SAND2011-3802P

Leveraging Formal Methods and Confronting Complexity for Digital System Reliability and Security

Computer Sciences and Information Systems
Sandia National Laboratories, Livermore, California

About Sandia

- DoE national lab.
  - Primary mission is develop, engineer, test the non-nuclear components of nuclear weapons
  - R&D in arms control, nonprolifieration, waste disposal.
  - Research in computer science and supercomputing, computational biology, mathematics, alternative energy

- Located in Albuquerque, NM and in Livermore, CA

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Our digital systems

- Embedded systems for high reliability
- Command and Control networks.
- Software for simulation

We view formal verification as one facet of the digital complexity problem

- Includes issues in cyber security, reliability and safety
- Complexity causes digital systems to have unknowable, and in general, unanalyzable faults, vulnerabilities
- Formal methods are currently relegated to simple systems or high levels of abstraction
  - New approaches are improving on this

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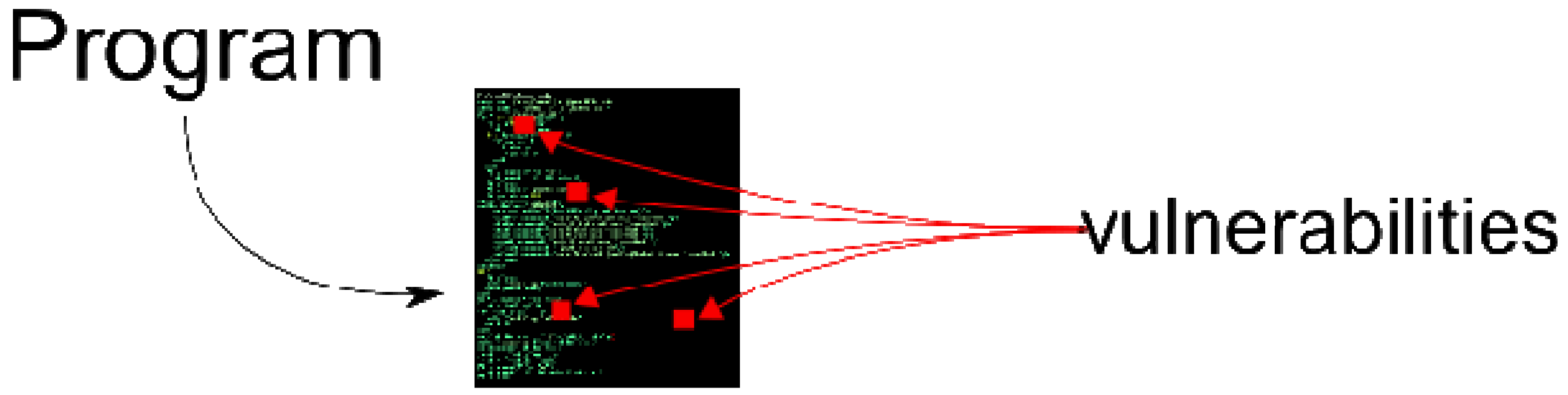
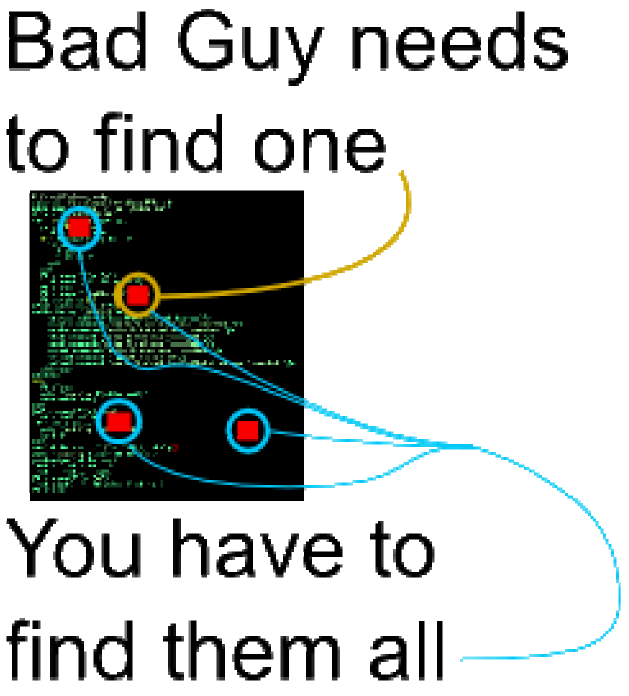
Securing an arbitrary code is not just hard; it's impossible

- **Restated: Generic code has vulnerabilities that are unprovable and unknowable**
  - *Not* statistical, even in principle
  - Turing completeness demands that a generic code is undecidable



- **So now what?**

Complexity makes cyber threats *asymmetric*



- **Developer, user, *and attacker* all don't know where the vulnerabilities are (*undecidable*)**
- **Worse, attacker may have planted a vulnerability**
- **Asymmetry: One vulnerability compromises the whole code**
  - Developer has to find all of them (impossible in general)
- **No one can guarantee "this code is clean" or even quantify improvement**

