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Uses Runtime Verification Workshop, Budapest, March 2008
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Formal Methods and Certification

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Overview

- Standards- vs. goal-based safety cases
- Formal methods in goal-based safety cases
- Multi-legged safety cases
- Compositional approaches to system properties

Frameworks for Certification

- Certification provides assurance that deploying a given system does not pose an unacceptable risk of adverse consequences

- Current methods explicitly depend on
    - Standards and regulations
    - 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 Certification

- E.g., airborne s/w (DO-178B), security (Common Criteria)
- Applicant 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 certification methods depends on implicit factors such as safety culture, conservatism
- Current business models are leading to a loss of these
  - Outsourcing, COTS, complacency, innovation
- Surely, a credible certification regime should be effective on the basis of its explicit practices
- How else can we cope with challenges of the future?

Standards and Goal-Based Assurance

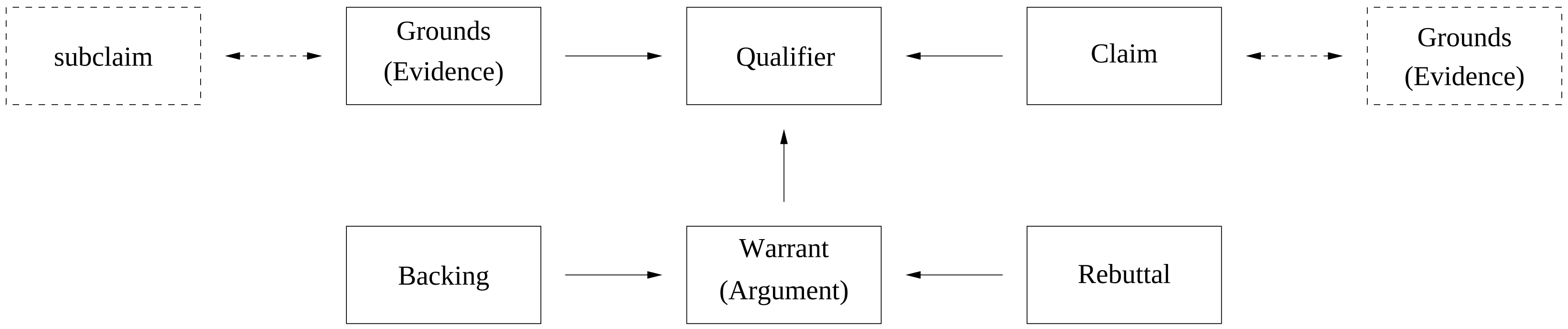
- All assurance is based on **arguments** that purport to justify certain **claims**, based on documented **evidence**
- Standards usually define only the evidence to be produced
- The claims and arguments are implicit
- Hence, hard to tell whether given evidence meets the intent
- E.g., is MC/DC coverage 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 Certification

- E.g., UK air traffic management (CAP670 SW01), UK defence (DefStan 00-56), growing interest elsewhere
- Applicant develops a safety 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
- Generalized to security, dependability, assurance cases
- The case is evaluated by independent assessors
  - Explicit claims, evidence, argument

Toulmin's Model of Argument

- Certification is ultimately a judgement
- So classical formal reasoning may not be entirely appropriate
- Advocates of assurance cases often look to Toulmin's model of argument
- Toulmin stresses justification rather than inference



- Supported in safety cases by notations (e g., GSN), tools (e.g., ASCE); also tools for intelligence agencies

Toulmin’s Model of Argument (ctd.)

Claim: This is the expressed opinion or conclusion that the arguer wants accepted by the audience

Grounds: This is the evidence or data for the claim

Qualifier: An adverbial phrase indicating the strength of the claim (e.g., certainly, presumably, probably, possibly, etc.)

