EECS 219C: Computer-Aided Verification

Introduction & Overview

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Computer-Aided Verification (informally)

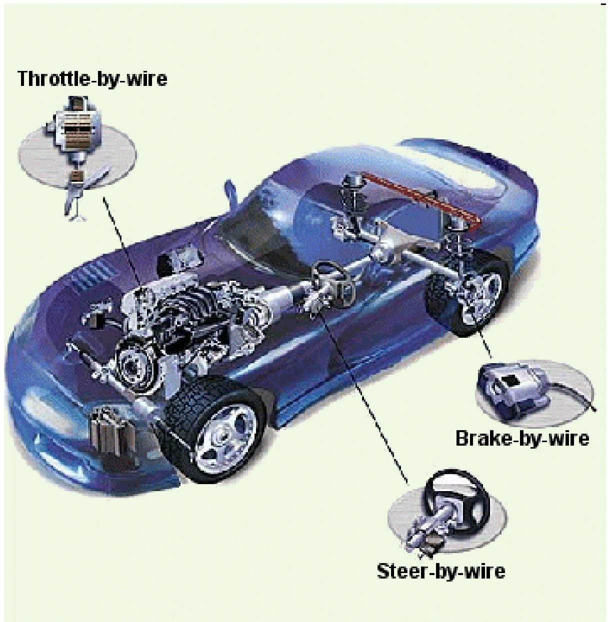
Does **the system** do
what it is supposed to do?

The End User's Perspective

Does **the system** do
what it is supposed to do?

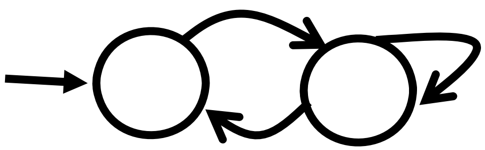
The Engineer's Perspective

Does **the implemented system** meet its **specifications**?



The Mathematician's Perspective

Prove or disprove (verify) that
the mathematical model of the system
satisfies a **mathematical specification**



$$\dot{x}(t) = f(x(t), u(t))$$

Formal Methods

Rigorous mathematical / algorithmic techniques for specification, design, verification and maintenance of computational systems.

The essence: It’s about PROOF

- Specify proof obligations
- Prove that system meets those obligations
- Synthesize provably-correct system

What we'll do today

- Introductions: to Sanjit and others
- Brief Intro. to the main course topics
  - Motivation
  - Temporal Logic, Model Checking, SAT, and Satisfiability Modulo Theories (SMT)
  - History, Opportunities, Challenges
- Course Logistics

My Research

"Formal Methods: Specification, Verification, Synthesis"

Theory

Computational Logic,
Algorithms,
Learning Theory,
Optimization

+

Practice

CAD for VLSI/Bio,
Computer Security,
Embedded Systems,
Education

Example: Learning+Verification for Auto-Grading Lab-based Courses

Class Introductions

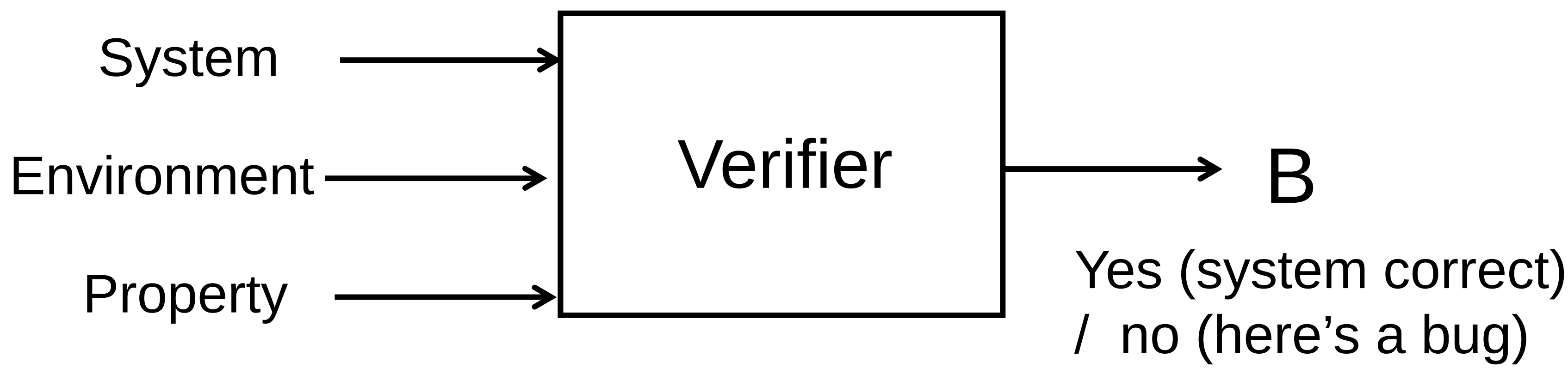
Please introduce yourselves

-- state name and research interests/areas

(Programming Systems, Computer Security, CAD, Embedded Systems, Synthetic Biology, Control Theory, etc.)

