Complete reworking of talks based on TSE 2012 paper with Bev Littlewood, plus new material from others at City

Explaining Software Certification

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Introduction

- Software certification seems to work
  - At least for industries and systems where public data are available
  - e.g., passenger aircraft, trains, nuclear power
  - No major software-induced calamity
  - Maybe not so well for medical devices
- But how and why does it work?
- Worth knowing before we change things
- Or try to extend to other areas
  - e.g., cars, security

Certification Goals

- Usually some variation on "nothing really bad will happen"
- But the world is an uncertain place and this cannot be guaranteed, so we need to bound the exposure and add "with high probability"
-
    - E.g., no catastrophic failure in the lifetime of all airplanes of one type
    - Or no release of radioactivity in 10,000 years of operation
- By arithmetic on these, we derive acceptable rates and probabilities for critical failures
    - e.g., for aircraft software, catastrophic failure rate $< 10^{-9}$ per hour sustained for duration of flight
    - Or for nuclear shutdown pfd $< 10^{-3}$

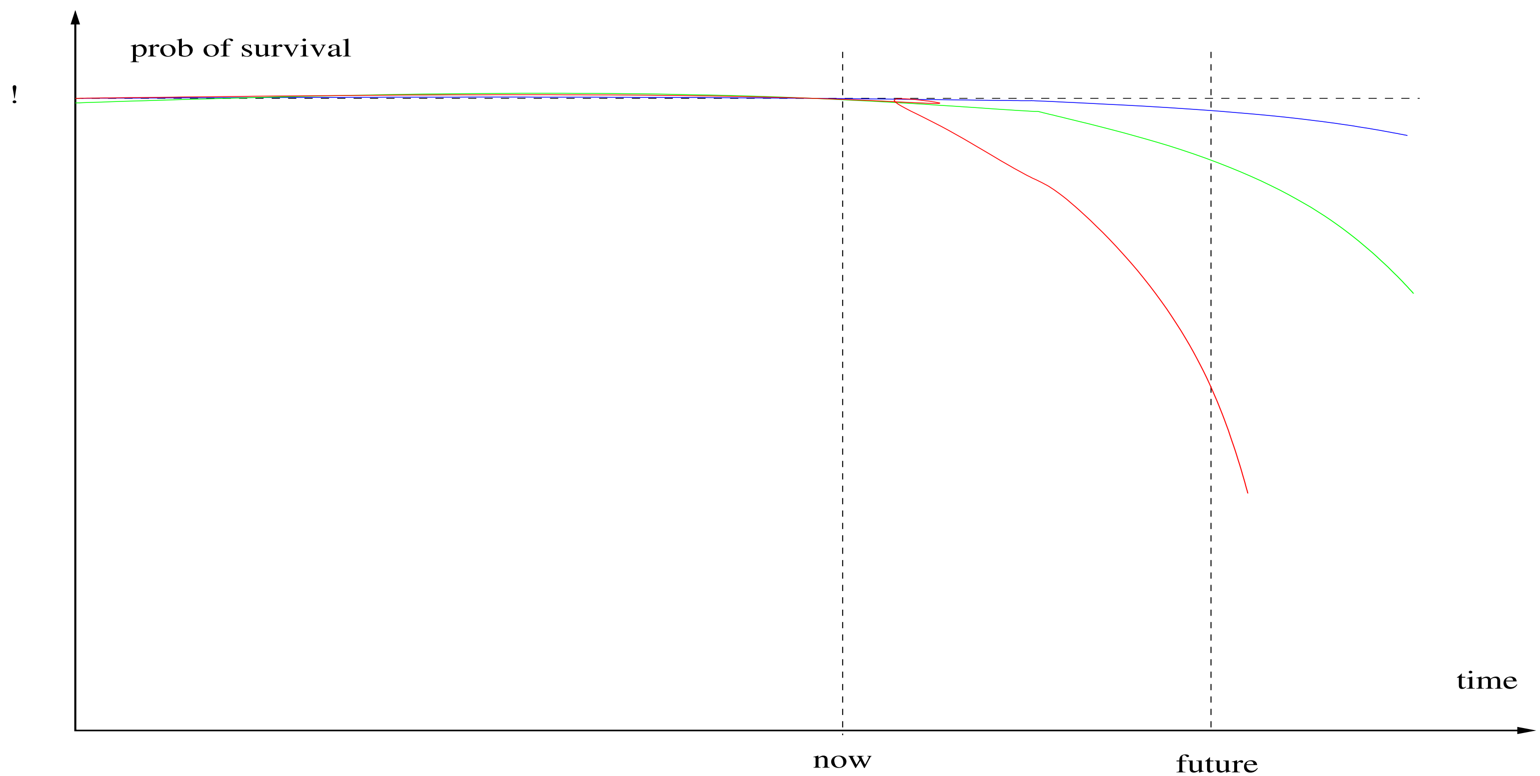
Certification Based on Experimental Quantification

