New Directions in V&V
Evidence, Arguments, and Automation

John Rushby

Computer Science Laboratory
SRI International
Menlo Park, California, USA

V&V for Fault Management

Ideally, we'd like to understand, consider, examine, test

- all possible behaviors

Which raises some interesting issues

- Define all possible
- However you define it, that's a lot of behaviors
- How can we handle that many?
- Can we do it subsystem by subsystem?
- Can we start the work early?

We need a framework and some technology and a methodology

Existing Frameworks for V&V

- V&V and the larger processes of certification/approval provide assurance that deploying a given system does not pose an unacceptable risk of failure or adverse consequences
- Current methods explicitly depend on
  - Standards, regulations, process
  - Rigorous examination of the whole, finished system

  And implicitly on
  - Conservative practices
  - Safety culture
- All of these are changing

The Standards-Based Approach to Software Assurance

- E.g., airborne s/w (DO-178B), security (Common Criteria)
- Developer follows a prescribed method (or processes)
  - Delivers prescribed outputs
    - ⋆ e.g., documented requirements, designs, analyses, tests and outcomes; traceability among these
- Works well in fields that are stable or change slowly
  - Can institutionalize lessons learned, best practice
    - ⋆ e.g. evolution of DO-178 from A to B to C
- But less suitable with novel problems, solutions, methods

A Recent Incident

- Fuel emergency on Airbus A340-642, G-VATL, on 8 February 2005 (AAIB SPECIAL Bulletin S1/2005)
- Toward the end of a flight from Hong Kong to London: two engines flamed out, crew found certain tanks were critically low on fuel, declared an emergency, landed at Amsterdam
- Two Fuel Control Monitoring Computers (FCMCs) on this type of airplane; they cross-compare and the "healthiest" one drives the outputs to the data bus
- Both FCMCs had fault indications, and one of them was unable to drive the data bus
- Unfortunately, this one was judged the healthiest and was given control of the bus even though it could not exercise it
- Further backup systems were not invoked because the FCMCs indicated they were not both failed

Implicit and Explicit Factors

- See also ATSB incident report for in-flight upset of Boeing 777, 9M-MRG (Malaysian Airlines, near Perth Australia)
- How could gross errors like these pass through rigorous assurance standards?
- Maybe effectiveness of current methods depends on implicit factors such as safety culture, conservatism
- Current business/contracting models and mission ambitions are leading to a loss of these
  - Outsourcing, COTS, complacency, innovation, complexity
- Surely, a credible certification regime should be effective on the basis of its explicit practices
- How else can we cope with the changes and challenges ahead?