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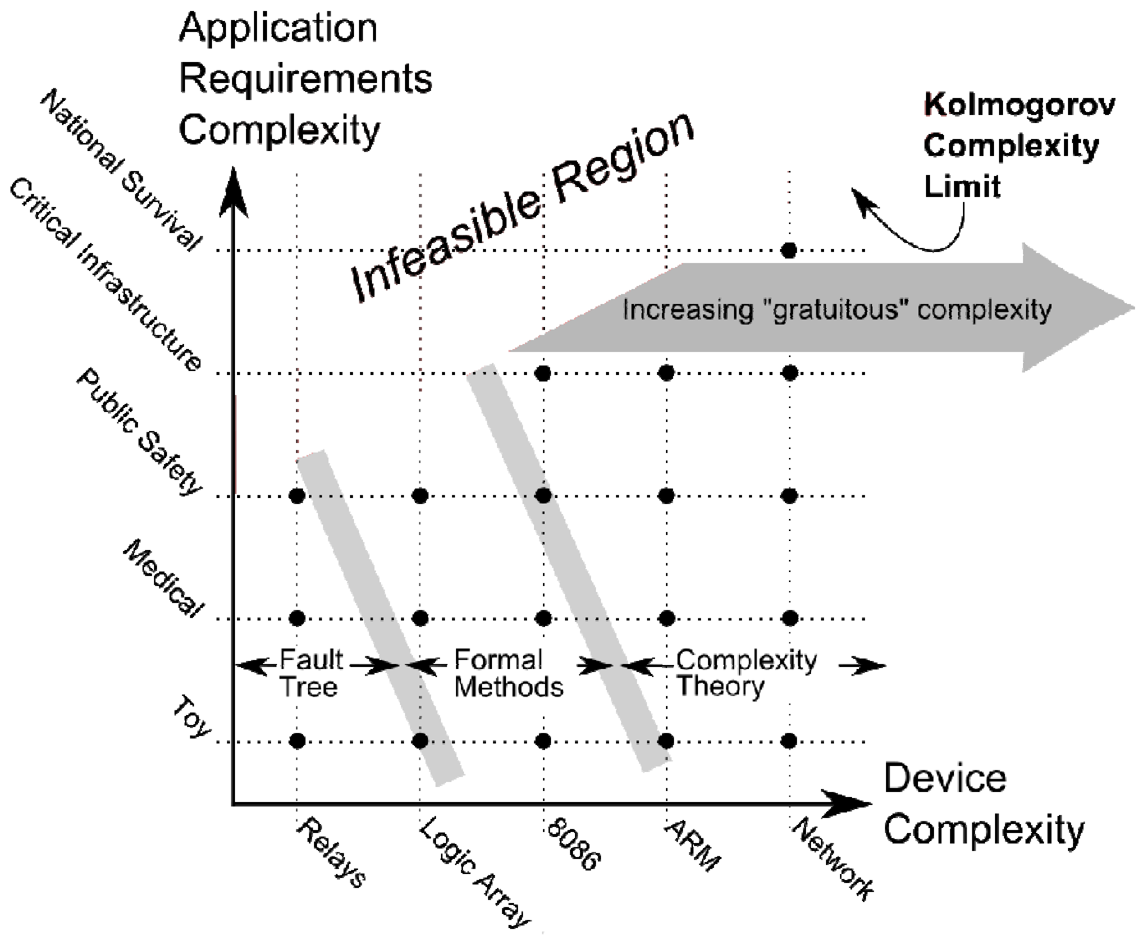
What is complexity?

- **Complex systems are characterized by large numbers of interacting entities where even a few entities can strongly affect system behavior**
- **Complex systems are irreducible; their behavior is emergent and not evident *a priori*, but is accessible via observation and simulation**
- **Examples are ubiquitous**
  - Living things and ecosystems
  - Human societies, economies, and institutions
  - Highly engineered artifacts – e.g., airplanes, NWs
  - Large-scale infrastructure – e.g., power grids
  - Computer software, hardware, and networks

Complexity space illustrates tradeoffs in device engineering and analysis



- **Pink region is what cannot be built**
- **Rest of plot shows how analysis can be done**

Formal methods are a bridge to complexity, filling an important gap

- **Formal methods use computer analysis to verify digital systems rigorously and exhaustively**
  - Applicable to less complex systems that are still beyond the reach of manual analysis
  - Widely used in high-consequence industrial applications
- **Verification of components does not generally translate to verification of whole system**
- **Irreducible complexity enters when exploring entire state space is infeasible**
  - Reliability and security assertions become probabilistic
- **Both formal verification and complexity science are vital for gaining confidence in digital systems**

Complexity science offers a new perspective on modeling and design

- **Most real-world systems are too intricate to analyze directly; they are irreducible**
- **Reductionism requires "bottom-up" understanding**
  - Use expert knowledge to model component entities
  - Validate system model vs. observations
  - Make each component entity as reliable as possible
  - Formal methods are the pinnacle of this approach
- **Complexity science provides "top-down" insight relating system structure to emergent behavior**
  - New modeling paradigm: Identify entities by abstraction from idealized models with known emergent behavior
  - New design paradigm: Build real systems based on models with desired emergent behavior