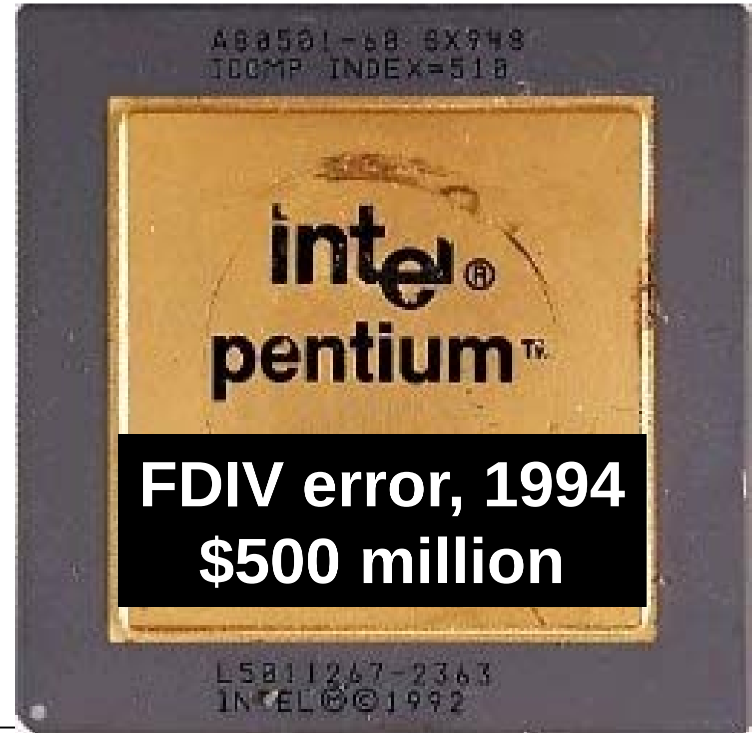
Computer-Aided Verification

- Automatically verifying the correctness of systems



- Questions for today:
  - Is it relevant?
  - Is it feasible?
  - What will we study?

Ariane disaster, 1996
$500 million software failure



FDIV error, 1994
$500 million

Toyota Recalls 1.9 Million Prius Hybrids Over Software Flaw

By Jeremy Hsu
Posted 12 Feb 2014 | 21:55 GMT

```
<msblast.exe> (the primary executable of the exploit)
I just want to say LOVE YOU SAN!!
billy gates why do you make this possible ? Stop
making money and fix your software!!
windowsupdate.com
start %s
tftp -i %s GET %s
%d.%d.%d.%d
%i.%i.%i.%i
```

Estimated worst-case worm cost: > $50 billion

Bugs cost Time, Money, Lives, …

An Example from Embedded/Cyber-Physical Systems

Medical devices run on software too… software defects can have life-threatening consequences.

[Journal of Pacing and Clinical Electrophysiology, 2004]

[different device]

"the patient collapsed while walking towards the cashier after refueling his car […] A week later the patient complained to his physician about an increasing feeling of unwell-being since the fall."

"In 1 of every 12,000 settings, the software can cause an error in the programming resulting in the possibility of producing paced rates up to 185 beats/min."

“It’s an Area with a Pessimistic View!” No, not really.

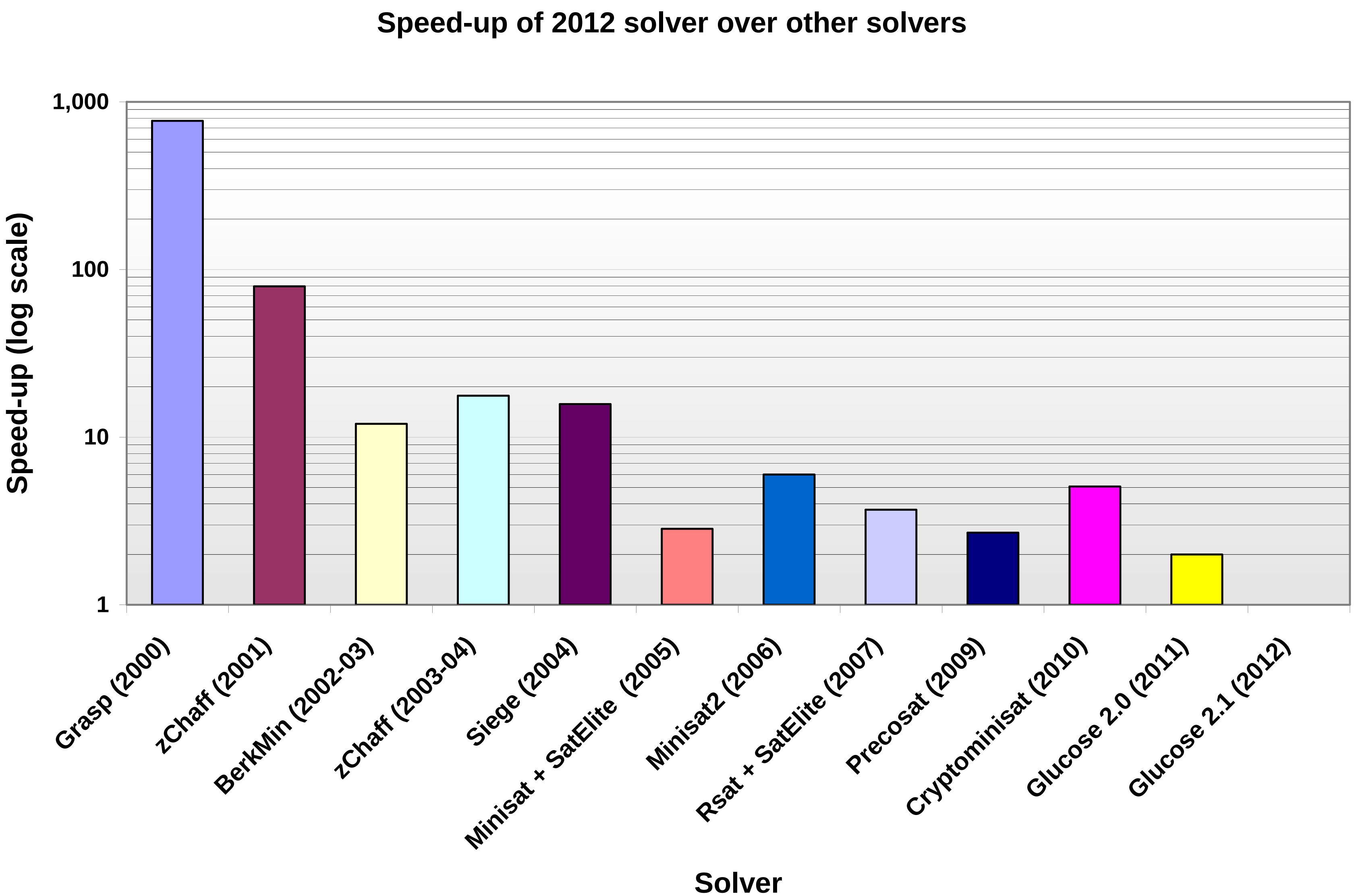
- The theory underlying algorithmic verification is beautiful
- It’s about the notion of PROOF
- It’s interdisciplinary
- The implementations are often non-trivial
  - Scaling up needs careful hacking
- It’s fun to work on!