Warrant: The reasoning or argument (e.g., rules or principles) for connecting the data to the claim

Backing: Further facts or reasoning used to support or legitimate the warrant

Rebuttal: Circumstances or conditions that cast doubt on the argument; it represents any reservations or “exceptions to the rule” that undermine the reasoning expressed in the warrant or the backing for it

Reconciling Toulmin's Approach with Formal Methods

- We do formal methods
- So the qualifier is always $\vdash$ or $\models$
- How can we reconcile these with the reasonable doubts manifested in Toulmin's approach?
- One idea
  - Implicit in the work of Jackson and Zave, Goodenough and Weinstock, and others

  Is to put them in the assumptions $A_1, \ldots, A_n$ under which the system S satisfies the requirements R

$$A_1, \ldots, A_n, S \vdash R$$

- Then do safety analysis on each assumption A_i
  - e.g., FMEA, HAZOP, FTA, other HA techniques

Other Proof Hazards

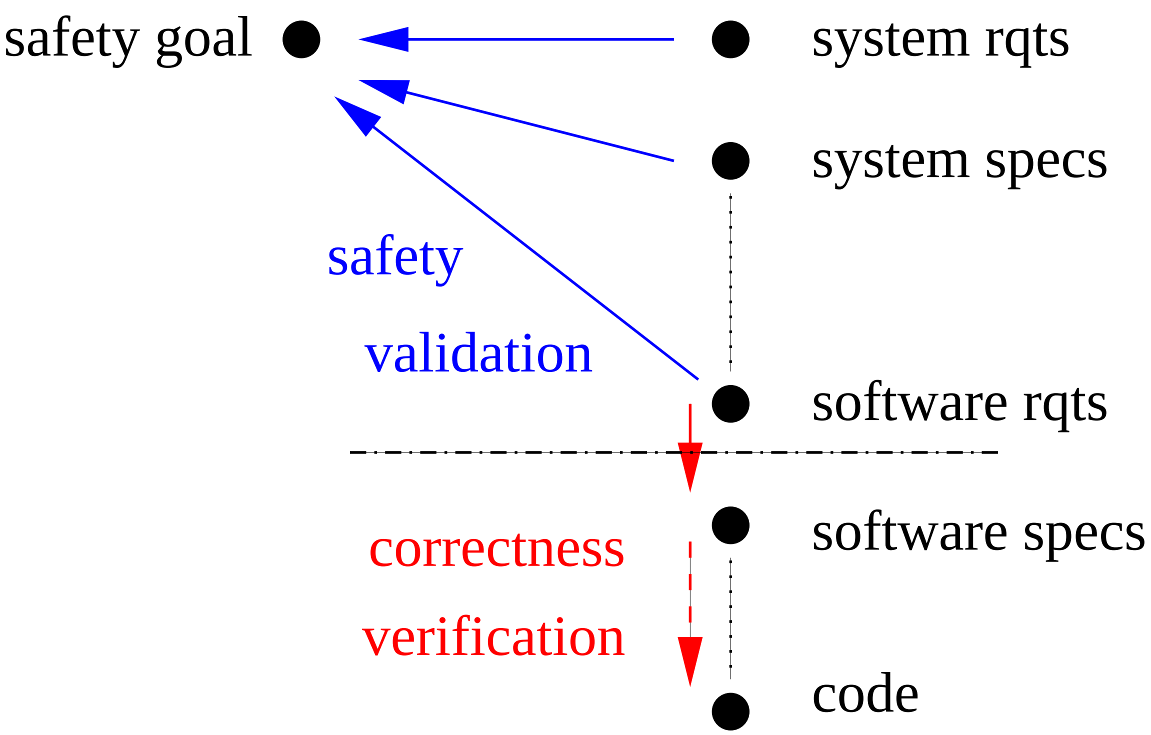
- The system specification S and requirements R should be analyzed similarly
- And there's a possibility the proof is flawed
  - Proof diversity may mitigate this

  Or deliberately unsound—e.g., static analysis
- And the implementation of the specification
  - Usually a subsidiary claim or claims
- Can do hazard analysis and mitigation on all these
- Observe this framework provides an uncontroversial and constructive treatment for the hysterical concerns of Fetzer

