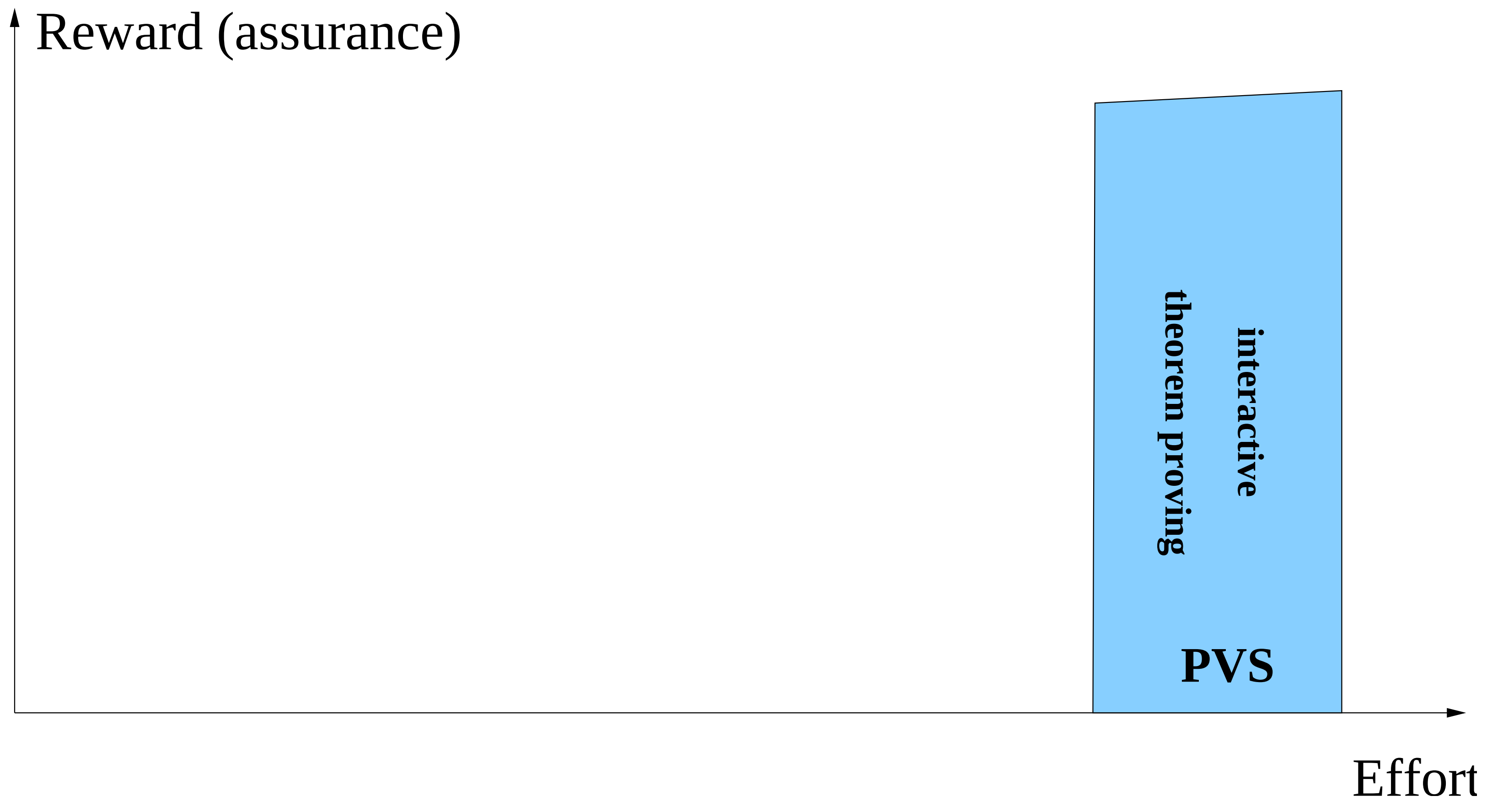
Invisible Formal Methods:

Generating Efficient Test Sets With a Model Checker

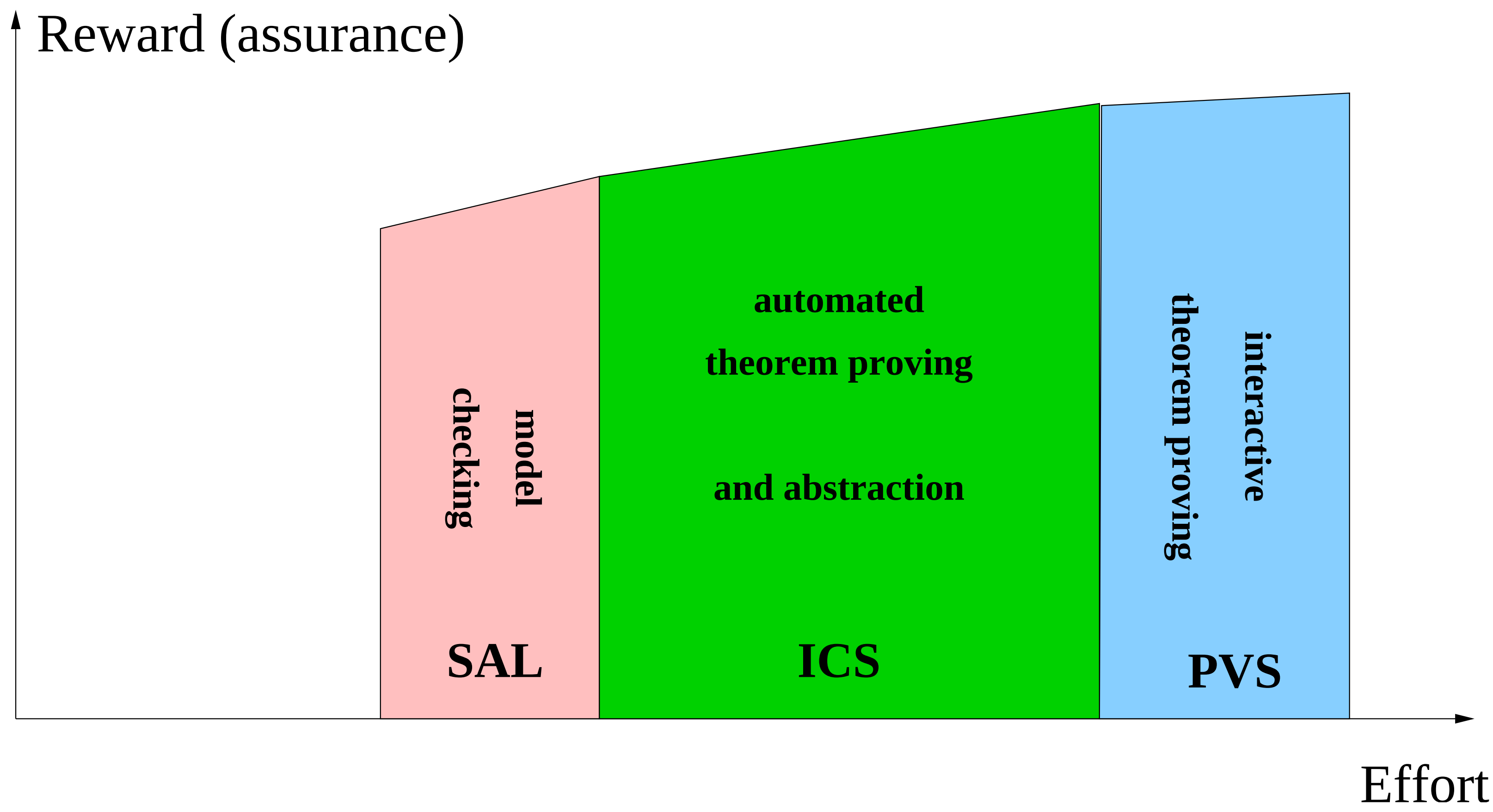
John Rushby
with Grégoire Hamon and Leonardo de Moura

