Introduction to Model Checking

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Temporal Logic Model Checking

➜ Model checking is an automatic verification technique for finite state concurrent systems

➜ Developed independently by Clarke and Emerson and by Queille and Sifakis in early 1980's

➜ Specifications are written in propositional temporal logic (Pnueli 77)

➜ Verification is an intelligent exhaustive search of the state space of the design

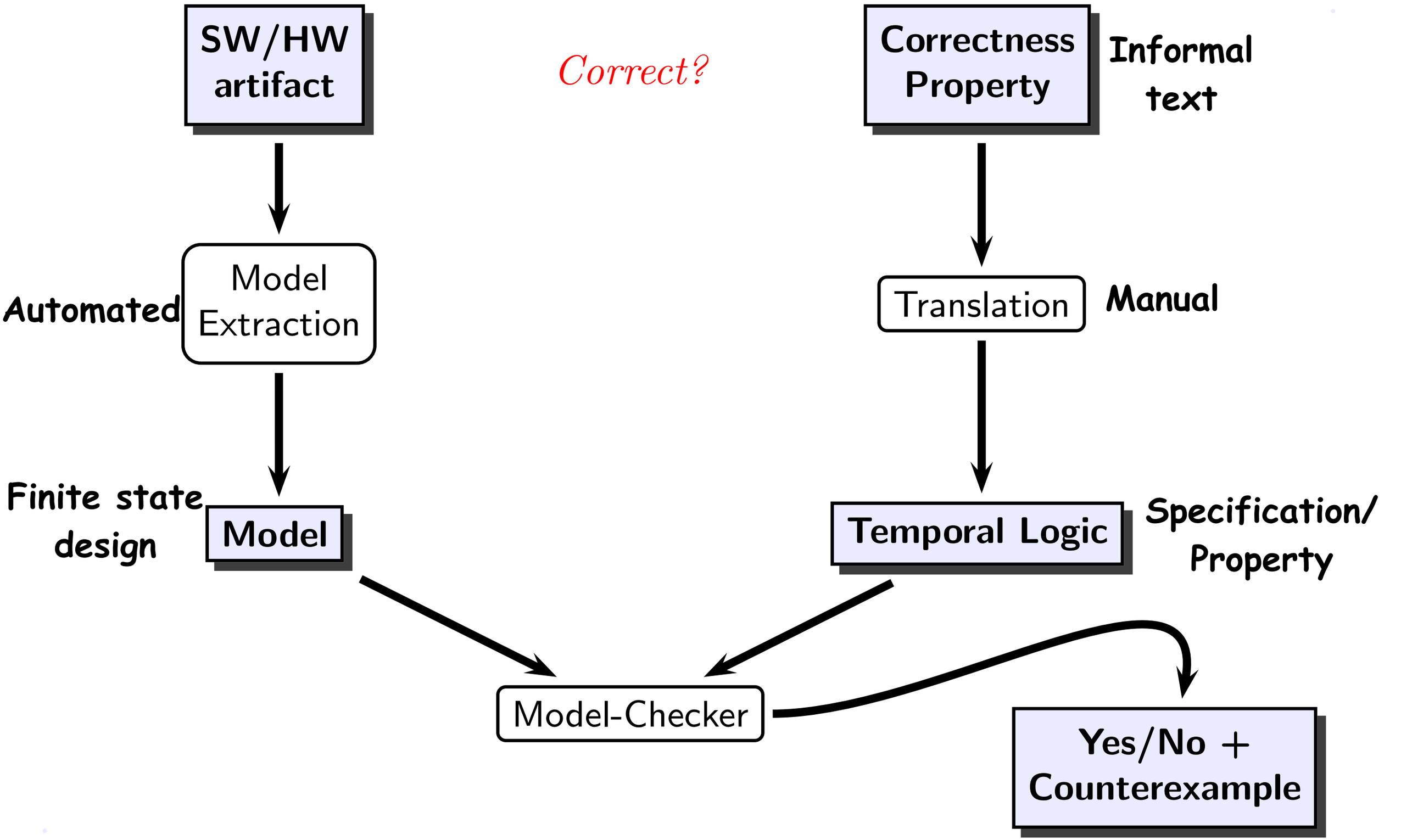
Advantages of Model Checking

- ➜ No proofs!
  - ➥ algorithmic rather than deductive
- ➜ Fast
  - ➥ Compared to other rigorous methods such as theorem proving
- ➜ Diagnostic counterexamples
- ➜ No problem with partial specification
- ➜ Logics can easily express many concurrency properties

Model Checking vs Testing

- Testing
  - Checks only some of the system executions
  - May miss errors, but scales better to larger systems
- Model Checking
  - Exhaustively explores all executions in a systematic way
  - Reports diagnostic counterexamples
  - does not scale to large systems
    - state explosion problem

