Integrating Induction and Deduction in Model Checking

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Clarke Symposium

September 19, 2014

Model Checking and Synthesis

E. M. Clarke and E. A. Emerson, 1981:

"We propose a method of constructing concurrent programs in which the ***synchronization skeleton of the program is automatically synthesized*** from a high-level (branching time) Temporal Logic specification."

(1st sentence of their seminal model checking paper)

Three Messages in this Talk

[Seshia DAC'12; Jha & Seshia, SYNT'14]

1. **Verification by Reduction to Synthesis**
   - **Many (verification) tasks involve synthesis**
2. **Induction + Deduction + Structure: An Effective Approach to Synthesis:**
   - ***Induction*: Learning from examples**
   - ***Deduction*: Logical inference and constraint solving**
   - ***Structure*: Hypothesis on syntactic form of artifact to be synthesized**
   - **"Syntax-Guided Synthesis"** [Alur et al., FMCAD'13]
     - Inspired by Counterexample-guided abstraction refinement (CEGAR) [Clarke et al., CAV'00]
3. **Machine Learning Theory + Formal Methods**
   - **Analysis of Counterexample-Guided Synthesis**
     - **Sample Complexity, Convergence, Search Strategies**

Artifacts Synthesized in Verification

- Inductive invariants
- Abstraction functions / abstract models
- Auxiliary specifications (e.g., pre/post-conditions, function summaries)
- Environment assumptions / Interface specifications
- Interpolants
- Ranking functions
- Intermediate lemmas for compositional proofs
- Theory lemma instances in SMT solving
- Patterns for Quantifier Instantiation
- …

Formal Verification as Synthesis

- Inductive Invariants

- Abstraction Functions

One Reduction from Verification to Synthesis

NOTATION

Transition system $M = (I, \delta)$

Safety property $\Psi = G(\psi)$

VERIFICATION PROBLEM

Does M satisfy Ψ?

↓

SYNTHESIS PROBLEM

Synthesize ϕ s.t.

$$I \Rightarrow \phi \wedge \psi$$

$$\phi \wedge \psi \wedge \delta \Rightarrow \phi' \wedge \psi'$$

Two Reductions from Verification to Synthesis

NOTATION

Transition system $M = (I, \delta)$, S = set of states

Safety property $\Psi = G(\psi)$

VERIFICATION PROBLEM

Does M satisfy Ψ?

SYNTHESIS PROBLEM #1

Synthesize ϕ s.t.

$$I \Rightarrow \phi \wedge \psi$$

$$\phi \wedge \psi \wedge \delta \Rightarrow \phi' \wedge \psi'$$

SYNTHESIS PROBLEM #2

Synthesize $\alpha : S \rightarrow \hat{S}$ where

$$\alpha(M) = (\hat{I}, \hat{\delta})$$

s.t.

