Integrating Induction, Deduction and Structure for Synthesis

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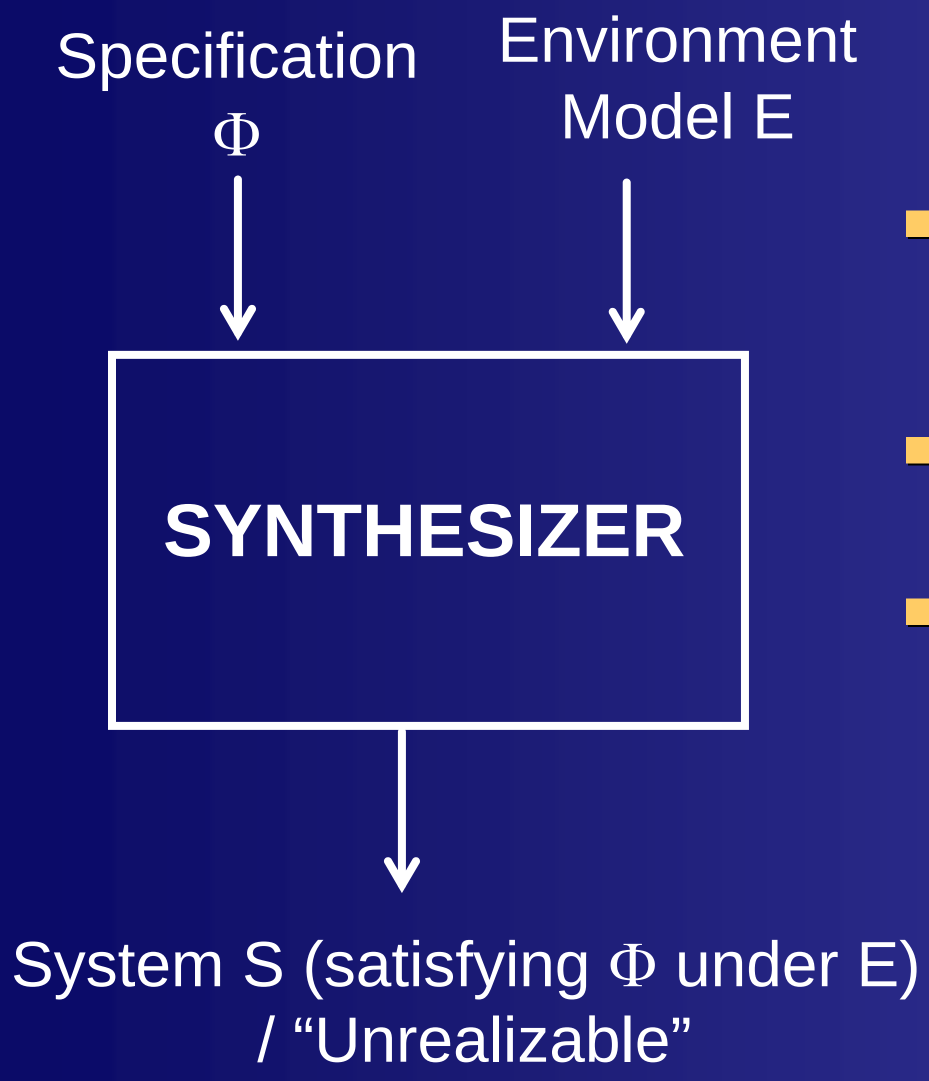
Synthesis and Its Challenges



- **Specification can be incomplete or difficult to use**
- **Environment model might be deficient**
- **High Complexity of synthesis**

Reverse Engineering Malware

Obfuscated code:

<u>Input:</u> y   <u>Output:</u> modified value of y

```
{ a=1; b=0; z=1; c=0;
  while(1) {
   if (a == 0) {
   if (b == 0) { y=z+y;
   b=~b;  c=~c; if (~c)
  else {
    z=z+y; a=~a; b=~b; c=~c;
    if (~c) break; } }
   else if (b == 0) {z=y << 2; a=~a;}
    else { z=y << 3; a=~a; b=~b;}
 } }
```

CHALLENGE:
SPECIFICATION CONTROLLED BY 'ATTACKER'

What it does:

y = y * 45

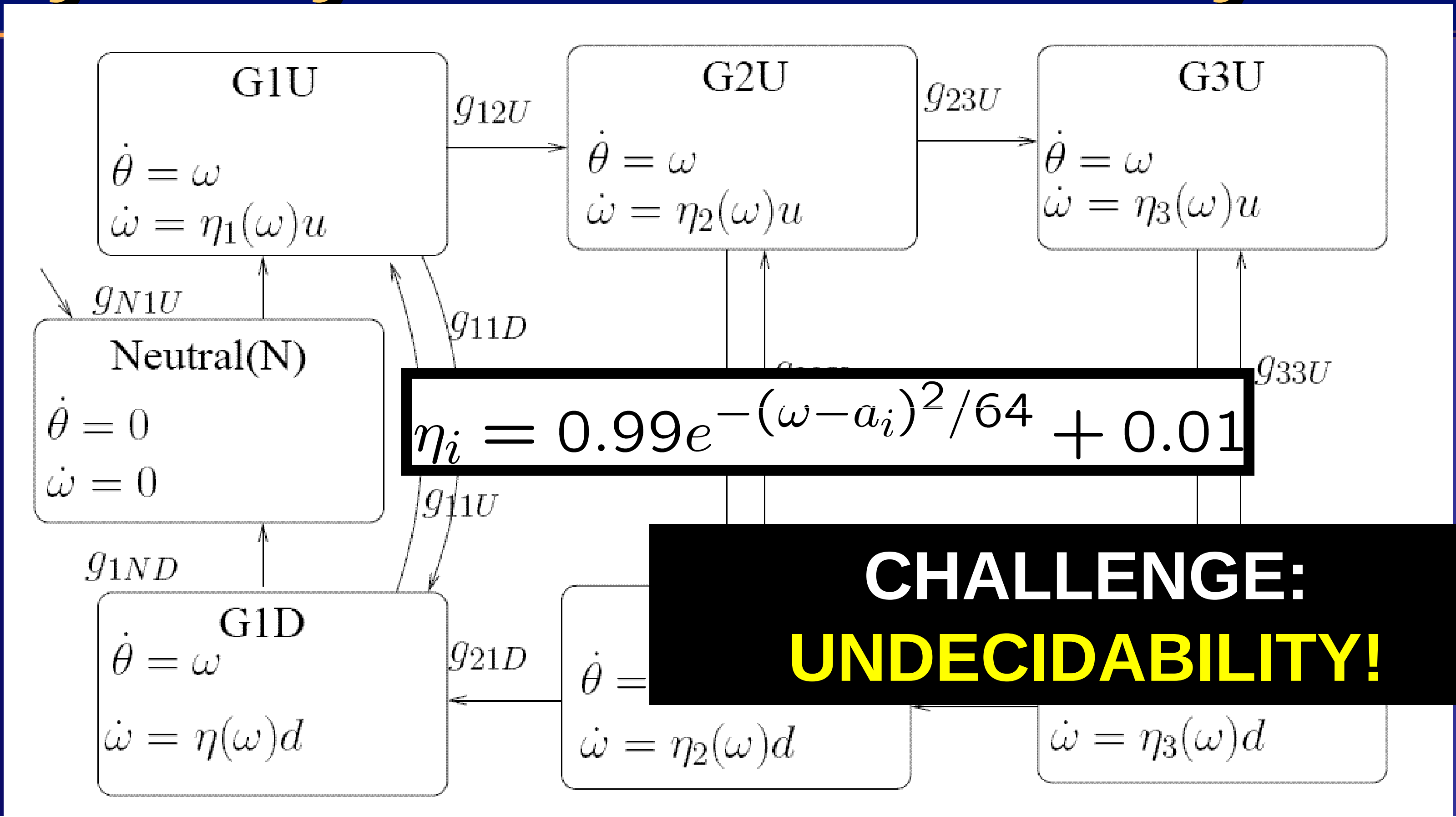
using

esis.

FROM
CONFICKER WORM

Paper: S. Jha et al., "Oracle-Guided Component-Based Program Synthesis", ICSE 2010.

Synthesizing Switching Logic (Hybrid Systems with Nonlinear Dynamics)



$$\eta_i = 0.99e^{-(\omega - a_i)^2/64} + 0.01$$

CHALLENGE:
UNDECIDABILITY!

Synthesize switch between the gears such that
- Efficiency η_i always exceeds 0.5 when $\omega \geq 5$
- Distance to be covered takes minimum time.

Paper: S. Jha et al., "Synthesizing Switching Logic for Safety and Dwell-Time Requirements", Intl. Conf. on Cyber-Physical Systems, April 2010.

Reactive Synthesis from LTL

CHALLENGE:
ENVIRONMENT SPECIFICATION

Often due to missing environment assumptions!

Paper: W. Li et al., "Mining Assumptions for Synthesis", MEMOCODE 2011.

Strategies to Address Challenges

- **Human Input / Insight**
  - Hypothesis on the form of artifact to be synthesized
  - "Structure Hypothesis"
  - Examples:
    - Sketch [Bodik, Solar-Lezama, et al.]
    - Component library [Jha et al., …]
- **Induction + Deduction**
  - Induction: specific examples → general rules
    - Learning from examples
  - Deduction: general rules → specific conclusions
    - Logical inference and constraint solving
  - Purely deductive approach is inefficient / inapplicable
  - Purely inductive approach gives no guarantees

Approach: Sciduction

Structure-Constrained Induction and Deduction

Structure Hypotheses
(on artifacts to be synthesized)

SKETCH,
TEMPLATE,
Etc.