Standards and Goal-Based Assurance

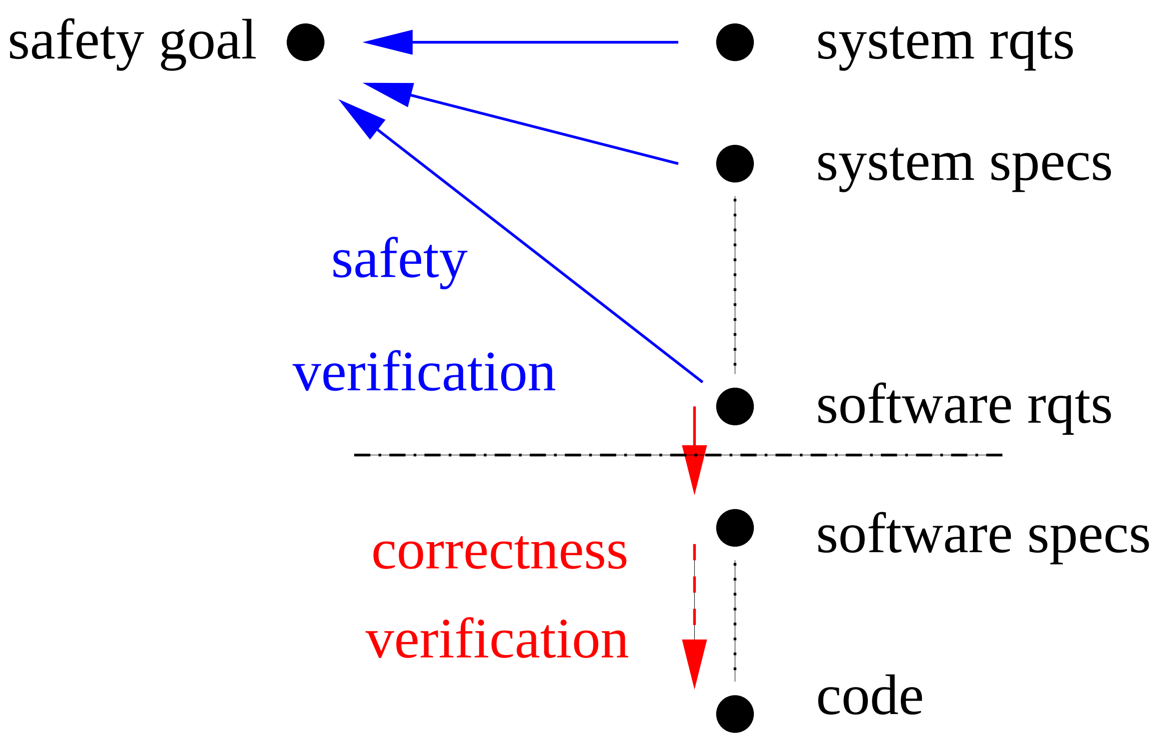
- All assurance is intellectually based on **arguments** that purport to justify certain **claims**, based on documented **evidence**
- Standards usually define only the evidence to be produced
- The claims and arguments are implicit
- Hence, hard to tell whether given evidence meets the intent
- E.g., is MC/DC coverage evidence for good testing or good requirements?
- Recently, goal-based assurance methods have been gaining favor: these make the elements explicit

The Goal-Based Approach to Software Assurance

- E.g., UK air traffic management (CAP670 SW01), UK defence (DefStan 00-56), growing interest elsewhere
- Developer provides an assurance case
  - Whose outline form may be specified by standards or regulation (e.g., 00-56)
  - Makes an explicit set of goals or claims
  - Provides supporting evidence for the claims
  - And arguments that link the evidence to the claims
    - ⋆ Make clear the underlying assumptions and judgments
    - ⋆ Should allow different viewpoints and levels of detail
- Can be specialized to safety, security, dependability cases
- The case is evaluated by independent assessors
- Key point: explicit claims, evidence, argument

Assurance Cases Allow Customization

- Standards such as DO-178B focus on correctness
- i.e., on verification more than validation

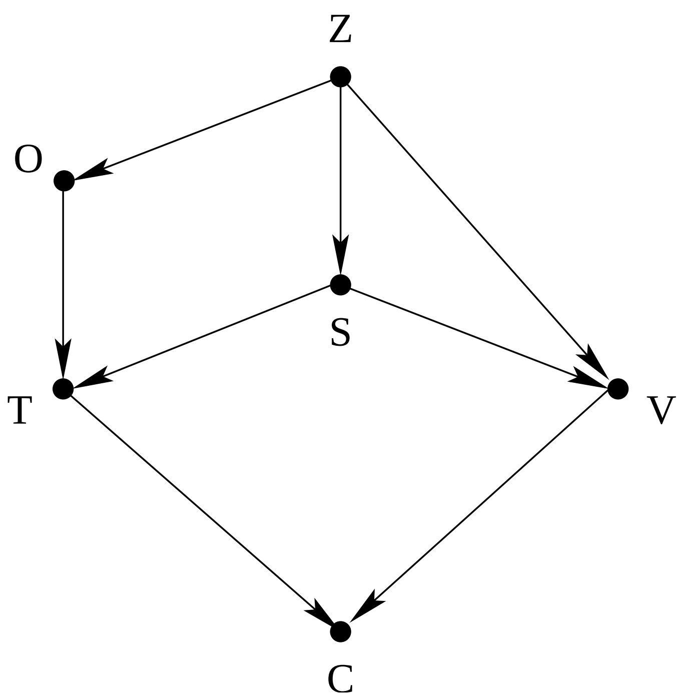


- Whereas assurance cases liberate us to customize our V&V

System-Focused Claims

- Goal-based assurance cases are driven by risk assessment
- Focus on hazards, risks, and their mitigations
- At the system level
- Flow down into subsystems and allow prioritization
- Multi-legged cases allow evidence for testing, say, to be combined with analysis in a rational way using Bayesian Belief Nets (BBNs)