Overview of Model Checking



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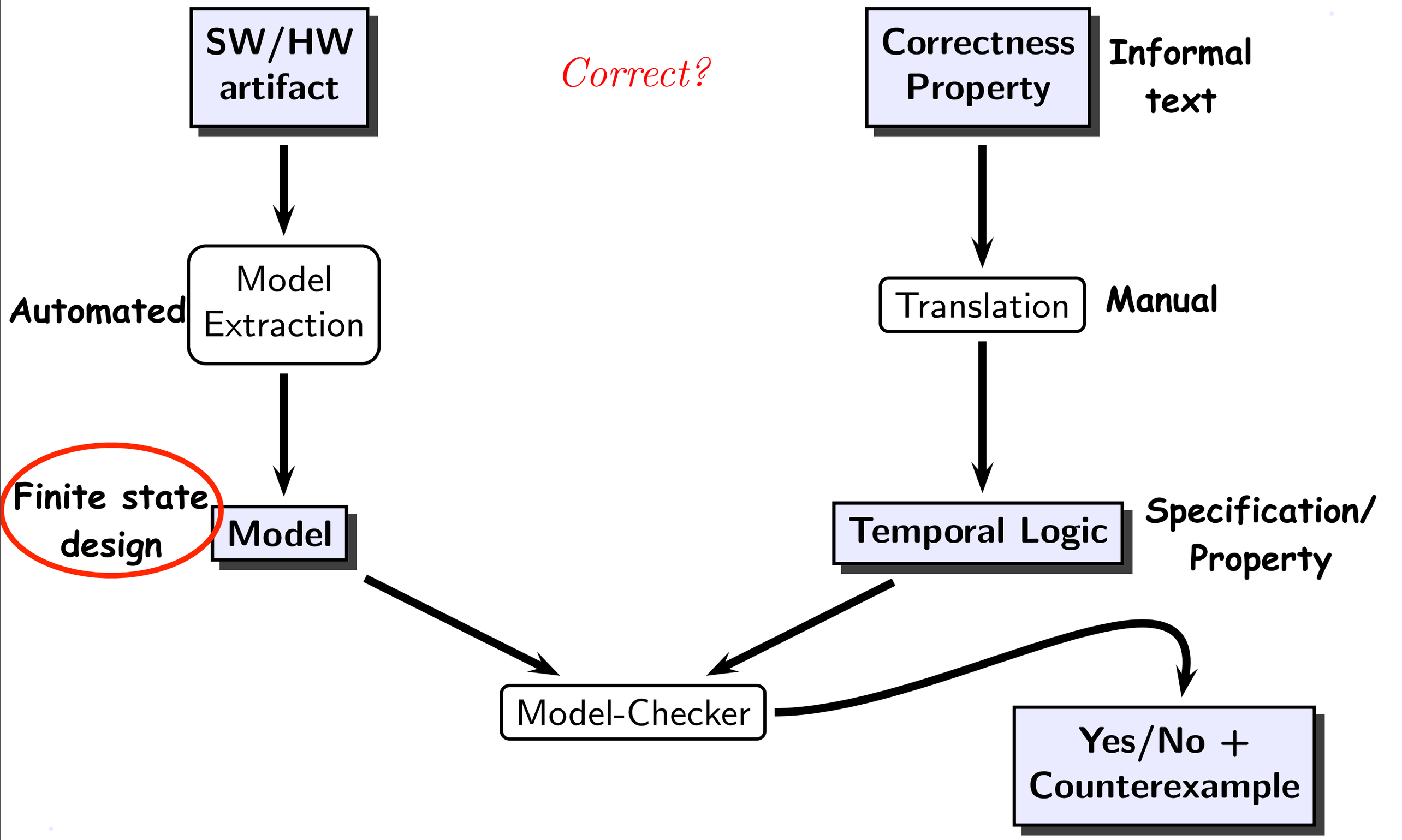
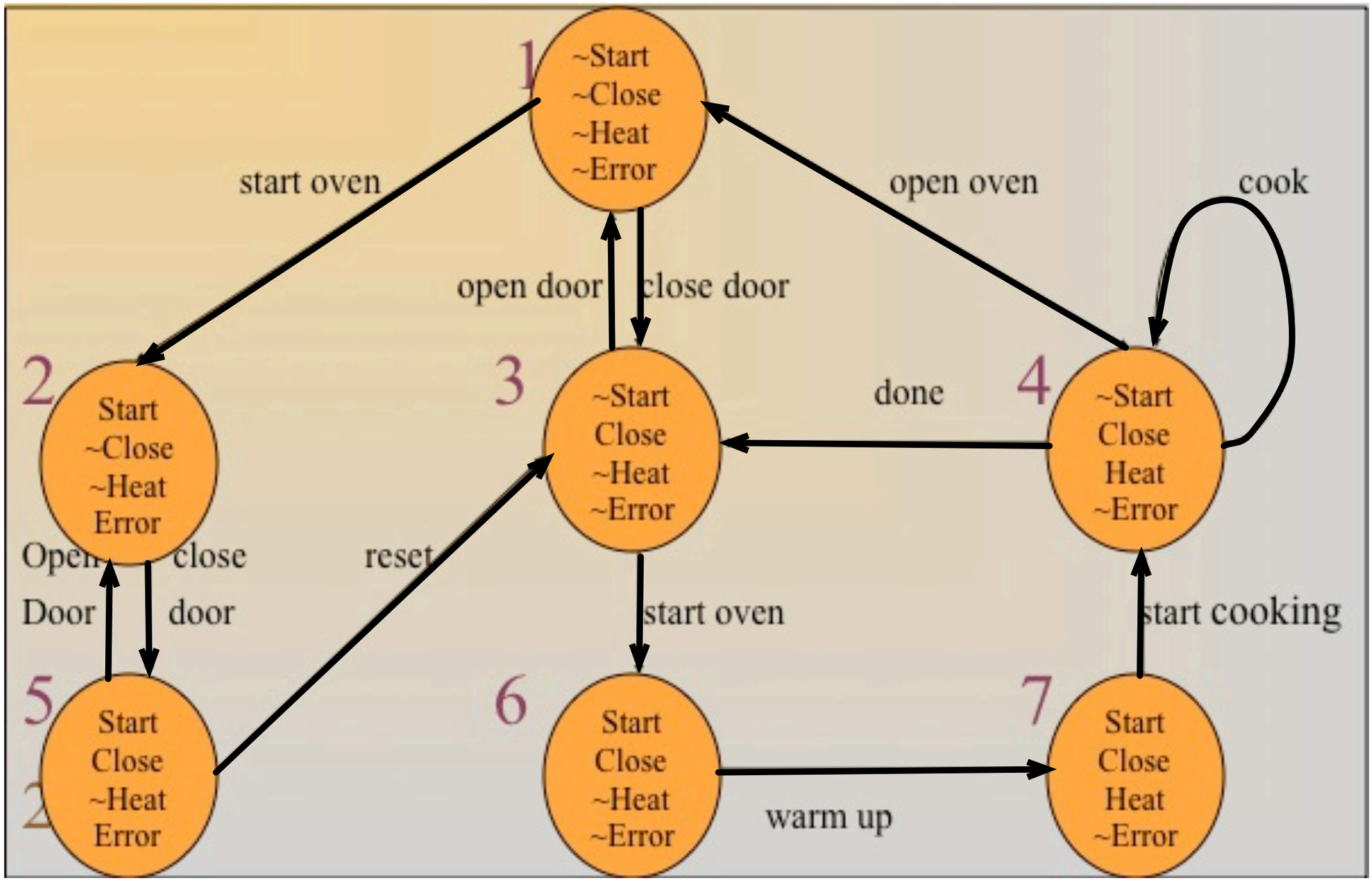
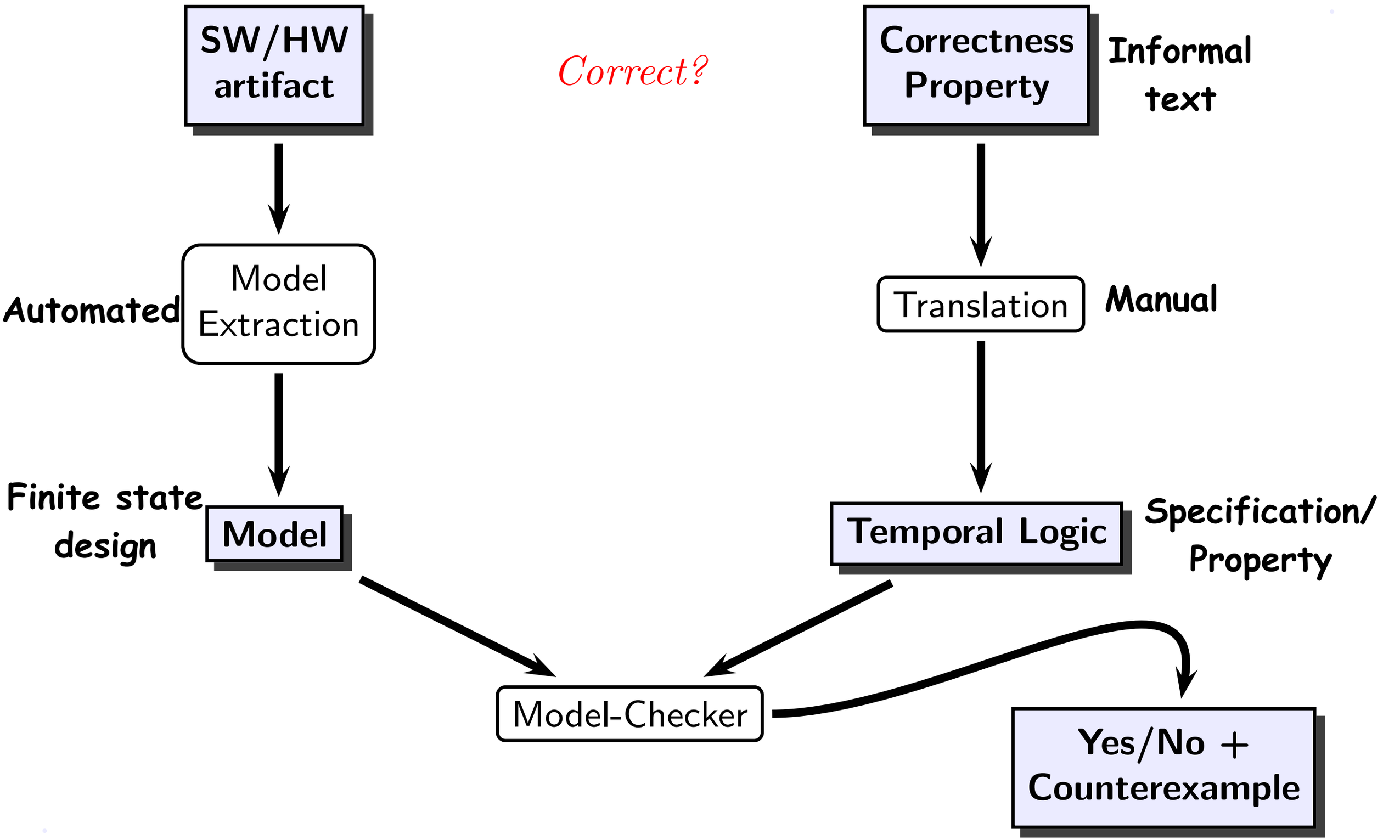