Deductive Procedure
"Lightweight": solves lower complexity problem or special case of original decision problem

Inductive Procedure
Active Learning: selects examples to learn from

S. A. Seshia, "Sciduction: Combining Induction, Deduction, and Structure for Verification and Synthesis", DAC 2012

Outline

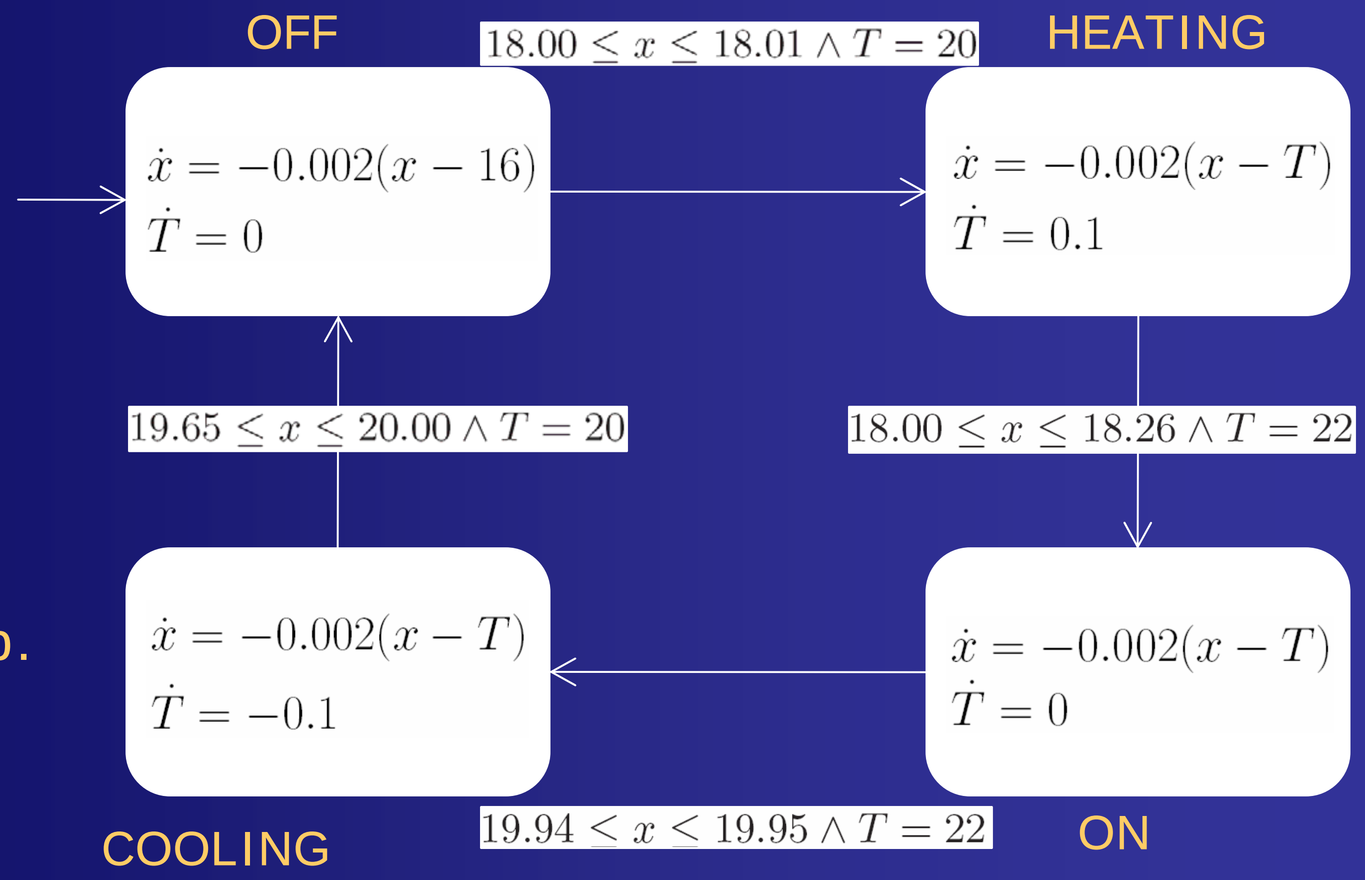
- Switching Logic Synthesis for Hybrid Systems
- Reflections on the Approach
- Synthesizing Environment Assumptions for Reactive Synthesis from LTL
- Conclusions and Future Directions

Hybrid Automata

Dynamics: Location → Ordinary Differential Equations (ODEs)

Switching Logic ⊆ Location X Location → Predicates

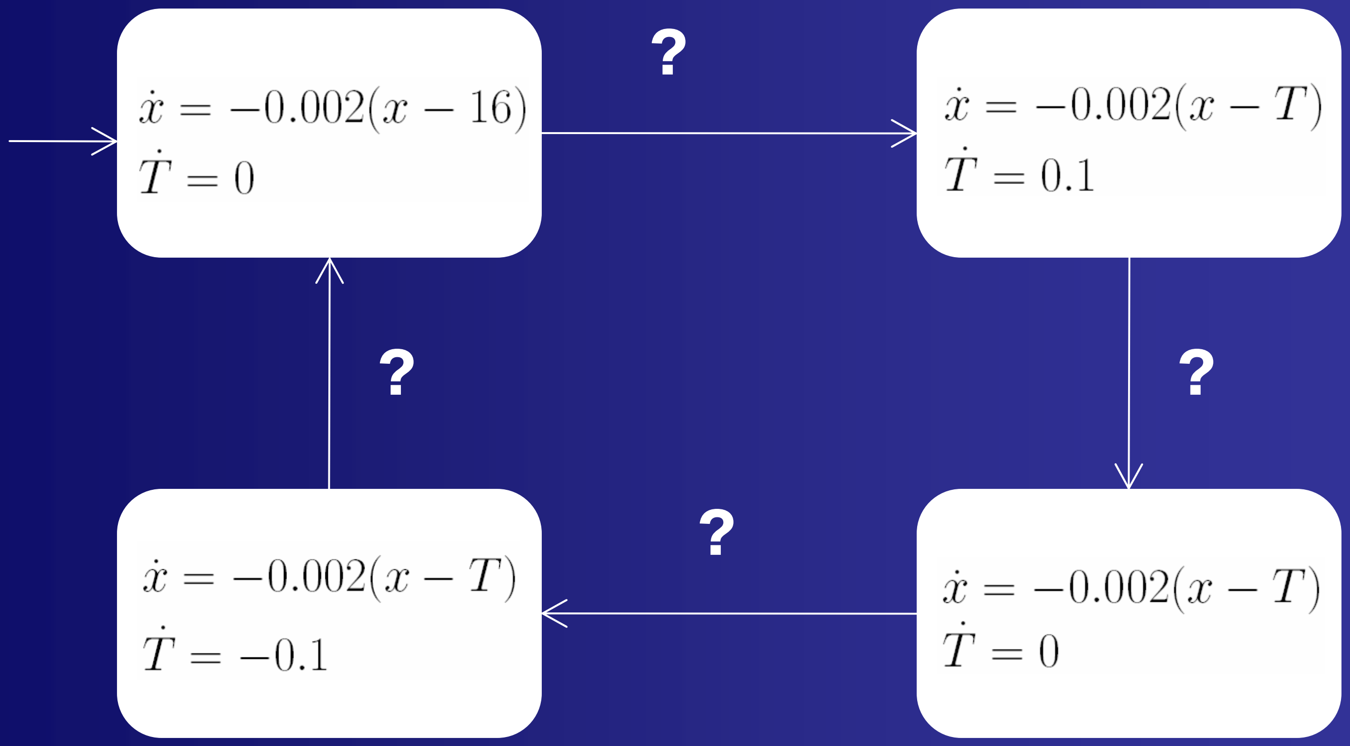
A guard is taken as soon as it is enabled.



x – room temp.

T – coil temp.

Switching Logic Synthesis Problem



- SAFETY: Temperature x must lie between 18 and 20 C.
  - In general: safe region is a hyperbox
- OPTIMALITY: Minimize switching between the modes

Our Solution

Structure Hypothesis:
Guards are Hyperboxes

+

Inductive Inference:
Learning Hyperbox from Examples

+

Deductive Procedure:
Numerical Simulation within a mode

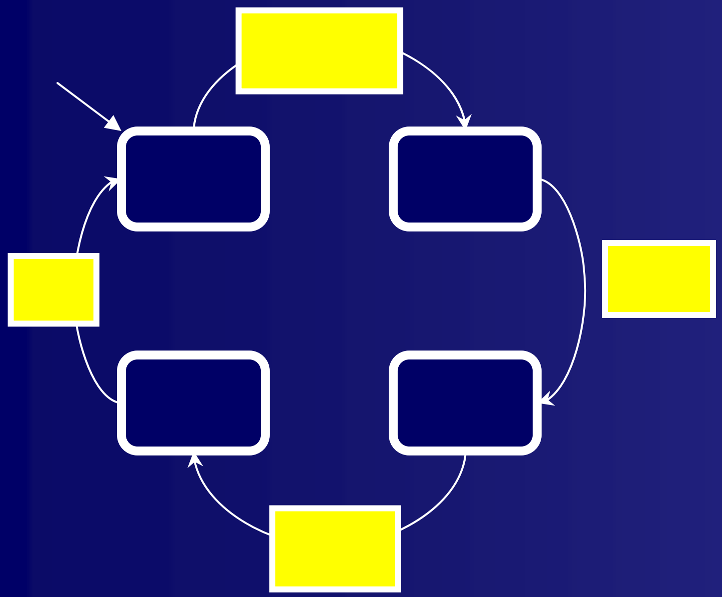
Related Work

- Synthesis through Game Solving or Reachability [Asarin et al, IEEE 2000; Koo et al., HSCC 01]
- Reduce to finite state automata synthesis [Tabuada, SCL 08]
- Constraint-based approach [Taly et al. VMCAI 09]

- Our approach is different in:
  - Hypothesis about guard structure
  - Use of hyperbox learning from examples
  - Numerical simulation as a 'decision procedure'

Overview of Approach

Fixpoint computation connects
Learning and Numerical Simulation



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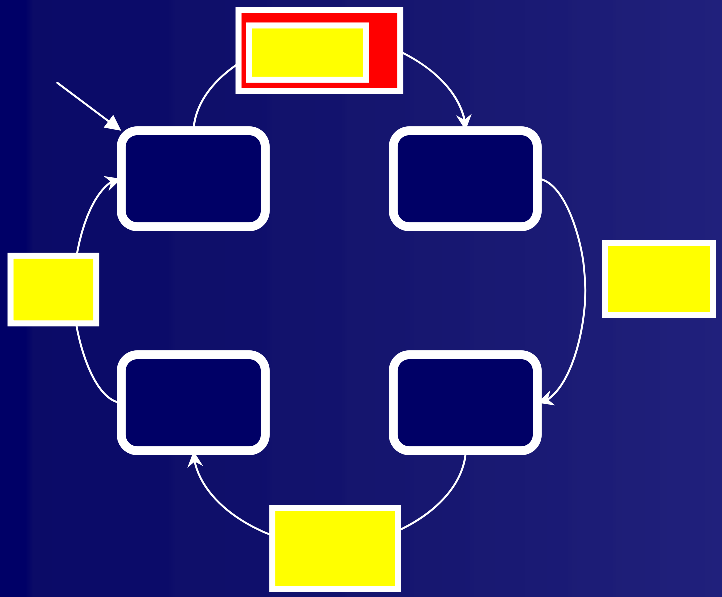

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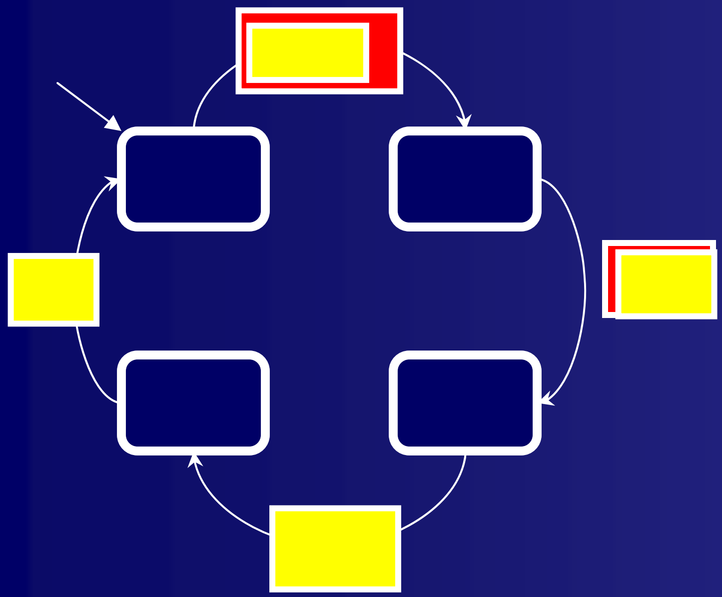