Is Verification Feasible?

- “Easiest” non-trivial verification problem is NP-hard (SAT)

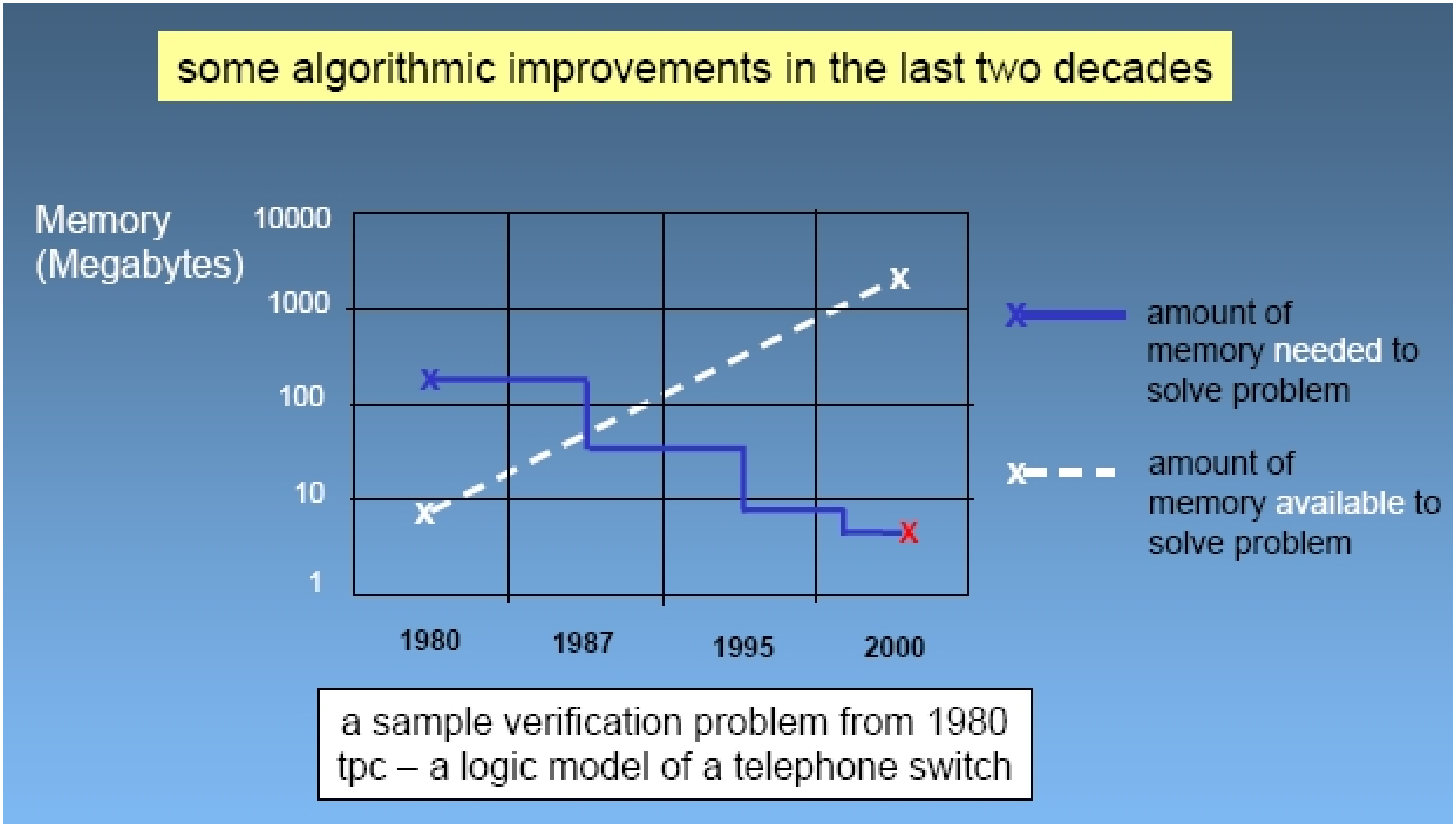
- But the outlook for practice is less gloomy than for theory…
  - More hardware resources
  - Better algorithms