Finite State Design



State transition graph describes the system evolving over time

Overview of Model Checking



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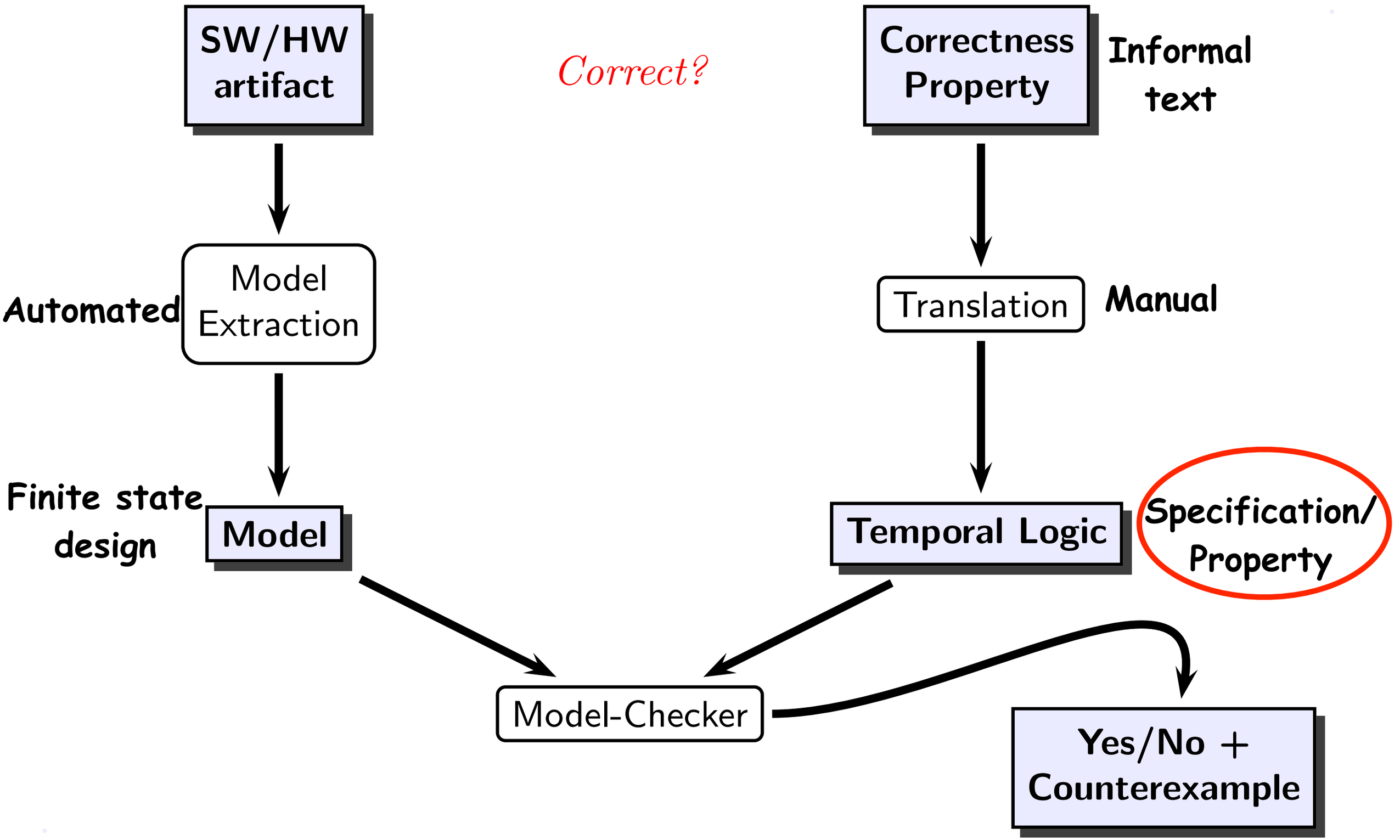


System Properties

➜ The oven does not heat up until the door is closed

➜ Not heat_up holds until door_closed

➜ (¬ heat_up) U door_closed

Properties in Temporal Logic

➜ Express properties of event orderings in time

➥ Mutual exclusion

$$\text{always } \neg(\text{proc1} \wedge \text{proc2})$$

➥ Non starvation

$$\text{always } (\text{request} \Rightarrow \text{eventually granted})$$

➥ Sanity check

$$\text{eventually request}$$

➥ Communication protocols

$$\neg\text{get-message until send-message}$$

➥ Fairness

$$\text{always eventually control-granted}$$

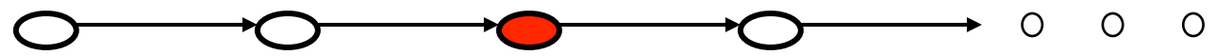
LTL - Linear Time Logic (Pn 77)

➜ Determines patterns of infinite traces

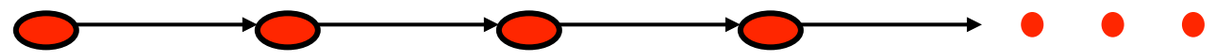
➥ Every moment has a unique successor

➢ The symbol 'p' is an atomic proposition, e.g., "Device Enabled"

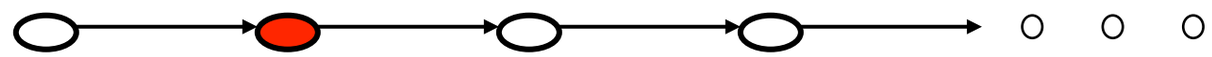
➢ F p - p holds sometime in the future



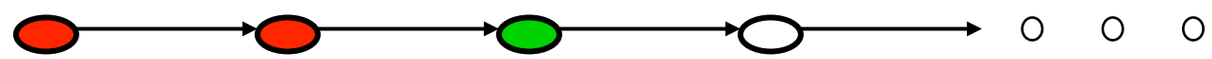
➢ G p - p holds globally in the future



➢ X p - p holds next time



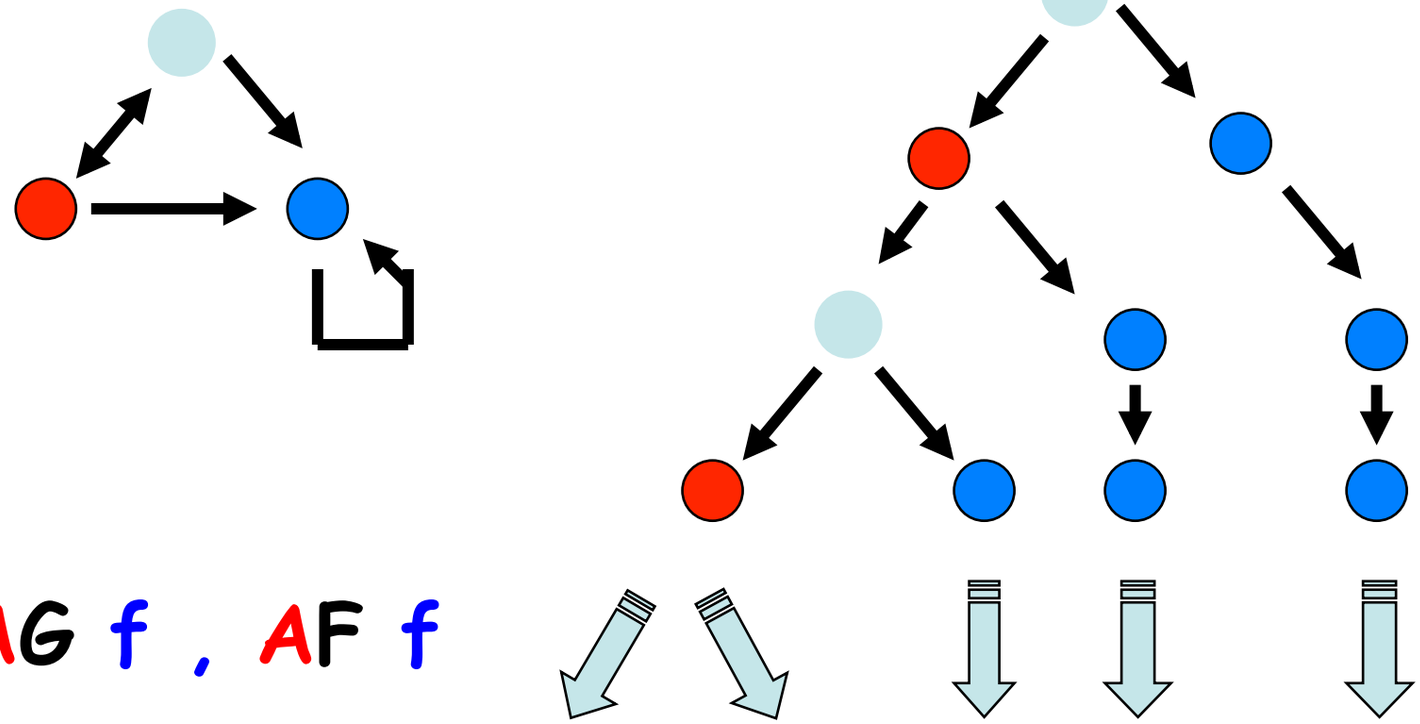
➢ p U q - p holds until q holds



CTL - Computational Tree Logic (CES 83)

➜ Determines patterns of infinite trees

➥ Every moment has several successors



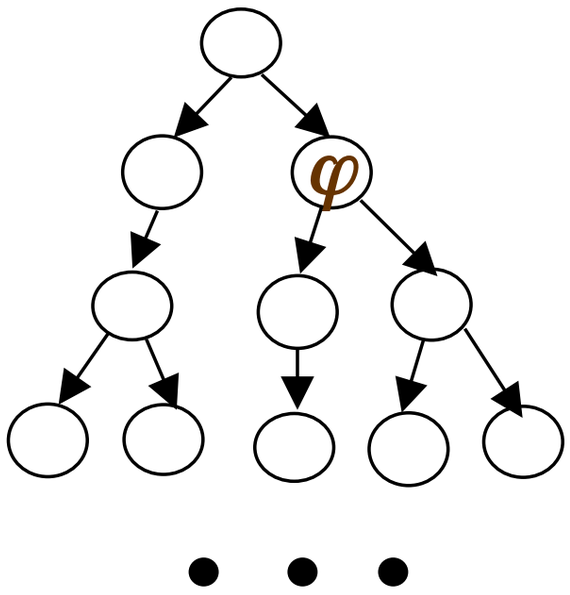
Universal formulas:

- AX f, A(f U g), AG f , AF f

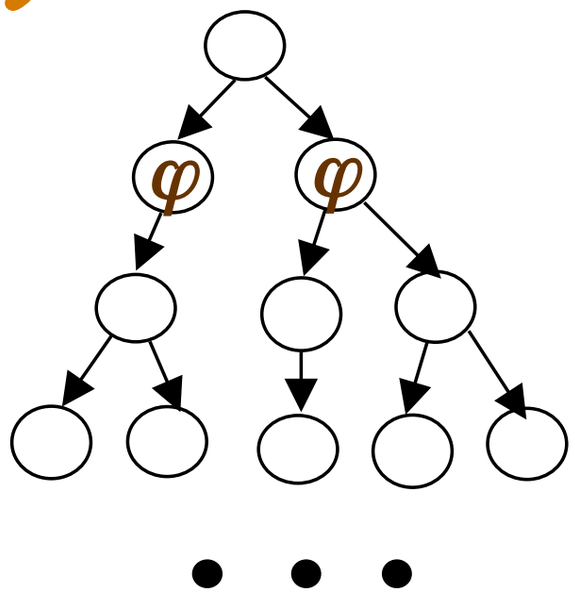
Existential formulas:

- EX f, E(fUg), EG f , EF f

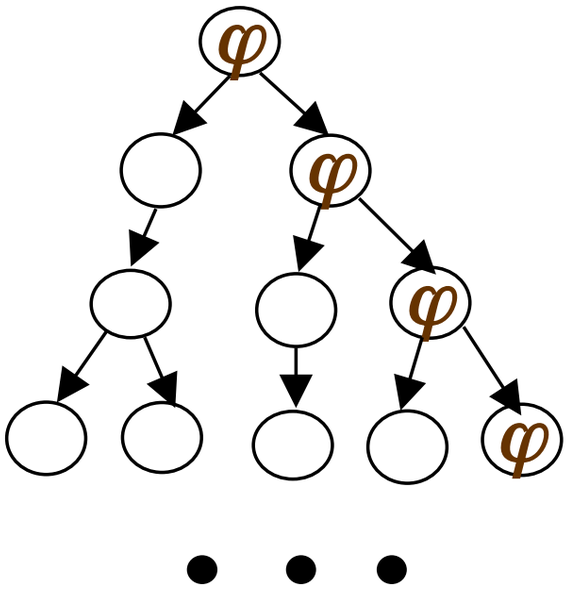
CTL (Cnt'd)



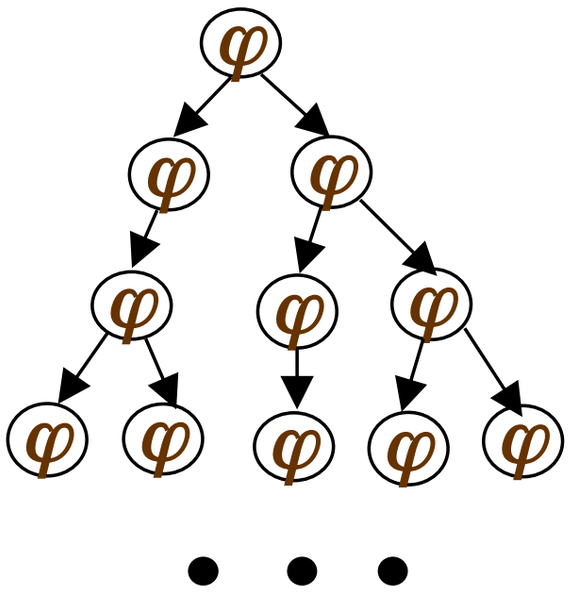
EX (exists next)



AX (all next)

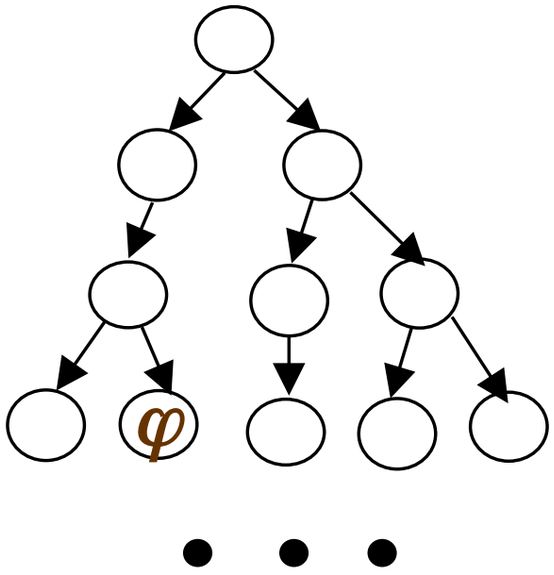


EG (exists global)

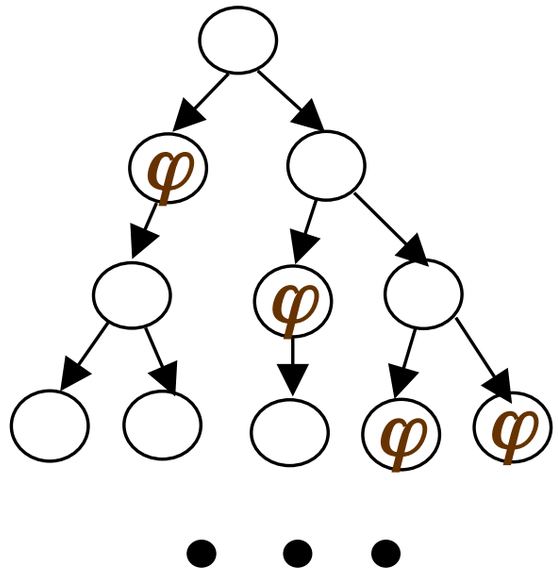


AG (all global)

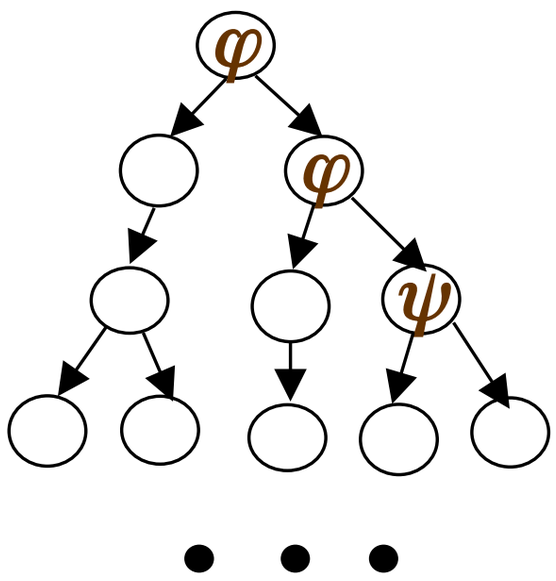
CTL (Cnt'd)



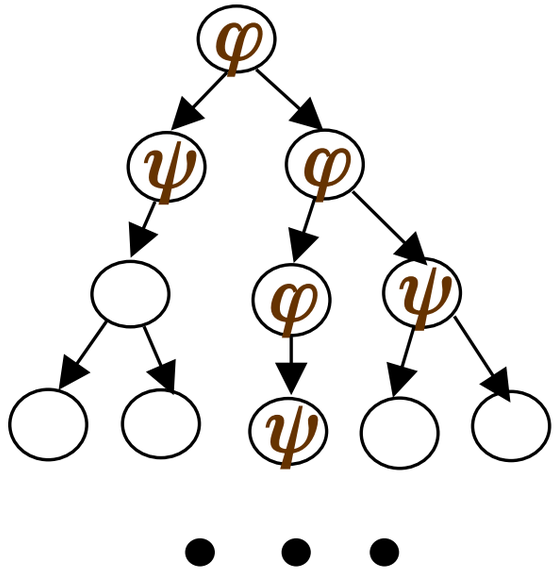
EF (exists future)



AF (all future)



EU (exists until)



AU (all until)