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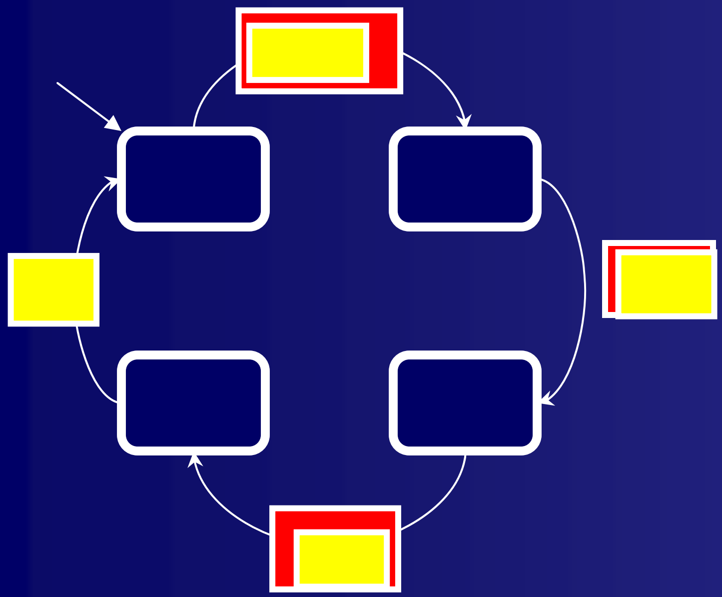

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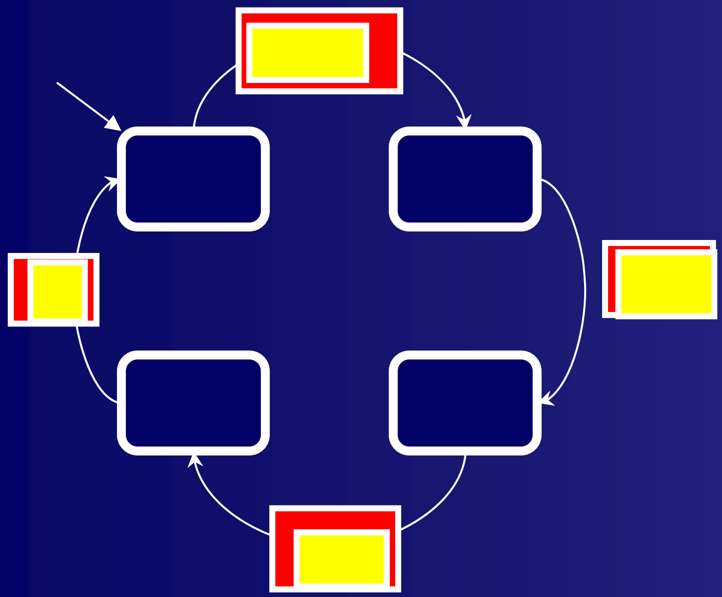

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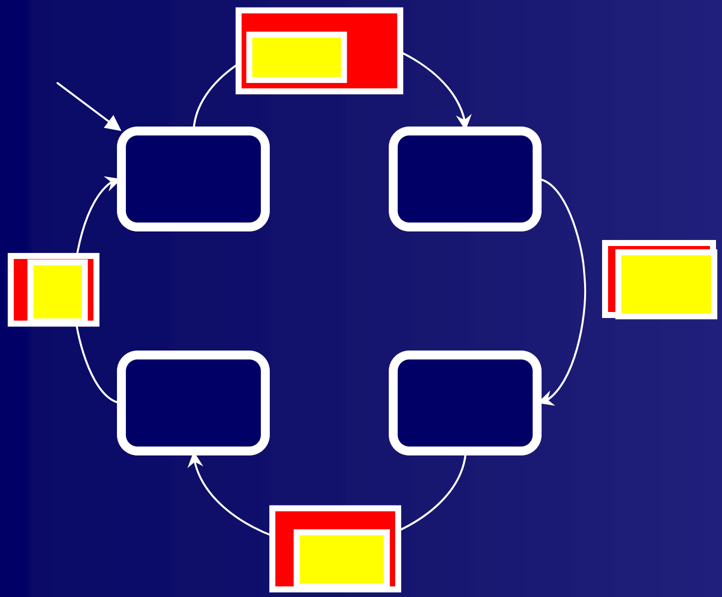

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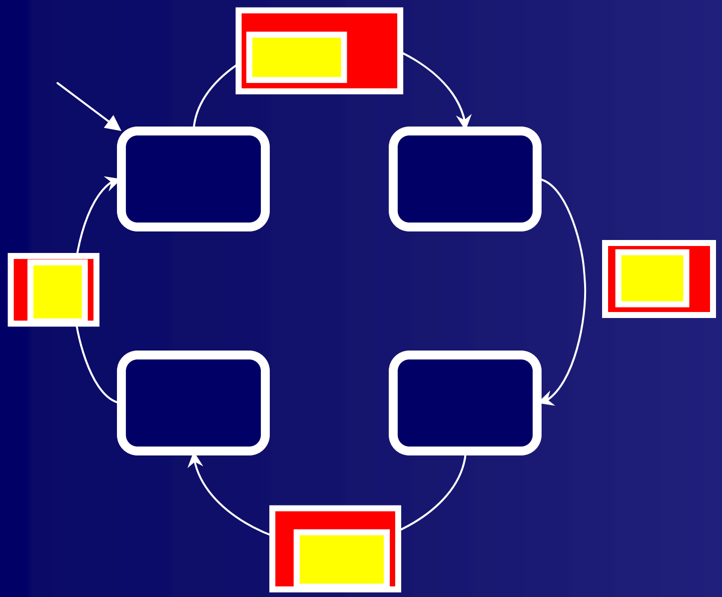

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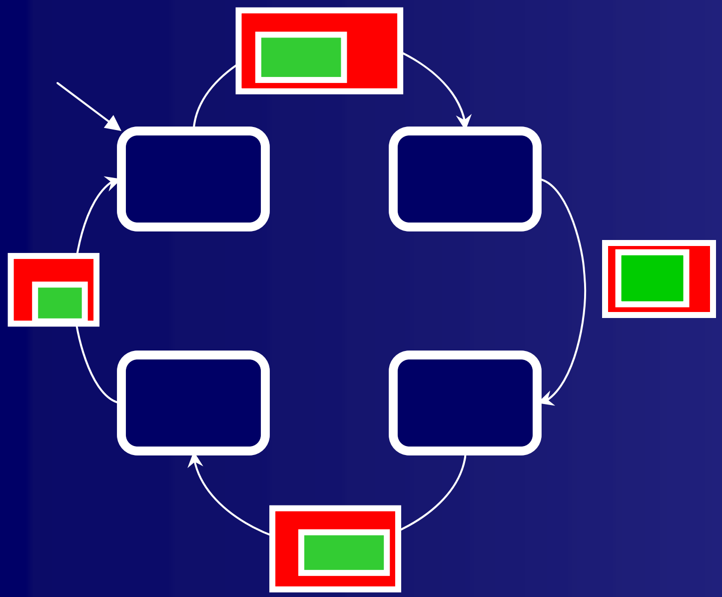

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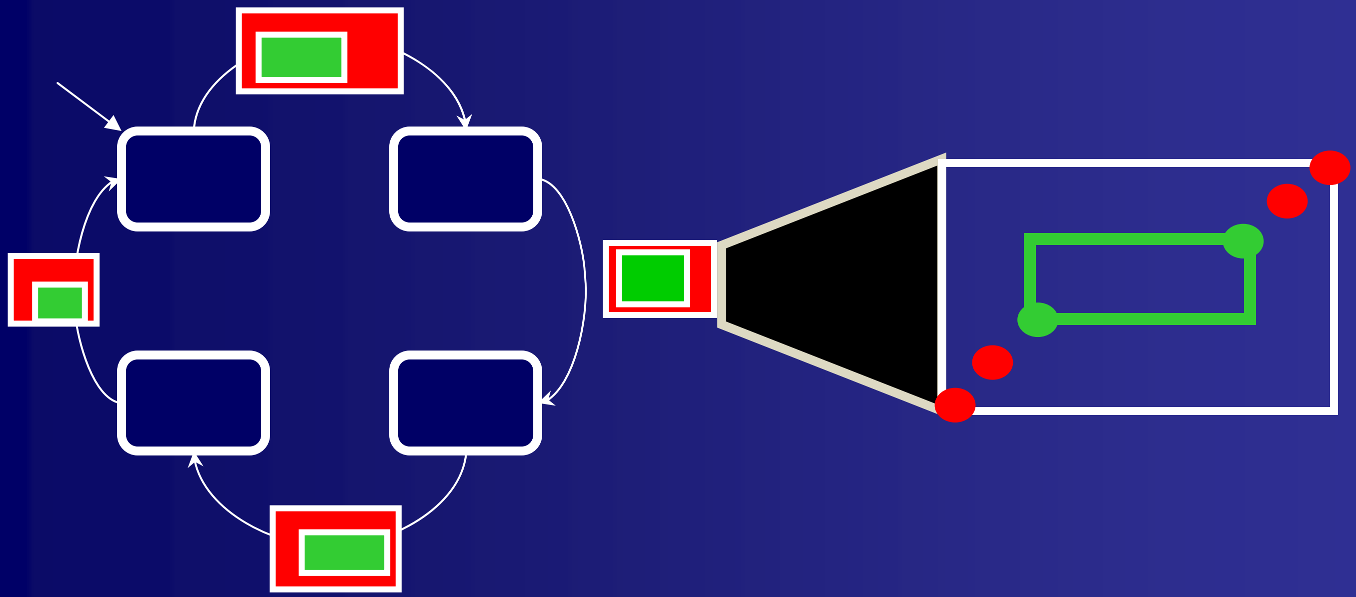

