL Semantics – Part 3

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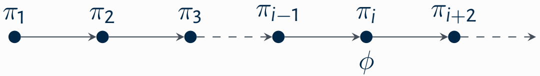

Formal Specification
LTL Semantics – Part 3

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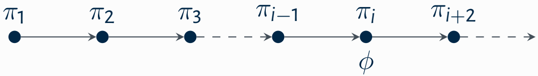
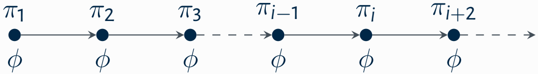


- $\pi \models \mathsf{G}\phi$ iff ϕ holds **globally** (now and in every future moment);



The LTL Model Checking problem

Given a Kripke Structure $\mathcal{M}$ and an LTL formula ϕ, we say that

$$\mathcal{M} \models \phi$$

iff $\pi \models \phi$, for each behaviour π of $\mathcal{M}$.

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Given a Kripke Structure $\mathcal{M}$ and an LTL formula ϕ, we say that

$$\mathcal{M} \vDash \phi$$

iff $\pi \vDash \phi$, for each behaviour π of $\mathcal{M}$.

LTL Model Checking

The Model Checking problem amounts to decide whether $\mathcal{M} \vDash \phi$.

The LTL Model Checking problem
Some examples

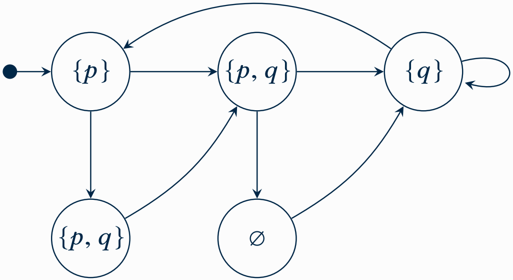

Figure: The Kripke Structure $\mathcal{M}$

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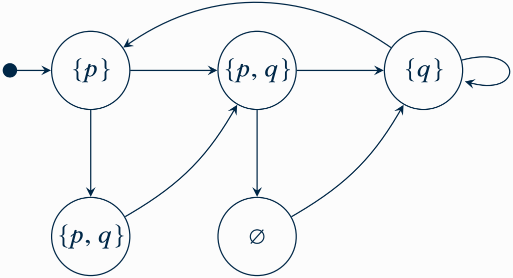

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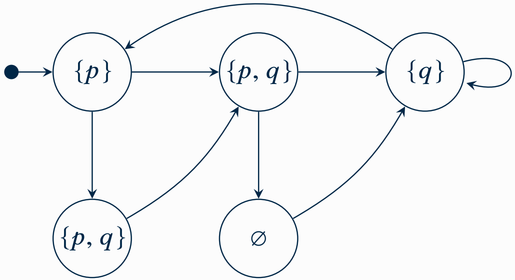

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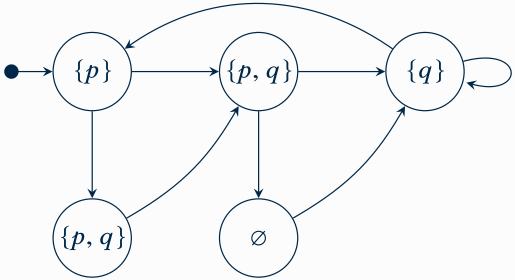

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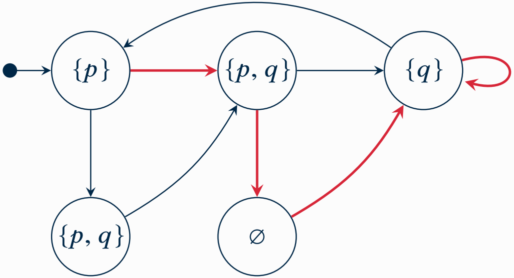