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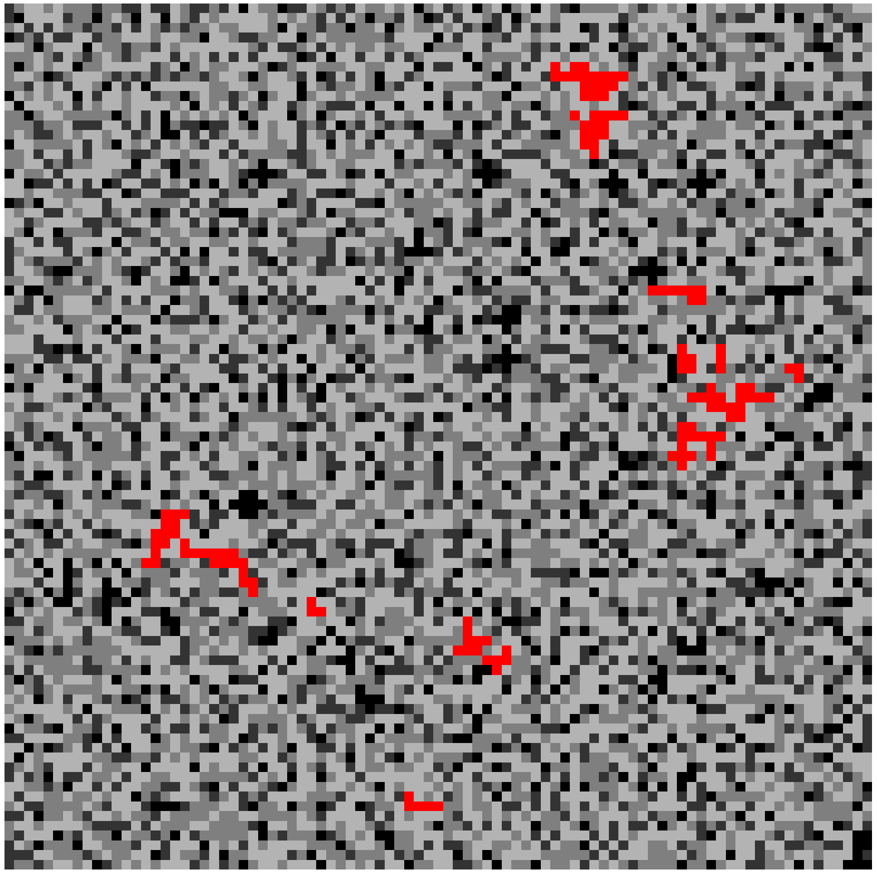
Self-organized criticality is a simple example of emergent behavior

- **"Sandbot": cyber model of coordinated malware**
- **SOC is *spontaneous* development of multi-scale phenomena with power-law distributions**
  - Similar to thermodynamic criticality but without tuning
- **Illustrated by sandpile model: physics-like cellular automaton**
  - Sand is sprinkled randomly
  - Avalanches occur at all scales



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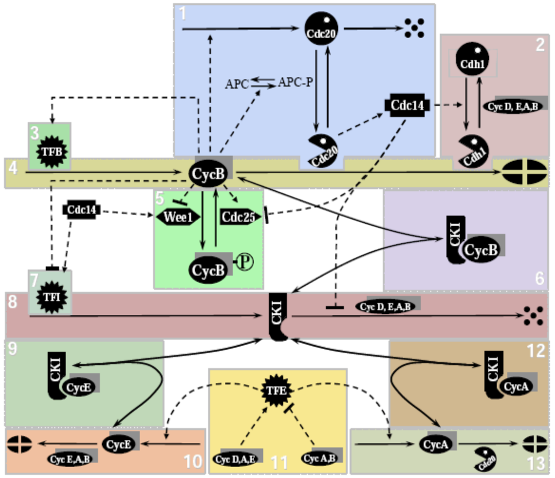
Complexity is a fact of "life"

- **Biological phenomena are a prototype and inspiration for many complex domains**
  - Life involves a large chemical regulatory network



Eukaryotic cell-cycle regulation

  - "Game of Life" model is based on population dynamics
  - Bio concepts pervade computing (viruses, mutations)
- **Biology typifies complex couplings of manmade systems – economy, energy, cybersecurity**

Robustness is key to understanding real-world systems with "organic" behavior

- Highly optimized tolerance (HOT): Systems *designed* or *selected* to perform well despite perturbations
- Robustness is necessary for biological evolution and for effective engineering
- HOT systems exhibit power-law distributions like SOC but have organic structure (not self-similar)
- Adapted robustness to one set of perturbations induces extra fragility to different perturbations
- Indeed, rare but catastrophic failures are seen in highly engineered/evolved systems
  - Electrical blackouts, cyber shutdown of Estonia, financial panics, hacker penetration of bank database, etc.