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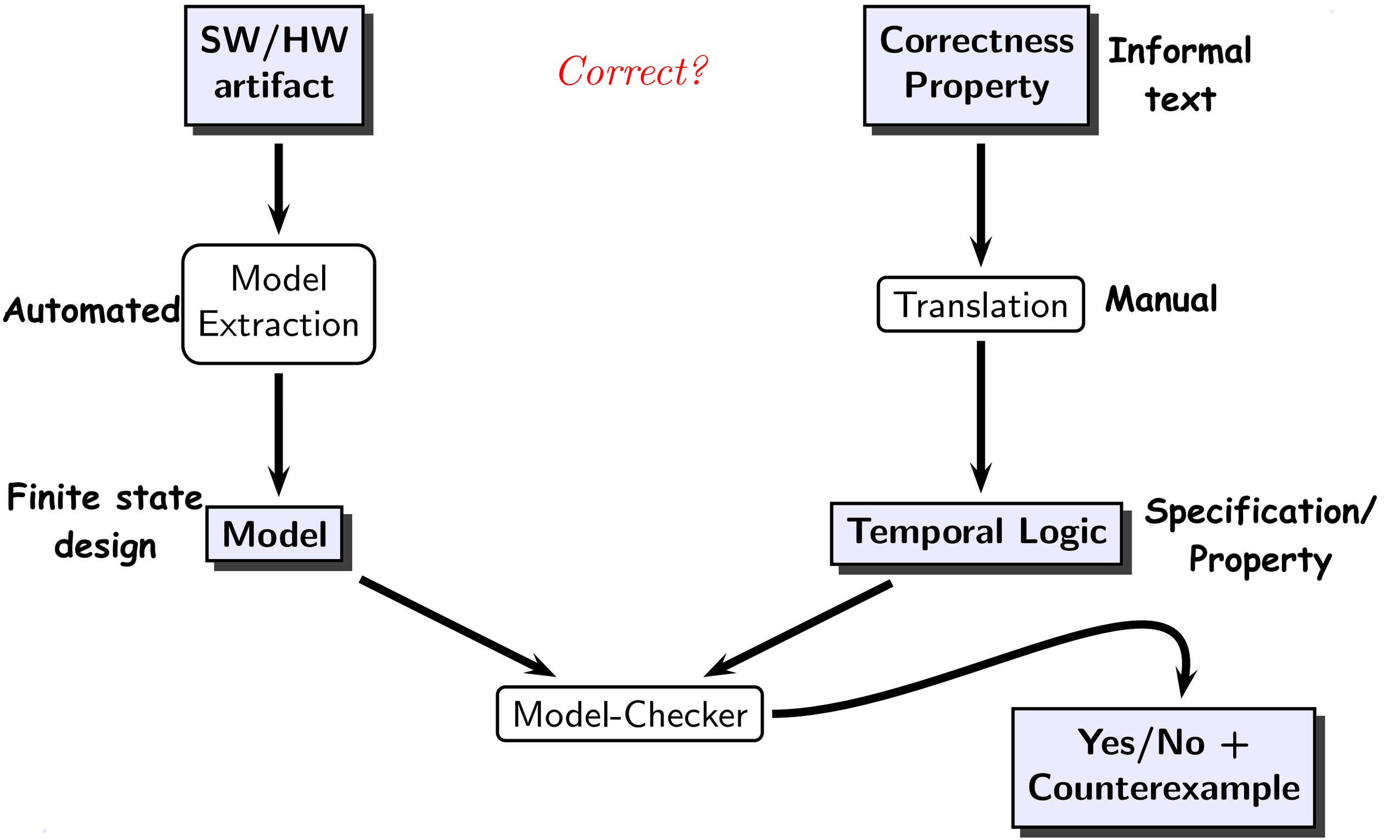

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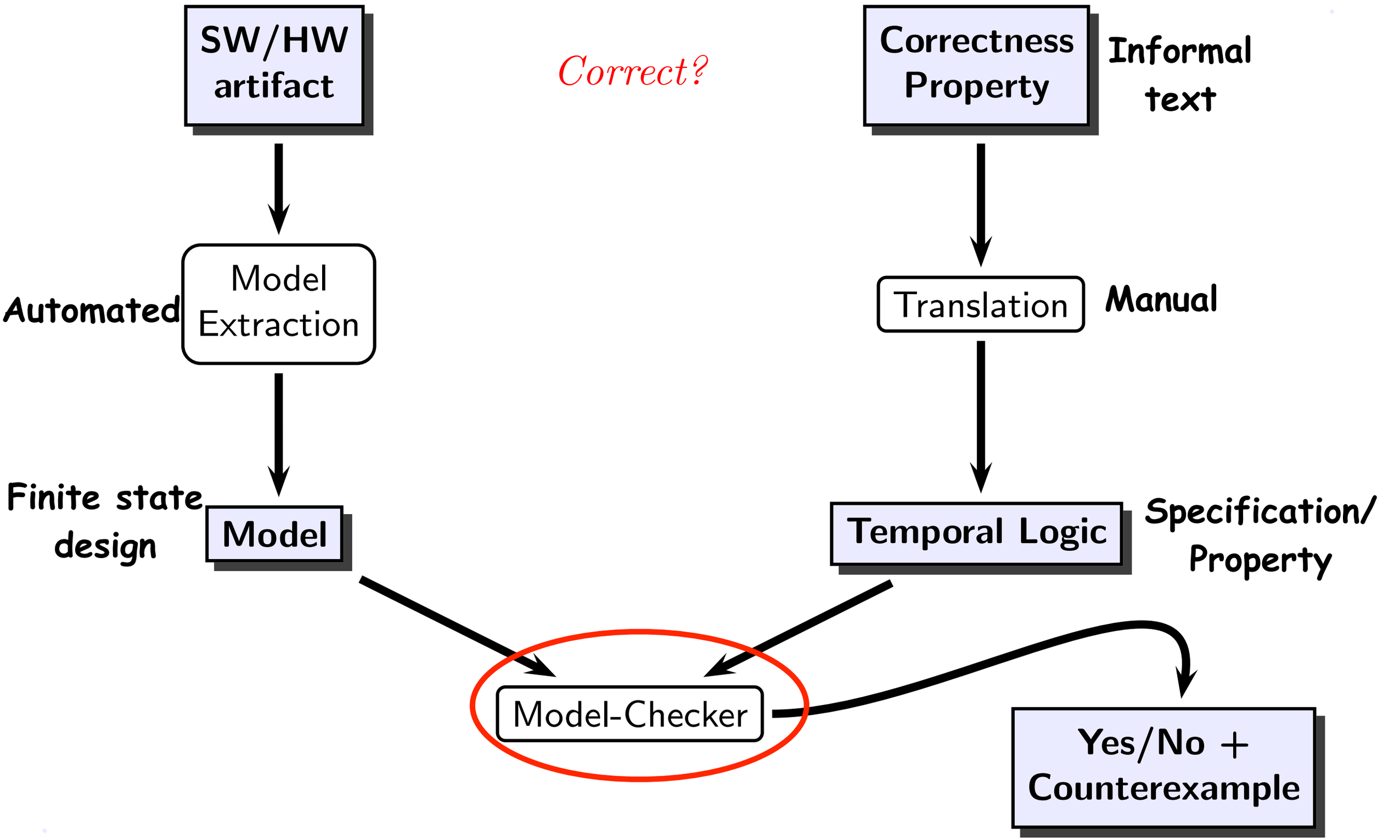
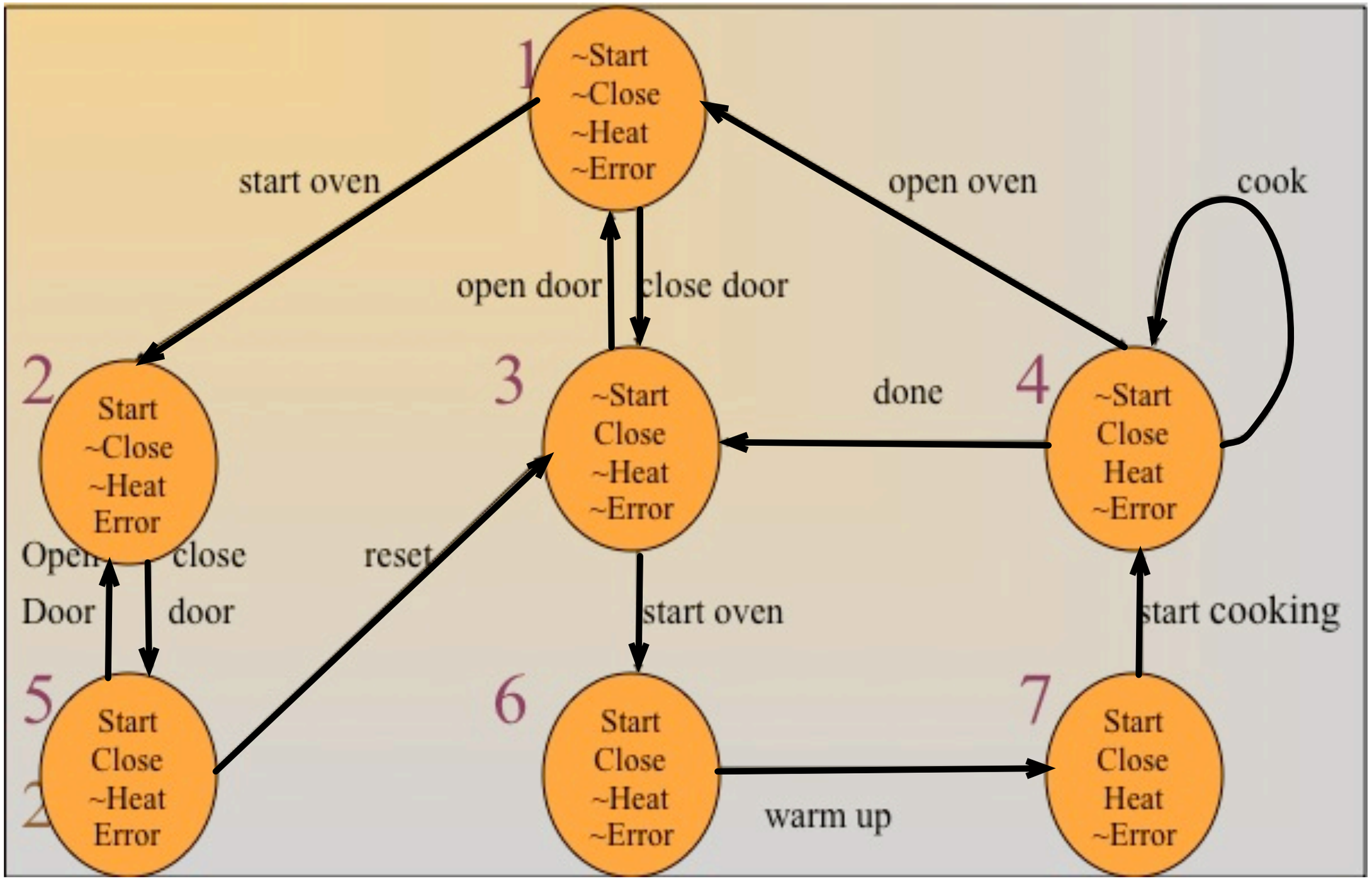