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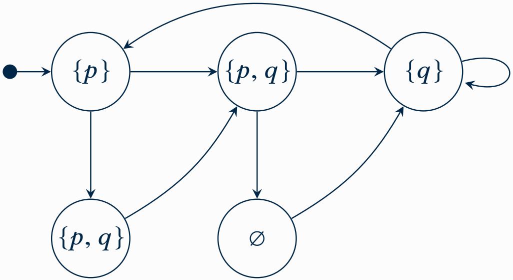

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$$\mathcal{M} \overset{?}{\models} \mathsf{G}((p \land q) \Rightarrow \mathsf{X}q)$$

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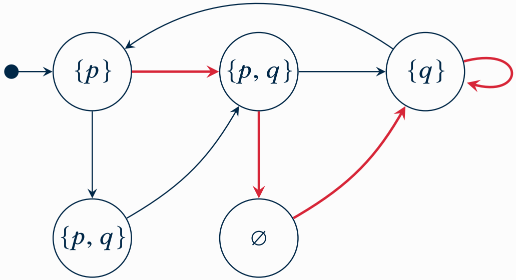

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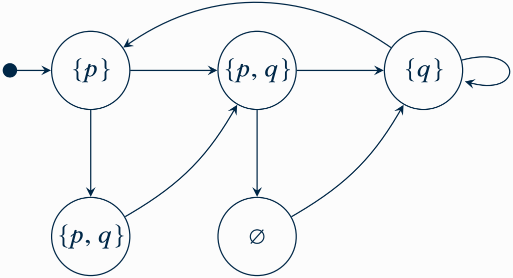

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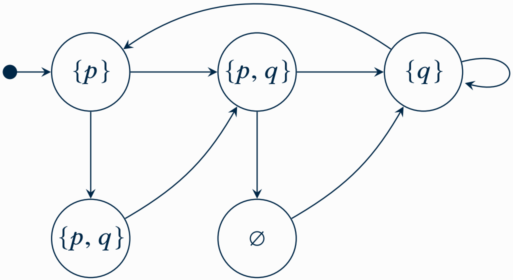

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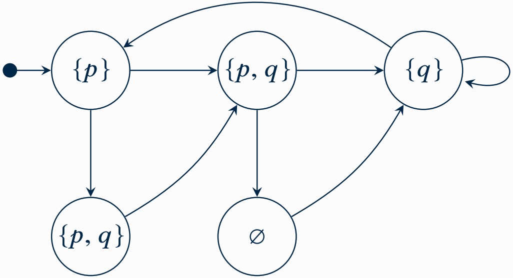

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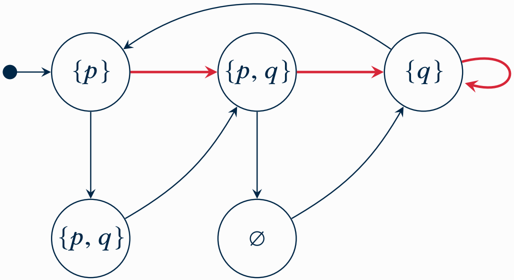

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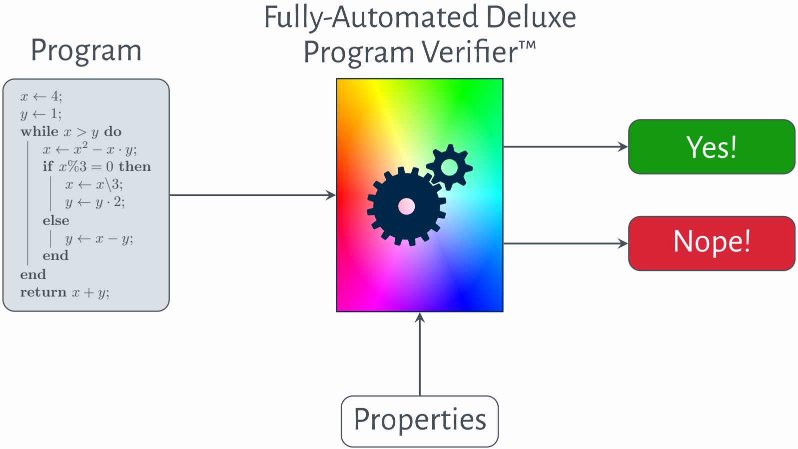
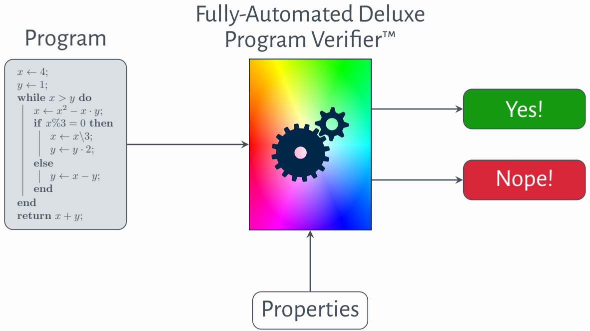
The dream of Automatic Verification