Computer Science Laboratory
SRI International
Menlo Park, California, USA

Full Formal Verification is a Hard Sell: The Wall

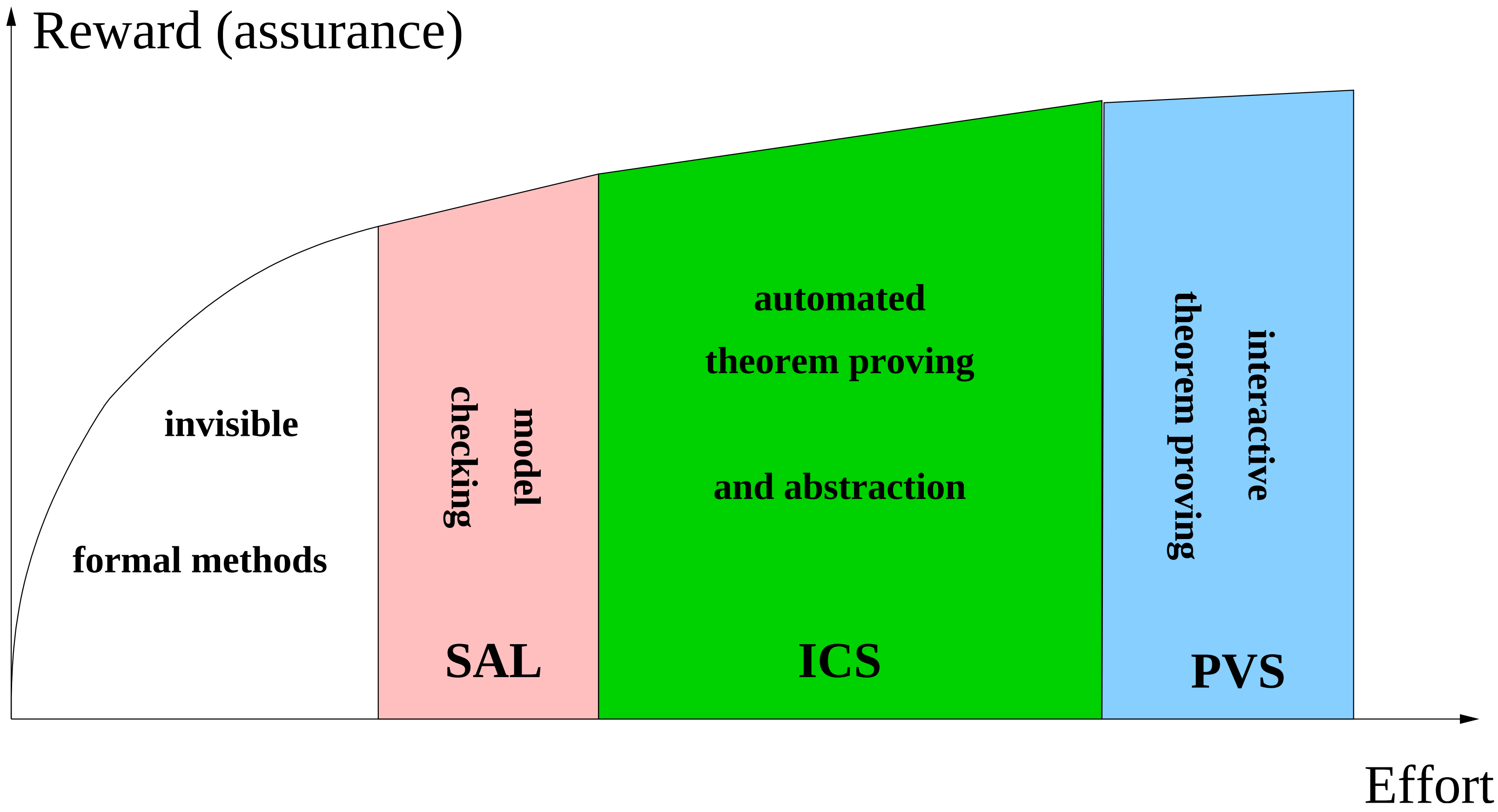


Newer Technologies Improve the Value Proposition



But only by a little

The Unserved Area Is An Interesting Opportunity



Conjecture: reward/effort climbs steeply in the invisible region

Invisible Formal Methods

- Use the technology of formal methods
  - Theorem proving, constraint satisfaction, model checking, abstraction, symbolic evaluation
- To augment traditional methods and tools
  - Compilers, debuggers
- Or to automate traditional processes
  - Testing, reviews, debugging
- To do this, we must unobtrusively (i.e., invisibly) extract
  - A formal specification
  - A collection of properties
- And deliver a useful result in a familiar form