- This means statistically valid random testing
- Need the operational profile
- It's difficult and you need a lot of tests
- Can just about get to 10^{-3}, maybe 10^{-4} this way
- Butler and Finelli calculated 114,000 years on test for 10^{-9}
- Actually the Airbus A320 family has about 10^{8} hours of operation with no catastrophic software failure
- So, based on this alone, how much confidence can we have in another 10^{8} hours?

Certification Based on Experimental Quantification (ctd.)

Roughly speaking, if p_f is probability of failure per demand (a complete flight, say), then we are interested in probability of n demands without failure

$$p_{srv}(n) = (1 - p_{fnp})^n$$



Certification Based on Experimental Quantif'n (ctd. 2)

- So, based on this alone, how much confidence can we have in another 10^8 hours?

-
  - About 50-50
  - We have $n = 10^8$ and no failures, from this estimate p_f and extrapolate to $p_{srv}(2 \times 10^8)$.

- And for the remaining lifetime of the fleet (say 10^9 hours)?
  - Very little

- Need additional information—i.e., "priors"

- Aha! That's what software assurance does for us—but how?

Maybe It's Perfect

- Given 10^8 hours of operation for the A320 family, the best we can say with no priors is that its catastrophic failure rate is probably no worse than 10^{-8}
- That's an extremely low rate
- It is almost easier to believe that it has no faults
  - i.e., is perfect

  Than that it has faults that occur at a rate below 10^{-8}
- No amount of failure-free operation can confirm perfection
- Need some priors
- Aha! Maybe that's how software assurance works

System Safety

- Think of everything that could go wrong
  - Those are the hazards

  Design them out, find ways to mitigate them
  - i.e., reduce consequences, frequency

  This may add complexity (a source of hazards)

- Iterate until you've dealt with everything

- And then recurse down through subsystems

- Until you get to widgets
  - Build those correctly

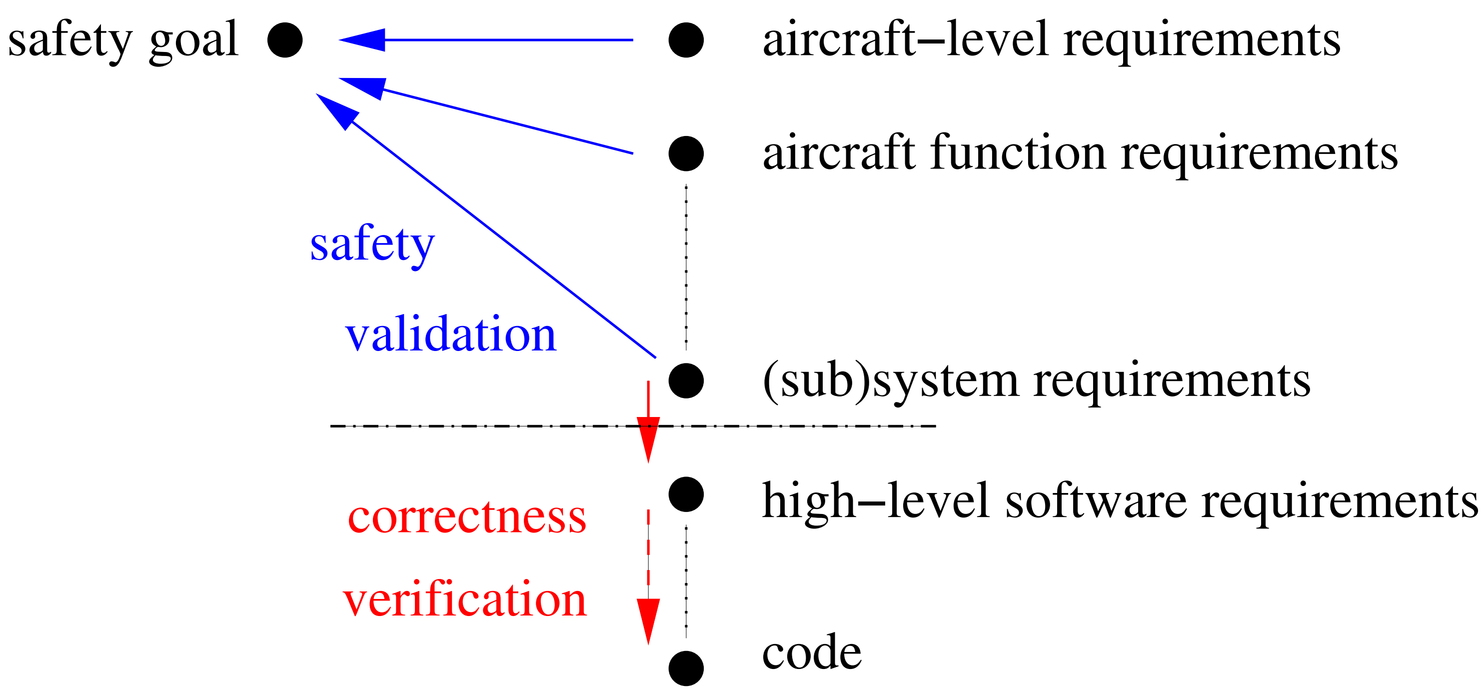
- Provide assurance that you have done all this successfully