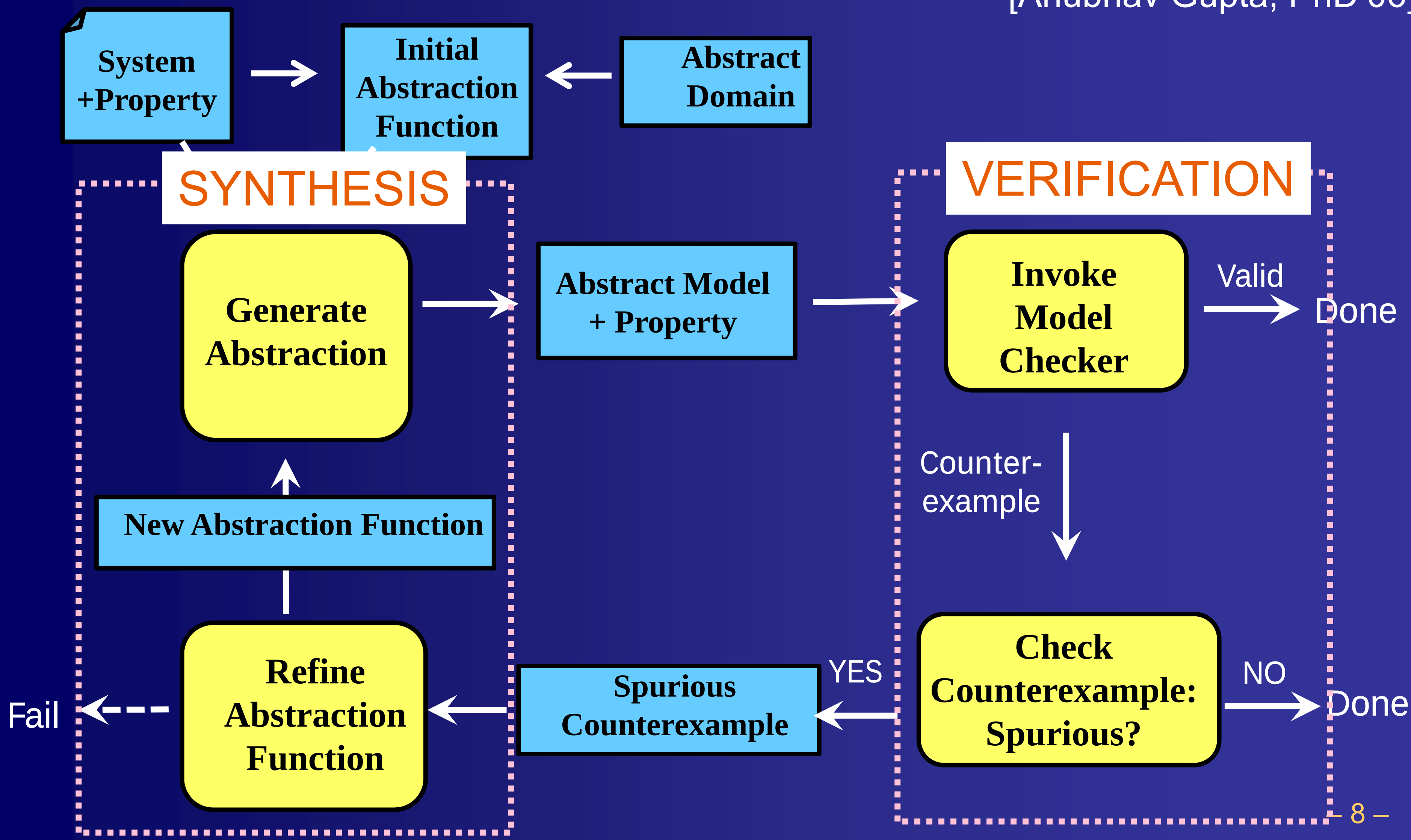
$\alpha(M)$ satisfies Ψ

iff

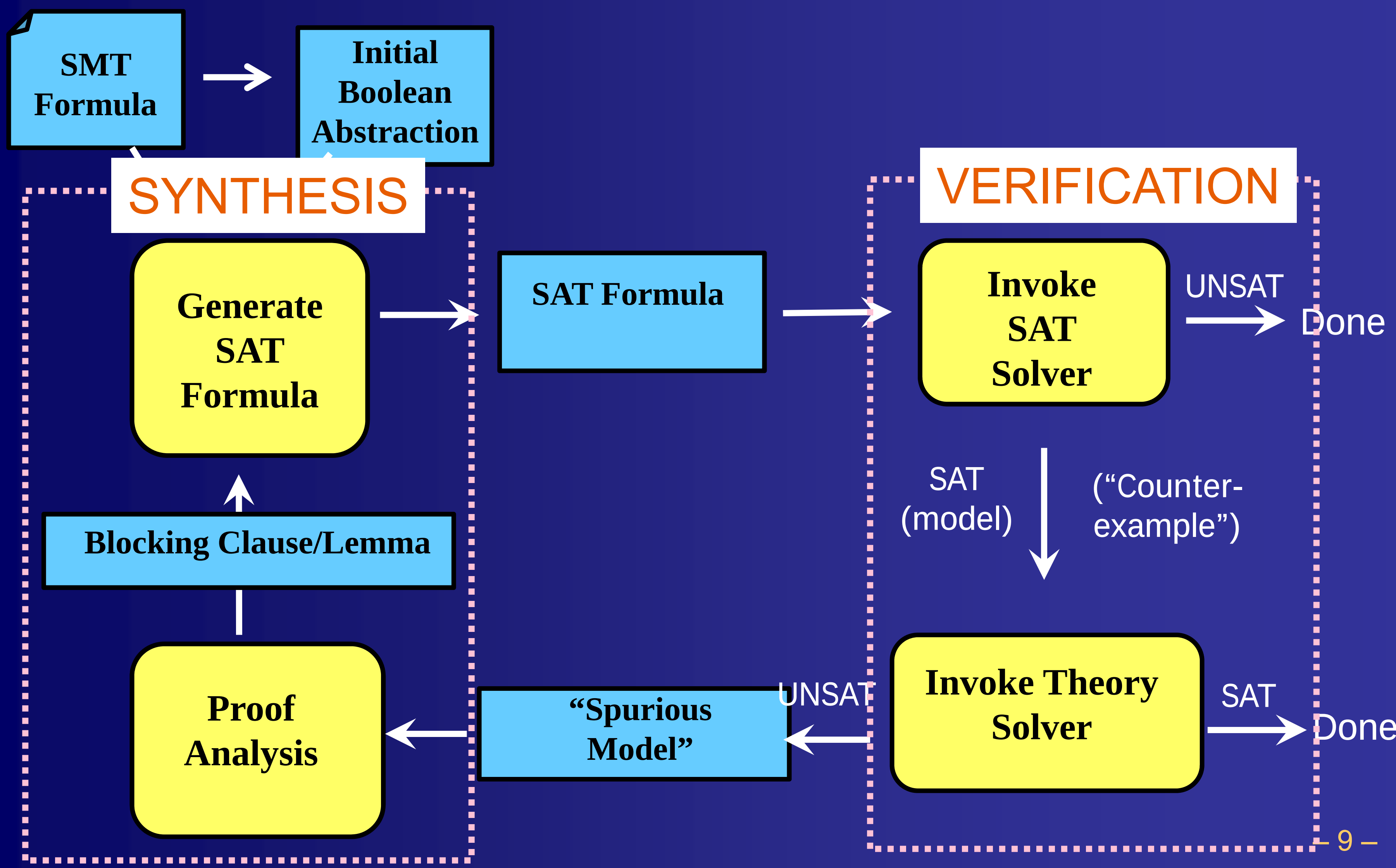
M satisfies Ψ

Counterexample-Guided Abstraction Refinement is "Inductive" Synthesis

[Anubhav Gupta, PhD'06]