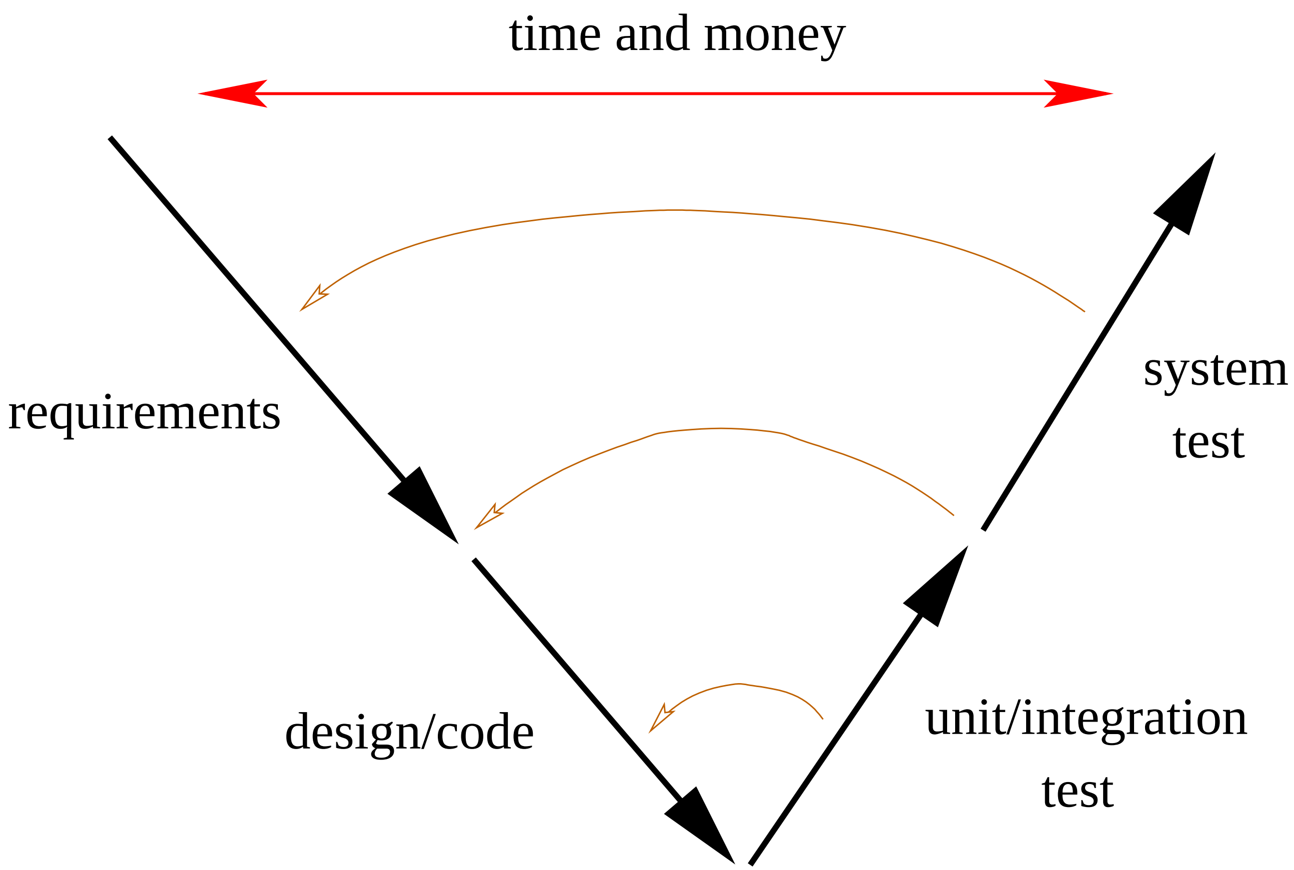
Invisible Formal System Specifications

- Traditionally, there was nothing formal (i.e., mechanically analyzable) prior to the executable program
  - Requirements, specifications, etc. were just natural language words, and pictures
- So one response is to apply formal methods to programs
  - E.g., extended static analysis
- But for embedded systems, industry has adopted model based design (MBD) at a surprisingly rapid pace
  - Matlab (Simulink/Stateflow): over 500,000 licenses
  - Statecharts
  - Scade/Esterel
- Some of these (e.g., Stateflow) have less-than-ideal semantics, but it's possible to cope with them
  - E.g., our paper in FASE '04

Invisible Property Specifications

- MBD provides formal specifications of the system
- But what properties shall we apply formal analysis to?
- One approach is to analyze structural properties
  - E.g., no reliance on 12 o'clock rule in Stateflow
  - Similar to table checking in SCR
  - Prove all conditions are pairwise disjoint
  - And collectively exhaustive
- Another is to generate structural test cases
- Either for exploration
  - E.g., "show me a sequence of inputs to get to here"
- Or for testing in support of certification and verification

Simplified Vee Diagram



Vast resources are expended on testing embedded systems

Invisible FM Example: Generating Unit Tests

- Let's focus initially on testing individual units of a program
- Executable model provides the oracle
- Various criteria for test generation

  Functional tests: tests are derived by considering intended function or desired properties of the unit (requires higher-level specifications, which we do not have)

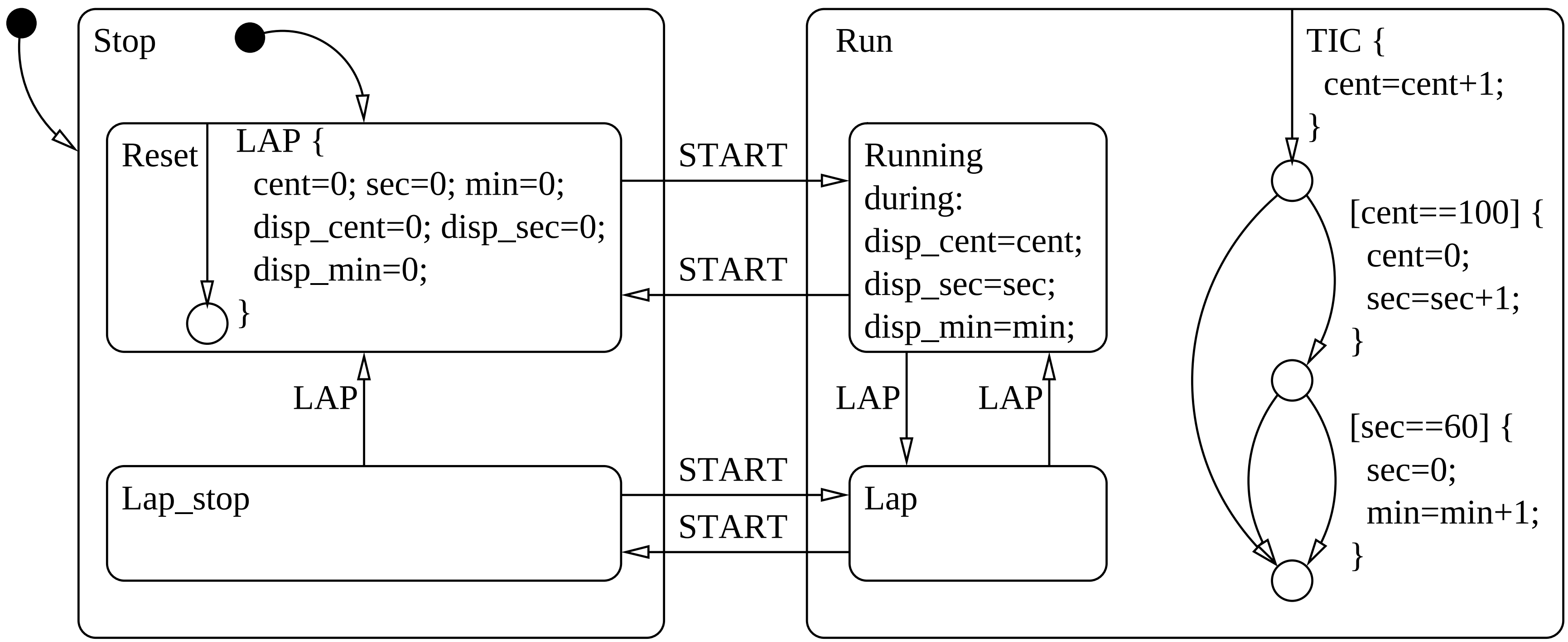
  Boundary tests: tests designed to explore inside, outside, and on the boundaries of the domains of input variables

  Structural tests: tests are designed to visit interesting paths through the specification or program (e.g., each control state, or each transition between control states)

- Let's look at the standard method for structural test generation using model checking

Example: Stopwatch in Stateflow

Inputs: START and LAP buttons, and clock TIC event



Example test goals: generate input sequences to exercise Lap_stop to Lap transition, or to reach junction at bottom right