A BBN Example



Z: System Specification

O: Test Oracle

S: System's true quality

T: Tests

V: Analysis

C: V&V decision

Example joint probability table: successful test outcome

Correct System		Incorrect System	
Correct Oracle	Bad Oracle	Correct Oracle	Bad Oracle
100%	50%	5%	30%

Technology and Automation

- Goal-based assurance cases give us a framework to approach V&V in a customized but rational way, focusing on system-level hazards
- Traditional methods for assurance at the systems level, such as hazard analysis (HA), FMEA, FTA, HAZOP
- Are really abstracted (i.e., approximate) ways to do reachability analysis
    - Enumeration of all the states that a system can get into through interaction with its environment
- In other words, they are ways of exploring all possible behaviors
- How about if we could do this for more detailed levels of design?

Informal Reachability Analysis

- Given a system model made up of interacting state machines
- i.e., the software design, hardware components
  - And the environment
  - Which can inject faults (think of it as the test harness)
- Work forward from the initial states to see if you can reach a state where something bad happens (HA)
- Or work back from the bad states to see if you can reach an initial state (FTA)
- Made feasible to do by hand by focusing on only certain transitions (FMEA)
- And by using abstracted models (HAZOP)
- But suppose we could automate it?

Automated Reachability Analysis

- We need "machinable" models of the system and its environment; not PowerPoint pictures, not code
- E.g., Statecharts, UML, AADL, Simulink/Stateflow
- If we "downscale" these to finite state
  - E.g., discretize continuous values
- Then we can do brute-force reachability analysis
- By running or simulating the system, backtracking to take alternate paths, and remembering where we have been
- This is what an explicit state model checker (e.g., Spin) does
- Can handle tens of millions of reachable states
- Gives counterexample when an error found
- Errors defined by observer models, or property language