My Experience with SAT Solving



Experience with SPIN Model Checker

[G. Holzmann]



Topics in this Course

- Computational Engines
  - Boolean satisfiability (SAT)
  - Satisfiability modulo theories (SMT)
  - Model checking
  - Syntax-guided synthesis (SyGuS)
- Advanced Topics ("Research Frontiers")
  - Quantitative/Probabilistic verification
  - Deduction + Inductive Learning
  - Synthesis from multi-modal specifications
  - Human-Computer Interaction & Verification
  - New application domains
  - … (more later in this lecture)

Topics of this Course (another view)

Application Domains

Circuits, Software, Networks, Hybrid Systems, Biological Systems, etc.

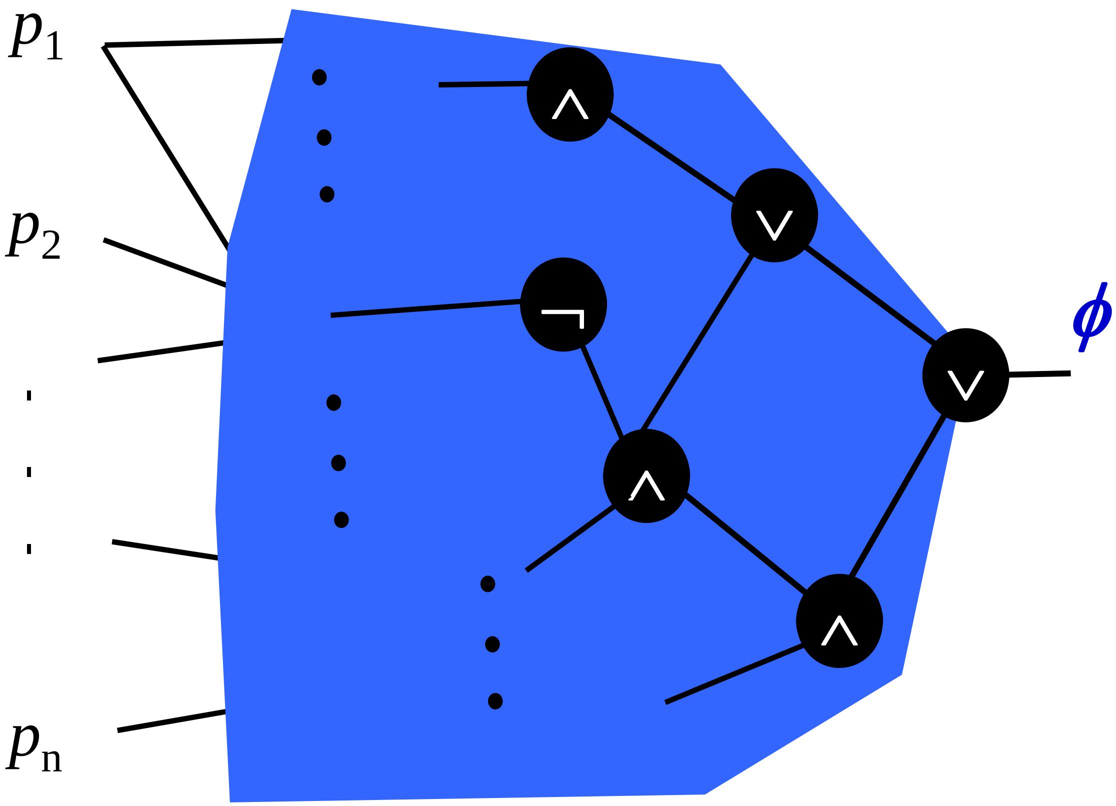
Verification Strategies

Automata-theoretic, Symbolic, Abstraction, Learning, etc.

Computational Engines

SAT, BDDs, SMT

Boolean Satisfiability (SAT)