The dream of Automatic Verification

Achievable?



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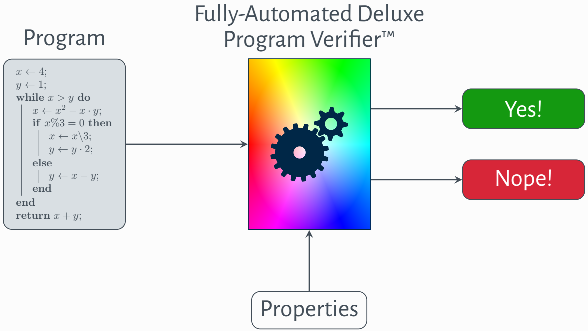

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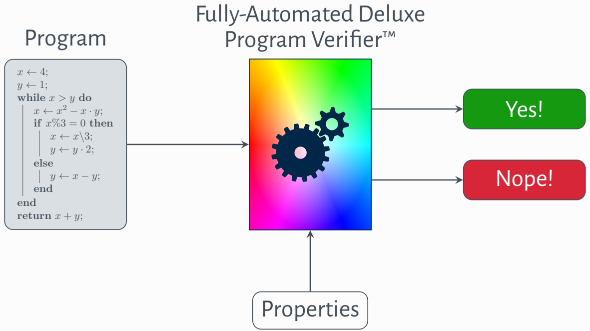

- we know that some properties of programs are undecidable, e.g. termination! (remember the halting problem?)
- perhaps other interesting properties are decidable? Bad news...

The foundamental limit
Undecidability

Rice's theorem [RVG]

Every non-trivial semantic property of programs is undecidable.

- a property is non-trivial if it neither is true for every program nor it's false for every program;
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An example

The property of returning 0 for some input is undecidable by Rice's Theorem.

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Implicit in Rice's Theorem is an idealized program model.

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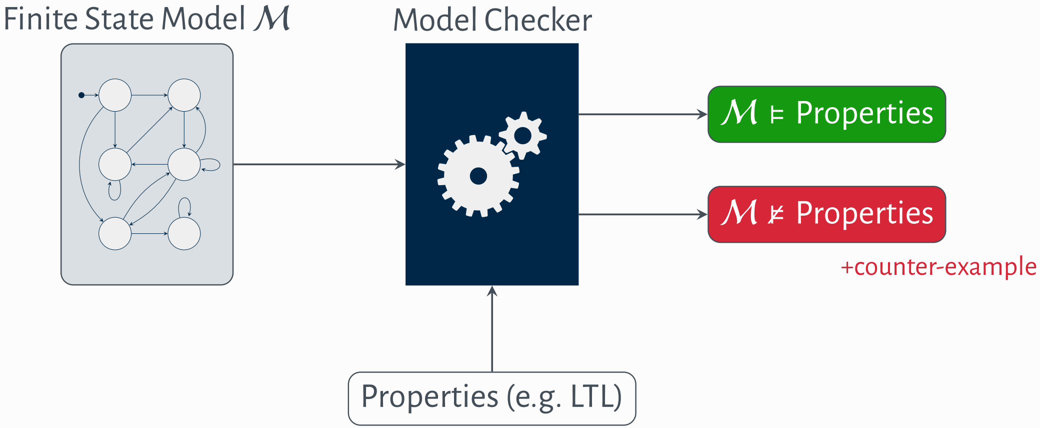
Concrete computing devices have **bounded** resources!