Formal Reachability Analysis

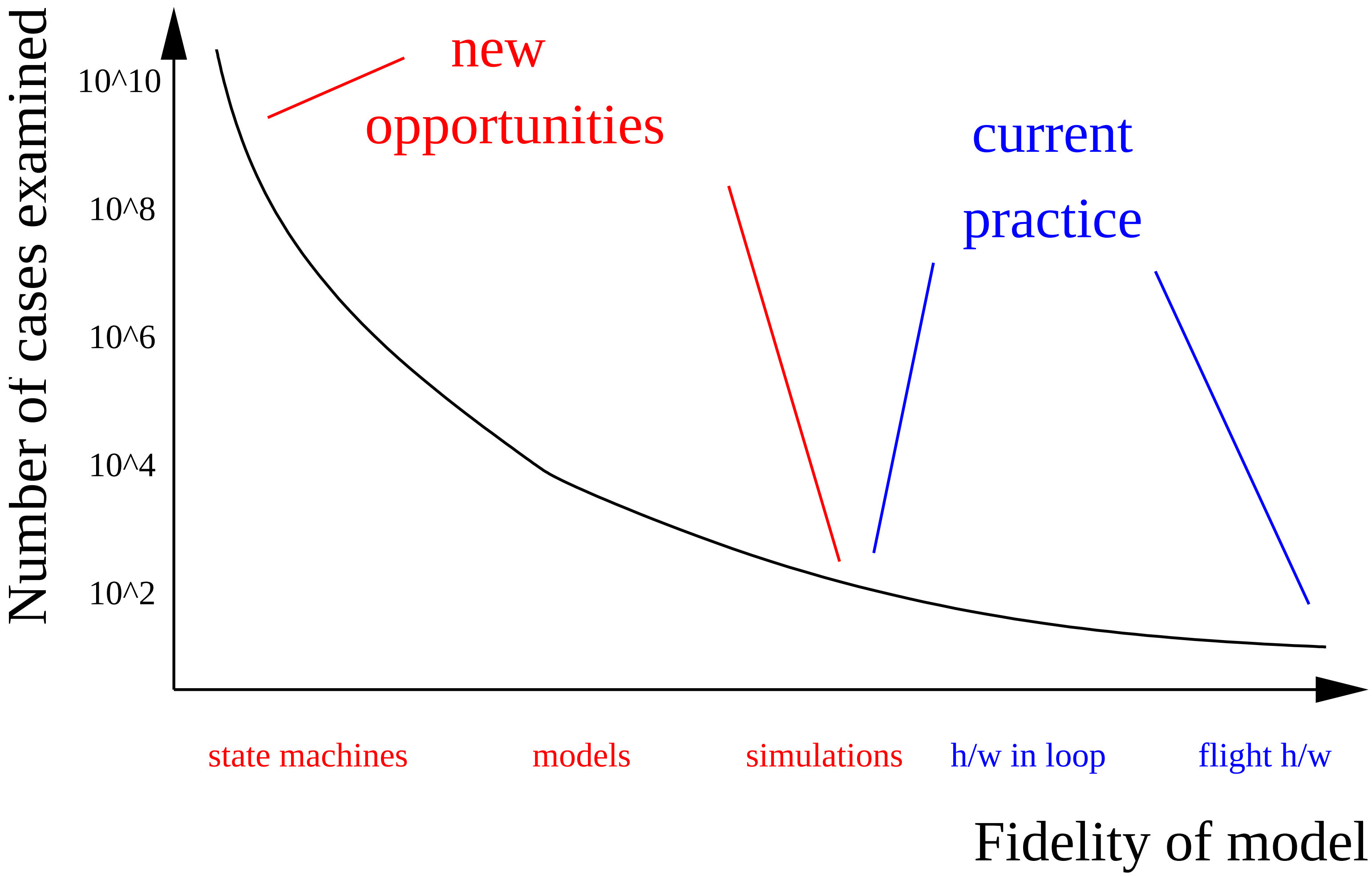
- Ten million states is only 23 or 24 state bits
- Symbolic methods of reachability analysis can often handle bigger systems. . . trillions of states, even infinite
- By representing states as formulas rather than explicit values
  - e.g., $x < y$ represents an infinite number of explicit states: (0,1), (0,2), ... (1,2), (1,3)...
- Symbolic model checkers (e,g., nuSMV, SAL)
  - Use Binary Decision Diagrams (BDDs)
- Bounded model checkers (e,g., nuSMV, SAL)
  - Use Boolean satisfiability (SAT) solvers
- Infinite bounded model checkers (e,g., SAL)
  - Use solvers for satisfiability modulo theories (SMT)
- BDDs, SAT, SMT solvers are commodities

Reachability Analysis for Fault Management

- Construct state machine models for components, environment, the FM algorithms (e.g., monitors and responses) in some modeling notation
- Connect a model checker to the modeling tool set
  - E.g., Mathworks' own Design Verifier for Simulink/Stateflow
  - Or build your own—as Rockwell has
- And you will absolutely find large numbers of issues such as those described for New Horizons fault management, or Space Station architecture with negligible effort
- Find vastly more problems by examining all the behaviors of a simplified model than by testing some of the behaviors of the real thing

A Spectrum of V&V Activities

A wealth of opportunities to the left; can apply them early, too



Reachability Analysis for Fault Management V&V

- V&V is more than debugging
- Want to make strong inference when the model checker no longer finds bugs
- Requires judgement in modeling
    - Often less is more: constraints rather than details
- And more sophisticated automation (research topics)
    - K-induction rather than bounded model checking
    - Counterexample-guided abstraction refinement (CEGAR)
    - Hybrid systems (state machines plus differential equations)
- And we need ways to keep different models, simulations, real system in sync

