VI

ASSURANCE FOR DEPENDABLE SYSTEMS (DISAPPEARING FORMAL METHODS)

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Assurance for Dependable Systems (Disappearing Formal Methods)

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Overview

- Assurance for Safety, Security, and other critical properties
  - Process- vs. product-based assurance
- Formal methods
- Problems with current methods
- Two big ideas
- From refutation to verification
- Disappearing formal methods

Evidence For Safety, Security, And Other Dependability Properties

- How is it done for traditional systems?
  - E.g., an airplane wing
- How is it done for software?
  - Or software-intensive systems
  - E.g., a flight-control system

Safety Cases for Traditional Systems

- Mostly done by mathematical modeling and analysis
  - Build mathematical models of the design, its environment, and requirements
  - Use calculation to establish that the design in the context of the environment satisfies the requirements
  - Only useful when mechanized

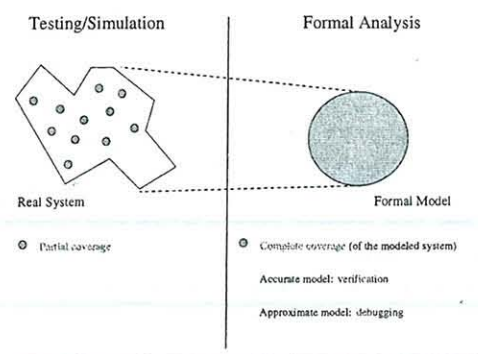
  E.g., finite elements analysis
- The modeling is validated by tests
  - Limited testing is sound because we are dealing with continuous systems
- This is product-based certification
  - It concerns properties of (mathematical models of) the product

Safety Cases for Software Systems

- Mostly done by controlling, monitoring, and documenting the process used to create the software
  - Different industries have different recommended processes (e.g., DO-178B for avionics)
- This is process-based certification
  - Provides no direct evidence about the product

    "We cannot show how well we've done, so we'll show how hard we tried"
- NB. Testing is product-based, but cannot provide evidence beyond 10^{-4} because we are dealing with discrete systems
  - Complete testing is infeasible: 114,000 years test for 10^{-9}
  - And extrapolation from incomplete tests is unjustified

Formal Methods In Pictures



Product-Based Certification For Software

- Build mathematical models of a design, its environment, and requirements
  - The applied math of Computer Science is formal logic
  - So models are formal descriptions in some logical system:
- Use calculation to establish that the design in the context of the environment satisfies the requirements
  - Calculation in formal logic is done by theorem proving or model checking

    $$assumptions + design + environment \vdash requirements$$

    Formal calculations can cover all modeled behaviors, even if numerous or infinite (the power of symbolic reasoning)
- Only useful when mechanized
  - So need automated theorem proving or model checking

Formal Methods for Product-Based Assurance and Certification

- Want highly accurate formal models, so that calculations support strong claims—i.e., verification
- Then, using formal calculations, some activities that are traditionally performed by reviews
  - Processes that depend on human judgment and consensus

  can be replaced or supplemented by analyses
  - Processes that can be repeated and checked by others, and potentially so by machine

  Language from DO-178B/ED-12B
- That is, formal methods help us move from process-based to product-based assurance

However...

- Most problems in continuous mathematics can be solved in polynomial time: typically n^2 or n^3
- All problems in automated deduction are at least NP-hard, most are superexponential (2^{2^n}), nonelementary ($2^{2^{2^{\cdot^{\cdot^{\cdot}}}}}\}^n$), or undecidable
- Why? Have to search a massive space of discrete possibilities
- Which exactly mirrors why it's so hard to provide assurance for algorithmic systems
  - Have to consider vast number of different behaviors
  - Absence of continuity means extrapolation from finite testing is unreliable
- And which is why formal calculations pay off
  - Practical way to examine all possibilities

So...

- Full automation of formal calculations is impossible in general
- Must rely on heuristics (guesses) which will sometimes fail
  - Heuristic theorem proving
- Or rely on human guidance
  - Interactive theorem proving
- Or trade off accuracy or completeness of the model for tractability and automation of calculation
  - Model checking

The Difficulty With Theorem Proving Is...