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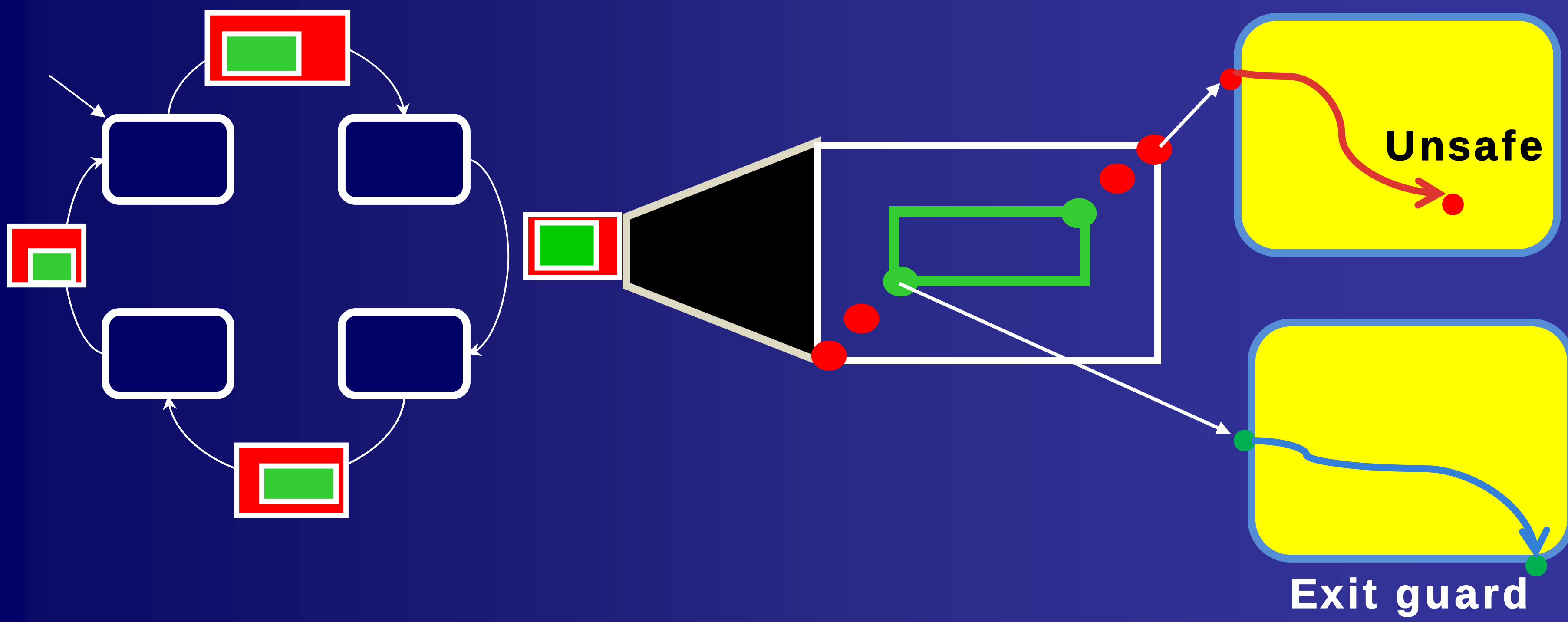
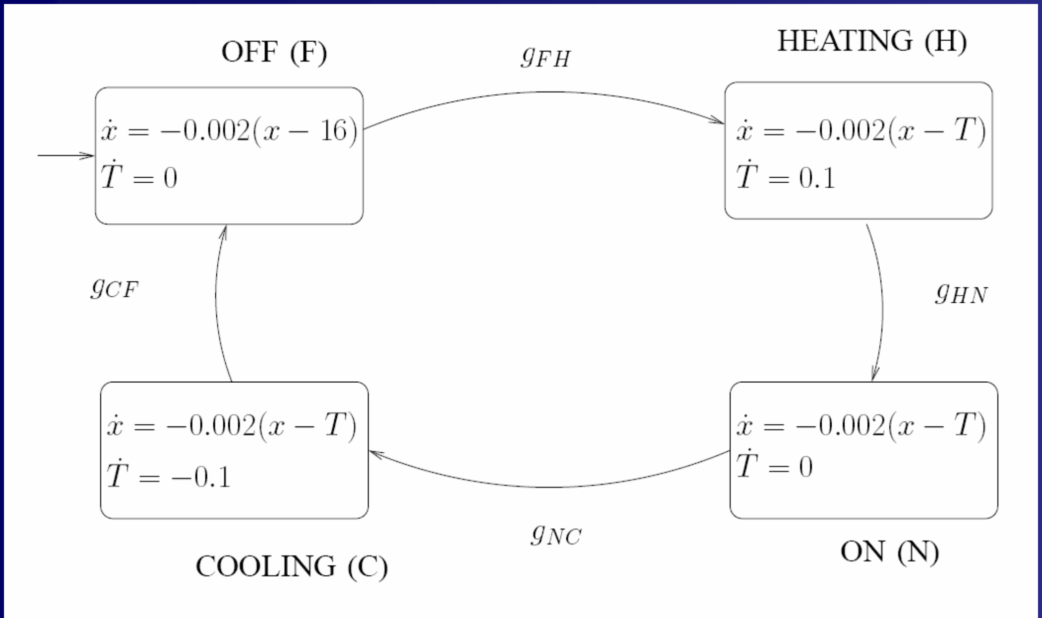


Fixpoint Computation Constraints

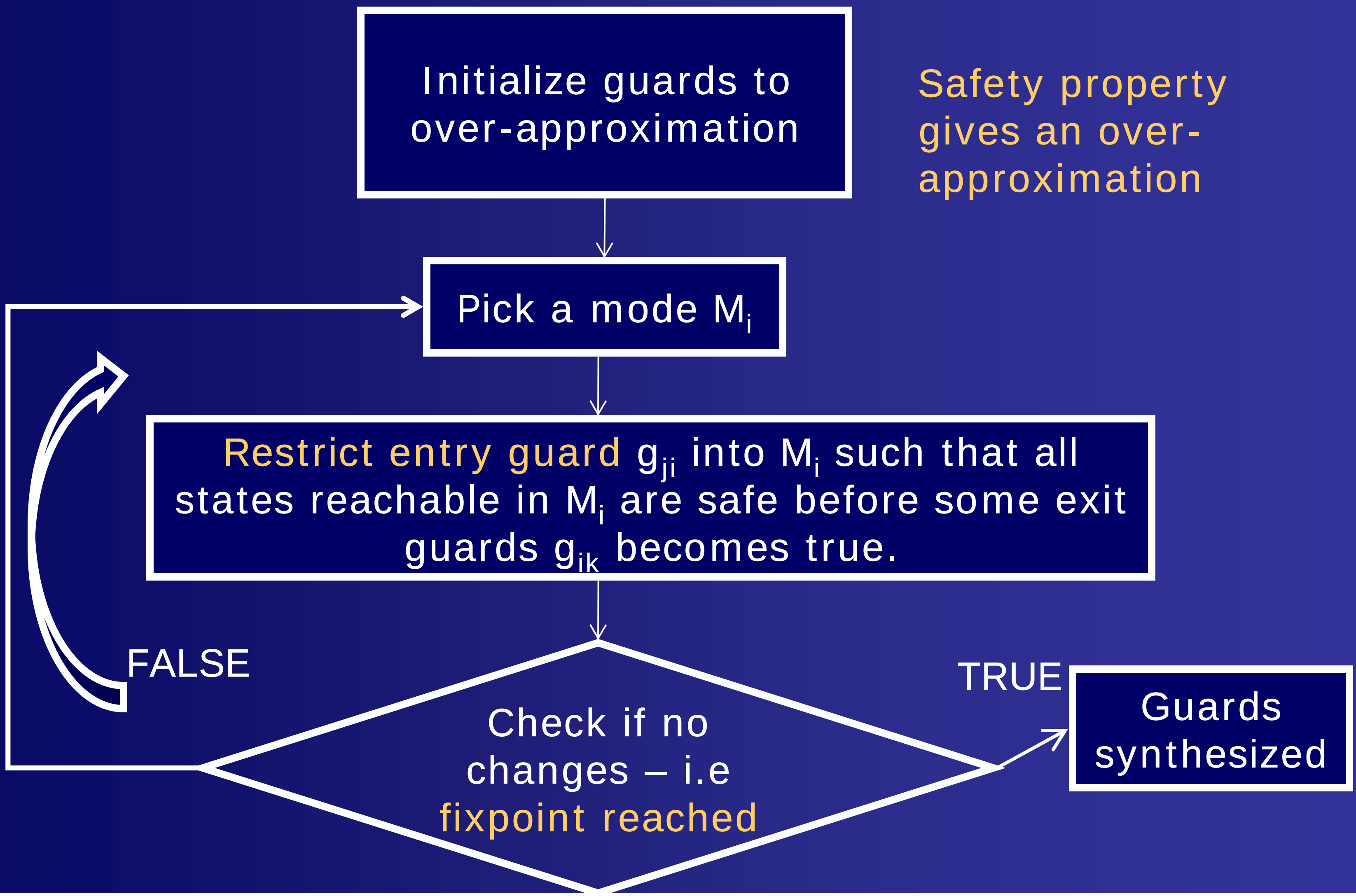
$$Mode_1,\ I \models \phi_S \mathbf{W}(\bigvee_{k \in M} g_{1k})$$

$$Mode_i, \bigvee_{j \in M} g_{ji} \models \phi_S \mathbf{W}(\bigvee_{k \in M} g_{ik}) \text{ for } i = 1..k$$



$$F, I \models \phi_S\ \mathbf{W}\ g_{FH}$$
$$F, g_{CF} \models \phi_S\ \mathbf{W}\ g_{FH}$$
$$H, g_{FH} \models \phi_S\ \mathbf{W}\ g_{HN}$$
$$N, g_{HN} \models \phi_S\ \mathbf{W}\ g_{NC}$$
$$C, g_{NC} \models \phi_S\ \mathbf{W}\ g_{CF}$$

Fixpoint Computation



Structure Hypothesis

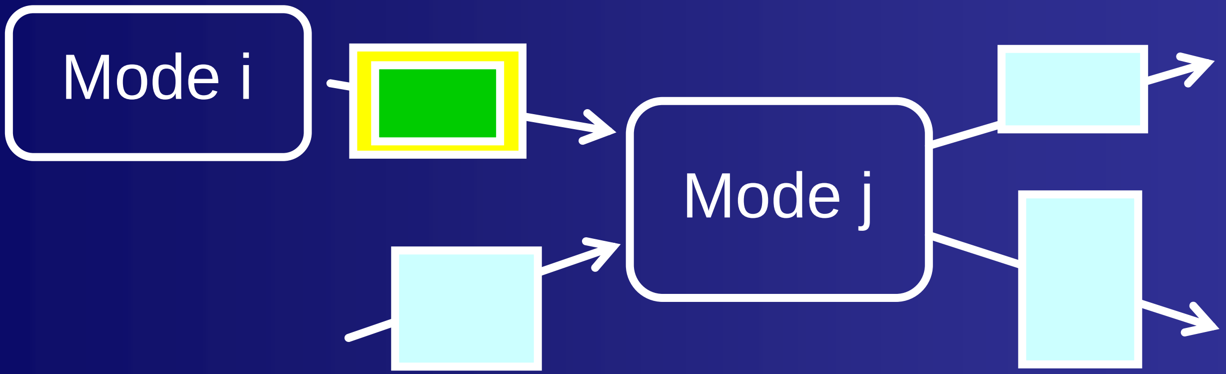
- Guard region has a restricted geometric form
- Equivalently: guard is a restricted type of logical formula
- Hyperbox:

  Interval logic: $c1 \leq x \leq c2 \wedge c3 \leq y \leq c4$

Learning Problem

- **Given:**
  - An overapproximate hyperbox for guard g_{ij}
  - Overapproximate hyperboxes for all other guards in/out of Mode j
  - One safe switching state from Mode i to Mode j
  - Reachability oracle for single switching pts into Mode j