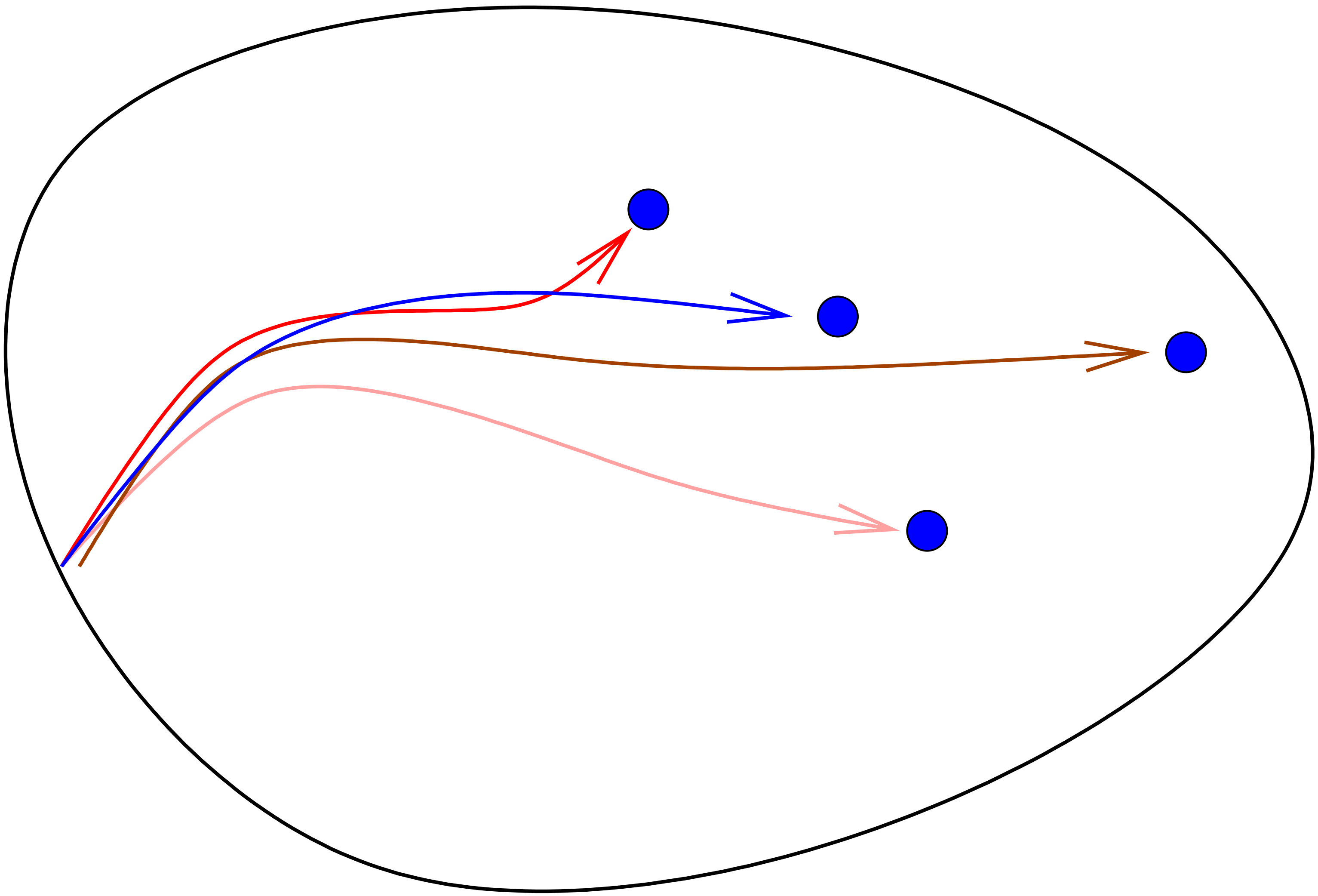
Generating Structural Tests

- Problem: find a path that satisfies a desired test goal
  - E.g., reach junction at bottom right
- Symbolically execute the path, then solve the path predicate to generate concrete input sequence that satisfies all the branch conditions for the path
  - If none, find another path and repeat until success or exhaustion
- Repeat for all test goals
- Solving path predicates requires constraint satisfaction over theories appearing in the model (typically, propositional calculus, arithmetic, data types)
  - E.g., ICS and its competitors
  - For finite cases, a SAT solver will do
- Can be improved using predicate abstraction (cf. Blast)

Generating Tests Using a Model Checker

- Method just described requires custom machinery
- Can also be done using off-the-shelf model checkers
  - Path search and constraint satisfaction by brute force
- Instrument model with trap variables that latch when a test goal is satisfied
  - E.g., a new variable jabr that latches TRUE when junction at bottom right is reached
- Model check for "always not jabr"
- Counterexample will be desired test case
- Trap variables add negligible overhead ('cos no interactions)
- For finite cases (e.g., numerical variables range over bounded integers) any standard model checker will do
  - Otherwise need infinite bounded model checker as in SAL

Tests Generated Using a Model Checker



Model Checking Pragmatics

Explicit state: good for complex transition relations with small statespaces

- **Depth first search**: test cases generally have many irrelevant events and are too long
  - E.g., 24,001 steps to reach junction at bottom right
- **Breadth first search**: test cases are minimally short, but cannot cope with large statespaces
  - E.g., cannot reach junction at bottom right

Symbolic: test cases are minimally short, but large BDD ordering overhead in big models

- E.g., reaches junction at bottom right in 125 seconds

Bounded: often ideal, but cannot generate tests longer than a few tens of steps, and may not be minimally short

- E.g., cannot reach junction at bottom right

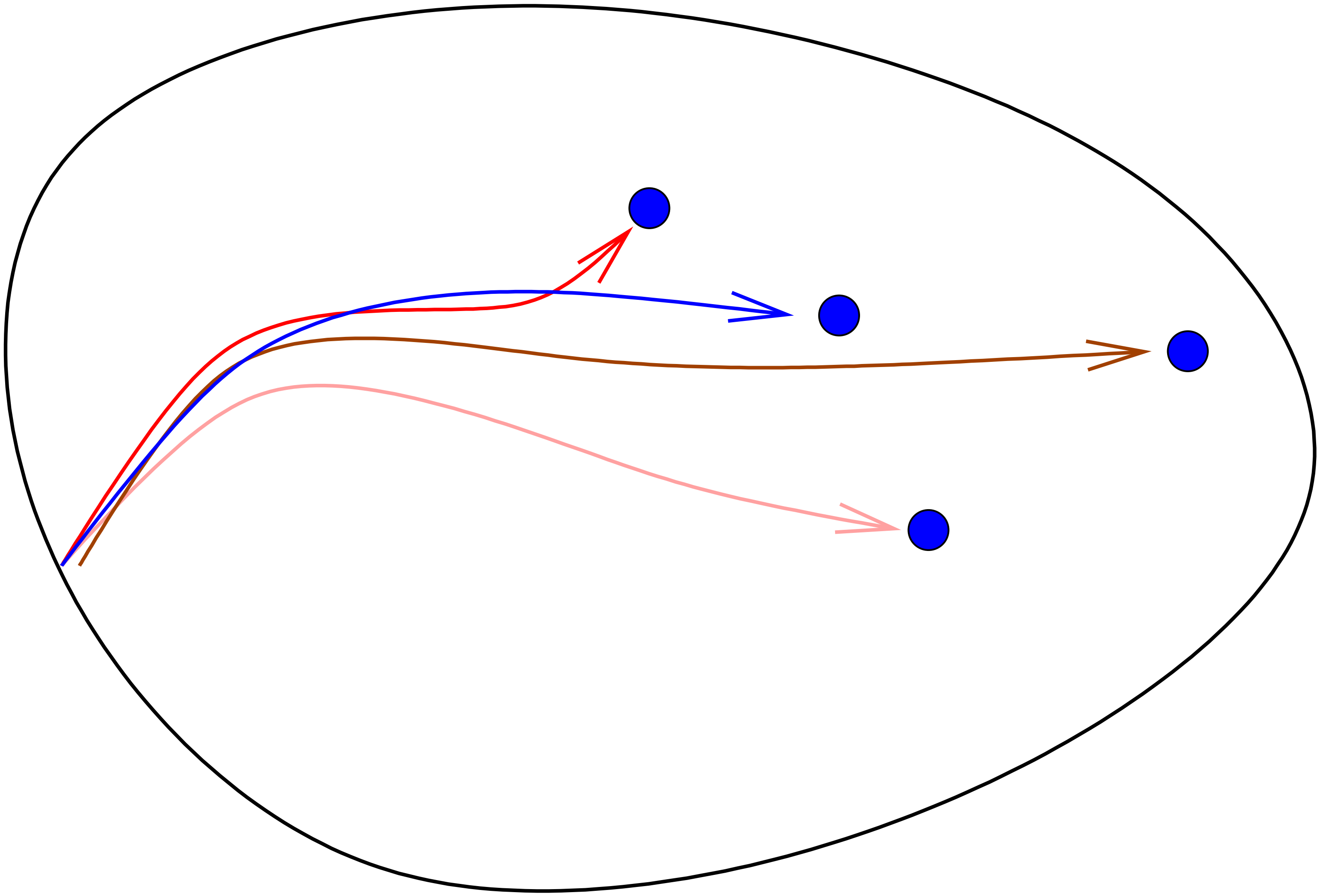
Useful Optimizations

- Backward slicing (called cone of influence reduction in model checking) simplifies model relative to a property by eliminating irrelevant state variables and input events
  - Allows explicit state model checker to reach junction at bottom right in 6,001 steps in just over a second (both depth- and breadth-first)
  - And speeds up symbolic model checker
- Prioritized traversal is an optimization found in industrial-scale symbolic model checkers
  - Partitions the frontier in forward image computations and prioritizes according to various heuristics
  - Useful with huge statespaces when there are many targets once you get beyond a certain depth

