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Runtime Certification

John Rushby

Computer Science Laboratory
SRI International
Menlo Park CA USA
Certification

- Certification and high-assurance and have long been supporters and customers of verification technology
- Big changes are under way in these areas
  - I'll describe some of them
- These create new opportunities for runtime verification
  - I'll point out some of these
Current Certification Practice

• 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

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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

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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
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., air traffic management (CAP670 SW01), UK defence

- Applicant develops an assurance case
  - Whose outline form may be specified by standards or regulation (e.g., MOD DefStan 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

- 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
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 ⊨ or ⊨

• 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 subsidiary analysis on each assumption $A_i$
Analysis of Assumptions

How do we know assumption $A_i$ is valid?

One or more of:

- It is justified as a subsidiary claim
- All our system tests succeeded
- It was not implicated in failed system tests
- Runtime check
Runtime Verification for Assumption Failure

- It is part of the assurance case

- So must be credible (sound, complete, . . .)

- Probably need a sensible recovery action
  - Not like Ariane 501
  - Systematic approaches may be feasible

- What runtime verification methods and specification languages are appropriate?—over to you
Other Proof Hazards

- The system specification $S$ and requirements $R$ should be analyzed similarly

- And the implementation of the specification
  - Usually a subsidiary claim or claims

- And there’s a possibility the proof is flawed

- Or deliberately unsound
  - E.g., static analysis

- Diversity may mitigate this

- 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 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**
- **And runtime verification may be able to check some safety properties directly—over to you**
Multi-Legged Arguments

- More evidence is required at higher Levels/EALs/SILs
- 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. $P(C \mid E)$

- Math gets difficult when the models are complex
  - i.e., when we have many conditional probabilities of the form $p(A \mid B \text{ and } C \text{ or } D)$

- **BBNs** provide a graphical representation for hierarchical models, and tools to automate the calculations

- Can allow principled construction of multi-legged arguments

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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

<table>
<thead>
<tr>
<th>Correct System</th>
<th>Incorrect System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correct Oracle</td>
<td>Bad Oracle</td>
</tr>
<tr>
<td>100%</td>
<td>50%</td>
</tr>
</tbody>
</table>
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., $P(E | C) - P(E | \text{not } C)$ vs. $P(C | E) - P(C)$
  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—over to you
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 to load-time, or even runtime
- 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

- 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 the MILS approach to security is about

- Other applications, such as spacecraft, medical device plug’n’play, are more difficult
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—over to you
- But we may still have problems with emergent behavior
Monitoring and Synthesis

- Certification rests on consideration of reachable states
- **Science-based certification** uses formal methods to calculate and analyze these at design time
- Instead, we could use these methods to construct monitors that **check** behavior at runtime
- Or to synthesize **controllers** to generate safe behavior
  - Ramage and Wonham: **controller synthesis**
Runtime Assurance

• Instead of design-time analysis of the actual implementation

• Use run-time monitoring or synthesis of behavior from models
  ○ Typically with a receding horizon (bounded lookahead)
  ○ Fewer possibilities to examine, known current state

• Each component makes its model available to others, pursues its own goals while ensuring that possible moves by others cannot trap it into following a bad path, or cause violation of safety
  ○ 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

- **Over to you**
Runtime 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 examines the models, trusts 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 runtime certification!

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Summary

- Standards-based approaches to certification have run out of steam
- **Goal-based certification methods create a framework in which potential contributions of runtime monitoring and synthesis can be better explored and understood**
- The big challenges and opportunities are in enabling compositional and incremental certification
- And certifiable runtime adaptation and synthesis
- Runtime verification can make important contributions here
- Some of this material is from “Just-In-Time Certification” and “What Use Is Verified Software?” IEEE ICECCS, Auckland New Zealand July 2007, available at http://www.csl.sri.com/~rushby/biblio

- Over to you