Implementation Hazards

- Currently, we apply safety analysis methods (HA, FTA, FMEA, HAZOP etc.) to an informal system description
  - Little automation, but in principle
  - These are abstracted ways to examine all reachable states
- Then, to be sure the implementation does not introduce new hazards, require it exactly matches the analyzed description
  - Hence, DO-178B is about correctness, not safety
- Instead, use a formal system description
  - Then have automated forms of reachability analysis
  - Closer to the implementation, smaller gap to bridge
- Analyze the implementation for preservation of safety, not correctness

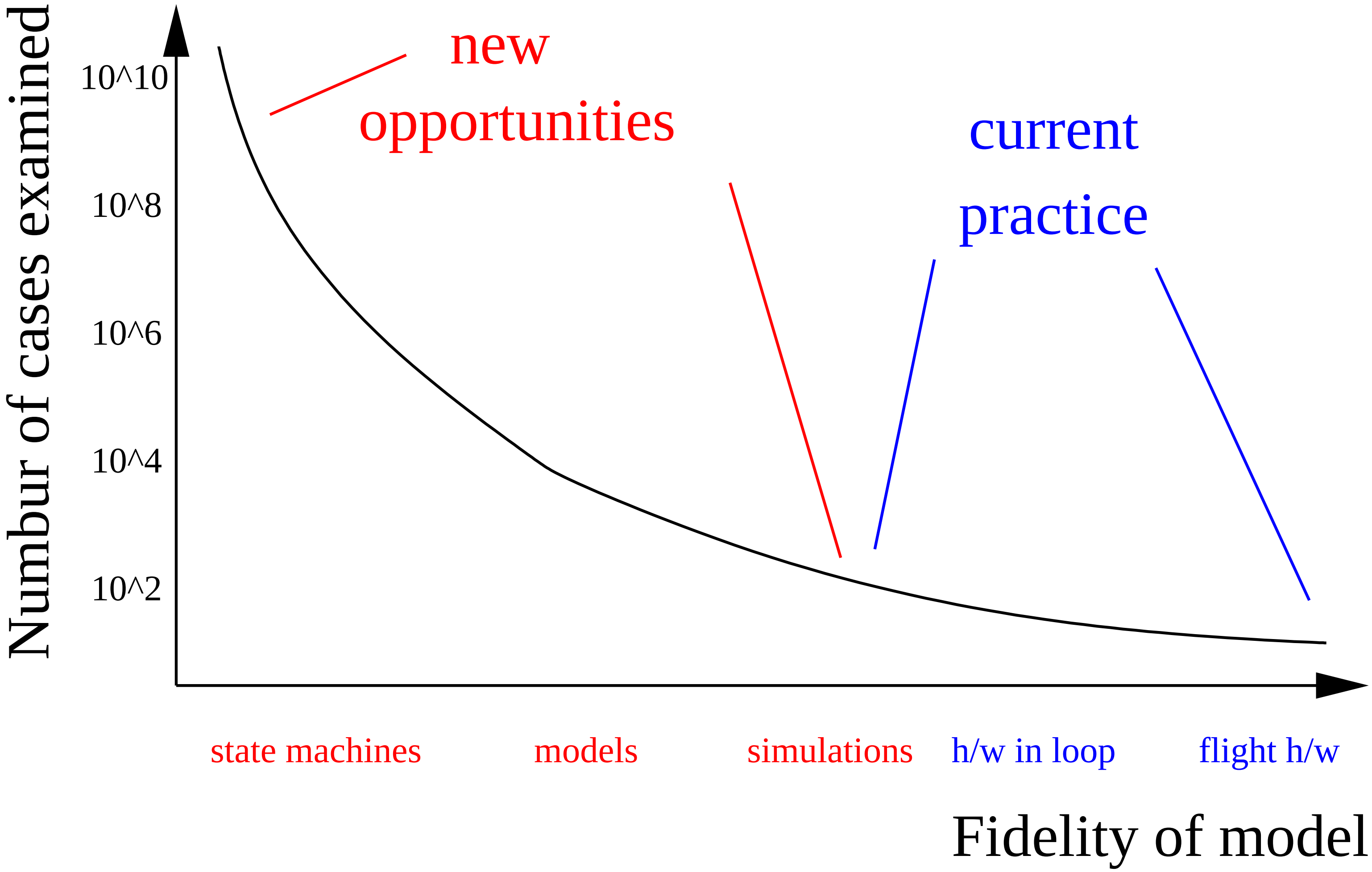
Implementation Hazards:
Standards Focus on Correctness Rather than Safety