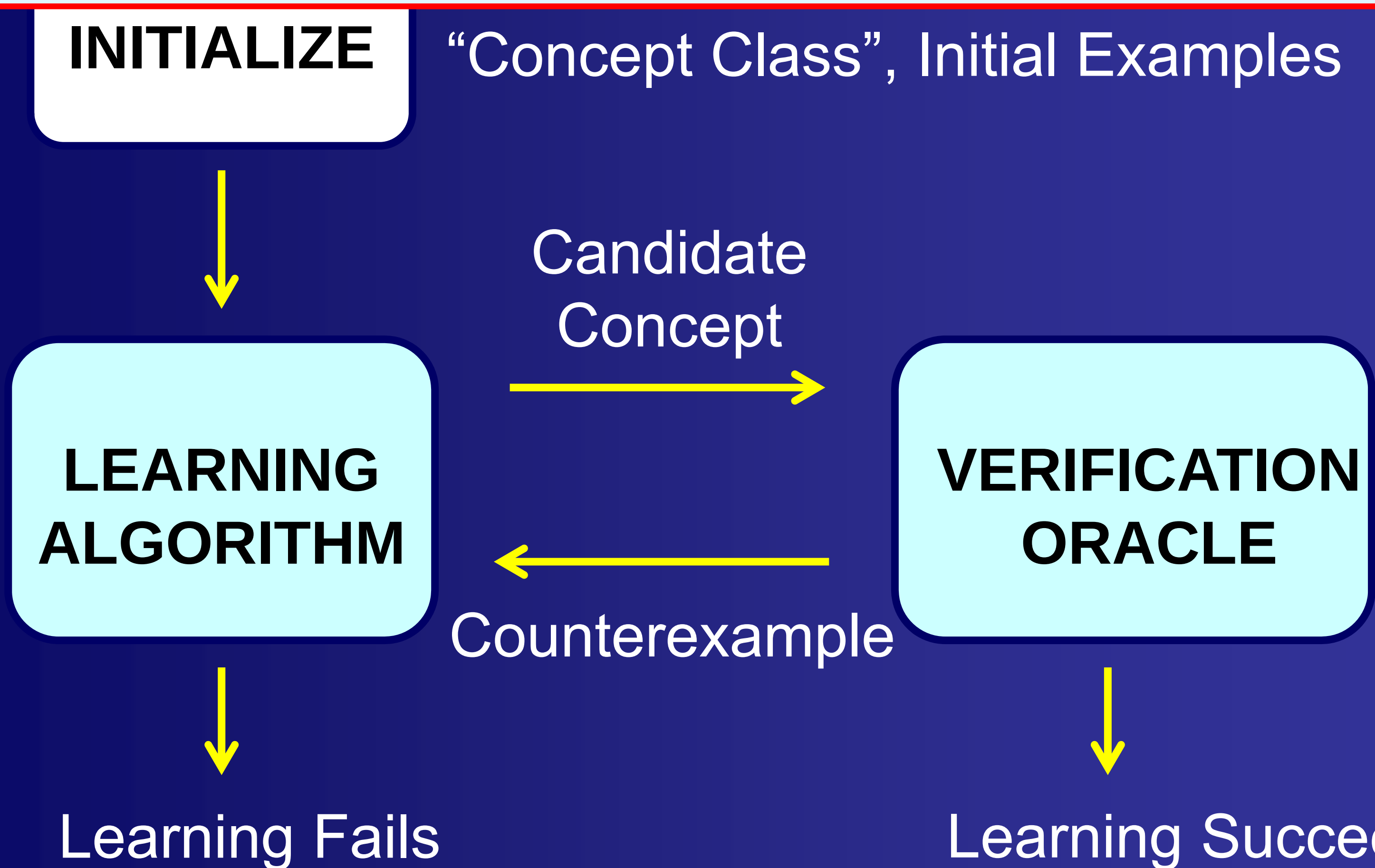


Lazy SMT Solving performs "Inductive" Synthesis (of Lemmas)



CEGAR & Lazy SMT perform Active Learning from (Counter)Examples

Difference from standard learning theory:
Learning Algorithm and Verification Oracle are typically "General" Solvers, independent of concept class



Machine Learning Theory ←→ Formal Methods: 2 Sample Results

- **Lower Bounds on Convergence of Counterexample-guided loop**
  - **Teaching Dimension (TD):** ***Minimum*** **number of (labeled) examples a teacher must reveal to** ***uniquely*** **identify any concept from a class**
  - **<u>Thm:</u> TD is a lower bound on # iterations for counterexample-guided synthesis**
- **Impact of "Quality" of Counterexamples**
  - **Does the type of counterexample affect convergence for** ***infinite-size*** **concept classes?**
  - **<u>Thm:</u> Minimum counterexamples are no better than arbitrary counterexamples**

[Jha & Seshia, SYNT'14]

Conclusion

- **Model Checking and Synthesis: many connections**
- **Verification by Reduction to Synthesis**
- **Approach for Synthesis: Induction + Deduction + Structure**
  - "Syntax-Guided Synthesis" [Alur et al., FMCAD'13]
  - Inspired by Counterexample-guided abstraction refinement (CEGAR) [Clarke et al., CAV'00]
- **Machine Learning Theory & Formal Methods: theoretical connections**
  - **Sample Complexity, Convergence, Search Strategies**