Software Safety

- Software is a widget in this scheme
- We don't analyze it for safety, we build it correctly
- In more detail. . .
  - Systems development yields functional and safety requirements on a subsystem that will be implemented in software; call these (sub)system safety requirements
    - ⋆ Often expressed as constraints or goals
  - From these, develop the high level software requirements
    - ⋆ How to achieve those goals
  - Elaborate through more detailed levels of requirements
  - Until you get to code (or something that generates code)
- Provide assurance that you have done all this successfully

Aside: Software is a Mighty Big Widget

The example of aircraft



- As more of the system design goes into software
- Maybe the widget boundary should move
- Safety vs. correctness analysis would move with it
- But has not done so yet

The Conundrum

- Cannot eliminate hazards with certainty (because the environment is uncertain), so top-level claims about the system are stated quantitatively
    - E.g., no catastrophic failure in the lifetime of all airplanes of one type ("in the life of the fleet")
- And these lead to probabilistic systems-level requirements for software-intensive subsystems
    - E.g., probability of failure in flight control $< 10^{-9}$ per hour
- To assure this, do lots of software assurance
- But this is all about showing correctness
- For stronger subsystem claims, do more software assurance
- How does amount of correctness-based software assurance relate to probability of failure?

The Conundrum Illustrated: The Example of Aircraft

- Aircraft failure conditions are classified in terms of the severity of their consequences
- Catastrophic failure conditions are those that could prevent continued safe flight and landing
- And so on through severe major, major, minor, to no effect
- Severity and probability/frequency must be inversely related
- AC 25.1309: No catastrophic failure conditions in the operational life of all aircraft of one type
- Arithmetic and regulation require the probability of catastrophic failure conditions to be less than 10^{-9} per hour, sustained for many hours
- And 10^{-7}, 10^{-5}, 10^{-3} for the lesser failure conditions

The Conundrum Illustrated: Example of Aircraft (ctd.)

- DO-178C identifies five Software Levels
- And 71 assurance objectives
  - E.g., documentation of requirements, analysis, traceability from requirements to code, test coverage, etc.
- More objectives (plus independence) at higher levels
  - 26 objectives at DO178C Level D (10^{-3})
  - 62 objectives at DO178C Level C (10^{-5})
  - 69 objectives at DO178C Level B (10^{-7})
  - 71 objectives at DO178C Level A (10^{-9})
- The Conundrum: how does doing more correctness-based objectives relate to lower probability of failure?

Some Background and Terminology

Aleatory and Epistemic Uncertainty

- Aleatory or irreducible uncertainty
  - is “uncertainty in the world”
  - e.g., if I have a coin with $P(heads) = p_h$, I cannot predict exactly how many heads will occur in 100 trials because of randomness in the world

  Frequentist interpretation of probability needed here

- Epistemic or reducible uncertainty
  - is “uncertainty about the world”
  - e.g., if I give you the coin, you will not know p_h; you can estimate it, and can try to improve your estimate by doing experiments, learning something about its manufacture, the historical record of similar coins etc.