Test Automation for Fault Management V&V

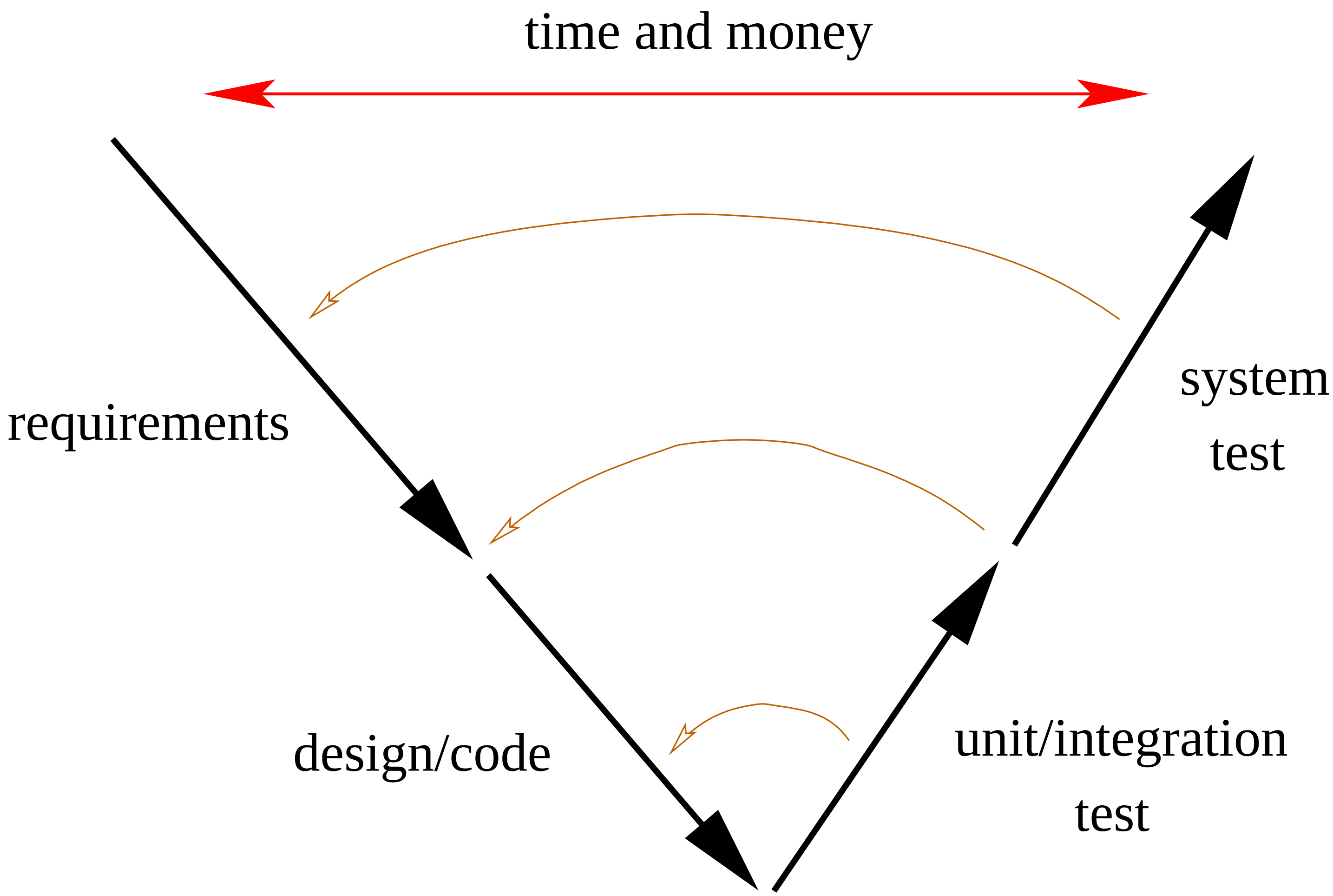
- The counterexamples from model checkers can be used to generate test cases to run on the implementation
  - Tests can target model coverage, corner cases, specific kinds of scenarios: focus shifts from constructing tests to specifying test objectives
- Unit tests are pretty easy to generate automatically
- Integration tests are more challenging
  - Depends how much control you have of other components
- Hardware in the loop is more difficult still (research)
  - Some of the models are hybrid systems
- Automation can be used to extend random tests into corners
  - There are very potent mixed concrete symbolic (concolic) methods