- **Find:** Safe hyperbox restriction of g_{ij}

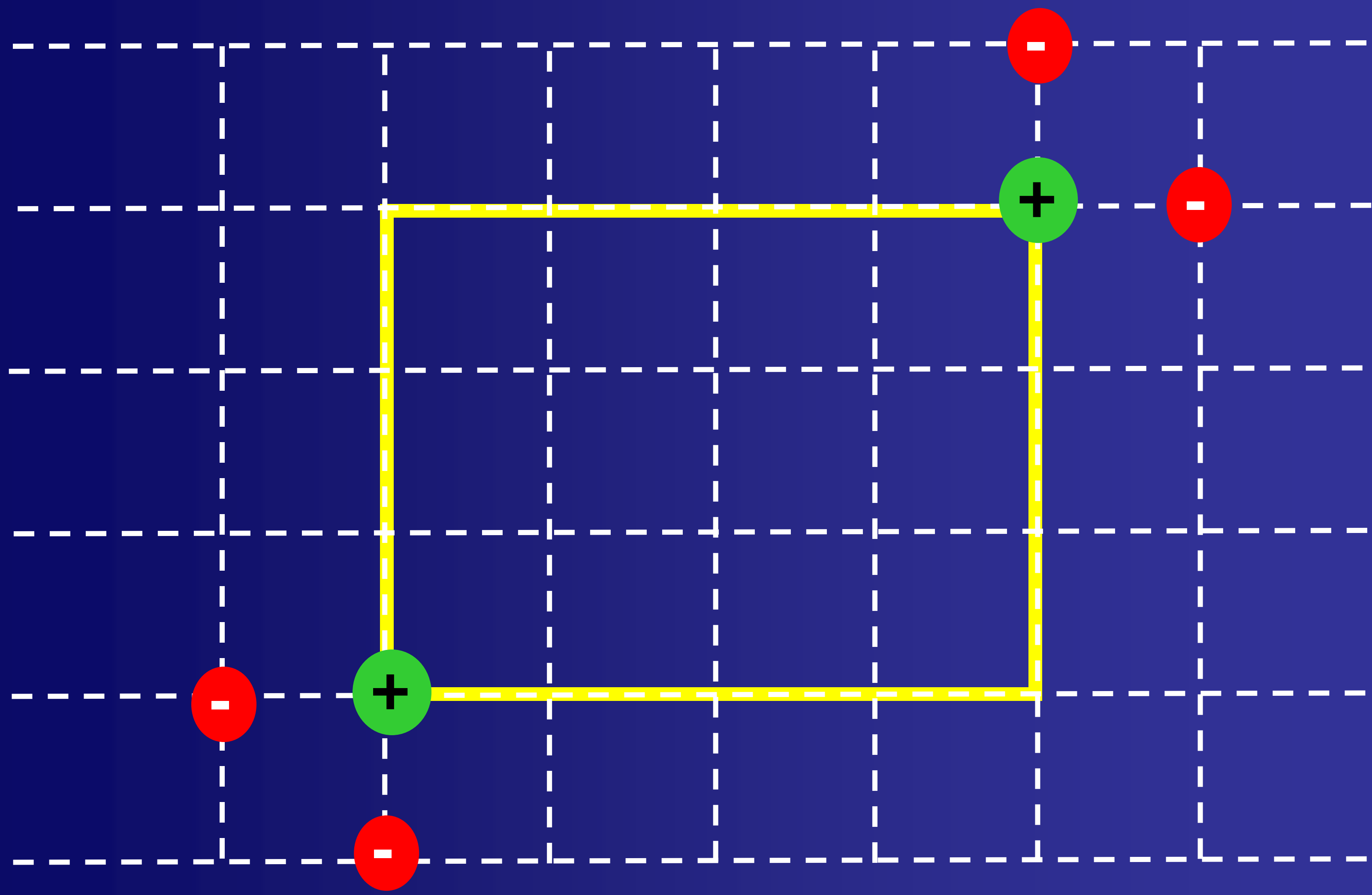


Optimal Teaching Sequence

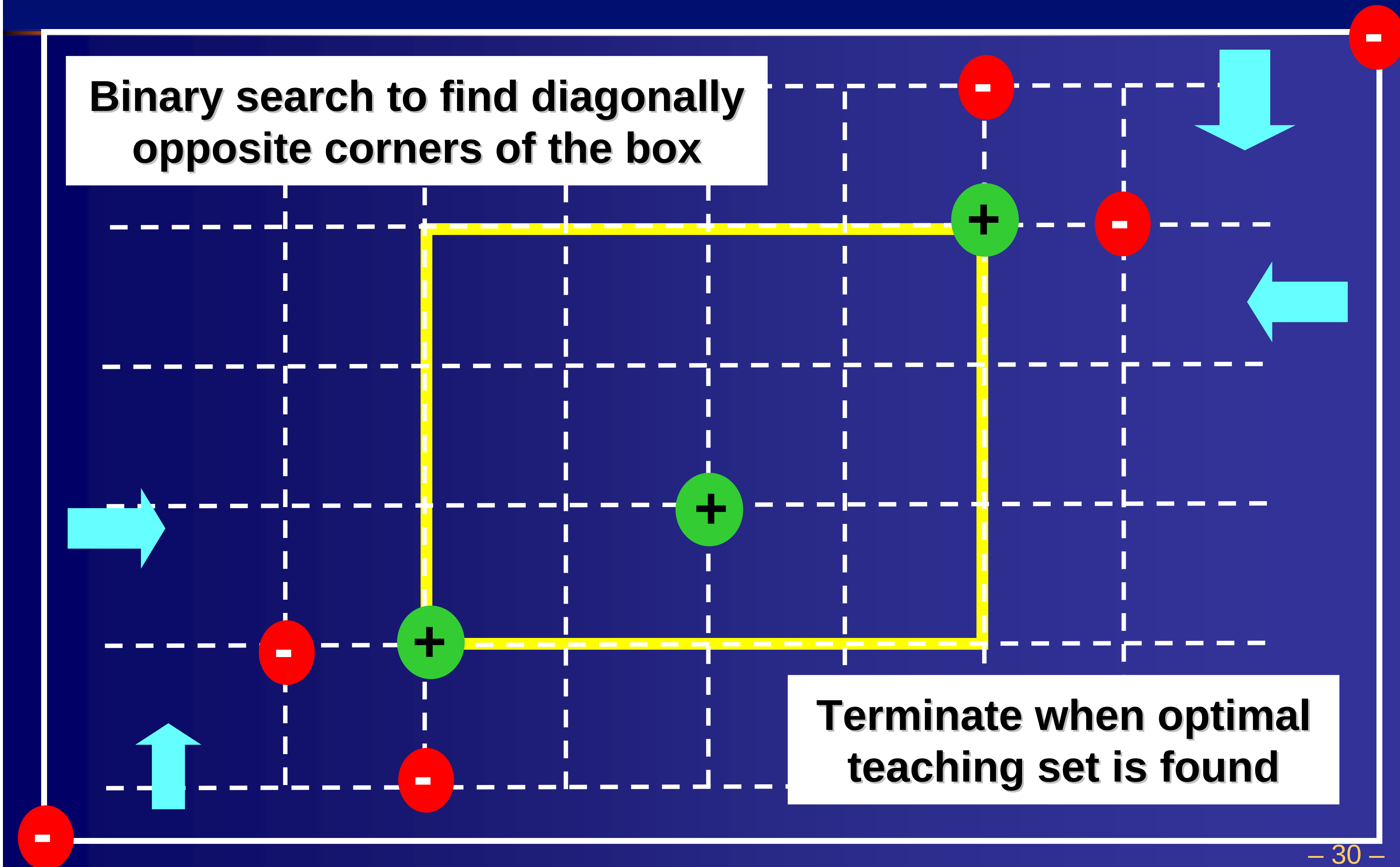
- **Teaching problem:**

  If we knew what the guard was, what is the smallest set of examples to give to a learner to uniquely identify it?

Teaching an N-dimensional Box



Learning an N-dimensional Box



Complexity

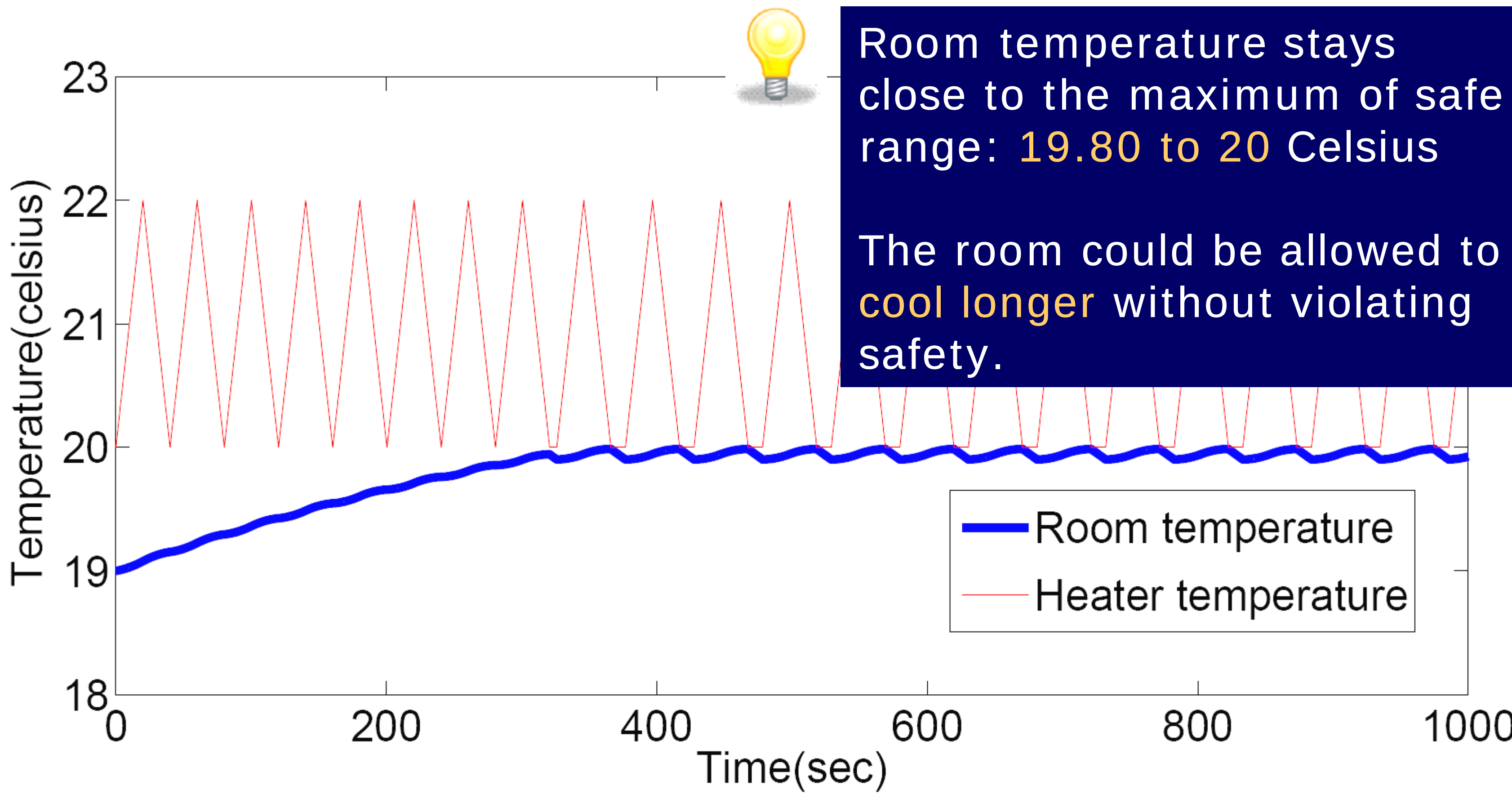
Number of simulations needed:

- Box (Conjunction of intervals): poly(log R, d)
- Linearly independent linear inequalities: poly(log R, d, n)
- Conjunction of arbitrary linear constraints: Exponential in d (best known)

(learning convex polygons is NP-hard – COLT94,98)

R is range of variables, d is number of variables (dimension), n is the number of constraints.