  Frequentist and subjective interpretations OK here

Aleatory and Epistemic Uncertainty in Models

- In much scientific modeling, the aleatory uncertainty is captured conditionally in a model with parameters

- And the epistemic uncertainty centers upon the values of these parameters

- As in the coin tossing example: p_h is the parameter

Software Reliability

- Not just software, any artifacts of comparably complex design
- Software contributes to system failures through faults in its requirements, design, implementation—bugs
- A bug that leads to failure is certain to do so whenever it is encountered in similar circumstances
  - There's nothing probabilistic about it
- Aaah, but the circumstances of the system are a stochastic process
- So there is a probability of encountering the circumstances that activate the bug
- Hence, probabilistic statements about software reliability or failure are perfectly reasonable
- Typically speak of probability of failure on demand (pfd), or failure rate (per hour, say)

Testing and Software Reliability

- The basic way to determine the reliability of given software is by experiment
  - Statistically valid random testing
  - Tests must reproduce the operational profile
  - Requires a lot of tests
- This is where we came in
- Note that the testing in DO-178C is not of this kind
  - it's coverage-based unit testing: a local correctness check
- So how can we estimate reliability for software?

Back To The Main Thread

Assurance is About Confidence

- We do correctness-based software assurance
- And do more of it when higher reliability is required
- But the amount of correctness-based software assurance has no obvious relation to reliability
- And it certainly doesn't make the software "more correct"
- Aha! What it does is make us more confident in its correctness
- And we can measure that as a subjective probability
  - More assurance, higher probability of correctness, roughly. . .
- But that still doesn't connect to reliability
- And is it really correctness that we want?

Correct but Imperfect Software: Example

- 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; each a self-checking pair with a backup (so 6-fold redundant in total); 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
- The backups were suppressed because the FCMCs indicated they were not both failed

Perfect Software

- Correctness is relative to software requirements, which themselves may be flawed
    - Actually, the main source of failure in aircraft software
- We want correctness relative to the critical claims in the (sub)system requirements
    - Or what those claims should have been
- Call that perfection (aka. fault-freeness)
- Software that will never experience a critical failure in operation, no matter how much operational exposure it has

Possibly Perfect Software

- You might not believe a given piece of software is perfect
- But you might concede it has a possibility of being perfect
- And the more assurance it has had, the greater that possibility
- So we can speak of a (subjective) probability of perfection
- For a frequentist interpretation: think of all the software that might have been developed by comparable engineering processes to solve the same design problem
    - And that has had the same degree of assurance
    - The probability of perfection is then the probability that any software randomly selected from this class is perfect

Probabilities of Perfection and Failure

- Probability of perfection relates to software assurance
- But it also relates to reliability:

  By the formula for total probability

$$
\begin{aligned}
& P(\text{s/w fails [on a randomly selected demand]}) \qquad (1)\\
= \;& P(\text{s/w fails} \mid \text{s/w perfect}) \times P(\text{s/w perfect}) \\
& + P(\text{s/w fails} \mid \text{s/w imperfect}) \times P(\text{s/w imperfect}).
\end{aligned}
$$

- The first term in this sum is zero, because the software does not fail if it is perfect (other properties won't do)
- Hence, define
  - p_{np} probability the software is imperfect
  - p_{fnp} probability that it fails, if it is imperfect
- Then $P(\text{software fails}) = p_{fnp} \times p_{np}$
- This analysis is aleatoric, with parameters p_{fnp} and p_{np}

Epistemic Estimation

- To apply this result, we need to assess values for p_{fnp} and p_{np}
- These are most likely subjective probabilities
  - i.e., degrees of belief
- Beliefs about p_{fnp} and p_{np} may not be independent
- So will be represented by some joint distribution $F(p_{fnp}, p_{np})$
- Probability of software failure will be given by the Riemann-Stieltjes integral

$$\int_{\substack{0 \le p_{fnp} \le 1 \\ 0 \le p_{np} \le 1}} p_{fnp} \times p_{np} \, dF(p_{fnp}, p_{np}). \quad (2)$$

- If beliefs can be separated F factorizes as $F(p_{fnp}) \times F(p_{np})$
- And (2) becomes $P_{fnp} \times P_{np}$

  Where these are the means of the posterior distributions representing the assessor's beliefs about the two parameters

Practical Application—Nuclear

- Traditionally, nuclear protection systems take no credit for the software assurance they do and base their certification on statistically valid random testing
- Very expensive to get to pfd of 10^{-4} this way
- Our analysis says $pfd \leq P_{fnp} \times P_{np}$
- They are essentially setting P_{np} to 1 and doing the work to assess $P_{fnp} < 10^{-4}$
  - Conservative assumption that allows separation of beliefs
- Any software assurance process that could give them $P_{np} < 1$
  Would reduce the amount of testing they need to do
  - e.g., $P_{np} < 10^{-1}$, which seems very plausible
  - Would deliver the the same pfd with $P_{fnp} < 10^{-3}$
  - Conservative methods available if beliefs not independent
- This could reduce the total cost of certification