The model checking problem is decidable if we restrict ourselves to finite-state models.

Automatic Verification
Model Checkers



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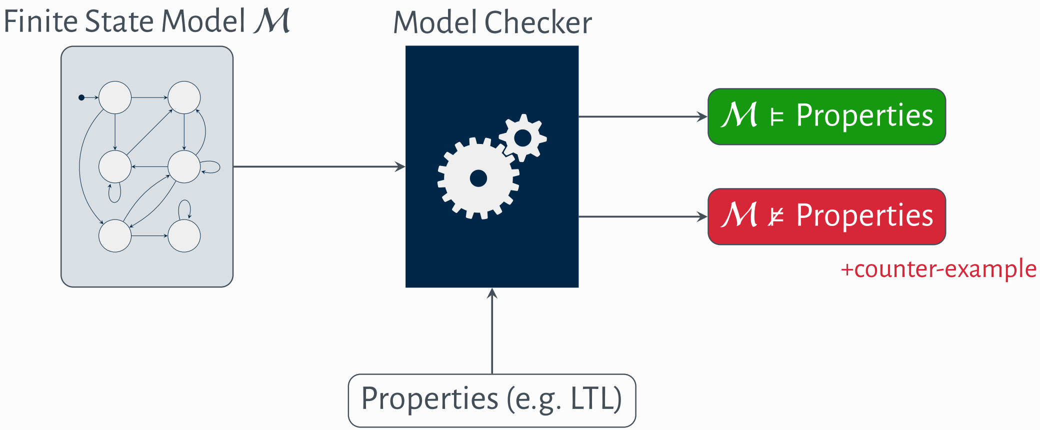

Some well-known model checkers are [SPIN], [nuSMV], [TLC], [JPF].

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- optimistic limit for a model checker? 10^{100} states [Kwo00].

Formal Methods in Software Engineering

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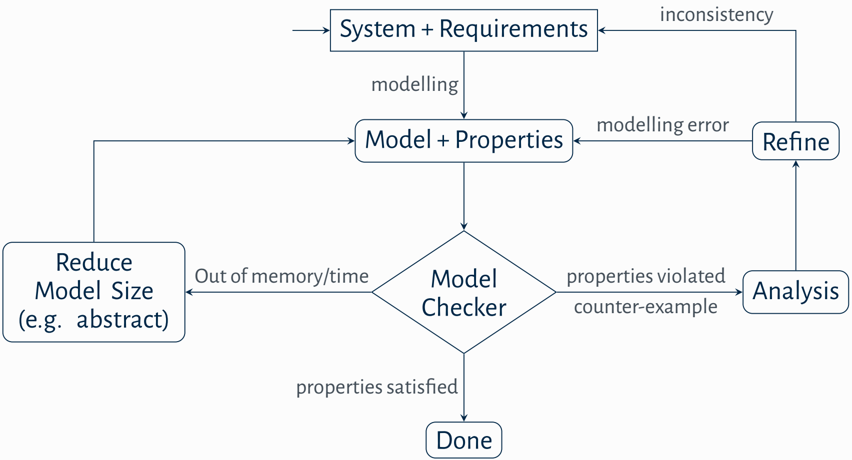
- During Verification, FM can:
  - increase the confidence on system reliability;
  - help with traditional verification techniques (e.g. test case generation).

The Model Checking process



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  - Formal Methods and Model Checking (using TLC).

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Formal Methods at Amazon Web Services – part 2

- In two week, they learned how to use TLA+/TLC and wrote a detailed specification;
- Model-checked the specification using 10 EC2 instances, each with 8 cores plus hyperthreads, and 23 GB of RAM;
- Found a data-loss bug if a particular sequence of failures and recovery steps was interleaved with other processing; the shortest error trace exhibiting the bug contained 35 high-level steps.