Efficient Test Sets

- Generally we have a set of test goals (to satisfy some coverage criterion)
- Want to discharge all the goals with
  - Few tests (restarts have high cost)
  - Short total length (each step in a test has a cost)
- Independent of the method of model checking, generating a separate test for each goal produces very inefficient tests
  - E.g., Lap to Lap_stop test repeats Running to Lap test
- Can "winnow" them afterward
- Or check in generation for other goals discharged fortuitously
  - So won't generate separate Running to Lap test if it's already done as part of Lap to Lap_stop test
  - But effectiveness depends on order goals are tackled

Tests Generated Using a Model Checker (again)

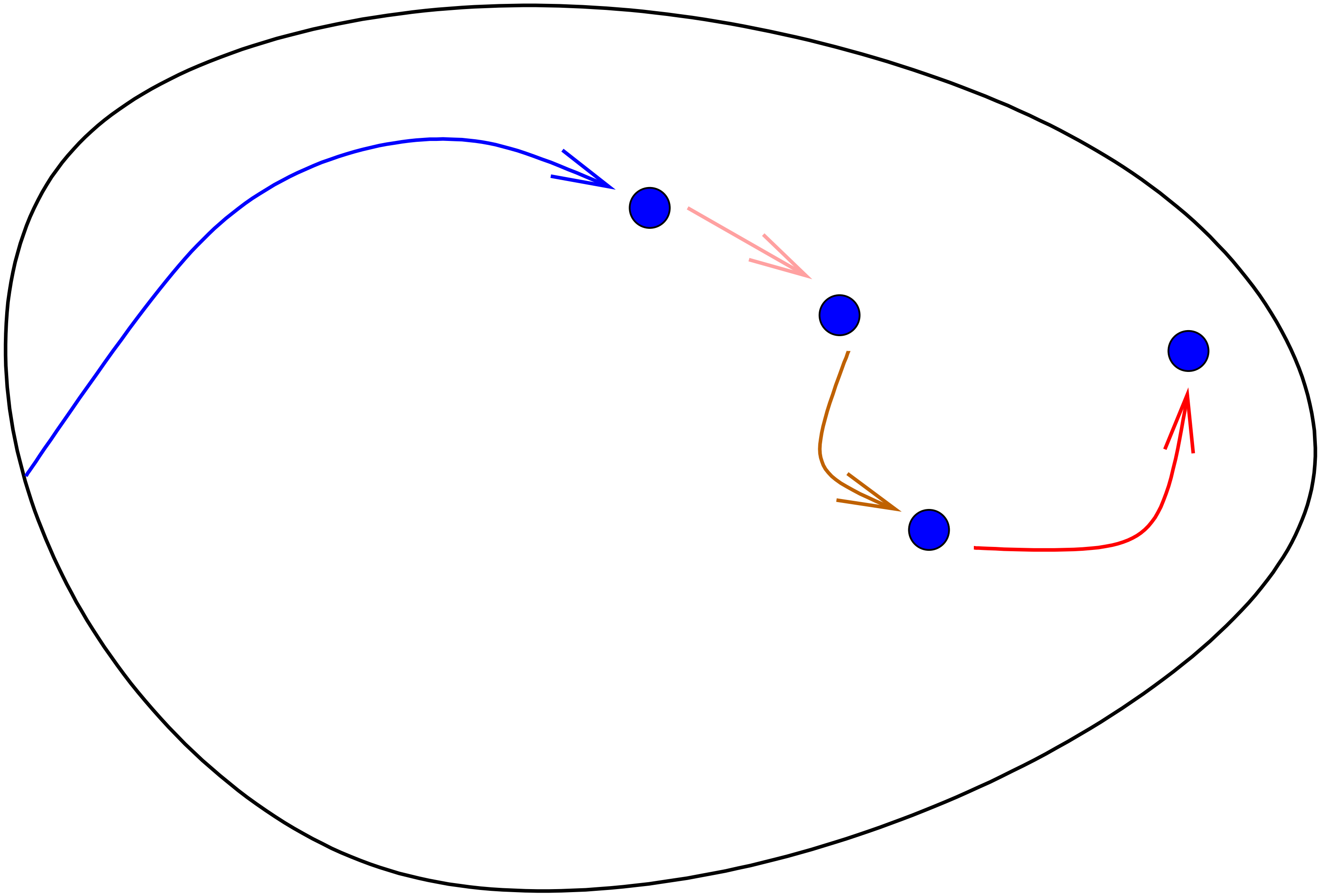


Lots of redundancy in the tests generated

Generating Efficient Test Sets

- Minimal tour-based methods: difficulty is high cost to compute feasibility of paths (or size of problem when transformed, e.g., to colored tours)
- So use a greedy approach
- Instead of starting each test from the the start state, we try to extend the test found so far
- Could get stuck if we tackle the goals in a bad order
- So, simply try to reach any outstanding goal and let the model checker find a good order
  - Can slice after each goal is discharged
  - A virtuous circle: the model will get smaller as the remaining goals get harder
- Go back to the start when unable to extend current test

An Efficient Test Set



Less redundancy, and longer tests tend to find more bugs

Scriptable Model Checkers

- But how do we persuade a model checker to do all this?
- Several modern model checkers are scriptable
- E.g., SAL is scriptable in Scheme
- For SAL, the method described is implemented in less than 100 lines of Scheme
  - Extensions use bounded model checking
    - ⋆ Parameterized incremental search depth
  - (Re)starts use either symbolic or bounded model checking
    - ⋆ Parameterized choice and search depth
  - Optional slicing after each extension or each restart
  - Optional search for non-latching trap variables
- Extending tests allows a bounded model checker to reach deep states at low cost
  - 5 searches to depth 4 much easier than 1 to depth 20

Outer Loop Of The SAL Test Generation Script

```
(define (iterative-search module goal-list
          scan prune slice innerslice bmcinit start step stop)
  (let* ((goal (list->goal goal-list module))
         (mod (if slice (sal-module/slice-for module goal) module))
         (path (if bmcinit
                   (sal-bmc/find-path-from-initial-state
                       mod goal bmcinit 'ics)
                 (sal-smc/find-path-from-initial-state mod goal))))
      (if path
          (extend-search mod goal-list path scan prune
              innerslice start step stop)
          #f)))
```