Practical Application—Aircraft, Version 1

- Aircraft software is assured by processes such as DO-178C Level A, needs failure rate $< 10^{-9}$ per hour
- They also do a massive amount of all-up testing but do not take (software) certification credit for this
- Our analysis says software failure rate $\leq P_{fnp} \times P_{np}$
- So they are setting $P_{fnp} = 1$ and $P_{np} < 10^{-9}$
- No plane crashes due to software, enough operational exposure to validate software failure rate $< 10^{-7}$, even 10^{-8}
- Does this mean flight software has probabilities of imperfection $< 10^{-7}$ or 10^{-8}?
- And that DO178C delivers this?

Practical Application—Aircraft, Version 2

- That seems unlikely!
  - Implies that of 10,000,000 software systems assured to Level A, just 1 would ever suffer a critical failure

- An alternative measure is $p_{srv}(n)$, the probability of surviving n demands without failure, where

$$p_{srv}(n) = (1 - p_{np}) + p_{np} \times (1 - p_{fnp})^n \quad (3)$$

- This doesn't help with 10^{-9}

- But can make n equal to "life of the fleet" and get there with modest p_{np} and p_{fnp}

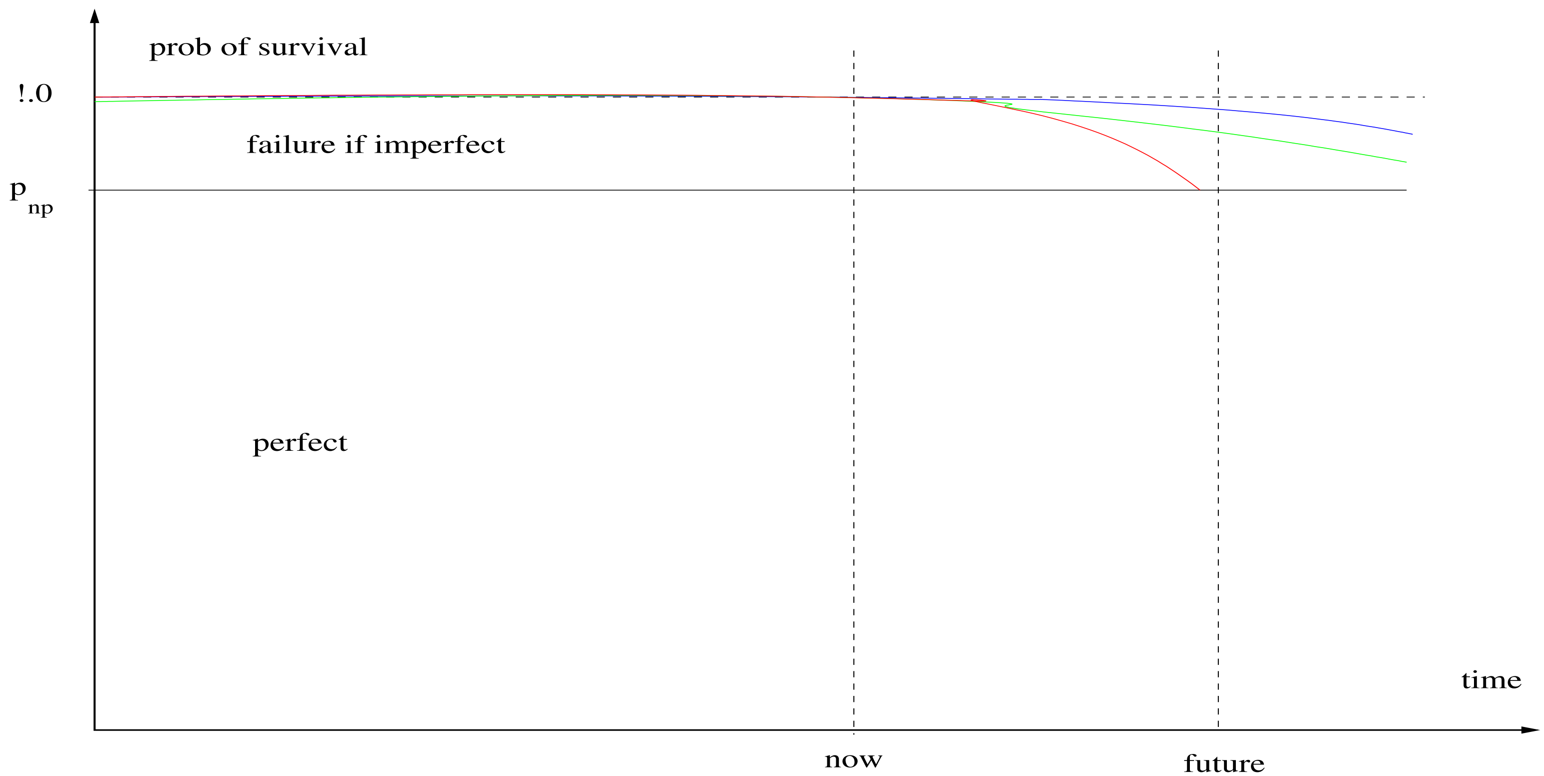
- Really?