- Theorem proving can handle accurate models, but requires heuristics and interactive human guidance
  - Focuses on proof, and idiosyncrasies of the prover and its heuristics, not on the design being evaluated
  - Difficult to interpret failure (bug, or bad proof?)

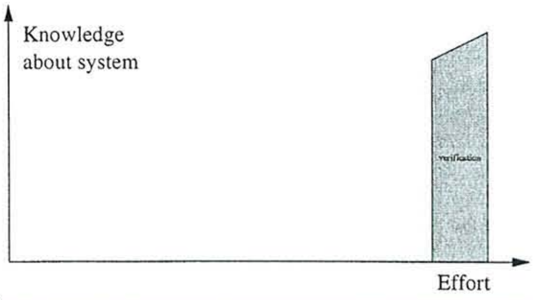
  "Interactive theorem proving is a waste of human talent"
- Also, must strengthen invariants to make them inductive
- And it's all or nothing
- Payoff is definitive assurance... with caveats
  - May also find subtle bugs

Inductive Invariants

- To establish an invariant or safety property (one true of all reachable states) by theorem proving, we invent another property that implies the one of interest and that is inductive
  - Includes all the initial states
  - Is closed on the transitions

  The reachable states are the smallest set that is inductive
- Trouble is, naturally stated invariants are seldom inductive
  - The second condition is violated
- Postulate a new invariant that excludes the states (so far discovered) that take you outside the desired invariant
- Iterate until success or exasperation
- Bounded retransmission protocol required 57 such iterations

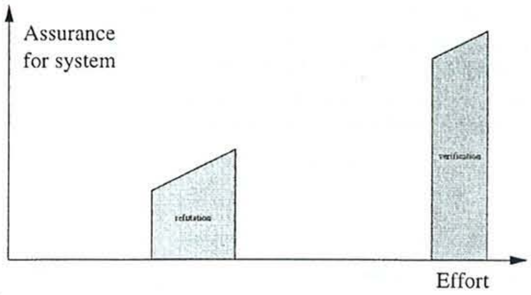
The Wall of Formal Verification



The Difficulty with Model Checking Is. . .

- The models (and properties) have to be simplified to make them tractable to fully automated analysis
- But simplified models may not be fully accurate with respect to the property of interest
  - And that's why they cannot be used for verification
- However, this approach works for refutation (finding bugs)
  - Experience indicates we learn more (find more bugs) by exploring all behaviors of a simplified model than by probing just some of the behaviors of the real thing (as with testing or simulation)
- But when to stop?
  - Lack of refutation is not the same as verification

Refutation and Verification



Formal Methods in Current Practice

- *Model checking saved the reputation of formal methods* (Daniel Jackson)
- Formal methods have achieved a modest degree of acceptance in some areas
  - E.g., hardware, protocols
- But mainly for purposes of refutation
  - That is, looking for errors
  - E.g., debugging, testing
- Verification is much less practiced
  - That is, showing the absence of errors

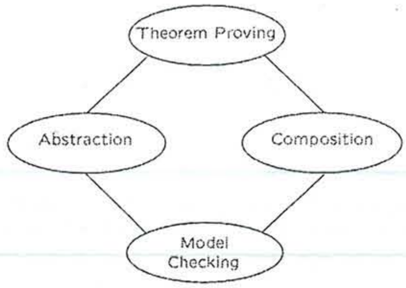
Summarizing

- Refut'n can be cost-effective, but doesn't get you to verif'n
  - Interaction concerns the model, the technology is automated, it resembles familiar activities
  - It is acceptable to practitioners

  Challenge: why cannot the technology of refutation (particularly model checking) be used for verification?
- Verif'n has high potential payoff, but few interm'd benefits
  - Interaction concerns the proof and the prover, technology is not automated, intimidating
  - It is not acceptable to practitioners

  Challenge: why cannot theorem proving be made automatic?
- Overall challenges: why cannot model checking and theorem proving work together? And why cannot we move smoothly from refutation to verification?