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Complexity can address "whole system" robustness and stability

- **Consider designing a digital circuit to add two 1-bit numbers (a "half adder")**
  - This is among the most basic functions appearing in microelectronics
- **There are many ways of composing logic gates to implement this functionality**
- **The next slide shows two such circuits; each performs as a half adder when run for twenty steps**
  - Shown correctly adding 1 + 1 to get the binary result 10
  - They also give correct answers for the other possible inputs

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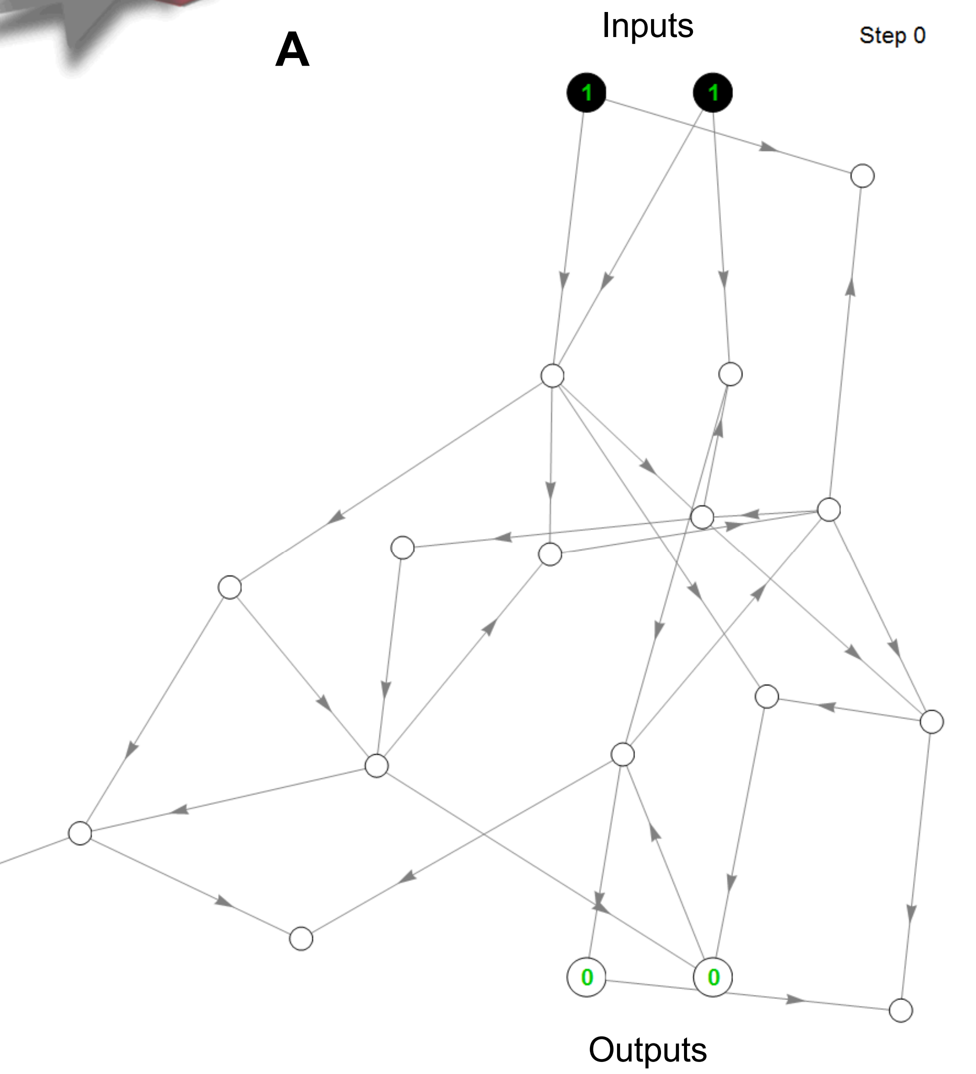
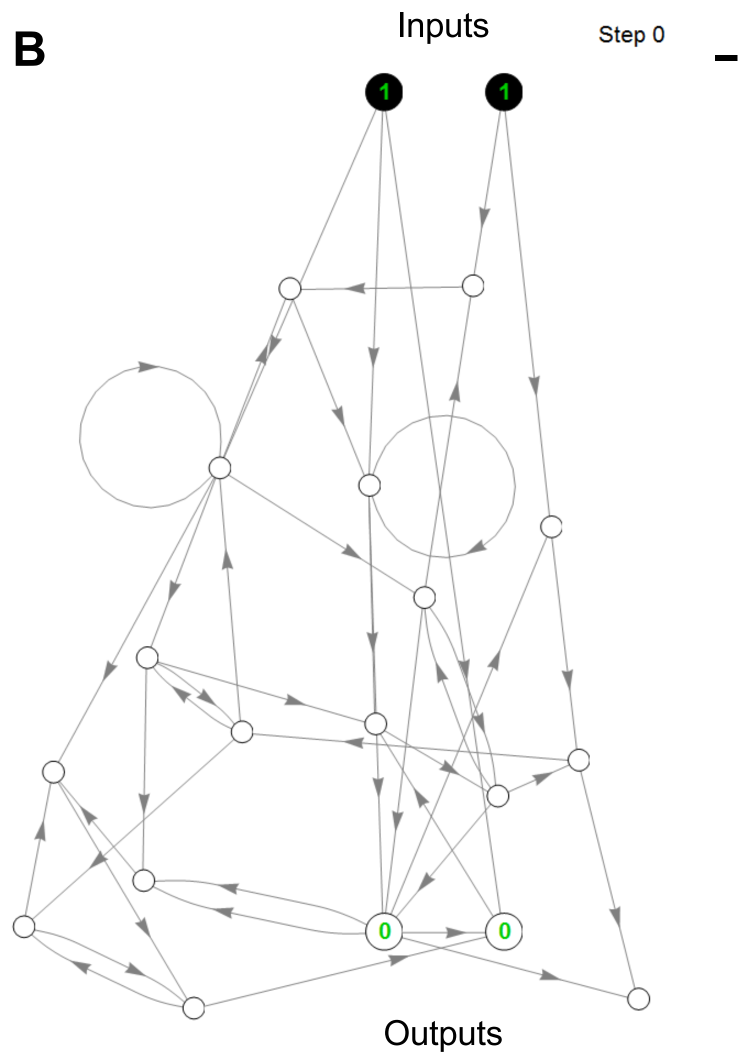