Long Run Failure-Free Operation

- Recall

$$p_{srv}(n) = (1 - p_{np}) + p_{np} \times (1 - p_{fnp})^n$$

- First term is independent of n
- Second term decays exponentially



How Software Certification Works

- Let's suppose Level A gives us $p_{np} < 10^{-2}$
- Not unreasonable
- Then we have a 99% chance of no catastrophic failures in the life of the fleet
- So we're done!
- Aah, but what about the other 1% chance?
  - Might crash every time
- So the term $10^{-2} \times (1 - p_{fnp})^n$ needs to be small
- Which is difficult when n is huge ($\approx 10^9$)
  - Looks like we're back to demonstrating $p_{fnp} < 10^{-7}$
- But on Day 1 do we really need the full lifetime of all airplanes of the type
  - In the first 6 months, say, we'll only have 10 planes
  - 10 planes for 6 months is quite a small n ($\approx 10^4$)

How Software Certification Works (ctd.)

- With a smaller n, modest p_{fnp} can do it (e.g., $p_{fnp} < 10^{-3}$)
- Could get that from the all-up system and flight tests
- Provides the "bootstrap" to have confidence in first few months of flight
- Thereafter, experience to date validates smaller p_{fnp} and provides confidence for next increment of exposure
  - See SafeComp13 paper by Strigini and Povyakalo for math
- I think this matches intuition
  - I've heard certifiers say they'll wait a while before flying

Aside: Monitoring

- In some systems, it's feasible to have a simple monitor that can shut off a more complex operational component
    - Turns malfunction and unintended function into loss of function
    - Prevents transitions into unsafe states
- It is a theorem that the possible perfection of the monitor is independent of the reliability of the operational channel
- Reliability of the whole is the product of these
    - At aleatoric level, more complex for epistemic
    - Must also deal with undesired monitor activation
- So formally synthesize monitor from formal safety constraints
    - Example: A340 fuel management

  Maybe $p_{np} < 10^{-3}$ is plausible

Further Aside: Representing and Analyzing Requirements

- One reason requirements are often flawed is there are no good notations or methods of analysis for very abstract descriptions
- Typically just boxes and arrows on a whiteboard and BOGSAT analysis (bunch of guys sitting around a table)
- So often use things like Simulink: premature implementation
- Want the abstractness of boxes and arrows with just enough semantics that it is feasible to express constraints and analyze for interesting properties
- Aha! Infinite Bounded Model Checking (Inf-BMC) can do this
- Inf-BMC allows use of uninterpreted functions, e.g., $f(x)$
- Constraints can be encoded as synchronous observers
- Inf-BMC can do automated model checking (using SMT solvers) and cover the entire modeled space

Summary

- I think this really is the explanation for certification
- It dissolves the conundrum
  - Connects assurance effort to confidence: p_{np}
  - And connects confidence to reliability
  - And long term survival
- It shows how testing/experience buttresses that
  - Without requiring extreme numbers
  - Because it works incrementally
- Observe this explanation works for lifetime of the fleet
  - US regulation
- But not for 10^{-9}
  - EU regulation (just illustrative in US)
- What do you think?

Future Work

- We need to get good estimates for the p_{np} delivered by DO-178C Level A, B, C
  - Maybe "chunk" the 71 objectives
  - Michael Holloway's retrospective safety case does this
  - Get expert opinions on each chunk
  - And use BBNs to combine them
- Also need estimates on p_{fnp} delivered by flight tests, first 6 months, first 2 years etc.
  - Recall, it is about 10^{-8} for A320 after 20 years
- Derive advice for new fields, certification regimes, assurance methods?