Abstraction is a Bridge Between Deductive and Algorithmic Methods And Between Refutation and Verification



Using Model Checking For Verification

- Model checking requires simple models (e.g., finite state)
- But can be used to verify properties of a complex model if it has a simple property-preserving abstraction
- Trouble is, it usually requires theorem proving to justify the abstraction
  - 45 of the 57 invariants required for BRP
- First Big Idea: use theorem proving to calculate the abstraction

Making Theorem Proving More Automatic

- The general theorem proving problem is undecidable
  - So full automation requires heuristics
  - Which will sometimes fail
- Classical verification poses correctness as a single "big theorem"
  - So failure to prove it (when true) is catastrophic
- Second Big Idea: "failure-tolerant" theorem proving
  - Prove lots of small theorems instead of one big one
  - In a context where some failures can be tolerated
- Aha! Automated abstraction provides this context

Abstraction

- Given a transition system G on S and property P, a property-preserving abstraction yields a transition system $\hat{G}$ on $\hat{S}$ and property $\hat{P}$ such that

$$\hat{G} \models \hat{P} \Rightarrow G \models P$$

- Strongly property preserving abstraction:

$$\hat{G} \models \hat{P} \Leftrightarrow G \models P$$

- A good abstraction typically (for universal properties) introduces nondeterminism while preserving the property
- Remaining problem: Construction of reasonably precise $\hat{G}$ and $\hat{P}$ given G and P

Data Abstraction [Cousot & Cousot]

- Replace concrete variable x over datatype C by an abstract variable x' over datatype A through a mapping $h : [C \rightarrow A]$.
- Examples: Parity, $mod\ N$, zero-nonzero, intervals, cardinalities, {0, 1, many}, {empty, nonempty}
- Given $f : [C \rightarrow C]$, construct $\hat{f} : [A \rightarrow set[A]]$:
(observe how data abstraction introduces nondeterminism)

$$b \in \hat{f}(a) \Leftrightarrow \exists x : a = h(x) \wedge b = h(f(x))$$

$$b \notin \hat{f}(a) \Leftrightarrow\ \vdash \forall x : a = h(x) \Rightarrow b \neq h(f(x))$$

- Theorem-proving failure affects accuracy, not soundness
- Mechanized in Bandera (Corbett, Dwyer and Hatcliff, KSU)

Predicate Abstraction [Graf-Saïdi]

- Abstracts out relations between variables, e.g., $x < y$, $x + y = z$
- Variables ranging over infinite datatypes can be replaced by Boolean variables representing the predicates on those variables
- Predicates can be extracted from guards, assignments, and the property of interest
- Guessing predicates is easier than invariant strengthening (and is also more general [Rusu & Singerman, TACAS 99])
- Mechanized in PVS (SRI)

Construction of Predicate Abstractions

- Given $\phi : [S \rightarrow \hat{S}]$ induced by the abstracted predicates, construct $\hat{G}$ by

$$\hat{G}(\hat{s}_1, \hat{s}_2) \Leftrightarrow \exists s_1, s_2 : \hat{s}_1 = \phi(s_1) \wedge \hat{s}_2 = \phi(s_2) \wedge G(s_1, s_2)$$

$$\neg\hat{G}(\hat{s}_1, \hat{s}_2) \Leftrightarrow\ \vdash \forall s_1, s_2 : \hat{s}_1 \neq \phi(s_1) \vee \hat{s}_2 \neq \phi(s_2) \vee \neg G(s_1, s_2)$$

- Theorem-proving failure affects accuracy, not soundness
- There is another method (exponentially more efficient) [Saïdi & Shankar, CAV 99]
- More powerful than data abstraction, but construction is more complex