Model Checking Algorithm



(¬ heat_up) U door_closed

Model Checking Algorithm (CTL)

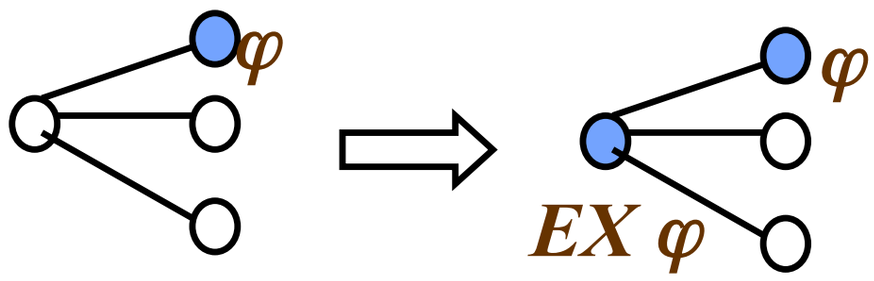
- **Receive:**
  - **Finite state Design**
  - **Temporal logic formula φ**
- **Assumptions:**
  - **Finite number of processes**
    - **Each having a finite number of finite-valued variables**
  - **Finite length of a CTL formula**
- **Algorithm:**
  - **Label states of *K* with subformulas of that φ are satisfied there and working outwards towards φ.**
  - **Output states labeled with φ**

Example: EX AG ($p \rightarrow$ E[p U q])

MC Algorithm (CTL) (Cnt'd)

EX φ

- **Label any state with EX φ if any of its successors are labeled with φ**



AF φ

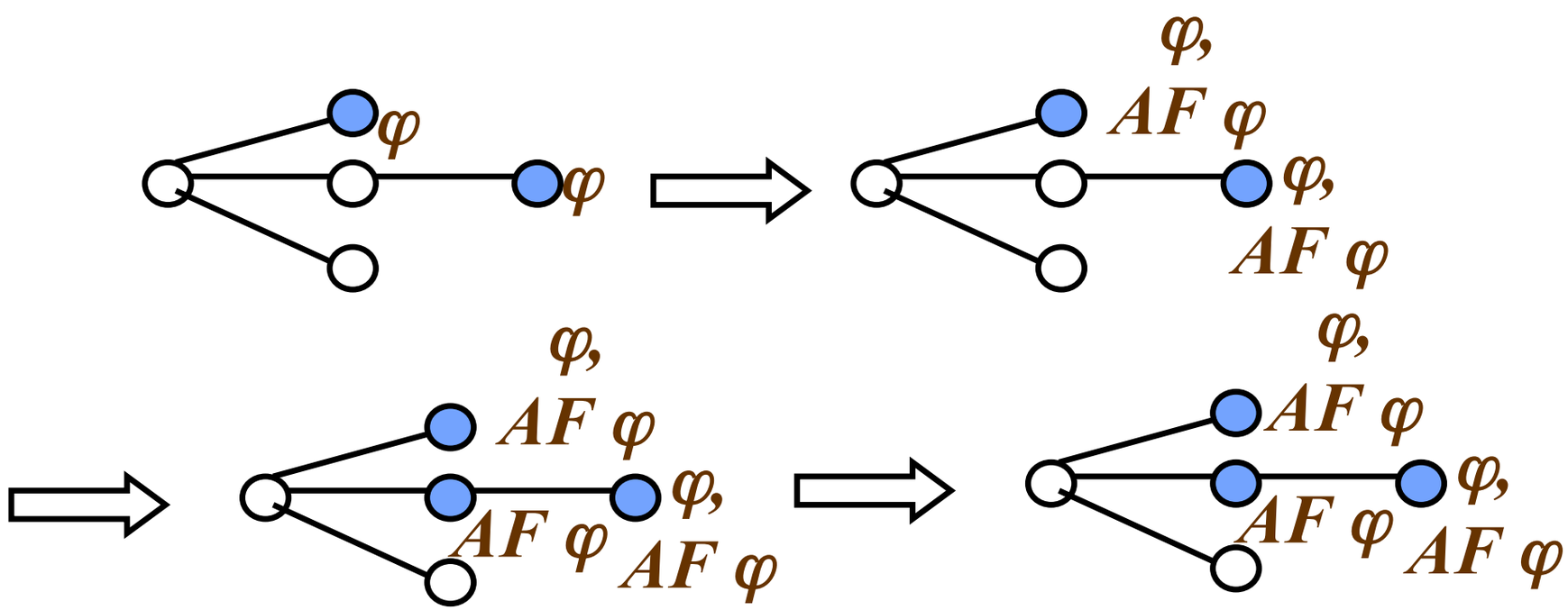
- **If any state s is labeled with φ, label it with AFφ**
- **Repeat:**