From Analysis to Synthesis

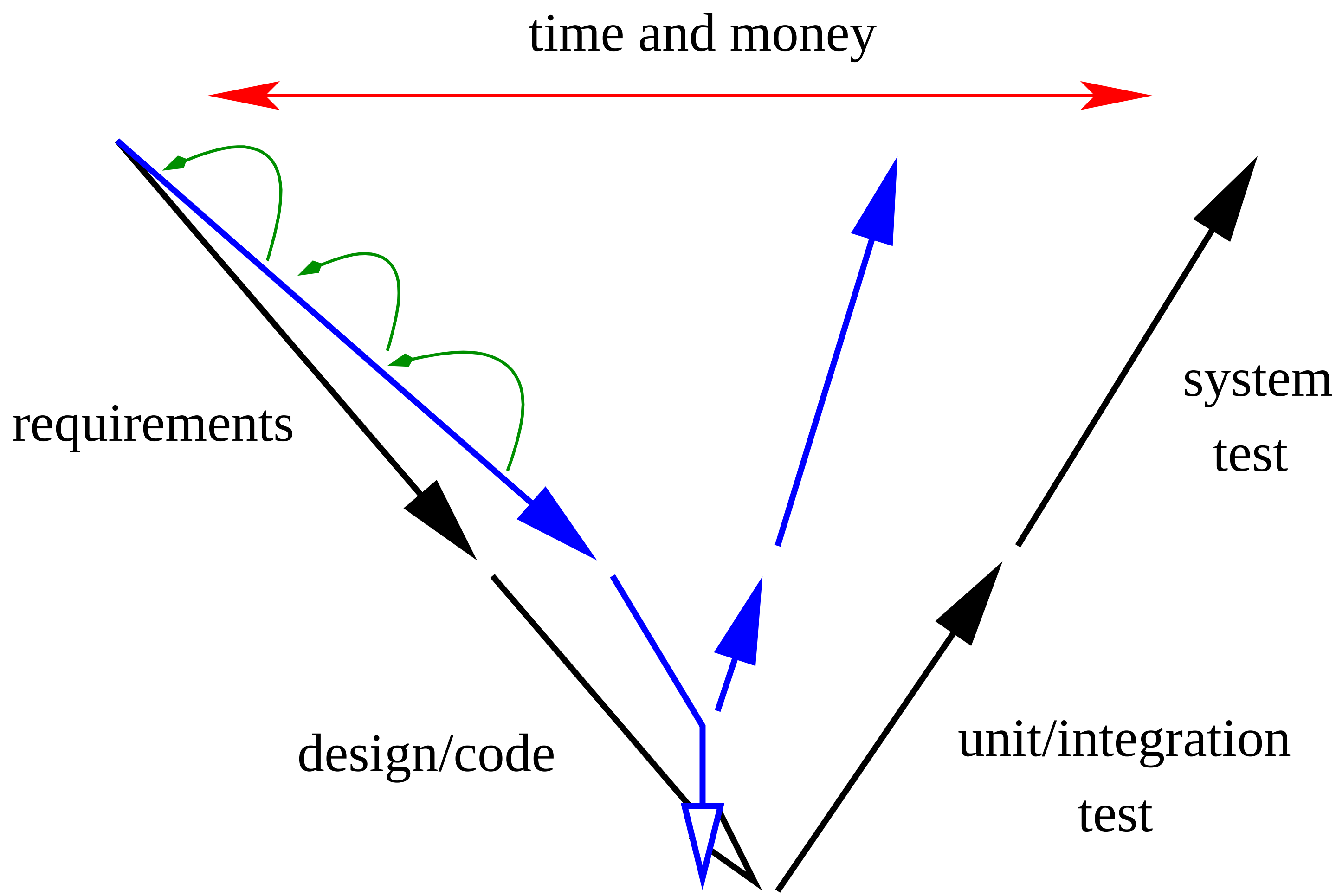
- The same reachability methods we use to analyze monitor-response fault management rules
- Could be used to synthesize the rules
  - Supervisory controller synthesis (Ramadge and Wonham)
  - Set up as a game between fault management and the environment
  - Use reachability analysis to synthesize rules so that from any state, no move by the environment can force us into a losing state
- Could be used statically on the ground
- Or dynamically onboard the spacecraft (next talk)