Automated Abstraction

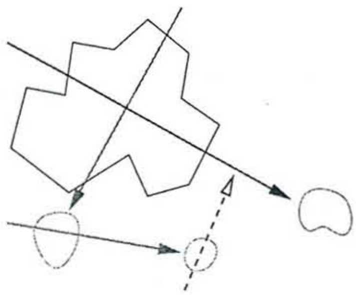
- Can often construct a simplified model that is faithful to the original (for a given property of interest)
  - The reduced model can by analyzed by model checking
  - And failure to detect bugs does certify their absence
- These reduced models can be constructed automatically by mechanized data or predicate abstraction
  - The construction is done by trying to prove lots of little theorems
    - If a proof fails, the abstracted model will be more conservative, but often still good enough
- But still the construction often requires auxiliary invariants

The Bridge Goes In Both Directions

- Model checkers often calculate the reachable stateset
  - Which is the strongest invariant

  And then throw it away
- The concretization of the reachable states of an abstraction is an invariant of the concrete system
  - And often a strong one
- So modify a model checker to return the reachable states as a formula that a theorem prover can manipulate
- Has been done (by Sergey Berezin) for CMU SMV and is used in InVeSt [Bensalem, Lakhnech & Owre, CAV 99]

Integrated, Iterated Analysis



Even More Integrated, Iterated Analysis!

- (Approximations to) fixpoints of weakest preconditions or strongest postconditions also generate invariants and can strengthen those extracted from an abstraction
  - Mechanized by theorem proving
  - (Strongest postconditions are equivalent to symbolic simulation, which is independently useful)
- Counterexamples from failed model check help distinguish bugs from weak abstractions, and also help refine the abstraction
  - Suggest additional properties (invariants) that will help the theorem prover construct a tighter model
  - Suggest additional predicates on which to abstract

Truly Integrated, Iterated Analysis!

- Recast the goal as one of calculating and accumulating properties about a design (symbolic analysis)
- Rather than just verifying or refuting a specific property
- Properties convey information and insight, and provide leverage to construct new abstractions
  - And hence more properties
- Requires restructuring of verification tools
  - So that many work together
  - And so that they return symbolic values and properties rather than just yes/no results of verifications
- This is what SAL is about: Symbolic Analysis Laboratory

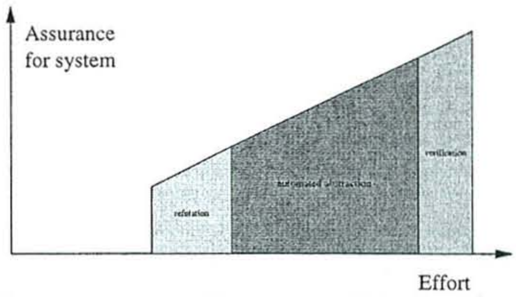
From Refutation to Verification

- By allowing unsound abstractions

$$\hat{G} \models \hat{P} \not\Rightarrow G \models P$$

  We can do refutation as well as verification
- By selecting abstractions (sound/unsound) and properties (little/big) we can fill in the space between refutation and verification
- Refutation lowers the barrier to entry
- Provides economic incentive: discovery of high value bugs
  - Can estimate the cost of each bug found
  - And can directly compare with other technologies
- Yet allows smooth transition to verification

From Refutation To Verification



Filling the Remaining Gap

- Model checking for refutation and (via automated abstraction) for verification imposes a much smaller barrier to adoption than old-style formal verification
- But the barrier is still there
- What about really low cost/low threat kinds of formal analysis?
- Make the formal methods disappear inside traditional tools and methods
  - Invisible formal methods, or
  - Ubiquitous formal methods

Examples of Disappearing Formal Methods

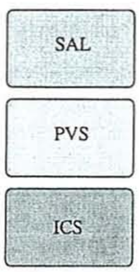
- Extended static checking (ESC) for Java (Compaq SRC)
- PVS-like type system (predicate subtypes) for any language
  - Traditional type systems have to be trivially decidable
  - But can gain enormous error detection by adding a component that requires theorem proving (lots of small theorems, failure generates a warning)
- Completeness/Consistency checkers for tabular specifications (cf. Ontario Hydro, RSML, SCR)
- Statechart/Stateflow property checkers (cf. OFFIS)
  - Show me a path that activates this state
  - Can this state and that be active simultaneously?
- Test case generators (cf. Verimag/IRISA TGV)