A
Inputs
Step 0
1
1
0
0
Outputs


B
Inputs
Step 0
1
1
0
0
Outputs

What distinguishes the two implementations? *Resilience*

- **For this very simple functionality, both circuits can be verified by exhaustive testing**
- **More realistic circuits cannot be tested exhaustively, so we need to understand the effect of untested states**
- **In this example, we introduce occasional gate errors to represent unanticipated behavior**
- **The next slide shows a typical run of each circuit with a 1% error rate per gate update**
  - States that deviate from the ideal run are outlined in red
- **Circuit A has much less error in the final output (greater resilience) than circuit B – why?**
  - In this case, average inputs per node (*k*) makes the difference

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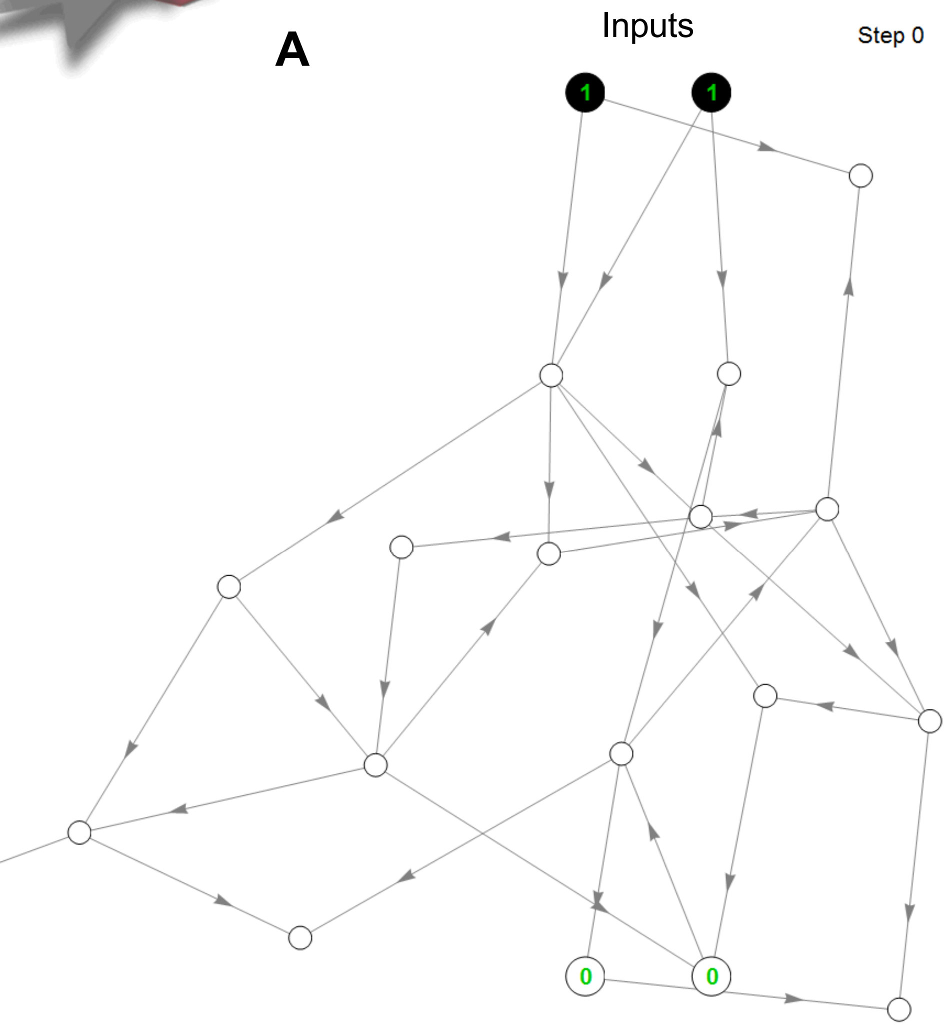
A