Overall V&V Process

Traditional Vee Diagram (Much Simplified)



Vee Diagram Tightened with Formal Analysis



Example: Rockwell-Collins

Systems and Subsystems

- The FAA certifies airplanes, engines and propellers
- Components and subsystems are certified only as part of an airplane or engine
- That's because it's the interactions that matter and it's not known how to provide assurance for these compositionally
- But modern engineering and business practices use massive subcontracting and component-based development that provide little visibility into subsystem designs
- So we are forced to contemplate compositional and incremental approaches to assurance and V&V
- Manifestation of noncompositionality in FM is the need to run tests for days or weeks to get into interesting states

Compositional and Incremental Assurance

- Compositional assurance means deriving the assurance case for the system from those of its subsystems
- Without going into all the subsystem details
- It is difficult because
  - The assurance case may not decompose along architectural lines
- Spacecraft have inherent subsystem coupling (through the plant)
- But we should surely eliminate unnecessary coupling
  - Computer to computer and bus communication issues
  - Partitioning
  - Information hiding interfaces

Computer to Computer and Bus Communications

- It's easy to mess these up
  - Bad fault modes (babbling—e.g., Clementine)
  - Timing (e.g., recent spysat?)
- It is known how to do it right (e.g., TTA, SPIDER)
- These are more than just buses—they are frameworks for integration
- That is, they facilitate compositional design

Integration Framework Anecdotes

Powertrain integration: car engines from one plant, gearboxes from another

- Typically months of work to get them to work together
- A few hours using TTA

Multi-channel FADEC integration: get single channel working, then add second channel

- Typically months of work to get both channels cooperating
- A few hours using TTA

Assurance benefits beyond those in integration

Partitioning

- Subsystems may share processor resources
- Don't want a fault in one subsystem to wreck others
    - By messing with its state, timing, etc.
- Integrated modular avionics (IMA) for aircraft use Partitioning RTOSs
- Similar RTOSs (but with higher assurance, called separation kernels) used in embedded applications for high security
- Again, best seen as integration frameworks rather than just protection mechanisms