  label any state with AFφ

  if all of its successors

  are labeled with AFφ

until there is no change



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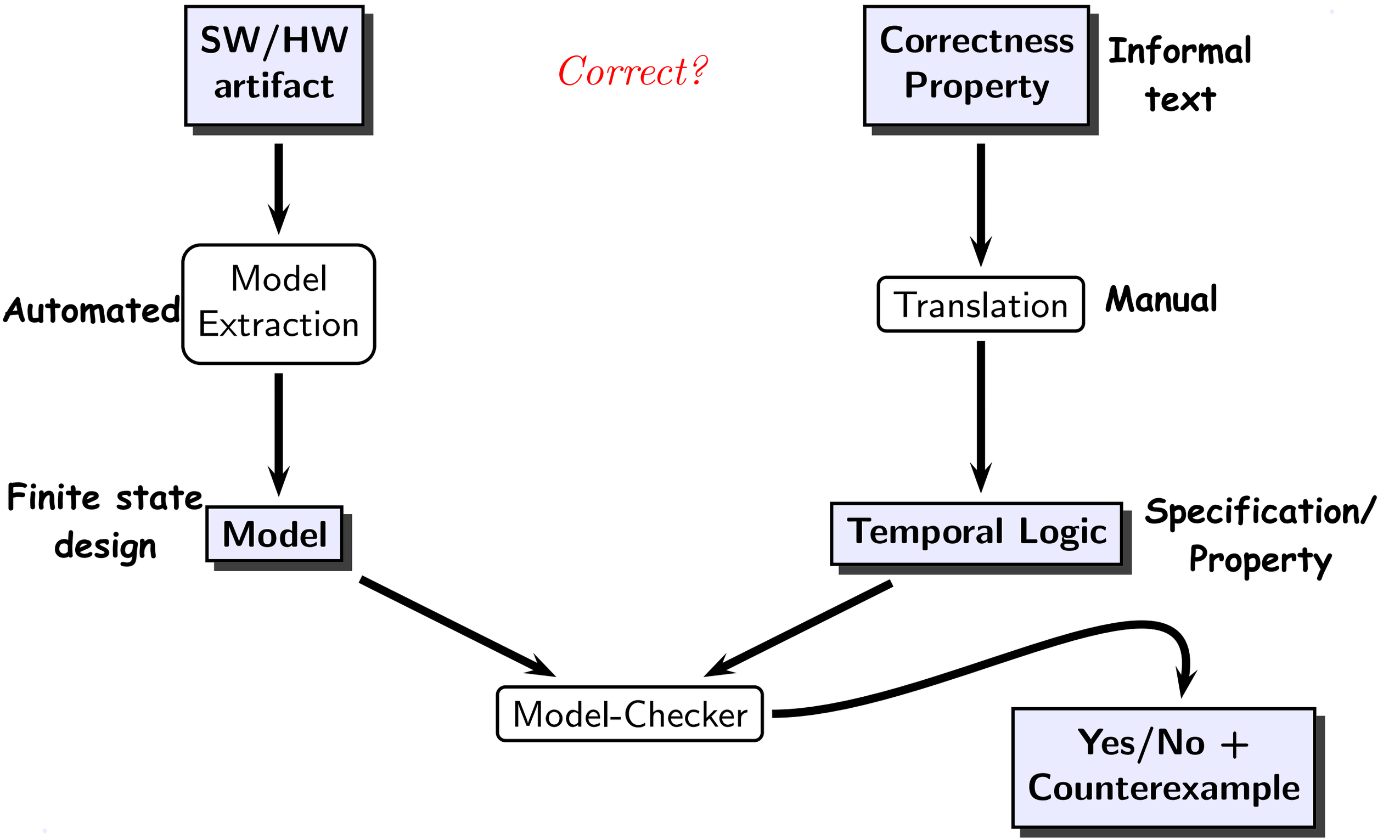

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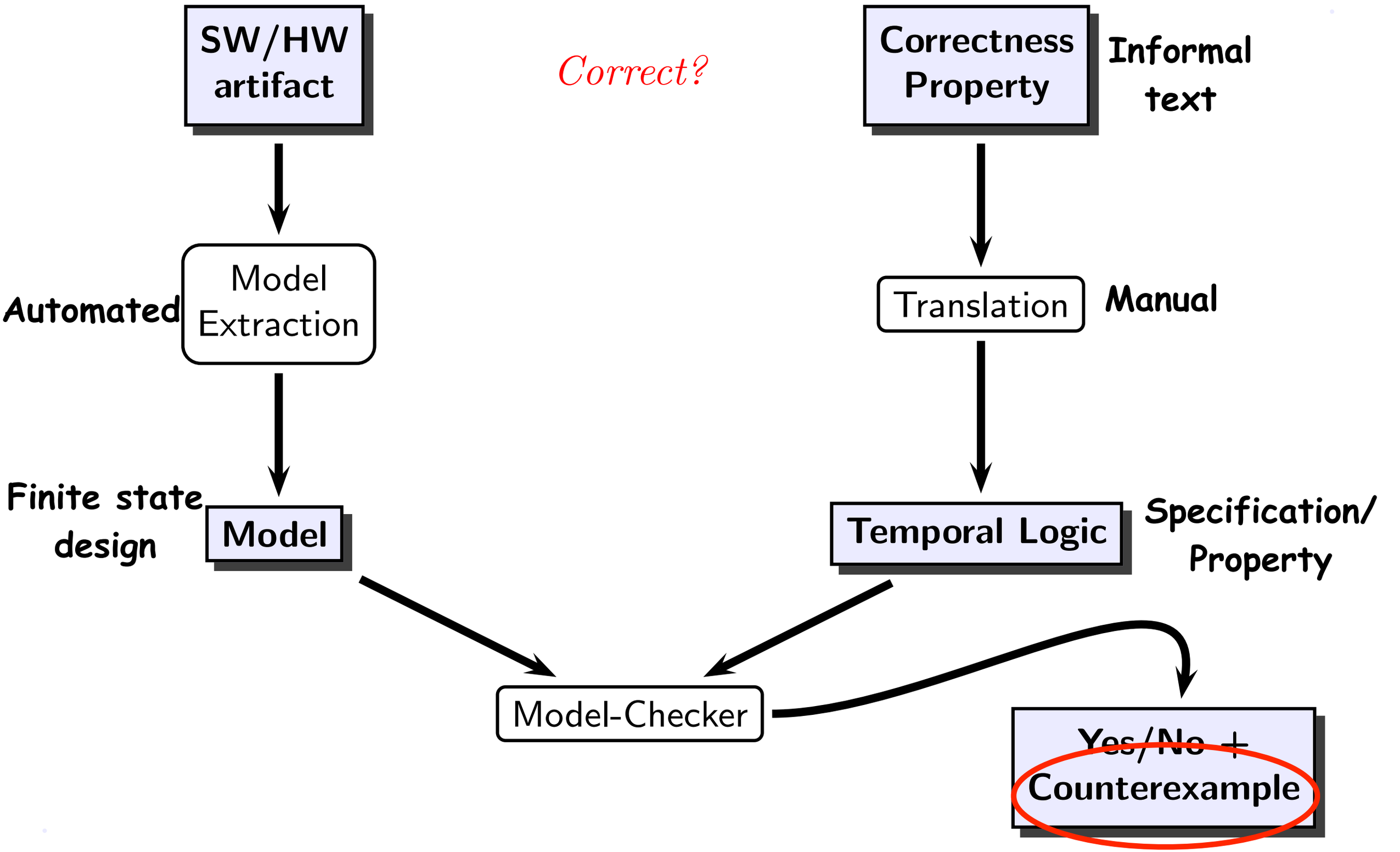
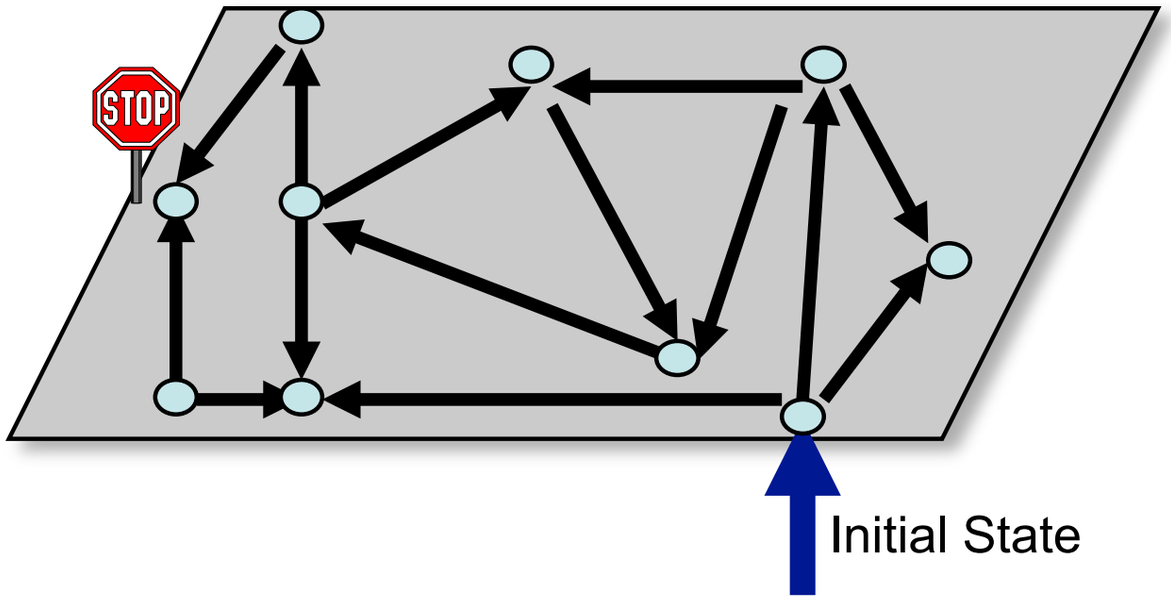