- Premature focus on correctness is hugely expensive
  goal-based methods could reduce this
- Could also allow runtime checking of safety properties

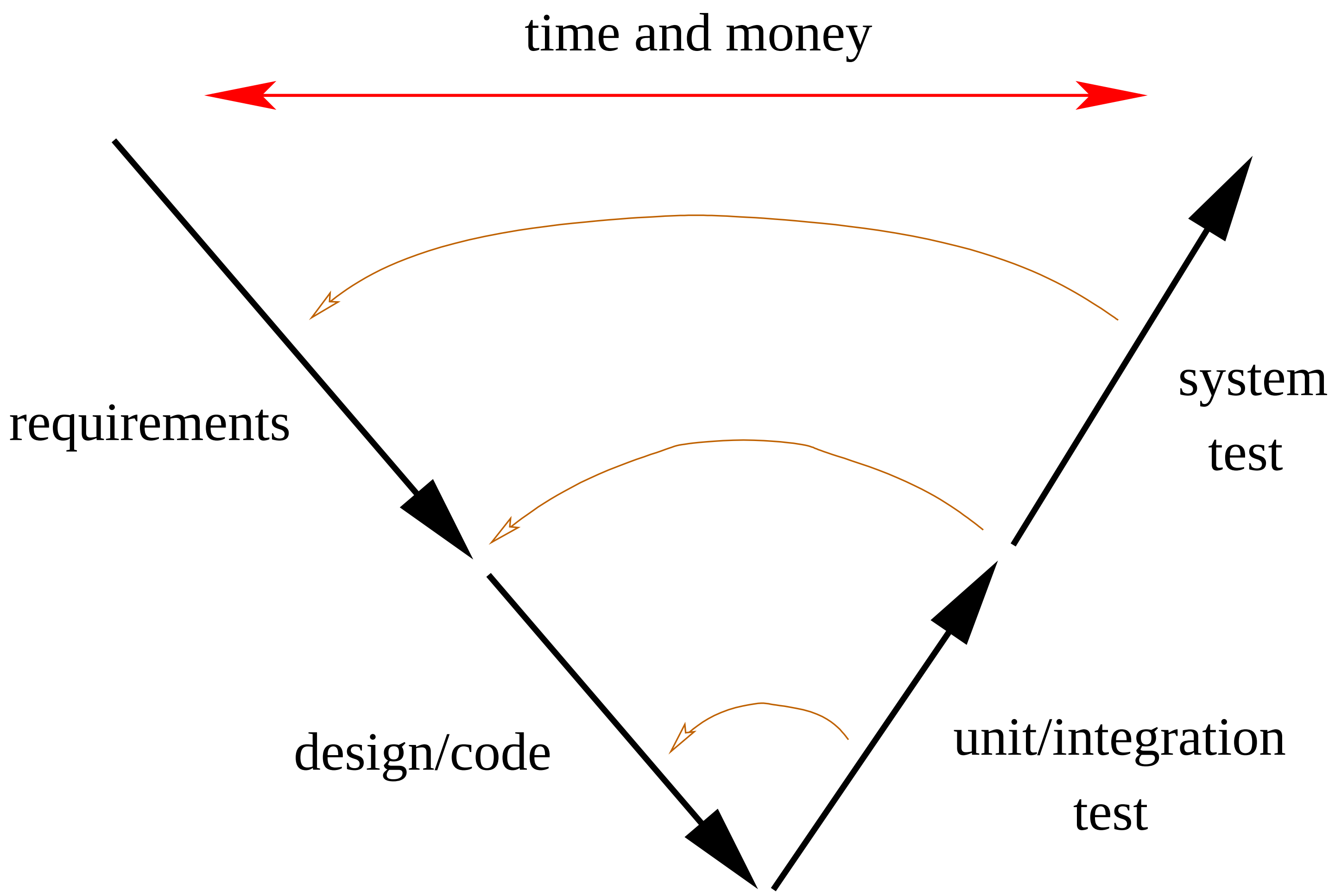
Even Weak Models Have Value

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

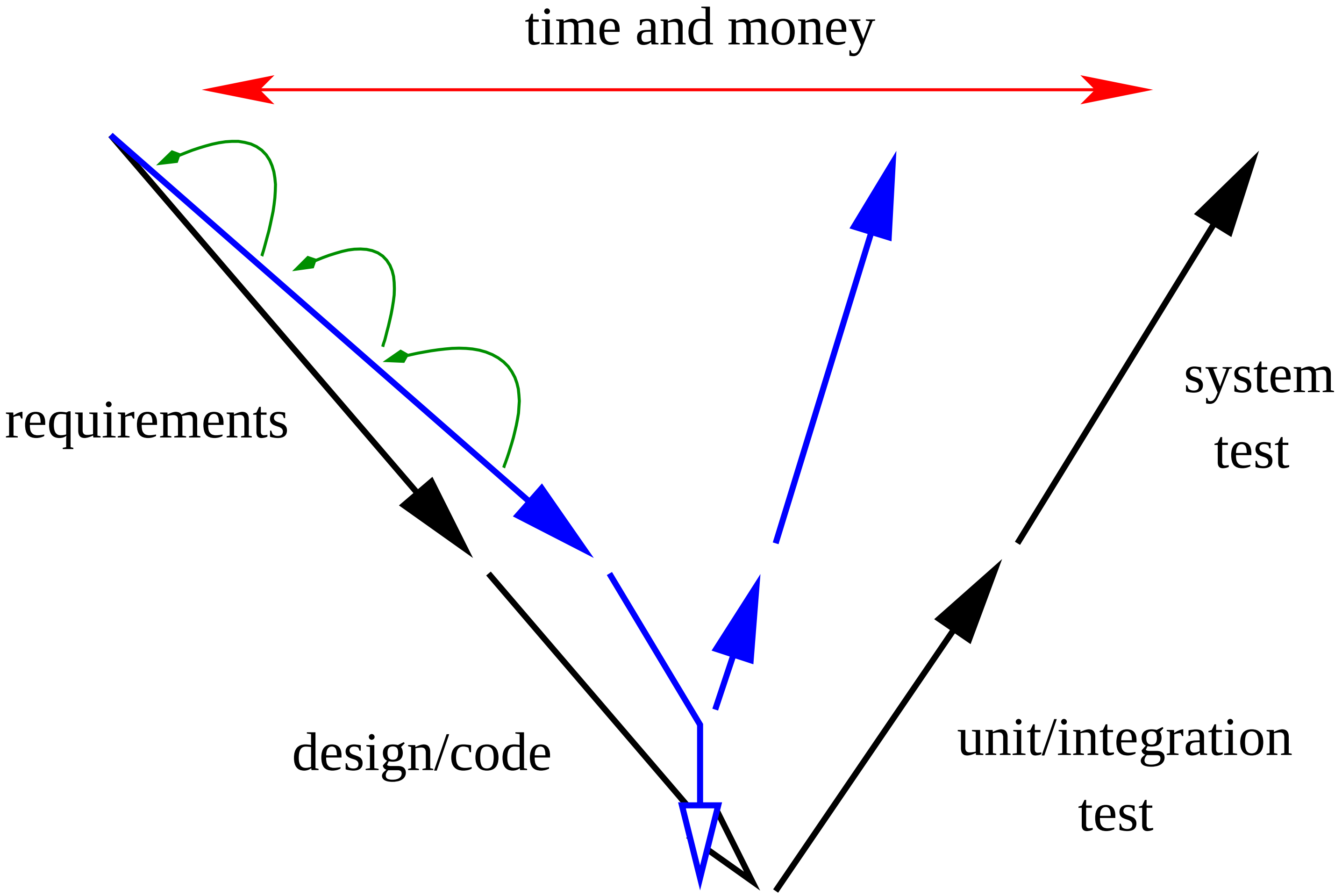


Overall V&V Process

Traditional Vee Diagram (Much Simplified)



Vee Diagram Tightened with Formal Analysis



Example: Rockwell-Collins

Runtime Assurance for Adaptive Systems

- What about adaptive systems that adjust or construct behavior at build-, load-, or run-time?
- Shouldn't some of the assurance move to runtime also?

  Modest approach: use runtime checking to constrain adaptive systems to safe regions

  - When is this feasible? (cf. Lui Sha's work)
  - Use runtime verification (checkers derived from formal analysis) to deliver assurance for certification

  Ambitious approach: use formal synthesis of adaptive systems themselves