Synthesized Thermostat for Safety Requirement



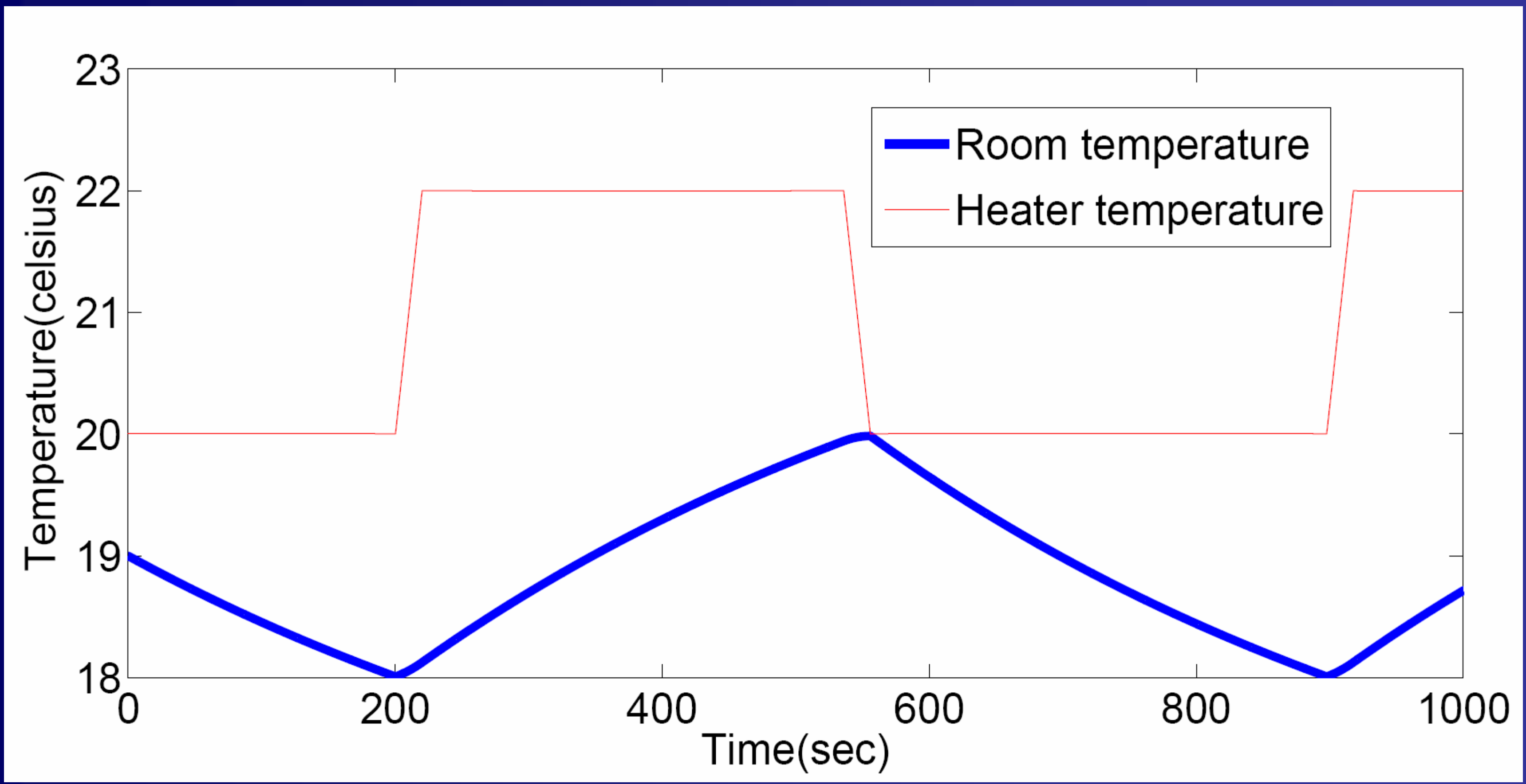
Room temperature stays close to the maximum of safe range: 19.80 to 20 Celsius

The room could be allowed to cool longer without violating safety.

Dwell Time Requirement

- Lower and/or upper bound on time spent in a mode.
- Approximates performance properties: minimize switching, reduce stay in “costly” modes etc.
- Key idea:
  - Restrict entry guards to decrease dwell-time
  - Restrict exit guards to increase dwell-time
  - Recompute fixed point to enforce safety properties

Synthesized Thermostat
300 s min dwell time in off and on mode



Theorems

- **Soundness:**

  Synthesized Design satisfies given safety objectives.

- **Completeness:**

  No Design Synthesized if and only if No Design Feasible with given safety objectives.

Assuming:

(1) Ideal Reachability Oracle for ODEs

- Necessary assumption

(2) Structure Hypothesis

- if ANY switching logic exists, there exists one with hyperbox guards (on a known grid reflecting precision of sensing)
- Assumption of “convenience”

Case Studies

Example	# of Iterations	Runtime (seconds)
Thermostat Controller		
v1	5	21.6
v2 Case A	6	26.2
v2 Case B	6	25.7
TCAS		
Case A	4	55.3
Case B	5	59.1
Automatic Transmission	6	83.6
Train Gate Controller		
Case A	3	22.5
Case B	4	28.3

Synthesis for Optimality [EMSOFT'11]

- **Minimize long-run cost** $\lim_{t \to \infty} \sum_{i=1}^{n} \frac{P_i}{R_i}(t)$

STRUCTURE HYPOTHESIS

Form of guard — Halfspace

+

DEDUCTIVE ENGINE

Synthesizes for special case — Numerical Simulation/ Optimization

+

INDUCTIVE INFERENCE (LEARNING)

Generalizes from special case results — PAC-learning of Halfspaces

Outline

- Switching Logic Synthesis for Hybrid Systems
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Structure Hypothesis gives only Conditional Soundness/Completeness

- **Synthesis procedure is sound (complete) assuming the structure hypothesis holds.**
  - Switching logic synthesis: If ANY switching logic exists, there exists one with hyperbox guards (on a known grid)
  - In practice: how do we know if hyperbox guards exist?

- **Can we restate this assumption in terms of the inputs to the synthesis process?**

YES. Sufficient conditions:

- **monotonicity of continuous dynamics in each mode**
- **safe region is hyperbox on the known grid**

Structure Hypothesis gives only Conditional Soundness/Completeness

- Another approach: Use a verifier to check that the synthesized system satisfies its specification
  – Verifier invoked in the loop or at the end
    - E.g. CEGIS loop used with Sketching
  – Requires efficient verification

Interaction between Inductive and Deductive Procedures in Switching Logic Synthesis

Structure Hypothesis defines Concept Class for Learning

INDUCTIVE ENGINE

Hyperbox Learning
(Active: selects examples)

What is the label (+/-) for this example

→

←

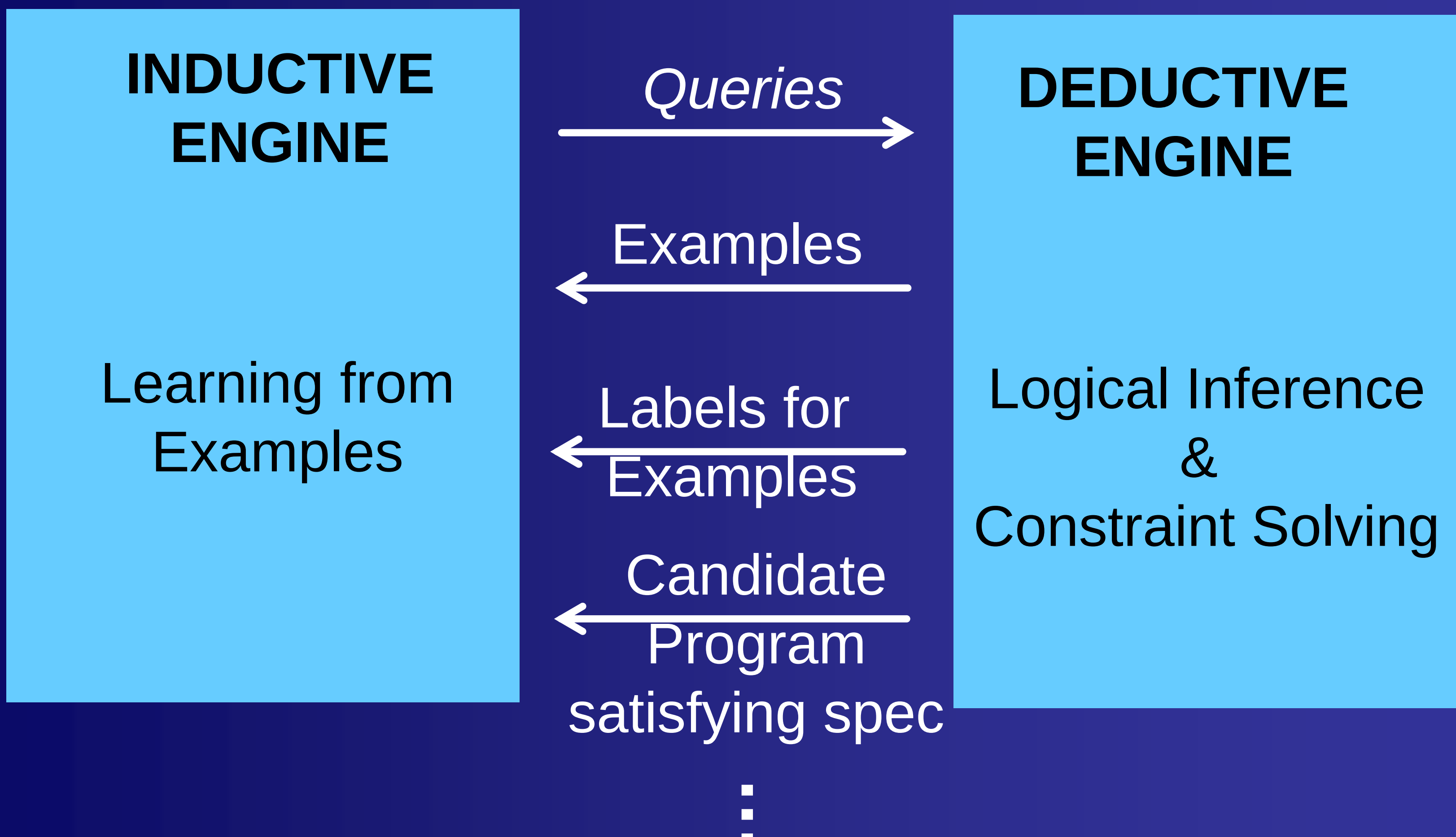
Labels
(safe/unsafe)

DEDUCTIVE ENGINE

ODE Reachability Oracle
(uses numerical simulation; special case of synthesis problem)