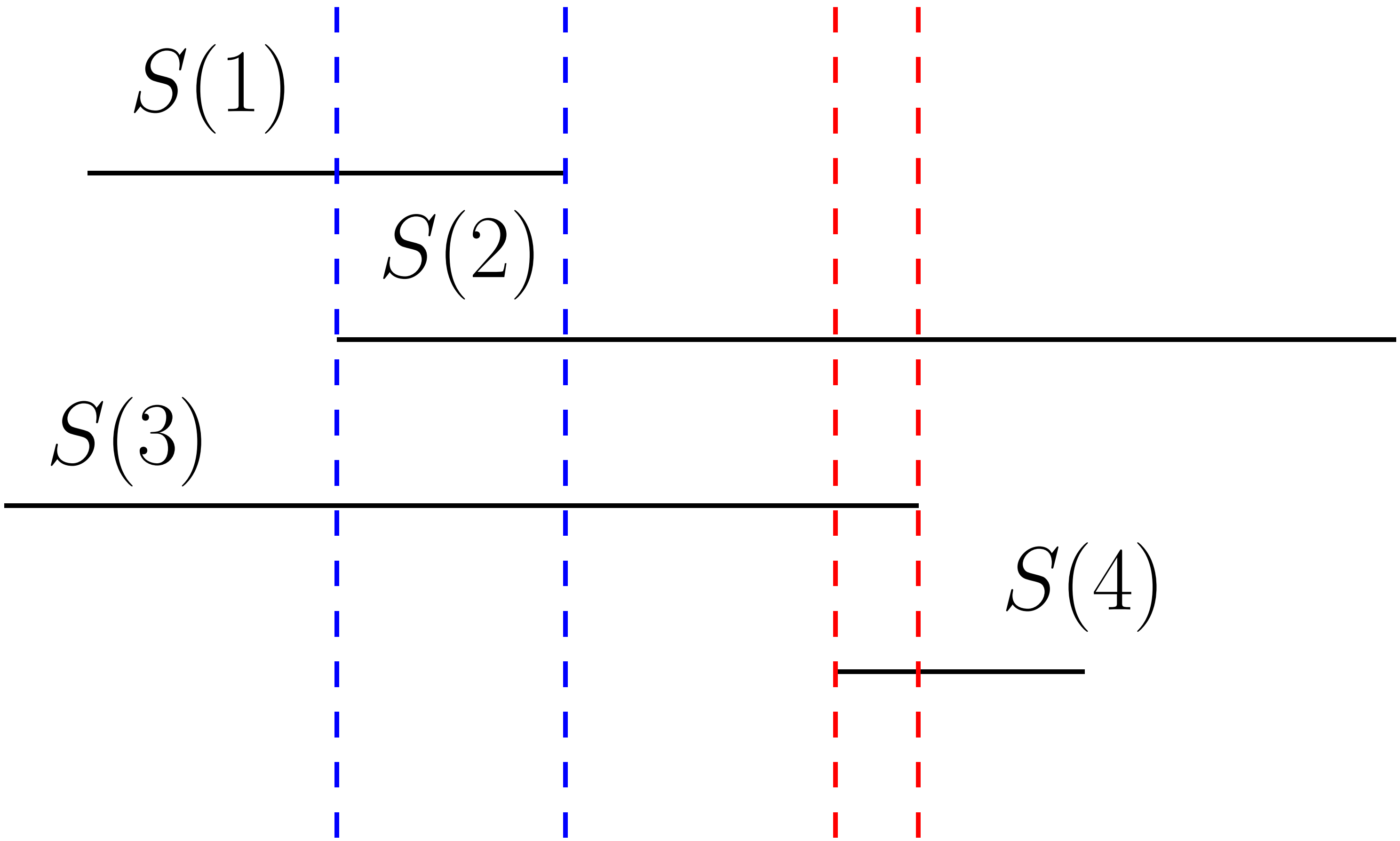
Information Hiding Interfaces

- Partitioning buses and RTOSs prevent propagation of faults
- And have the side effect of facilitating compositional design
- By eliminating unintended interactions and coupling
- We need to do this throughout the design
  - "Complexity containment regions"
  - That's what interfaces are
  - And architecture at a higher level

Information Hiding Interfaces: Sensor Example

- Typically, send raw sensor samples with timestamp
- To integrate multiple samples, need to know the fault-status and detailed behavior of each sensor
- Use complex variants of mid-value select to mask faults
- Instead, we could use intelligent sensor (knows its own status, does local diagnosis)
- Sends sample as an interval: true value guaranteed to be somewhere inside (if nonfaulty)
  - Narrow interval when healthy, good sample; wider if not
- With a "use by" date
- Known how to combine intervals, even when some are faulty
- System does not need to know subsystem details

True Value In Overlap Of Nonfaulty Intervals



Compositional V&V

- Reachability analysis with a model checker examines whether interacting components satisfy some requirement
  - e.g, device, control, environment $\models$ requirement
- We can try to find the weakest model D for the device that still does the job (might have to adjust control)
  - i.e., D, control', environment $\models$ requirement
- Then, later, show that the real device satisfies D
  - i.e., device $\models$ D
- So reachability tools can help develop interfaces that promote compositional assurance

Summary

- If we want to improve cost and effectiveness of V&V, we need a framework to help us rethink it
  - Goal based assurance cases are a promising framework
  - Explicit claims, evidence, argument
- Model-based design opens the door to reachability analysis
  - aka. model checking, formal methods
  - This is automated, can be done early, examines vast numbers of behaviors including interactions
  - Preserves the valuable high-fidelity testbed
- Strong interfaces promote compositional assurance
  - Reachability analysis can help develop these
- Autonomy is surely the way of the future; let's get the V&V right (reliable, early, affordable; enabler, not impediment)