  - Synthesize controllers to generate safe behavior
    - ⋆ Ramage and Wonham: controller synthesis
    - ⋆ Analyzed as a game: guarantee a winning strategy
- Instead of using model checking and other formal methods for analysis, we use them for monitoring and synthesis

Runtime Assurance: Examples

- AI planning
  - Check generated plans
  - Do the generation (cf. bounded model checking)
- Model-based diagnosis and repair
  - Check the diagnoses and proposed repairs
  - Do the diagnosis and repair generation: cf. qualitative reasoning and hybrid abstraction
- Adaptive control
  - Fixed model, tune the parameters
  - Hybrid systems model checking (box stability etc.)
- CMAC (cerebellum model articulation control)
  - And other connectionist models: discover the model
  - Can possibly synthesize a safe envelope

Just-In-Time Certification

- Some of the verification and certification activity is moved from design-time to run-time
- We trust automated verification methods for analysis, so why not trust them for monitoring and synthesis?
  - Certification would examine the models, trust the synthesis
- Will need to consider time-constrained synthesis
  - Anytime algorithms
  - Seek improvements on safe default
- Some analysis methods can deliver a certificate (e.g., a proof); used for synthesis that would truly be just-in-time or runtime certification!

Multi-Legged Arguments

- Runtime assurance might put too many eggs in one basket
- So we'd like to combine it with other methods
- Higher Levels of DO-178B/EALs/SILs also demand multiple forms of evidence
- What's the argument that these deliver increased assurance?
- Generally an implicit appeal to diversity
  - And belief that diverse methods fail independently
  - Not true in n-version software, should be viewed with suspicion here too
- Want to distinguish rational multi-legged cases from nervous demands for more and more and . . .
- Need to know the arguments supported by each item of evidence, and how they compose