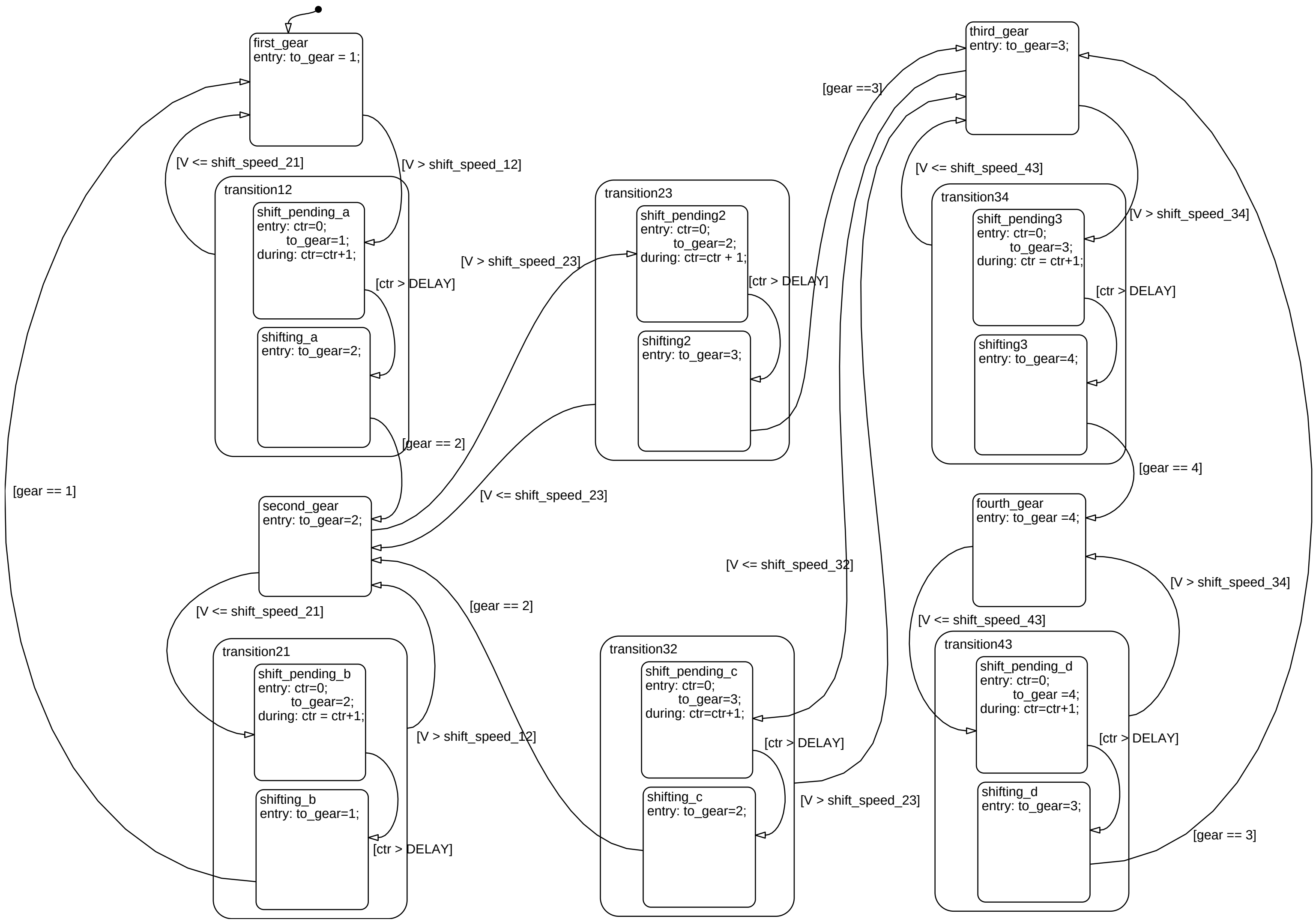
Core Of The SAL Test Generation Script

```
(define (extend-search module goal-list
         path scan prune innerslice start step stop)
   (let ((new-goal-list (if prune (goal-reduce scan goal-list path)
                            (minimal-goal-reduce scan goal-list path))))
    (cond ((null? new-goal-list) (cons '() path))
          ((> start stop) (cons new-goal-list path))
          (else
           (let* ((goal (list->goal new-goal-list module))
                  (mod (if innerslice
                           (sal-module/slice-for module goal) module))
                  (new-path
                   (let loop ((depth start))
                        (cond ((> depth stop) '())
                              ((sal-bmc/extend-path
                                 path mod goal depth 'ics))
                              (else (loop (+ depth step)))))))
             (if (pair? new-path)
                 (extend-search mod new-goal-list new-path scan
                                prune innerslice start step stop)
               (cons new-goal-list path)))))))
```

Some Experimental Results

- Generates full state and transition coverage for stopwatch with three tests in a couple of minutes
  - 12 steps for the statechart
  - 101 steps for mid right junction (actually redundant)
  - 6,001 steps for junction at bottom right
- Generates full state and transition coverage for shift scheduler from a 4-speed automatic transmission in two tests
  - Lengths 31 and 55 (total 86)
  - Standard method used 25 tests and 229 steps
  - Model has 23 states and 25 transitions

Shift Scheduler



Some Experimental Results (ctd)

- Rockwell Collins has developed a series of flight guidance system (FGS) examples for NASA
- SAL translation of largest of these kindly provided by UMN
- Model has 490 variables, 246 states, 344 transitions
- Single test case of length 39 covers all but 3 transitions
  - How can that be?

  The three outstanding goals are genuinely unreachable
- Also working on large medical device example
  - Exposes weaknesses in current Stateflow translator

  And insertion of trap variables for MC/DC tests

Optimizations (TBD)

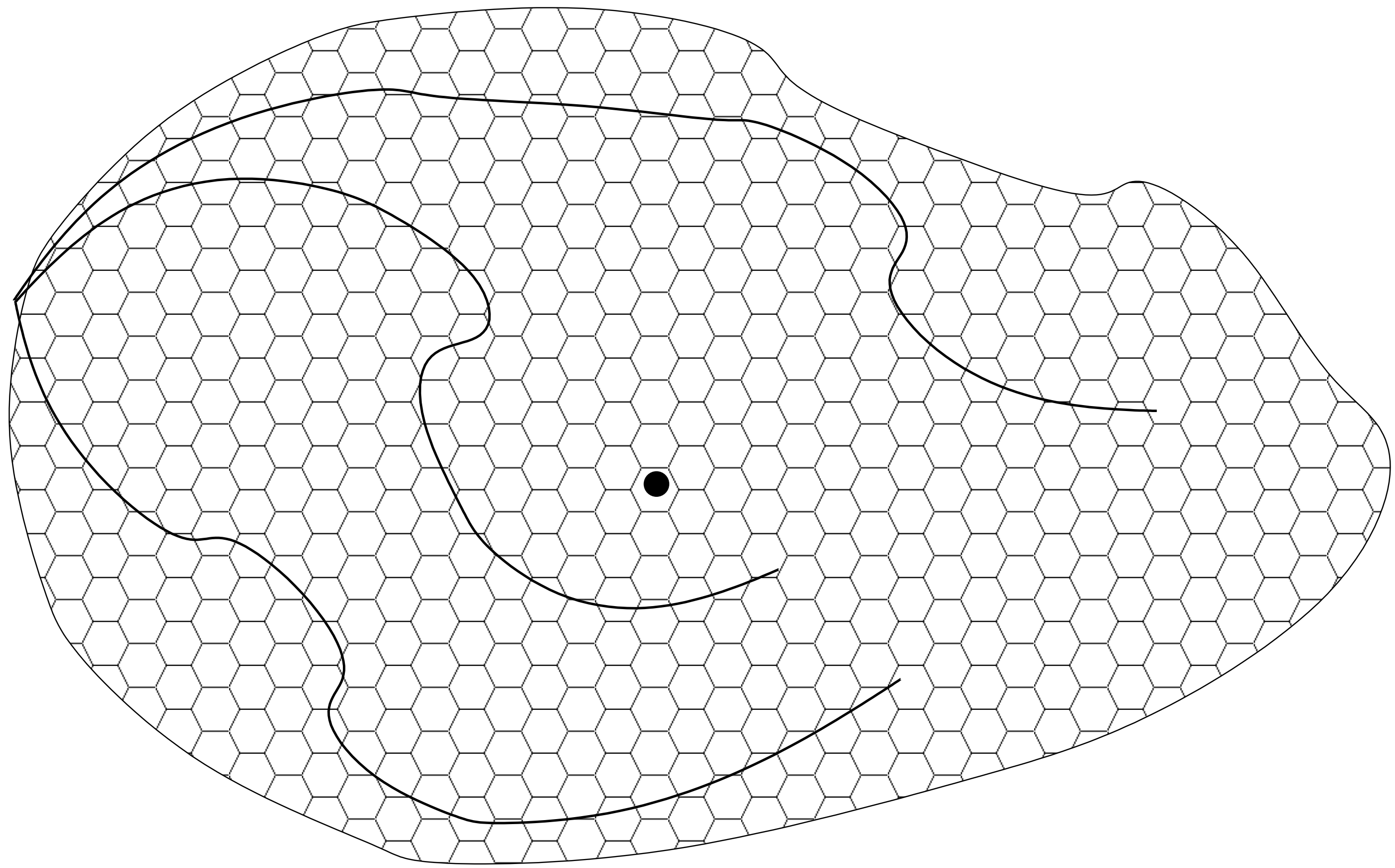
- Symbolic model checking
  - Precompute the reachable states (as a BDD)
  - Tests can then be "read off"
  - Infeasible for big systems (unless sliced)
- Bounded model checking
  - Precompute the k-fold composition of the transition relation
  - May also be able to learn hints for the SAT solver