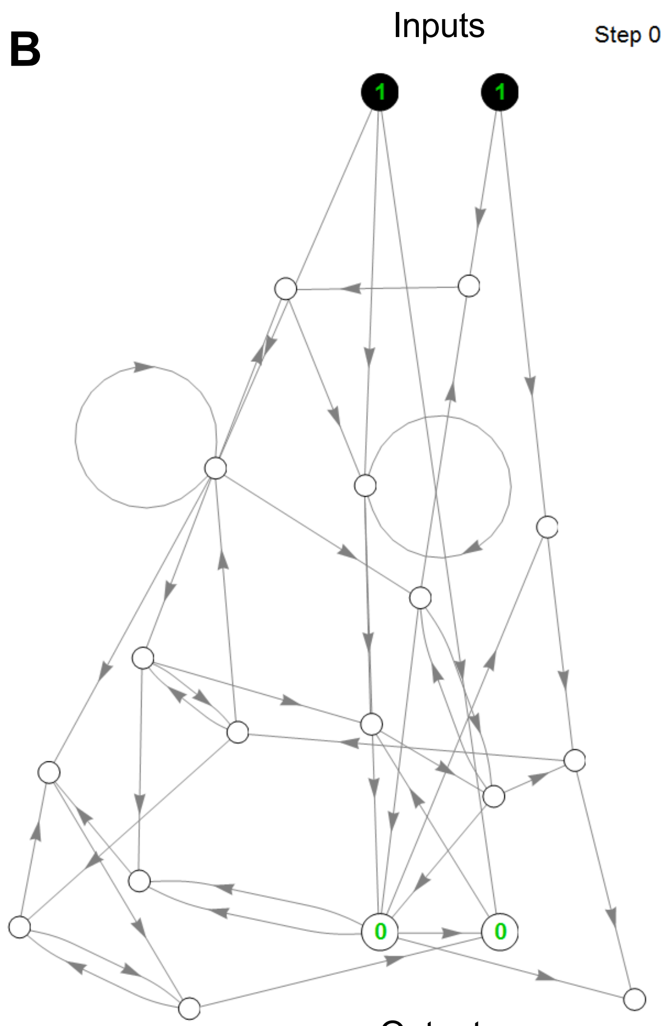
k = 1.5



Outputs
(Average incorrect bits: 0.10)

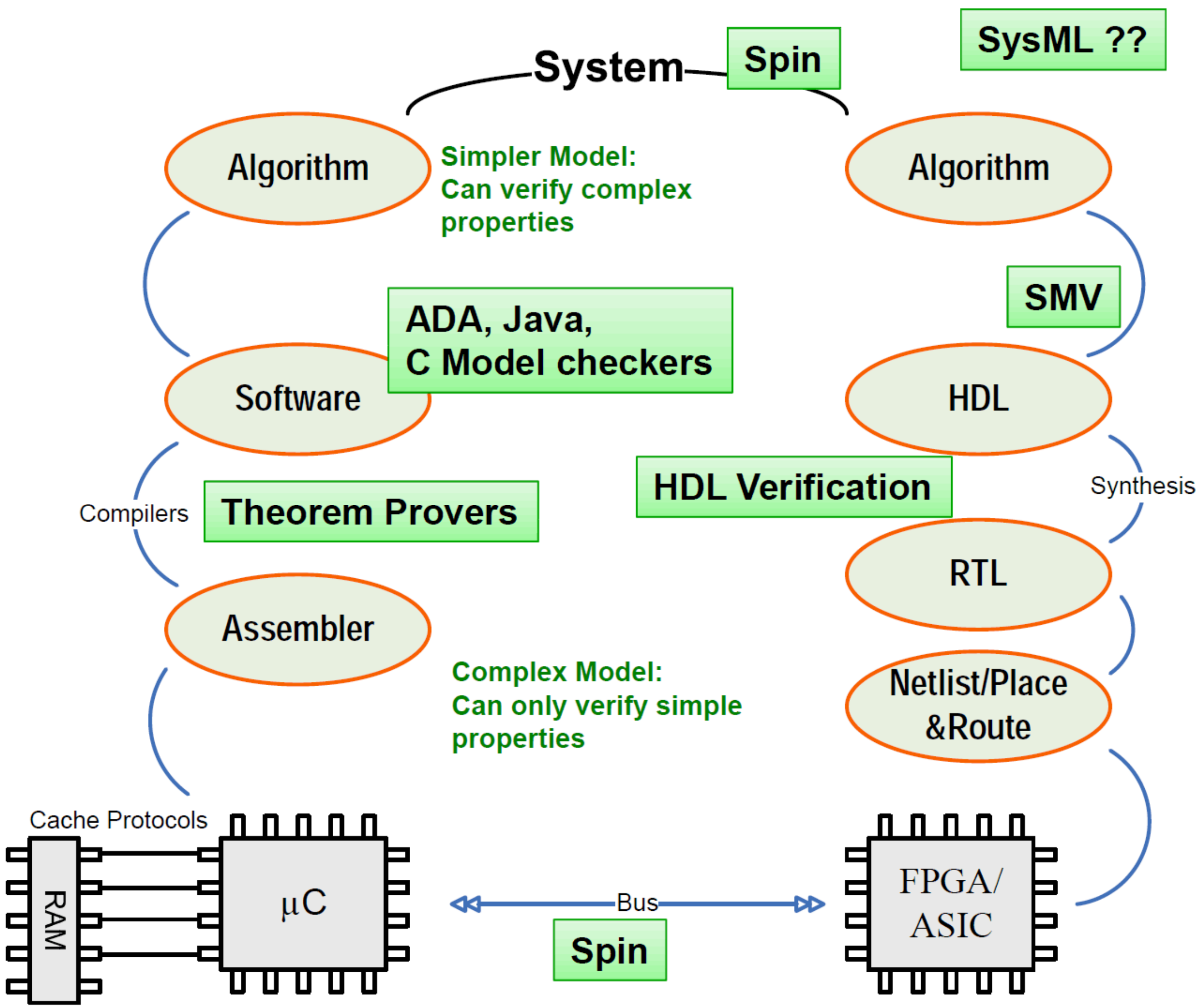
B

k = 2.5



Outputs
(Average incorrect bits: 0.73)