Tools To Realize These

- Abstraction and model checking
- Automated theorem proving built on powerful decision procedures
  - Combination of: propositional satisfiability, equality over uninterpreted function symbols with (linear) arithmetic, arrays, datatypes
  - Quantifier elimination for decidable fragment of the above

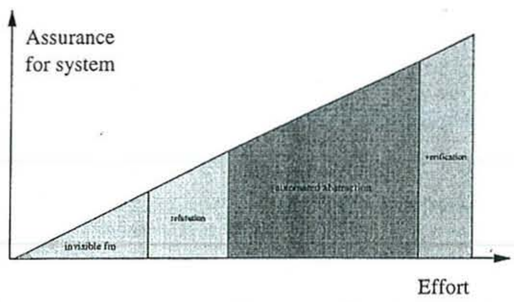
  We are making these available as ICS
- Also decision procedures for more powerful theories (e.g., Mona for WS1S, available in PVS)
- These can be extended to model checking
  - E.g., Lossy-Channel Systems (LCS)
  - Just as ordinary model checking builds on BDDs and SAT

What We Are building



ICS = Integrated Canonizer-Solver (= ICanSolve)

Disappearing Formal Methods



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To Learn More

- Check out papers and technical reports at `http://www.csl.sri.com/programs/formalmethods`
- Information about our verification system, PVS, and the system itself are available from `http://pvs.csl.sri.com`
  - Freely available under license to SRI
  - Built in Allegro Lisp for Solaris, or Linux
  - Version 2.3 includes predicate abstraction
- Released ICS in July 2001: `http://www.ICanSolve.com`
- Plan to release SAL in late 2001

DISCUSSION

Rapporteur: V Khomenko

Lecture One

Dr Horning asked who develops abstractions. Dr Rushby replied that ideally it is the designer, since he knows how things work inside. But a lot of the content of an abstraction can be seen from the description, by looking at the predicates present there. Therefore, even without understanding the description, it is sometimes possible to build an approximation which is good enough to do the job.

Then a question was asked about the role of simulation checkers. Dr Rushby replied that there are many sub-problems inside the overall testing approach, e.g. test case generation, construction of oracles, and finding feasible paths of the program. Almost all these require theorem proving, solving inequalities etc. Therefore, significant fragments of the theorem proving technology can be applied. Traditional testing of non-reactive (transformation) programs requires generating test data, whereas the real problem is the testing of concurrent reactive systems, where the tester is not just data but a program driving the system to the state it wants to get it into. And it can be hard to control the environment.

Professor Malek mentioned that the gap between the refutation and verification is immense, and he doubts that automated abstraction can fill it. Dr Rushby replied that automated verification is computationally very expensive and usually it is impossible for non-trivial systems. But safety-critical systems are usually explicitly constructed to be simple, and it is often possible to calculate automatically their critical properties. Having enough time, patience and skill, one can theorem-prove almost anything, though it may require too much time, patience, and skill.

Professor Schneider mentioned that the problem of getting good specifications was completely ignored, and that it seems that light-weight verification methods make certain assumptions about how easy it is to write down those specifications. Dr Rushby replied that many well-known techniques, e.g. type systems, can be efficiently used. One can assume that the code to be verified is mostly correct and mine it. In this way, many bugs can be found. Therefore, even without specification, one can deliver some interesting results. Also, sometimes designers are prepared to write some kind of a specification or comments to give a clue what is going on in the system.

Dr. Moszkowski mentioned that commercial companies use temporal logics for testing. Dr Rushby agreed that there are many approaches in-between testing and model checking.

Professor Littlewood asked how this approach is related to probabilistic safety. Dr Rushby replied that there are works on probabilistic model checking, but they are quite complicated. There is a belief that in discrete design we deal with errors, and the probabilistic part comes from what the environment does to your system and how likely certain external events are.