Inductive Strategy at the Top-Level

Structure Hypothesis defines Concept (Program) Class



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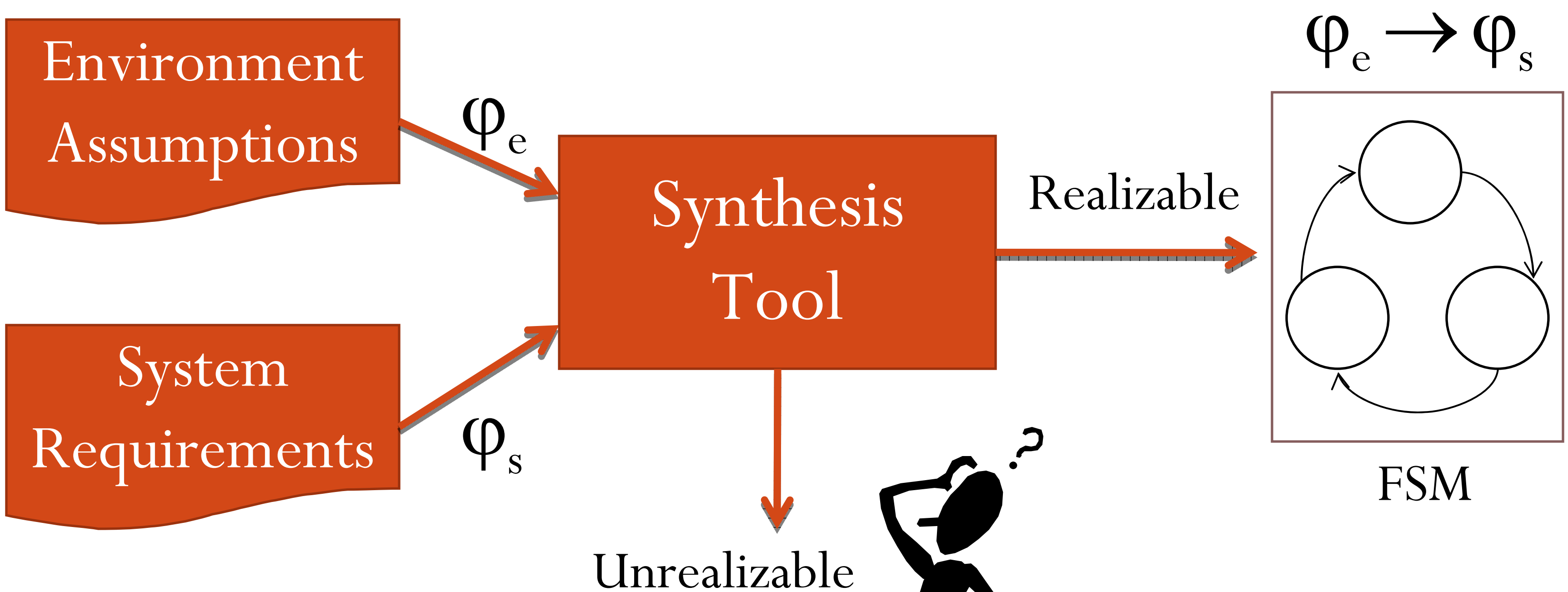
A Personal Story of Synthesis from LTL

- Long, long ago…
- … we embarked on a "synthesis from LTL" project.
- Verified Electronic Voting Machine
  - Verilog design, list of LTL properties [Sturton et al.,CCS 2009]
  - http://uclid.eecs.berkeley.edu/vvm/
- Attempt 1: Synthesizer *ran forever* (~a week), no output
- Idea: synthesize individual modules (selections within contests, navigation between contests, etc.)
- Attempt 2,3,…: Unrealizable! Too many *environment assumptions* needed (at interfaces between modules)

Problem



Often due to incomplete environment assumption!

Satisfiability and Realizability

- A LTL formula φ is satisfiable if there exists an infinite word (i.e. sequence of inputs and outputs) that satisfies φ.

- A LTL specification φ is realizable if for all inputs, there exists a finite-state transducer M (e.g. a Moore machine) which generates computations that satisfies φ.

Problem Description

- <u>Goal:</u>

  Generate additional assumptions to enable synthesis

- <u>Context:</u>

  Original specification is *satisfiable* but *unrealizable*

- <u>Assume:</u>

  - Given only a few interesting user scenarios (satisfying traces)

  - Specifications are in the GR(1) class

- <u>Challenge:</u>

  - Space of possible additional assumptions is huge

  - Want assumptions that can be understood and analyzed by a human user

Our Contribution [MEMOCODE 2011]

Counterstrategy-guided synthesis of environment assumptions

- Demonstrated to generate useful/intuitive environment assumptions for digital circuits and robotic controllers

Sciduction for Synthesizing Environment Assumptions

Structure Hypothesis:
Environment Assumptions are Restricted GR(1) properties

+

Inductive Inference:
Version Space Learning

+

Deductive Engine:
(Finite-state) Model Checking

GR(1) Synthesis [Piterman, Pnueli, Saar]

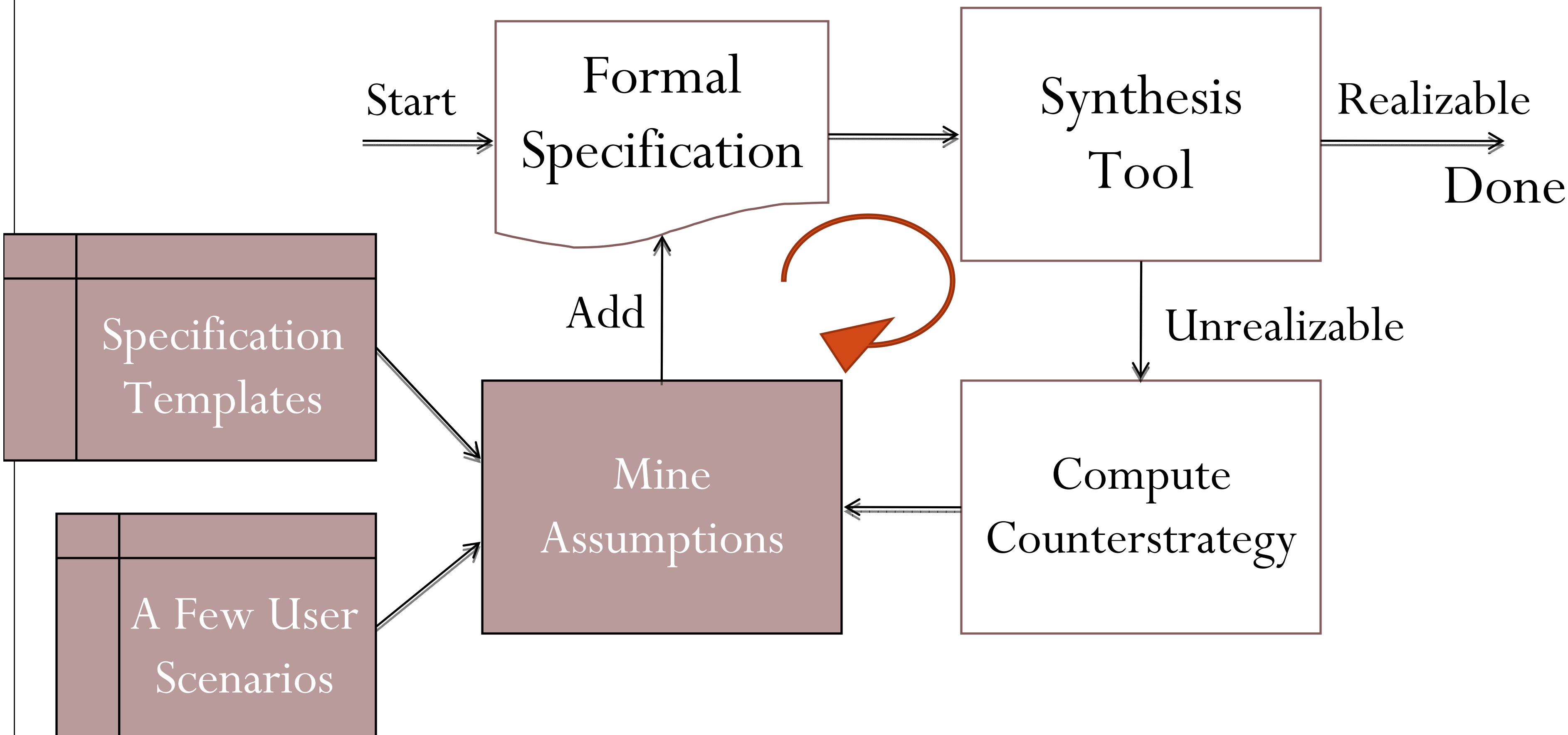
- Formulas in the form: $\varphi_e \rightarrow \varphi_s$
  - Input and output partitions ***I*** and ***O*****.**
  - φ_α^i: initial state formulas. $\alpha \in \{e, s\}$
  - φ_α^t: transition formulas, in the form of **G** *B*, where *B* is a Boolean combination of variables in $\boldsymbol{I} \cup \boldsymbol{O}$ and expressions **X** *u*, $u \in \boldsymbol{I}$ if $\alpha = e$ and $u \in \boldsymbol{I} \cup \boldsymbol{O}$ if $\alpha = s$.
  - φ_α^f: fairness formulas, in the form of **G F** *B*, where *B* is a Boolean formula over $\boldsymbol{I} \cup \boldsymbol{O}$.
- Synthesis as a turn-based <u>two-player game between the system and the environment</u>
  - Realizable if the system has a winning strategy, otherwise env wins; Strategy representable as finite-state transducer