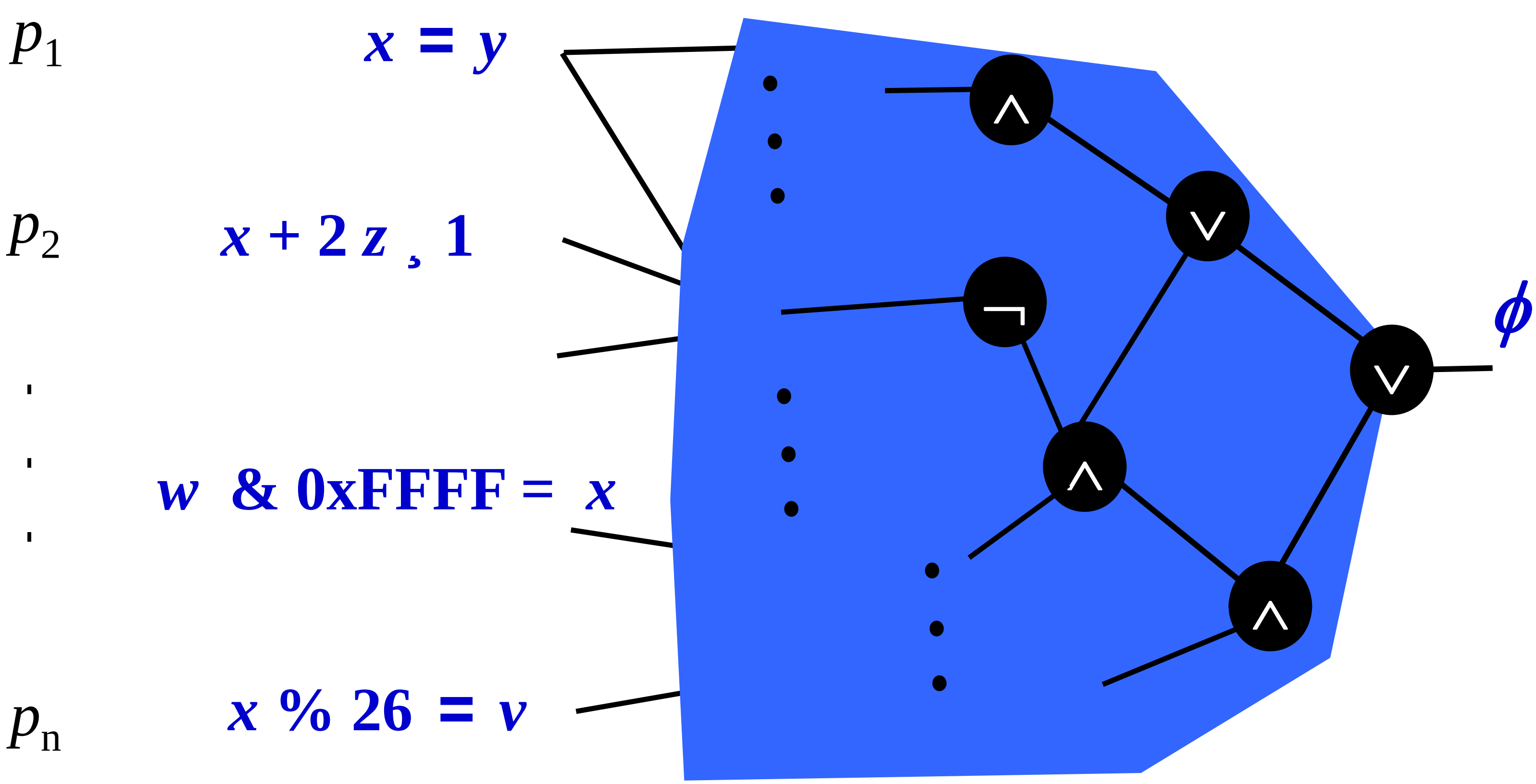


Is there an assignment to the p_i variables s.t. ϕ evaluates to 1?

Two Applications of SAT

- Equivalence checking of circuits
  - Given an initial (unoptimized) Boolean circuit and its optimized version, are the two circuits equivalent?
  - Standard industry CAD problem
- Malware detection (security)
  - Given a known malicious program and a potentially malicious program, are these “equivalent”?
- Many other applications:
  - Cryptanalysis, test generation, model checking, logic synthesis, ….

Satisfiability Modulo Theories (SMT)



Is there an assignment to the *x,y,z,w* variables s.t. ϕ evaluates to 1?

Applications of SMT

- Pretty much everywhere SAT is used
  - The original problem usually has richer types than just Booleans!
- To date: especially effective in
  - software model checking
  - test generation
  - software synthesis
  - finding security vulnerabilities
  - high-level (RTL and above) hardware verification