Embellishments

- Method starts new test when current test cannot be extended
- Would do better to try to construct an extension from some intermediate point of some previous test
- Can search from all of these in parallel
  - Just initialize the search to the disjunction of all states encountered in previously generated tests
  - Expensive expression for bounded model checker but may have a compact BDD for symbolic model checker
- Have the code for this but haven't integrated it yet
- In general, can initialize the search with any states you already know how to reach
  - E.g., by random testing
  - Or previous campaign of functional testing

Some Commercial Tools Do Similar Things

- Ketchum (aka. FormalVera and Magellan) from Synopsys
- Reactis from Reactive Systems Inc (RSI)



- Related: 0-in, DART

Test Coverage

- Need criteria to suggest when we have tested enough
- Vast literature on this topic
- Many criteria are based on structural coverage of the program
- E.g., DO178B Level A, MISRA require MC/DC coverage
    - Not allowed to generate tests from the program structure
    - But generating tests from the structure of the model is ok and likely to achieve high coverage on the program
- Plausible methodology uses structural generation from model to pick up the uncovered goals following normal testing

So Are The Test Sets Any Good?

- Heimdahl et al. found (in a limited experiment using the Rockwell FGS examples) that tests generated by traditional model checking were poor at detecting seeded errors (random testing did better)
- They conjectured this was because the tests were so short (average length about 1.25)
- We hypothesize that long tests found by our method will be more effective
  - In process of checking this on UMN example
- Heimdahl also observed model checker often finds "sneaky" ways to achieve goals
- Good coverage criteria may not be so good for generation
- An invitation to invent new criteria for generation

Generating Good Test Sets

- Use different (better) structural coverage criteria
- Our method is independent of criteria chosen
    - We target trap variables
    - How you set them is up to you
- Require paths to satisfy some test purpose
- Derive tests from requirements and/or domain boundaries
- Possibly combined with coverage ideas

Test Purposes

- Constraints on the tests to be generated—for example
  - At least 7 steps
  - Keep x in $[-12..7]$ and different to y
  - No more than two `START` events in succession
- Specify test purpose (TP) as a state machine—for example
  - In Stateflow (engineers stay in familiar notation)
  - In system language of model checker
  - By automatic translation from property language

  Raise OK variable while input sequence satisfies the purpose
- Synchronously compose SUT and TP
  - I.e., TP is a synchronous observer
- Perform test generation as before but target conjunction of OK with trap variables

Requirement-Driven Tests

- Specify requirements by synchronous observers—for example
  - In Stateflow (engineers stay in familiar notation)
  - By automatic translation from property language
- Then target structural coverage in the observer
- Or cross product of observer and SUT
- Related idea in Motorola VeriState

Boundary Value Tests

- Currently, we use the symbolic and bounded model checkers of SAL
- The infinite bounded model checker would be ideal, but it currently does not generate concrete counterexamples (because ICS does not do full model generation)
- Next versions of ICS/SAL-inf-bmc will do counterexamples, and it will be possible to choose maximum, minimum, middle values for variables subject to arithmetic constraints
- Generate tests as before, but instantiate arithmetic variables to max, min, middle values

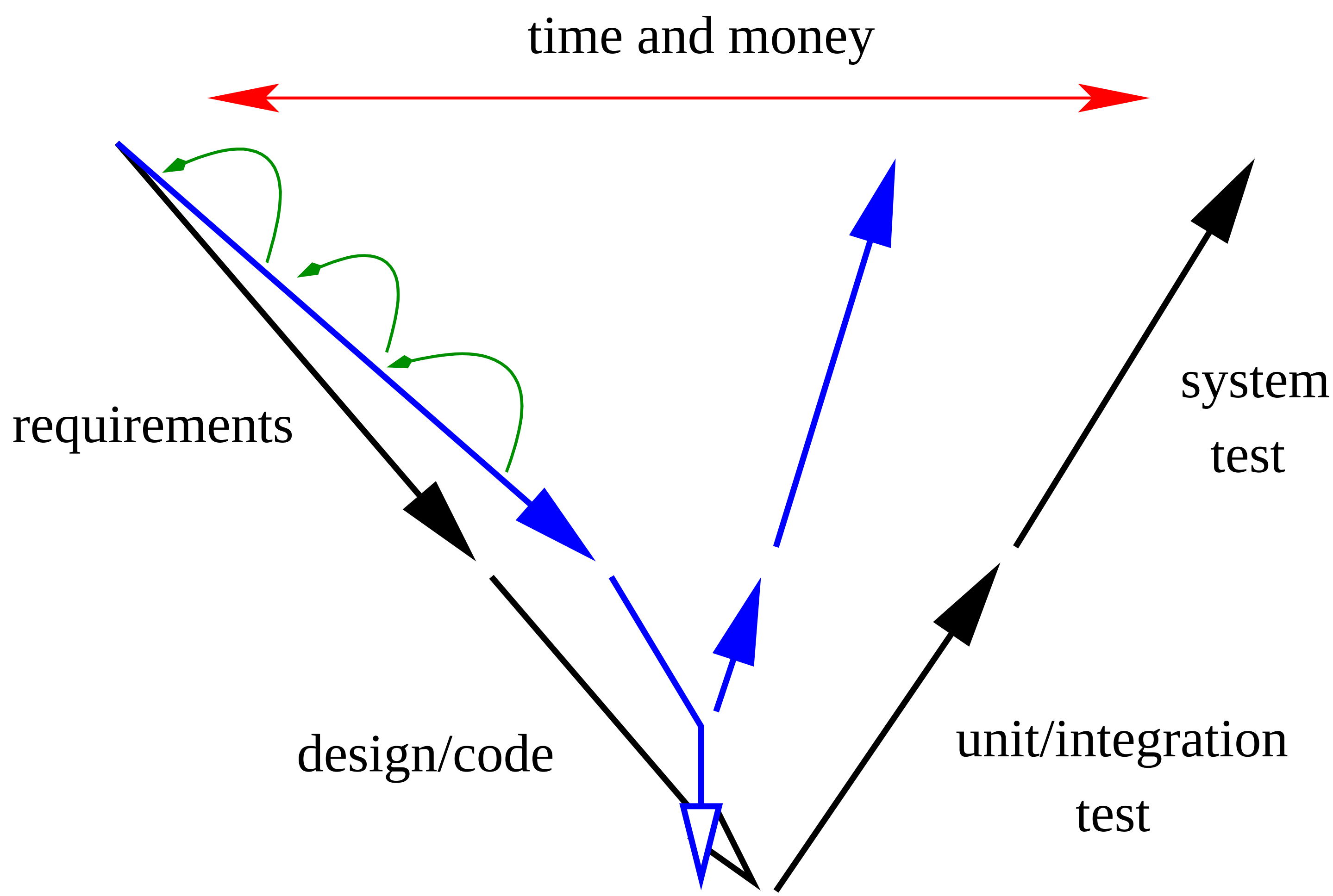
Higher Level Tests

- Higher-level tests are more challenging
- Integration tests: similar to compliance testing, well studied in telecom area
- System tests and hardware (or simulator) in the loop tests
  - Typically want to drive system to some interesting state
  - But composition may be nondeterministic
  - And we may not have control of all components
    - E.g., hardware network may or may not drop packets
- Test generation problem becomes one of controller synthesis
- This also can be solved by the technology of model checking
  - Witness model checker of SAL is intended for this