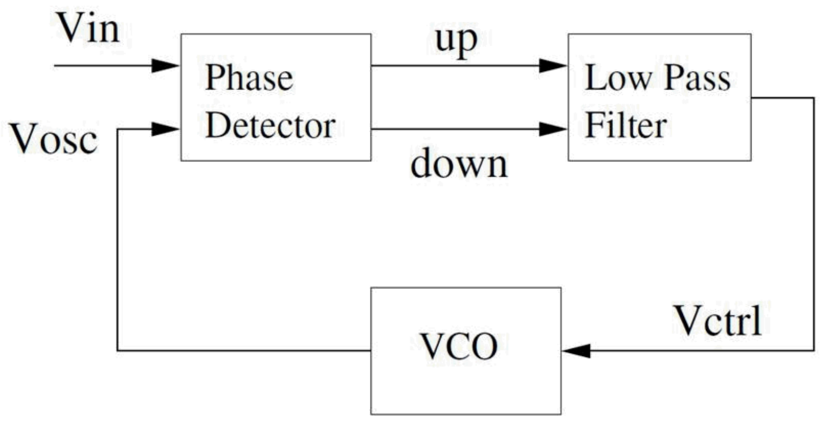
Formal methods can be applied at various levels of abstraction



Analog mixed signal control systems

Hybrid systems: Dynamical systems that exhibit both discrete and continuous change

- Their discrete variables are updated in discrete steps that consume no time (resulting in jumps)
- Their continuous real-valued variables (clocks and drifting clocks) are updated as continuous functions while time elapses (during delays, resulting in so-called “flows”)

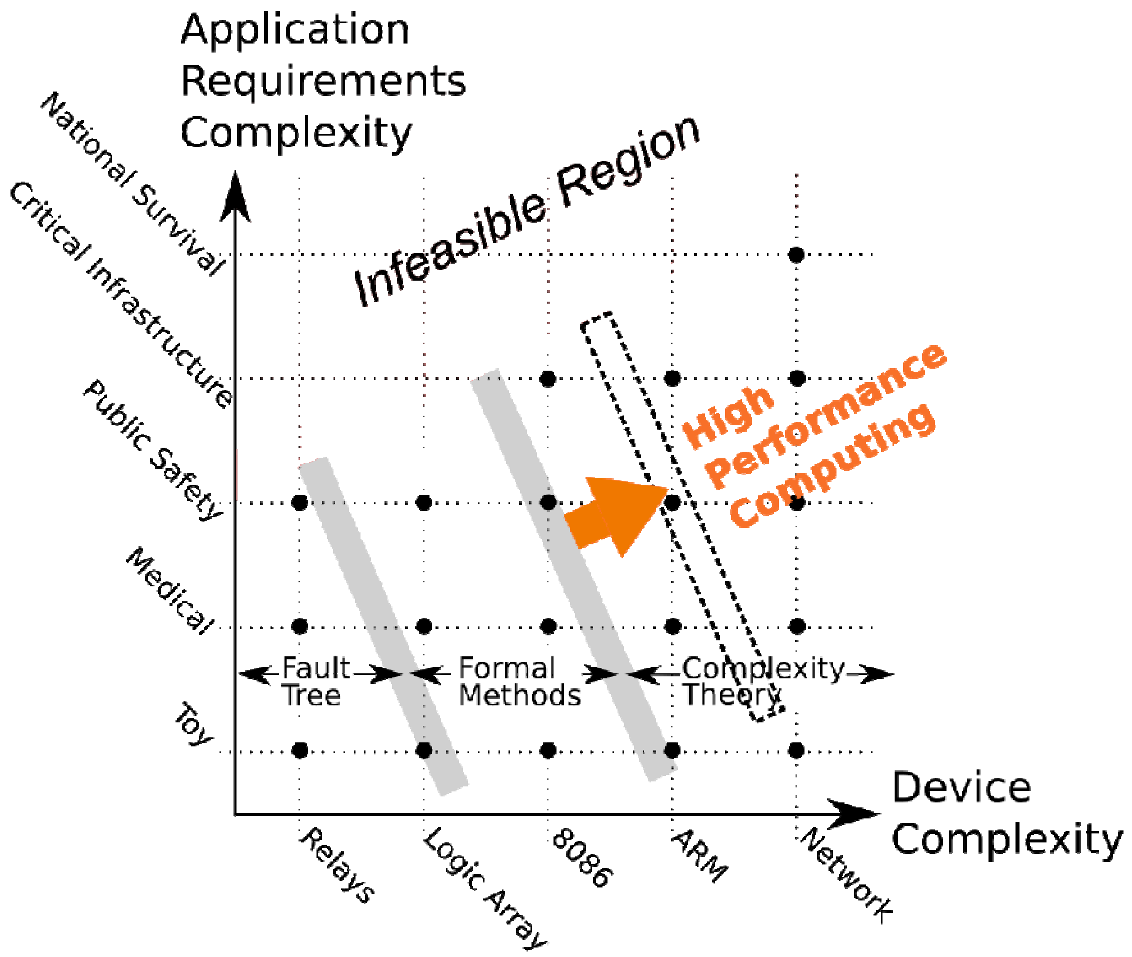


PLL diagram (Little et al, 2004)