Model Checking

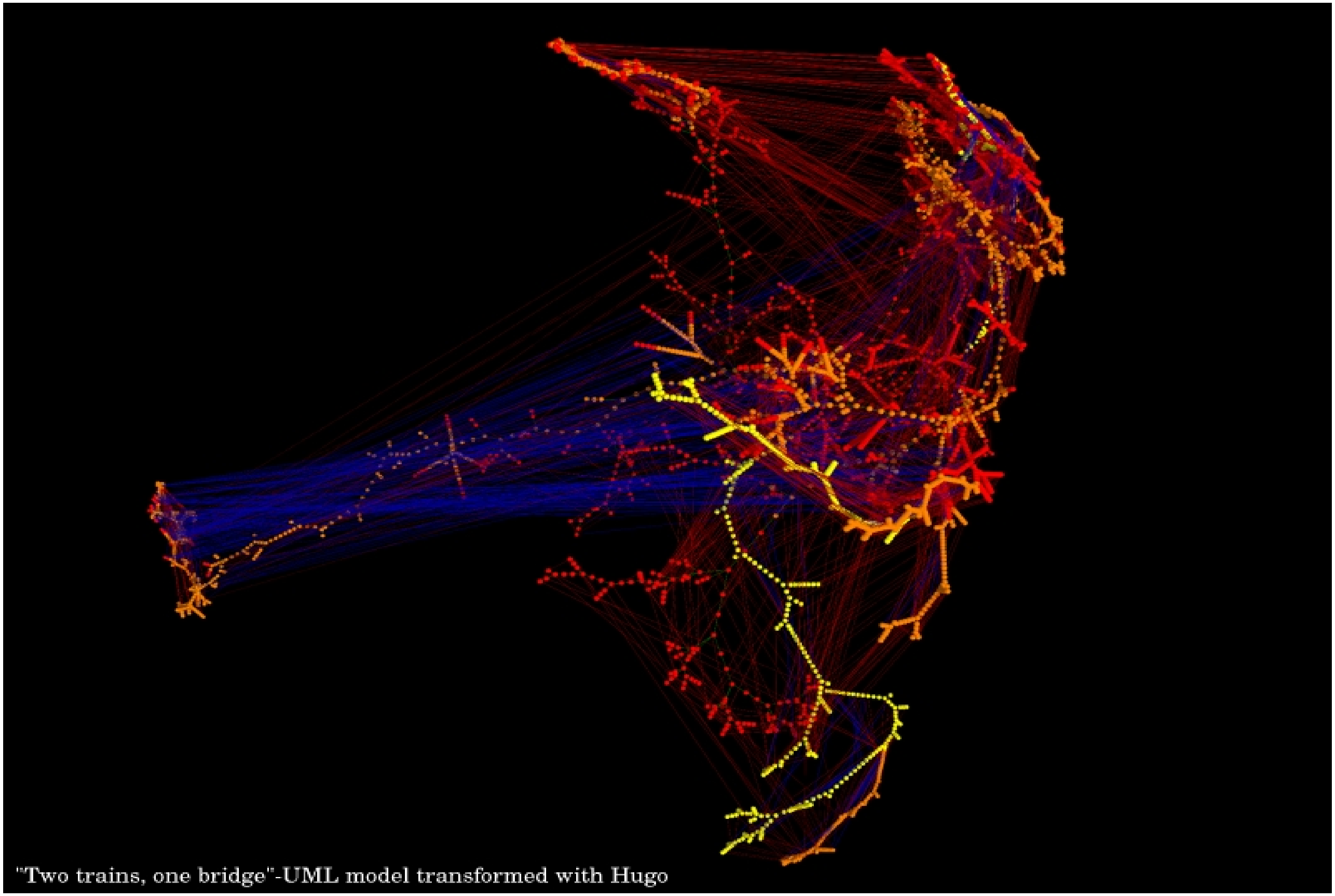
- Broad Defn:

A collection of **algorithmic methods** based on **state space exploration** used to verify if a **system satisfies a formal specification**.

- Original Defn: (Clarke)

A technique to check if a finite-state system is a model of (satisfies) a temporal logic property.

Visualizing Model Checking



[Moritz Hammer, Uni. Muenchen]

Model Checking, (Over)Simplified

- Model checking "is" graph traversal ?
- What makes it interesting:
  - The graph can be HUGE (possibly infinite)
  - Nodes can represent many states (possibly infinitely many)
  - How do we generate this graph from a system description (like source code)?
  - Behaviors/Properties can be complicated (e.g. temporal logic)
  - …

A Brief History of Model Checking

- 1977: Pnueli introduces use of (linear) temporal logic for specifying program properties over time [1996 Turing Award]
- 1981: Model checking introduced by Clarke & Emerson and Quielle & Sifakis
  – Based on explicitly traversing the graph
  – capacity limited by “state explosion”
- 1986: Vardi & Wolper introduce “automata-theoretic” framework for model checking
  – Late 80s: Kurshan develops automata-theoretic verifier
- Early - mid 80s: Gerard Holzmann starts work on the SPIN model checker

A Brief History of Model Checking

- 1986: Bryant publishes paper on BDDs
- 1987: McMillan comes up with idea for "Symbolic Model Checking" (using BDDs) – SMV system
  - First step towards tackling state explosion
- 1987-1999: Flurry of activity on finite-state model checking with BDDs, lots of progress using: abstraction, compositional reasoning, …
  - More techniques to tackle state explosion
- 1990-95: Timed Automata introduced by Alur & Dill, model checking algorithms introduced; generalized to Hybrid Automata by Alur, Henzinger and others

A Brief History of Model Checking

- 1999: Clarke et al. introduce "Bounded Model Checking" using SAT
  - SAT solvers start getting much faster
  - BMC found very useful for debugging hardware systems
- 1999: Model checking hardware systems (at Boolean level) enters industrial use
  - IBM RuleBase, Synopsys Magellan, 0-In FV, Jasper JasperGold
- 1999-2004: Model checking + theorem proving: software and high-level hardware comes of age
  - SLAM project at MSR, SAL at SRI, UCLID at CMU
  - Decision procedures (SMT solvers) get much faster
  - Software verifiers: Blast, CMC, Bandera, MOPS, …
  - SLAM becomes a Microsoft product "Static Driver Verifier"

A Brief History of Model Checking

- 2005-date: Model Checking is part of the standard industrial flow. Some new techniques and applications arise:
  - Combination with simulation (hardware) and static analysis/testing (software) [Many univ/industry groups]
  - Checking for termination in software [Microsoft]
  - Program synthesis [Berkeley, Microsoft, MIT, Penn, …]
  - Lots of progress in verification of concurrent software [Microsoft CHESS project]
- Clarke, Emerson, Sifakis get ACM Turing Award; SAT solving advances are recognized

WHAT'S NEXT?!