Counterexamples

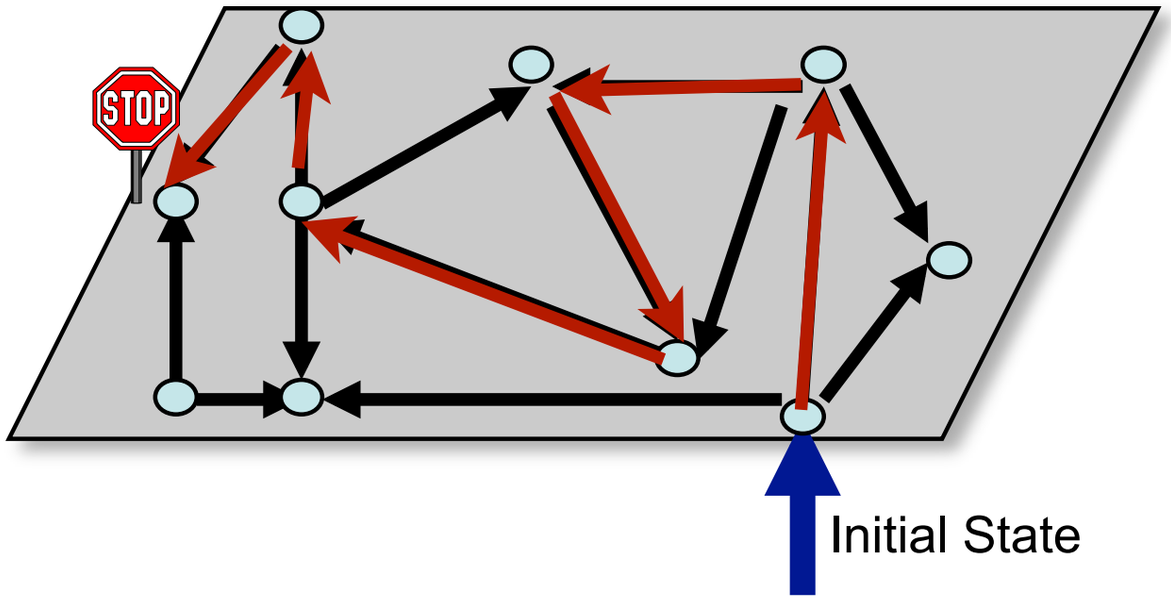


Safety Property:

bad state  unreachable

Counterexample

Counterexamples



Safety Property:

bad state  unreachable

Counterexample

Main Disadvantages of Model Checking

➜ Proving a program does not help you understand it!

➜ Temporal logic specifications are ugly

➥ Depends on who is to write them

➜ Writing specification is hard

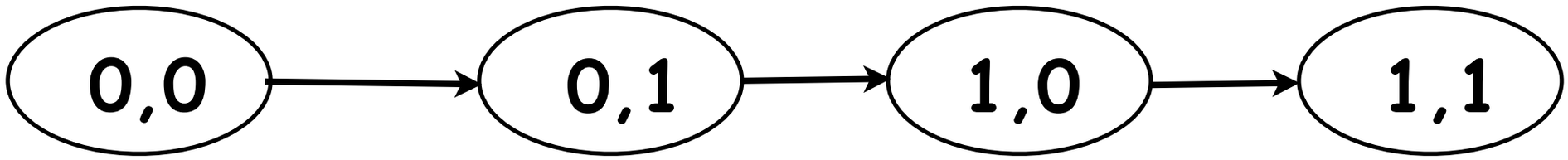
➥ True, but perhaps partially a matter of education

➜ State explosion is a major problem

➥ Model checking may not scale!

State Explosion problem

→ 2-bit counter



→ n-bit counter

➥ 2^n states

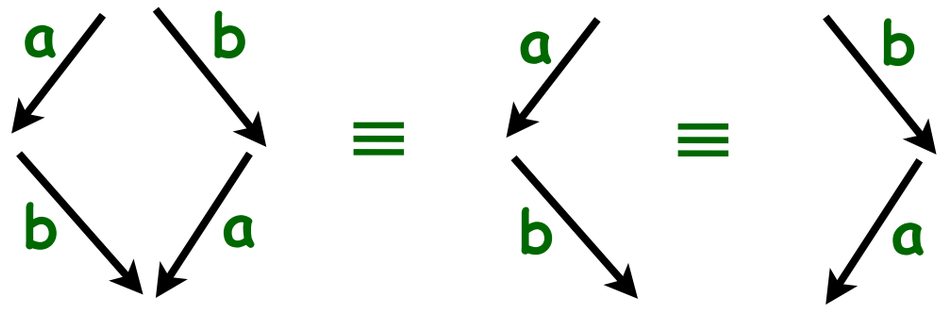
→ Parallel composition of processes

➥ m processes, each having n states

➢ #states of the composition = n^m

Some Remedies

- Symbolic Model Checking (McMillan 92)
  - Symbolic representations for state transition systems
    - using BDDs (Binary Decision Diagrams)
    - scales to 10^20 states
- Partial State Reduction (Godefroid 90)
  - Avoid checking different inter-leavings of independent actions
    - Asynchronous systems, 'a' and 'b' are independent actions



    - Implemented in Gerard Holzmann's SPIN

Some Remedies (Cnt'd)

- Bounded Model Checking (Biere et. al. 99)
  - Translate the model and the specification into a propositional formula
    - Use fast SAT solvers to check satisfiability
  - Unbounded MC
    - Can a given property fail over time?
  - Bounded MC
    - Can a given property fail in k-steps?
      - where k is bounded
  - Suitable for falsification, not verification

Dealing with Very Complex Systems

→ Special techniques are needed when Symbolic methods, the partial order reduction, and bounded MC do not work

➥ Compositional Reseaning

➢ Jamieson M. Cobleigh, Dimitra Giannakopoulou, Corina S. Pasareanu: Learning Assumptions for Compositional Verification. TACAS 2003: 331-346

➥ Abstraction

➢ Patrick Cousot, Radhia Cousot: Abstract Interpretation: A Unified Lattice Model for Static Analysis of Programs by Construction or Approximation of Fixpoints. POPL 1977: 238-252

➥ Symmetry Reduction

➢ Edmund M. Clarke, E. Allen Emerson, Somesh Jha, A. Prasad Sistla: Symmetry Reductions inModel Checking. CAV 1998: 147-158

➥ Induction and Parameterized Verification

➢ E. Allen Emerson, Kedar S. Namjoshi: Verification of Parameterized Bus Arbitration Protocol. CAV 1998: 452-463

Future Challenges

- Model Checking Software Programs
  - Why software is so difficult?
    - large/unbounded base types: int, float, string
    - User-defined types/classes
    - Pointer/aliasing + unbounded number of heap allocated cells
    - Procedure calls/recursion/overloading
    - Concurrency + unbounded number of threads
    - etc.
  - Some existing tools
    - SLAM
      - Developed at Microsoft Research early 2000 for model checking Windows device drivers
      - Uses static analysis to extract a finite model from device drivers code written in C
    - Other tools
      - Bandera (Kansas State), MAGIC (CMU), SATABS (CMU), BLAST (Berkley), F-Soft (NEC)

Future Challenges

- ➜ Exploiting the Power of SAT, Satisfiability Modulo Theories (SMT)
- ➜ Compositional Model Checking of both Hardware and Software
- ➜ Verification of Embedded Systems (Timed and Hybrid Automata)
- ➜ Model Checking and Theorem Proving (PVS, STEP, SyMP, Maude)
- ➜ Probabilistic and Statistical Model Checking
- ➜ Interpreting Counterexamples
- ➜ Scaling up even more!!

Some Model Checking Tools

- SPIN
  - http://spinroot.com/spin/whatispin.html
- NuSMV
  - http://nusmv.fbk.eu/
- Java Path Finder
  - http://babelfish.arc.nasa.gov/trac/jpf
- UPPAAL
  - http://www.uppaal.org/
- PRISM
  - http://www.prismmodelchecker.org/
- Contact me for more info!

Acknowledgments

➜ These slides are based on the lecture notes from

- ➥ Ed Clarke @ CMU, http://www.cs.cmu.edu/~emc/
- ➥ Orna Grumberg @ Technion, http://www.cs.technion.ac.il/~orna/
- ➥ Marsha Chechik @ UofT, http://www.cs.toronto.edu/~chechik/

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- Patrice Godefroid, Pierre Wolper: Using Partial Orders for the Efficient Verification of Deadlock Freedom and Safety Properties. *CAV* 1991: 332-342
- Edmund M. Clarke, Armin Biere, Richard Raimi, Yunshan Zhu: Bounded Model Checking Using Satisfiability Solving. Formal Methods in System Design 19(1): 7-34 (2001)
- Thomas Ball, Sriram K. Rajamani: The SLAM project: debugging system software via static analysis. *POPL* 2002: 1-3

Thank You!

Questions?