Counter-strategy and counter-trace

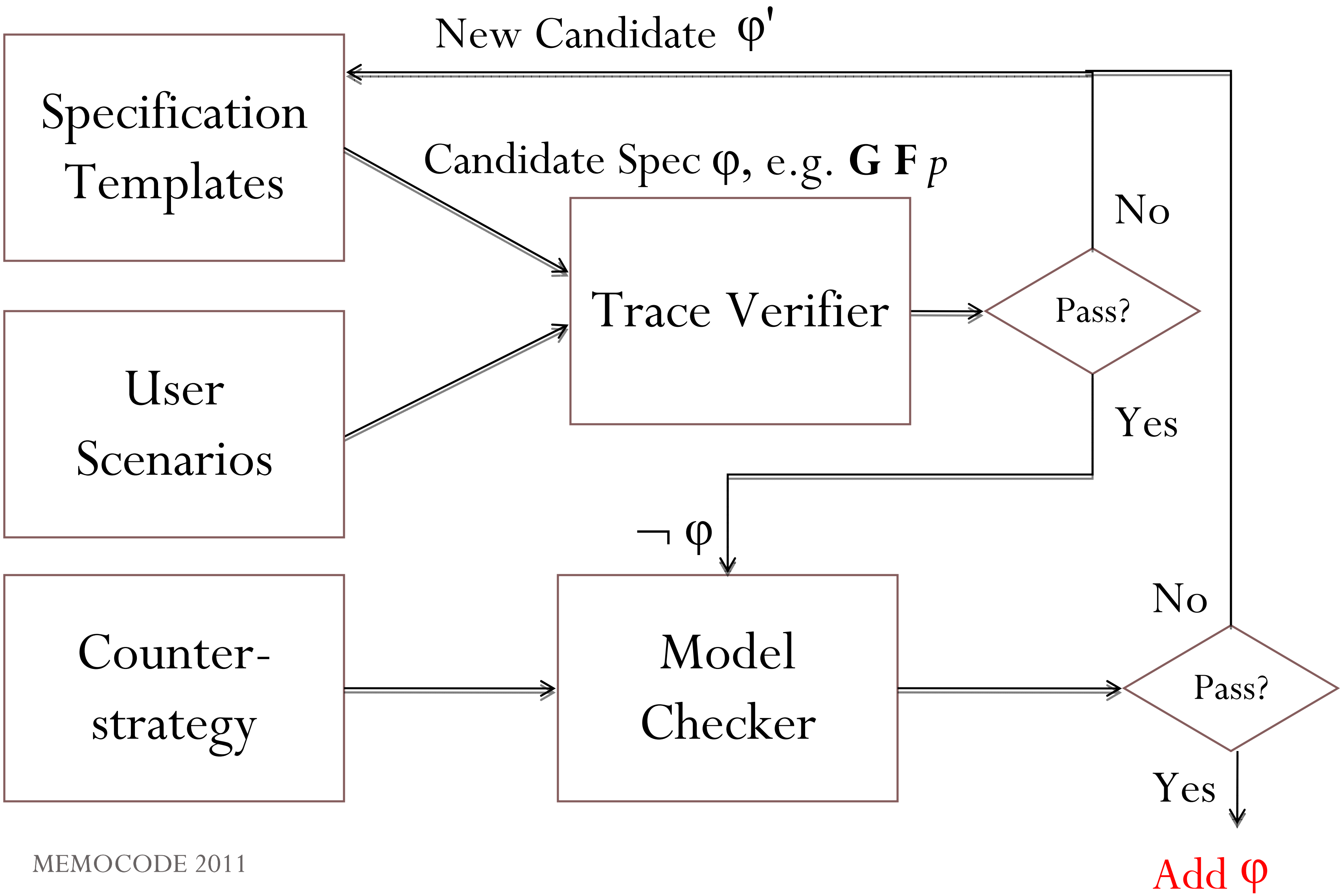
- Counter-strategy is a strategy for the environment to force violation of the specification.

- Counter-trace is a fixed input sequence such that the specification is violated regardless of the outputs generated by the system.

Assumption Mining to Assist Synthesis



Mining Algorithm

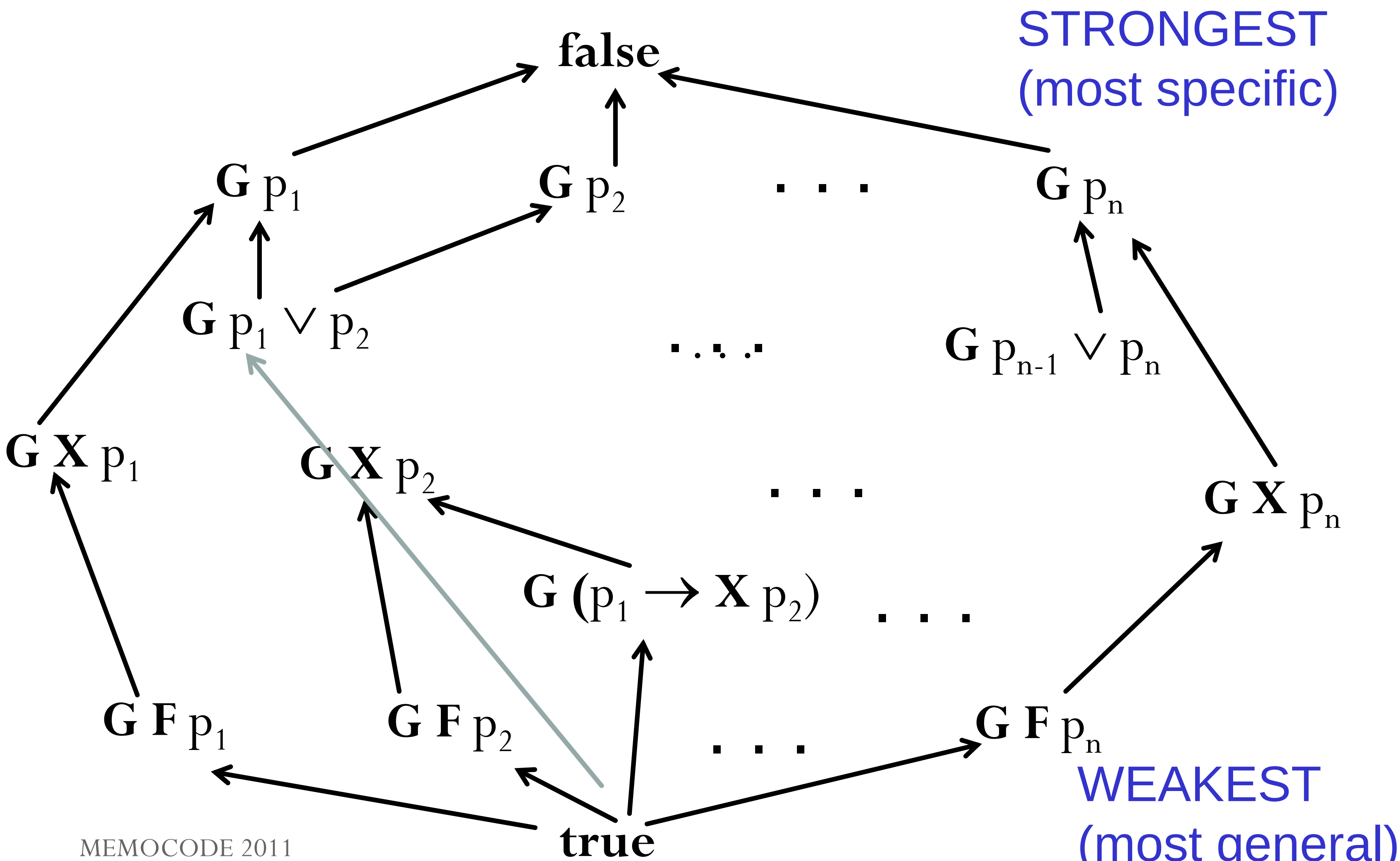


Assumption Templates follow GR(1)

- γ^1: $\mathbf{G}\ \mathbf{F}\ ?b$, where $b \in \boldsymbol{I}$
- γ^2: $\mathbf{G}\ (?b_1 \rightarrow \mathbf{X}\ ?b_2)$, where $b_1 \in \boldsymbol{I} \cup \boldsymbol{O}$ and $b_2 \in \boldsymbol{I}$
- γ^3: $\mathbf{G}\ (?b_1 \vee ?b_2)$, where $b_1, b_2 \in \boldsymbol{I}$

- The specification remains in GR(1) after the addition of new assumptions.
- How to pick candidate assumptions: (next slide)
  - Weakest to Strongest, with heuristics
  - **G F** b weaker than **G X** b weaker than **G** b
  - IMPORTANT: Check each assumption for consistency with existing set

Version Space Learning



Theoretical Results

- Theorem 1: A redundant environment assumption (implied by the existing assumptions) is never added.
  - Proof sketch: guaranteed by the counter-strategy guided approach.
- Corollary: The set of environment assumptions is minimal (but not minimum, in terms of number of properties).
  - Example: We may find G p and G q rather than G $(p \wedge q)$

- Theorem 2: [Completeness] If there exist environment assumptions under our structure hypothesis that make the spec realizable, then the procedure finds them (terminates successfully).
  - "conditional completeness" guarantee

- Theorem 3: [Soundness] The procedure never adds inconsistent environment assumptions.

Example

- Inputs: request r and cancel c
- Outputs: grant g
- System specification φ_s:
  - $\mathbf{G}\ (r \rightarrow \mathbf{X}\ \mathbf{F}\ g)$
  - $\mathbf{G}(c \vee g \rightarrow \mathbf{X}\ \neg g)$
- Environment assumption φ_e:
  - True
- No user scenarios.
- Not realizable because the environment can force c to be high all the time

Example

- System φ_s:
  - $\mathbf{G}\ (r \rightarrow \mathbf{X}\ \mathbf{F}\ g)$
  - $\mathbf{G}(c \lor g \rightarrow \mathbf{X} \neg g)$
- A counter-trace:

  r: 1 1 (1)

  c: 1 1 (1)
- Test assumption candidates by checking its negation:
  - $\mathbf{G}\ (\mathbf{F}\ c)$ ------------ ×
  - $\mathbf{G}\ (\mathbf{F} \neg c)$ ------------ √

- System φ_s:
  - $\mathbf{G}\ (r \rightarrow \mathbf{X}\ \mathbf{F}\ g)$
  - $\mathbf{G}(c \lor g \rightarrow \mathbf{X} \neg g)$
- Environment φ_e:
  - $\mathbf{G}\ (\mathbf{F} \neg c)$

Realizable!

Result Summary

- Experiment Setup:
  - Remove assumptions from an originally realizable specification
  - Use a few (often a single) satisfying traces of the original specification as representative user scenarios
  - Mine additional assumptions until the specification is realizable

- Use Cadence SMV to generate the satisfying traces and model check the counter-strategies
- Use RATSY [Bloem et al. 2010] to check realizability of the specifications and compute the counter-strategies and counter-traces in case of unrealizability

Result Summary

- Result Summary:
  - Case studies in existing literature: AMBA AHB, IBM Gen Buffer, robotic vehicle controller, etc.
  - Recovered the missing assumption in most cases
  - AMBA AHB Example:

Original assumption:

G (HLOCK[0] = 1 → HBUSREQ[0] = 1)

Master 0 requests locked access to the bus (HLOCK[0] = 1)

Master 0 requests access to the bus (HBUSREQ[0] = 1)

Mined assumption:

G (**F** HLOCK[0] = 0)

Related Work

- Constructing the "weakest" assumption needed for realizability from the game graph [Chatterjee et al. 2008]
  - Computes a safety assumption that removes a minimal set of environment edges form the game graph
  - Computes a liveness assumption that puts fairness on the remaining environment edges
  - The additional environment assumption is a single Büchi automaton which can be difficult for a normal human user to analyze or even understand.
- Computing counter-strategy for GR(1) synthesis [Konighofer et al. 2009]
  - Counter-strategies and counter-traces as explanations for unrealizability

Discussion

- Specification mining can generate useful environment assumptions to cope with unrealizability.
- Limitation: choice of templates
  - Can extend same approach with broader set of templates
- Can the same idea of learning from counter-strategies and counter-traces be applied to other synthesis tasks?
  - i.e., not just synthesis from LTL

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Induction + Deduction + Structure

- Structure Hypothesis encodes human insight about form of artifact
- Synthesis procedure combines inductive inference with deductive reasoning
- Several demonstrations
  - Synthesis of loop-free programs [Jha et al, '10]
  - Switching logic synthesis for safety and optimality [Jha et al '10,'11]
  - Environment assumptions for LTL synthesis [Li et al '11]
  - Fixed-point code from floating-point [Jha, Seshia, '11]

Future Directions

- Exploring Structure Hypotheses
  - Need for flexibility in hypotheses
  - Requires flexible (extensible) learning algorithms that can accommodate changes to hypotheses
- Providing unconditional guarantees
  - Techniques to verify if structure hypothesis holds for a given input
- Investigate strategies to combine induction & deduction
  - Interplay between Teaching & Learning