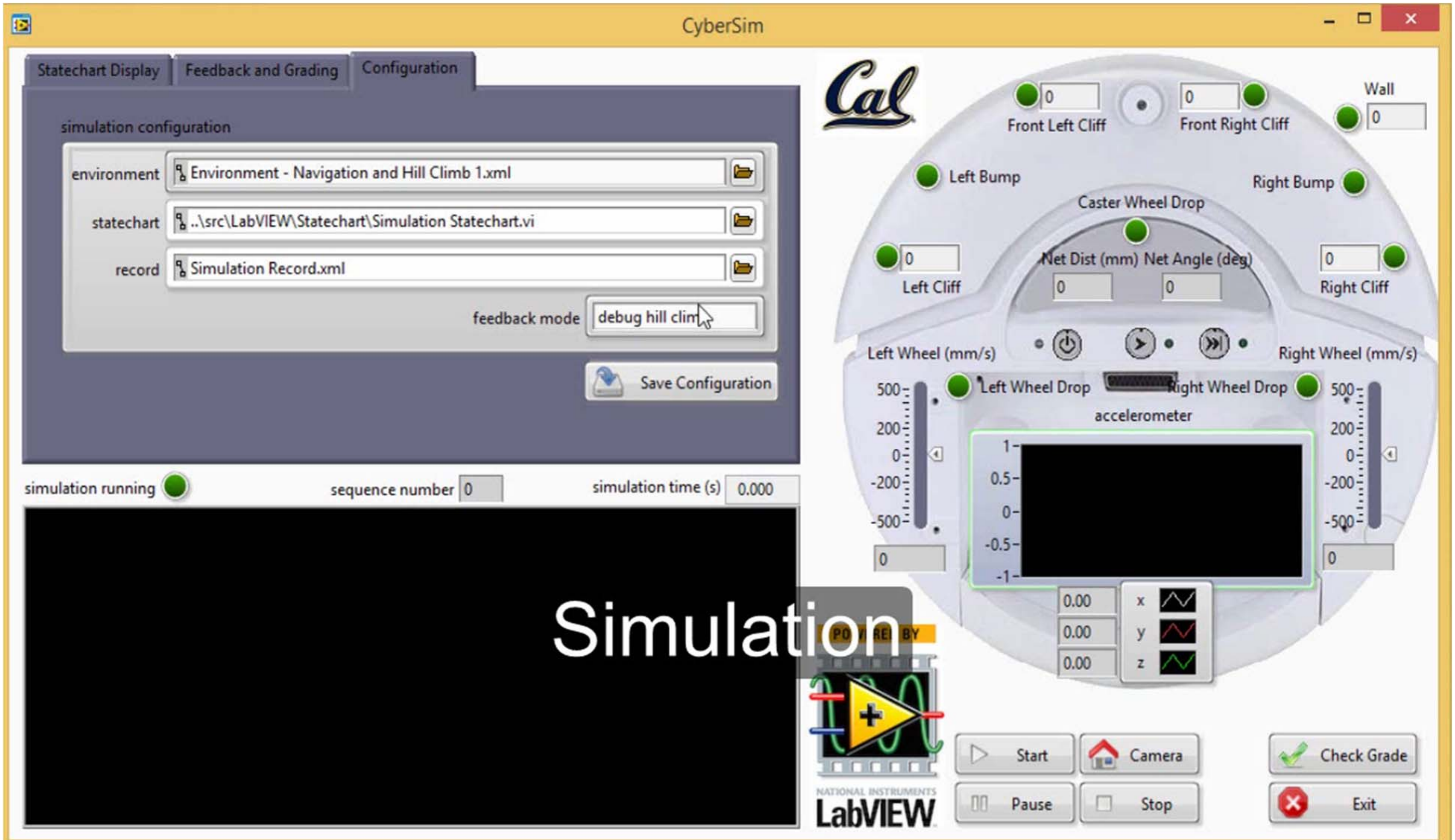
Research Frontiers in Formal Verification

- Three Themes:
  - – New Demands on Computational Engines
  - – New Applications
  - – The “Human Aspect”
    - Steps that require significant human input
    - Systems with humans in the loop

→ suggested project topics next week

Formal Methods for Education

Goal: To enable personalized learning for lab-based courses in science and engineering → CPSGrader, deployed on edX and on campus



Formal Methods for Robotics

Goal: To synthesize motion plans automatically for a group of robots with complex dynamics for Linear Temporal Logic (LTL) specification

Tool: ComPlan

VIDEO →

https://www.youtube.com/watch?v=pSjGwhH29Zs

Networks Tomorrow

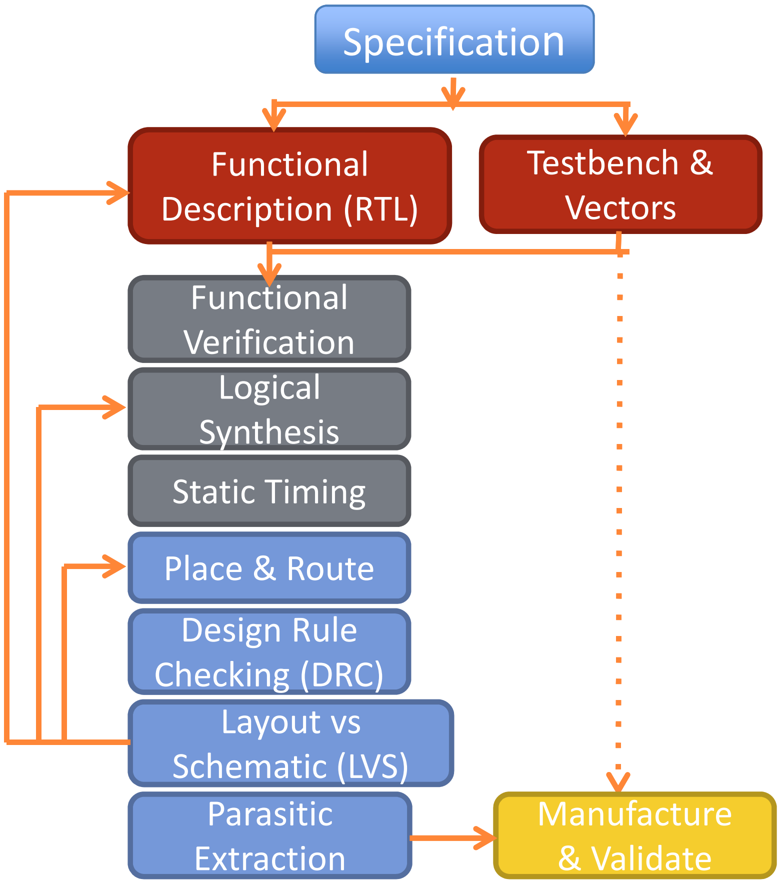
[slide due to G. Varghese]