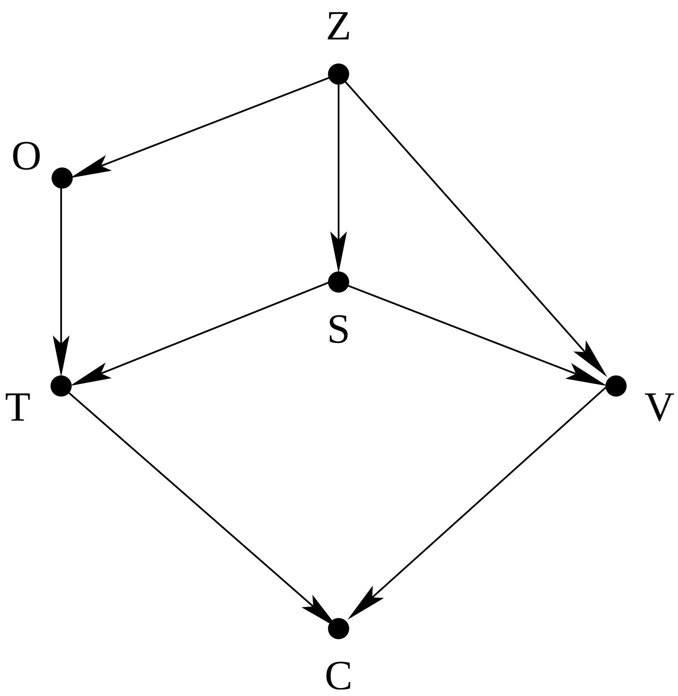
Two Kinds of Uncertainty In Certification

- One kind concerns failure of a claim, usually stated probabilistically (frequentist interpretation)
  - E.g., 10^{-9} probability of failure per hour, or 10^{-3} probability of failure on demand
- The other kind concerns failure of the assurance process
  - Seldom made explicit
  - But can be stated in terms of subjective probability
    - ⋆ E.g., 95% confident this system achieves 10^{-3} probability of failure on demand
    - ⋆ Note: this does not concern sampling theory and is not a confidence interval
- Demands for multiple sources of evidence are generally aimed at the second of these

Bayesian Belief Nets

- Bayes Theorem is the principal tool for analyzing subjective probabilities
- Allows a prior assessment of probability to be updated by new evidence to yield a rational posterior probability
  - E.g., P(C) vs. P(C | E)
- Math gets difficult when the models are complex
  - i.e., when we have many conditional probabilities of the form p(A | B and C or D)
- BBNs provide a graphical representation for hierarchical models, and tools to automate the calculations
- Can allow principled construction of multi-legged arguments

A BBN Example



Z: System Specification

O: Test Oracle

S: System's true quality

T: Test results

V: Verification outcome

C: Conclusion

Example joint probability table: successful test outcome

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

Absolute Claims in Multi-Legged Arguments

- Can get surprising results (Littlewood and Wright)
  - E.g., under some combinations of prior belief, increasing the number of failure-free tests may decrease our confidence in the test oracle rather than increase our confidence in the system reliability
- The anomalies disappear and calculations are simplified if one of the legs in a two-legged case is absolute
  - E.g., 95% confident that this claim holds. . . period
  - Formal methods deliver this kind of claim
- Aside: philosophers studying confirmation theory (part of Bayesian Epistemology) formulate measures of support differently than computer scientists
  - e.g., $P(E \mid C)$ - $P(E \mid \text{not } C)$ vs. $P(C \mid E)$ - $P(C)$

  However, these are related

Practical Considerations

- This approach assumes the verification leg considers the same system description and requirements as the other leg
- But this is seldom the case
  - Verification of weak properties: static analysis etc.
  - Verification of abstractions of the real system
  - Verification of specific critical properties (subclaims)
- Research needed to develop the theory to cover these issues
- And to factor runtime verification methods into the treatment

Systems and Components

- The FAA certifies airplanes, engines and propellers
- Components 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 certify these compositionally
- But modern engineering and business practices use massive subcontracting and component-based development that provide little visibility into subsystem designs
- Furthermore, the binding times for system architectures and for component behaviors are being delayed
- And adaptive systems may have undesired emergeent behavior due to interactions
- So we are forced to contemplate compositional and incremental approaches to certification

Compositional and Incremental Certification

- These are immensely difficult
  - The assurance case may not decompose along architectural lines
- But, in some application areas we can insist that it does
  - Goes to the heart of what is an architecture
- Need to ensure interactions use only known, intended mechanisms
  - No unprotected IPC channels
  - No signaling through cache occupancy, etc.
  - No unmodeled interaction through the controlled plant
- This is what IMA is about
- And the MILS approach to security