Today formal verification is limited to the digital domain

- **A computer model is generated for the digital logic**
  - Very accurate as long as:
    - **The circuit behaves digitally**
    - **Inputs remain in their expected range**
- **Not considered in formal verification:**
  - Digital circuit ceases to behave digitally because of extreme environments
  - Out-of-nominal digitized analog inputs appear from the external environment
- **We seek to broaden current techniques to verify function for digital systems in extreme environments**

Digital system analysis research will increase utility of HPC in simulation



- Complex system simulation leverages HPC but confronts issues of tractability and V&V that current research is addressing
- HPC, formal methods, and complexity theory can work together to expand our capabilities

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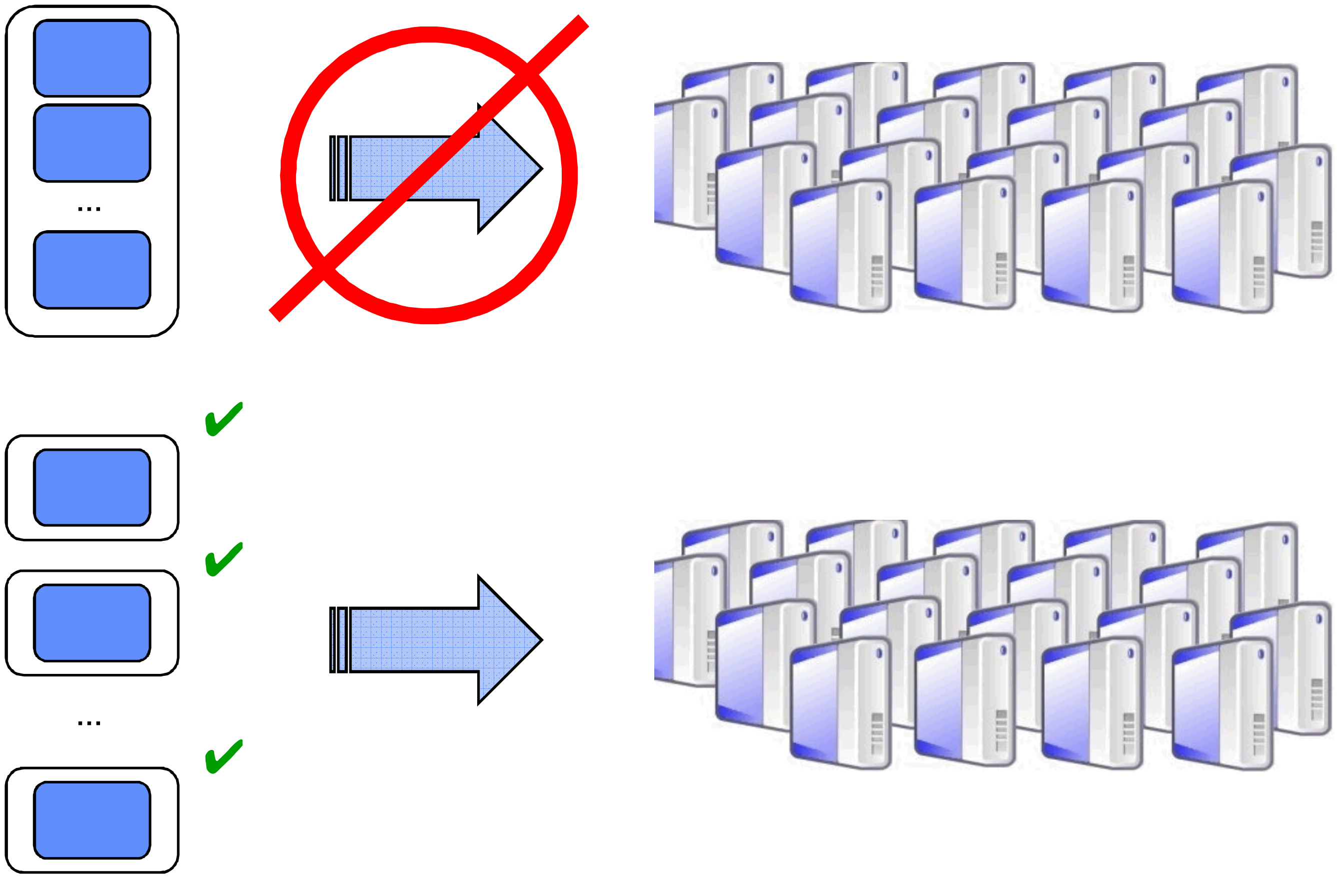
Composition of formally verified systems



Decomposing a complex digital design may enable component-level formal verification using HPC

Composition to the whole device is nontrivial, but the formal results can usefully constrain behavior