Still Higher Level Tests

- Can have hardware devices in the loop that are not discrete systems
  - E.g., engine and gearbox with their external loads
  - More generally, the plant and its environment
- These are described by continuous variables and differential equations (in Simulink)
  - Sometimes combined with discrete elements
  - I.e., hybrid systems
- Controller synthesis for hybrid systems is very hard
- Hybrid abstraction (in Hybrid SAL) reduces hybrid systems to discrete conservative approximations
- Can then do controller synthesis via model checking as before

Eventual Goal: Tightened Vee Diagram



Summary: Automated Test Generation

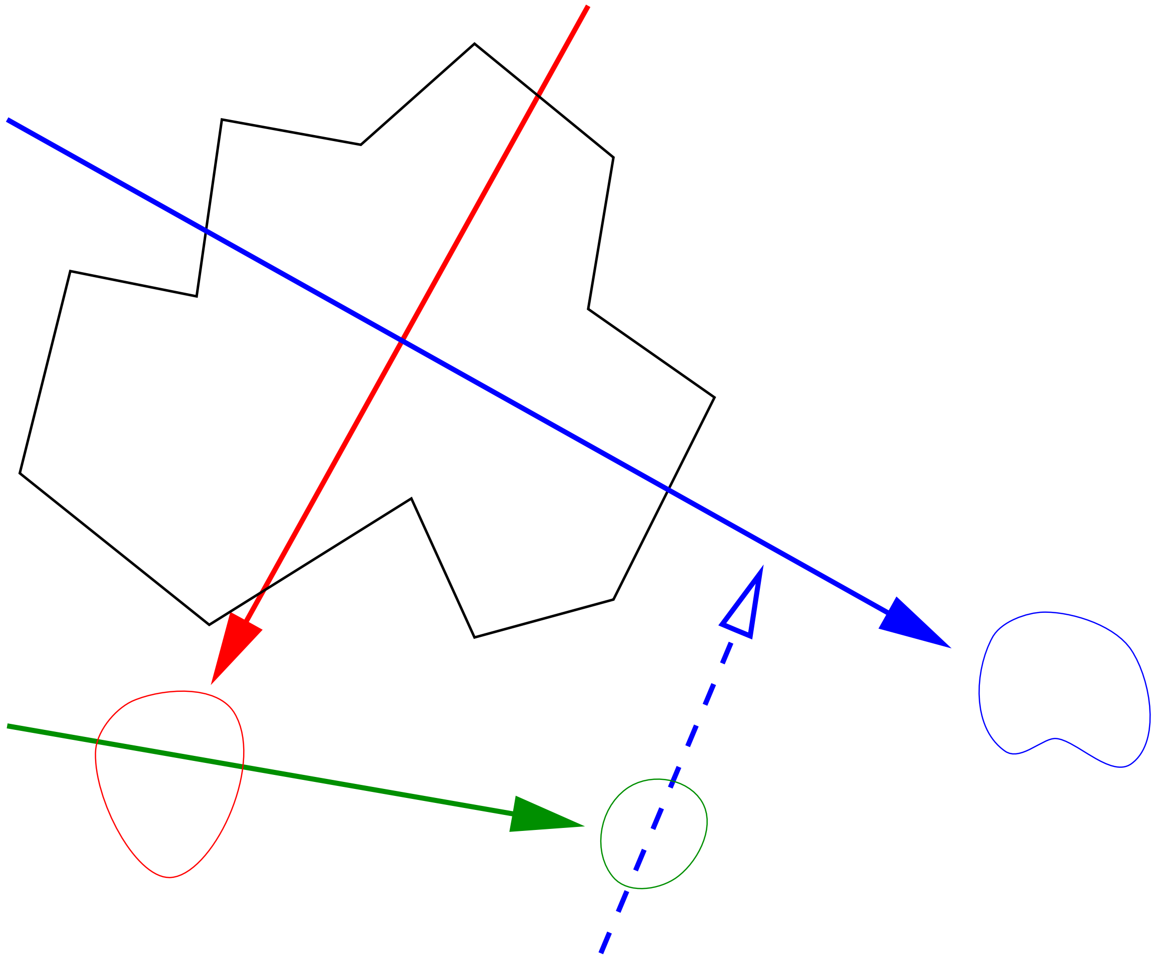
- Simple ideas that significantly improves the efficiency of test sets generated by a model checker
  - Extend current test to new goals
  - Search to any uncovered goal
  - Slice model as goals are covered
  - Further improvement: (re)start from any visited state
- Simple implementation in scriptable model checker (SAL)
- Generation is efficient also
- Independent of test criteria: just set the trap variables
- Many opportunities for further research in test generation
- The paper, SAL Scheme scripts, and examples, are available from `http://www.csl.sri.com/users/rushby/abstracts/sefm04`

Summary: Formal Methods

- It is now fairly routine to have model checkers as backends to theorem provers (e.g., PVS), or proof assistants as front ends to model checkers (e.g., Cadence SMV)
- But we envisage a larger collection of symbolic computational procedures
  - Decision procedures, abstractors, invariant generators, model checkers, static analyzers, test generators, ITPs
- Interacting through a scriptable tool bus
- The bus manages symbolic and concrete artifacts
  - Test cases, abstractions, theorems, invariants

  Over which it performs evidence management
- Focus shifts from verification to symbolic analysis
  - Iterative application of analysis to artifacts to yield new artifacts, insight and evidence

Integrated, Iterated Analysis



Summary: Invisible Formal Methods

- Model-based design methods are a (once-in-a-lifetime?) opportunity to get at formal artifacts early enough in the lifecycle to apply useful analysis within the design loop
- And formal analysis tools are now powerful enough to do useful things without interactive guidance
- The challenge is to find good ways to put these two together
  - Deliver analyses of interest and value to the developers
  - Or certifiers
  - But must fit in their flow

  So can shift from technology push to pull
- Invisible (or disappearing) formal methods is our slogan for this approach: apply formal automation to familiar practices

Summary: Technology

- The technology of automated deduction (and the speed of commodity workstations) has reached a point where we can solve problems of real interest and value to developers of embedded systems
- Embodied in our systems

  SAL.csl.sri.com: symbolic analysis laboratory

  - Provides state-of-the-art model checking toolkit (explicit, symbolic, witness, bounded, infinite-bounded)
  - Tool bus (soon)

  PVS.csl.cri.com: comprehensive interactive theorem prover

  ICS.csl.sri.com: embedded decision procedures
- And in numerous papers accessible from `http://fm.csl.sri.com`, including our Roadmap

Vision: 21st Century Software Engineering

- Symbolic analysis could become the dominant method in systems development and assurance
- And programming could be supplanted by construction of logical models
- And deduction will do the hard work

A Bigger Vision: 21st Century Mathematics

- The industrialization of the 19th and 20th century was based on continuous mathematics
    - And its automation
- That of the 21st century will be based on symbolic mathematics
    - Whose automation is now feasible

  Allows analysis of systems too complex and numerically too indeterminate for classical methods
- Example: symbolic systems biology
    - Knockouts in E.Coli (SRI; Maude)
    - Cell differentiation in C.Elegans (Weizmann; Play-in/out)
    - Delta-Notch signaling (SRI, Stanford; Hybrid SAL)
    - Sporolation in B.Subtilis (SRI; Hybrid SAL)