A success story
Formal Methods at Amazon Web Services – part 3

- This success led to management advocating TLA+ to other teams working on other products;

Product	Component	Benefits
DynamoDB	Replication & group-membership system	Found 3 bugs.
S3	Fault-tolerant low-level network algorithm	Found 2 bugs. Found further bugs in proposed optimizations.
	Background redistribution of data	Found 1 bug, and found a bug in the first proposed fix.
EBS	Volume management	Found 3 bugs.

Table: Benefits of using Formal Methods on different products at AWS

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- As with any tool, a model checker may contain software defects!

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- It can be easily integrated in existing development methodologies;
- It provides useful diagnostic counter-examples in case a property is violated;

Practice time!

A CONCURRENT PROGRAM


```
process P0 {
  while(true){
    // noncritical section
    flag_0 = 1;
    while (flag_1) {}
    // critical section
    flag_0 = 0;
    // noncritical section
  }
}
```

```
process P1 {
  while(true){
    // noncritical section
    flag_1 = 1;
    while (flag_0) {}
    // critical section
    flag_1 = 0;
    // noncritical section
  }
}
```

A CONCURRENT PROGRAM
MODELLING


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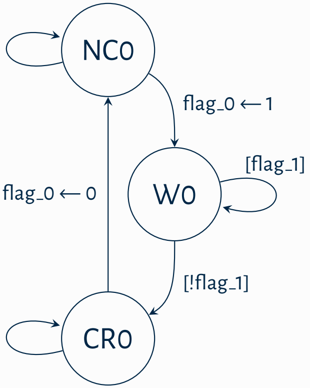
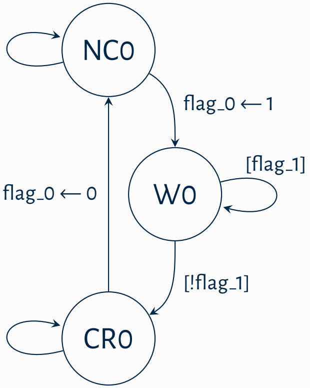


Figure: Model for process P0

A concurrent program
Modelling



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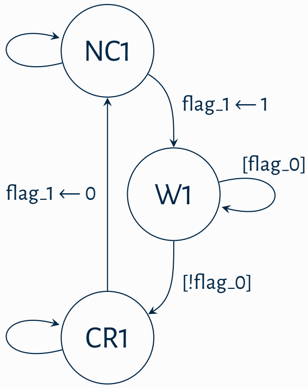

Figure: Model for process P1

A CONCURRENT PROGRAM

MODELLING: PARALLEL COMPOSITION

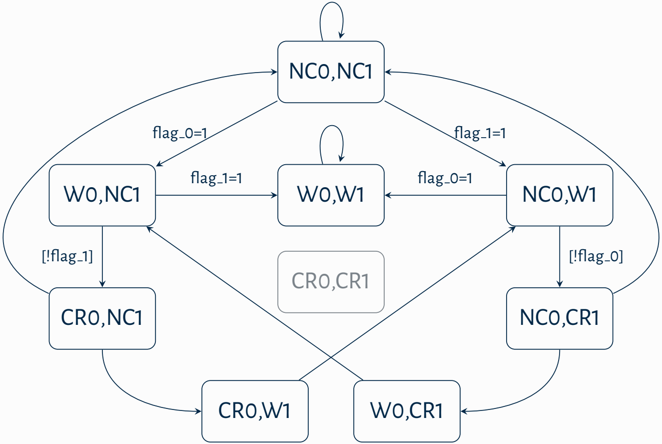

Figure: Asynchronous parallel composition of `P0` and `P1`

Demo time
Model Checking with NuSMV

Take Home Messages

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- Using Formal Methods;

You still there?

Any questions?

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