- Online services → latency, cost sensitive
- Merchant Silicon → Build your own router
- Rise of Data centers → Custom networks
- Software defined Networks (SDNs) → custom design "routing program"
- P4 (next generation SDN) → redefine hardware forwarding at runtime

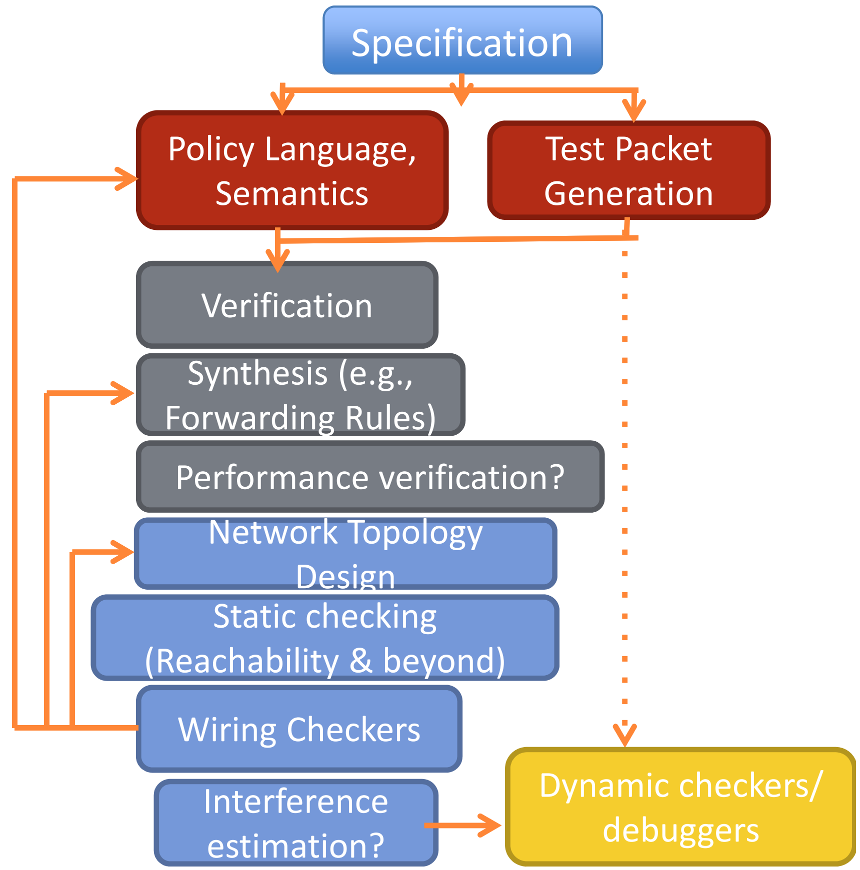
Opportunity to custom design networks to optimize goal.
Potential simplifications but complex interactions, hard to get right

Digital Hardware Design as Inspiration?

[slide due to G. Varghese]



Electronic Design Automation (McKeown SIGCOMM 2012)



Network Design Automation (NDA)?

Course Logistics

- Check out the webpage:
  www.eecs.berkeley.edu/~sseshia/219c

- Tentative class schedule will be up soon
  – 2007 Turing Award lecture (optional viewing)
  – IMP: Think about project topics!

Course Outline

- 2 parts
- Part I: Model Checking, Boolean reasoning (SAT, BDDs), SMT
  - Basics, how to use these techniques, and how to extend them further
- Part II: Advanced Topics
  - The challenging problems that remain to be addressed

Reference Books

- See list on the website
- Copies will be on reserve at Engg Liby
- e-Handouts for most material

Grading

- Scribing lectures (20%)
  - 2 lectures per person: Scribe one lecture, edit another lecture
  - Sign-up sheet next week
- Homework (10%)
  - First part of the course
- Paper discussions / class participation (10%)
  - Last month of the course
- **Project (60%)**
  - Do original research, theoretical or applied
  - Sample topics will be announced by end of next week
  - Project proposal due mid Feb.
  - Culminates in final presentation + written paper
  - *~50% of past projects led to conference papers!*

Misc.

- Office hours: W 1:30 – 2:30, and by appointment
- Pre-requisites: check webpage; come talk to me if unsure about taking the course
  - Undergraduates need special permission to take this class