The MILS Two-Level Approach

Policy/Functional Level: perform a decomposition to a federated virtual architecture (circles and arrows picture) and identify the trusted components and their local security/safety requirements and their communications channels

- Do this in a way that minimizes complexity of trusted components and their policies
- Assume components and communications are free

Resource Sharing Level: figure out how to allocate virtual components to physical resources

- MILS/IMA provides technologies (basically, separation) so that virtual components of various types, and their communications channels, can share physical resources without compromising the integrity of the policy level

Mapping to Flight Systems

- Policy/Functional Level: flight-critical software
- Sharing level: IMA, partitioning
- PPs: The Common Criteria for Information Technology Security Evaluation (CC) are specialized to classes of systems/components through Protection Profiles (PP) to Security Targets (ST) to Targets of Evaluation (TOE); e.g., there's a PP for High Robustness Separation Kernels

Two Kinds of Components, Two Kinds of PPs

The policy and sharing levels of the MILS architecture have different concerns and are realized by different kinds of components having different kinds of PPs

Policy/Functional level: components that provide or enforce application-specific security or safety functions

- Examples: downgrading, authentication, autoland
- Their PPs are concerned with the specific security/safety function that they provide

Sharing level: components that securely share physical resources among logical entities

- Examples: separation kernel, partitioning communication system, file system, or network stack
- Their PPs are concerned with partitioning/separation/secure sharing

Two Kinds of Components, Three Kinds of Composition

We need to consider three kinds of component compositions

policy/policy or fuctional/functional: need compositionality

sharing/policy or sharing/functional: need composability

sharing/sharing: need additivity

Take these in turn

Compositionality

Policy or functional components combine in a way that ensures **compositionality**

- There's some way to calculate the properties of interacting policy components from the properties of the components (with no need to look inside), e.g.:
    - Component A guarantees P if environment ensures Q
    - Component B guarantees Q if environment ensures P
    - Conclude that $A \,||\, B$ guarantees P and Q
- Assumes components interact only through explicit computational mechanisms (e.g., shared variables)

Composability

Sharing components ensure **composability** of policy or functional components

- Properties of a collection of interacting policy components are preserved when they are placed (suitably) in the environment provided by a collection of sharing components
- Hence sharing components do not get in the way
- And the combination is itself composable
- Hence policy components cannot interfere with each other nor with the sharing ones

Composability makes the world safe for compositional reasoning

Additivity

Sharing components compose with each other **additively**

- e.g., **composable(kernel)** + **composable(network)** provides **composable(kernel + network)**
- There is an asymmetry: partitioning network stacks and file systems and so on run as clients of the partitioning kernel

Impact On PPs

- We need to ensure resource sharing PPs ensure composability
  - Need formal and informal constraints for this
  - Tradeoffs in functionality/performance vs. ease of assurance
- And that they are additive
  - Compatible sets of foundational threats, assumptions, policies
- Policy PPs need to be compositional
  - Need formal and informal constraints for this

Controlled Interfaces

- If we have successfully controlled what interfaces exist
- The next task is to ensure they are used correctly
- That is, ensure interactions follow their prescribed protocol
- Can be done statically for preplanned compositions
- Or dynamically for opportunistic ones
  - ○ E.g., interface automata
  - ○ With runtime verification
- But we may still have problems with emergent behavior
  - ○ E.g., coupling through the controlled plant
  - ○ Unmanned spacecraft have a lot of experience
  - ○ Some aircarft will need comparable autonamy (e.g., UAVs, unmanned freighters)

Research opportunities here

Summary

Have described four elements for a science-based certification framework

- Goal based safety cases
- Formal methods in goal-based safety cases
    - Including runtime monitoring and synthesis
- Multi-legged safety cases
- Compositional approaches to system properties