PVS, SAL, and the ToolBus

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Overview

- Backends (PVS) and frontends (SAL)
- What's wrong with that?
- A Tool Bus
- Trust and evidence
- An Evidential Tool Bus

PVS and its Backends

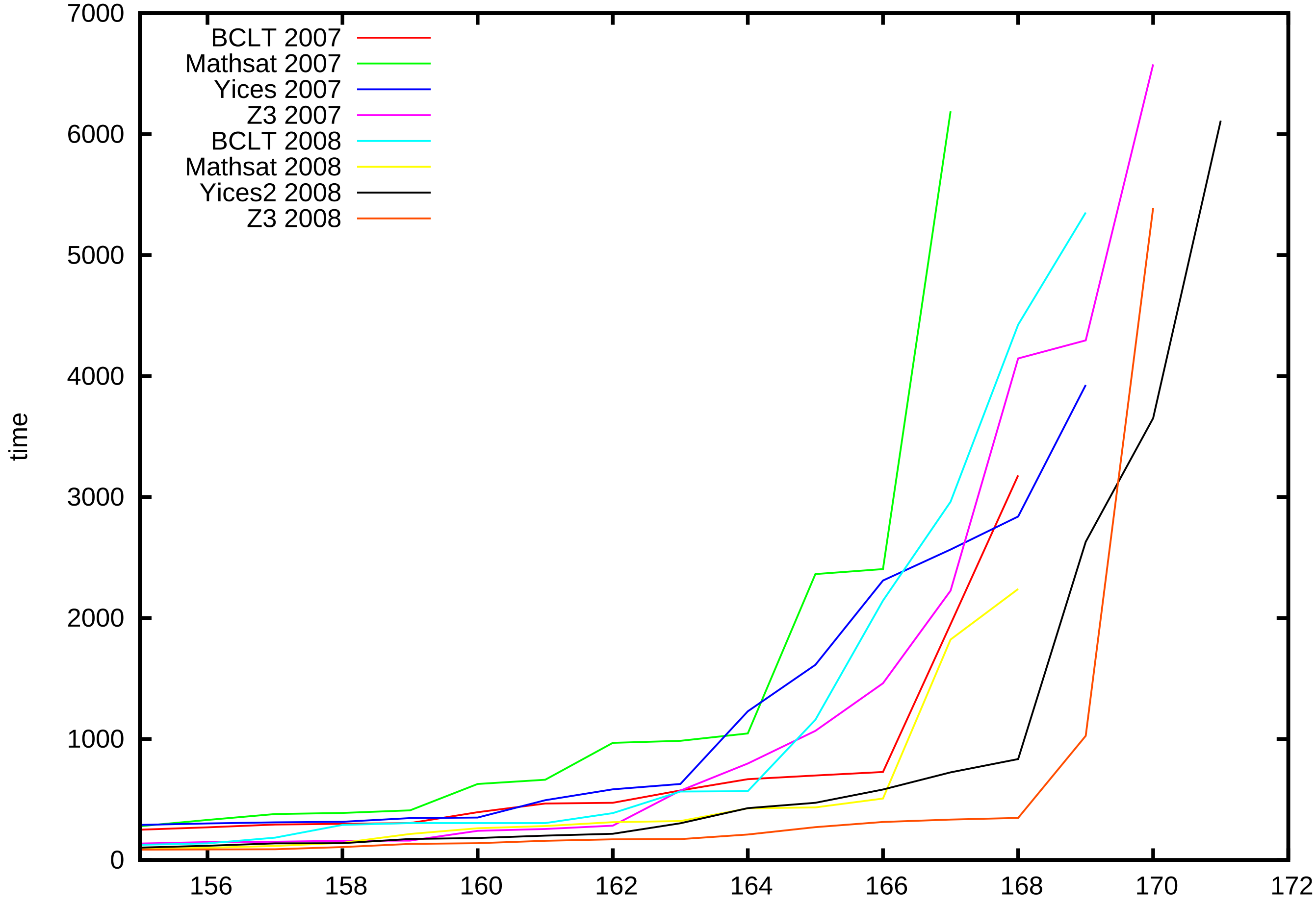
PVS included powerful automation since its first release (1993)

- Shostak's combination of integer and real linear arithmetic with uninterpreted functions
  - Previously in STP (1980) and Ehdm (1988)
  - Conjunctions only
- Propositional calculus at an outer level
  - Using BDDs (1995)
- Rewriting and heuristic quantifier instantiation
- Symbolic model checking for CTL (1995)
- Predicate abstraction
  - Invented and first realized as a PVS extension (1996)
- WS1S, via Mona library (2000)
- Execution (2001) and computational reflection, semantic attachments (2001, PVSio 2003), random tester (2005)

PVS and its Backends (ctd.)

- Nonlinear arithmetic
  - RAHD (Real Algebra in High Dimensions)
    - By Grant Passmore (2008)
  - Not tightly integrated with other DPs, but loses little
- SMT solvers (Satisfiability Modulo Theories)
  - ICS (2002)
    - The "lazy" integration of decision procedures and a SAT solver (supplanted the earlier "eager" integration)
  - Yices 0.1 and Simplics (2005)
  - Yices 1 (2006), integrated with PVS (2008)
  - Decides the combination of uninterpreted function symbols with equality, linear real and integer arithmetic, scalar types, recursive datatypes, tuples, records, extensional arrays, fixed-size bit-vectors, quantifiers, and lambda expressions

SMT Solving is a Competitive Sport



Progress of 2007 and 2008 competitors on real difference logic

How Best to Exploit the Power of SMT Solvers?

- SMT solvers routinely solve problems with tens of thousands of variables and constraints
  - A disruptive innovation
- You don't interact with formulas this big
- So an uncomfortable match for interactive provers like PVS
  - Only useful for endgames; elsewhere `grind` is better
- But SMT solvers also provide satisfying assignments
- Hence a natural application is bounded model checking over "infinite" domains ("infinite BMC," SAL 2002)
  - Extends to verification via k-induction (SAL 2003)

The Awesome Power of SMT Solvers

Example: biphase mark

- An asynchronous communications protocol with realtime constraints

ACL2: Moore (1994), one of his "10 best ideas"

PVS: three different versions

  - One by Groote and Vaandrager used PVS + UPPAAL
  - Required 37 invariants, 4,000 proof steps, hours of prover time to check

SAL: Brown and Pike (2006)

  - Compact, readable specification
  - Verification by infinite BMC with k-induction
  - Three trivial lemmas
  - And one large systematic one (disjunctive invariant)
  - Under 5 seconds of prover time

SAL and its Frontends

- SAL is a model checking environment

  Finite state: symbolic (BDD), and bounded (SAT)

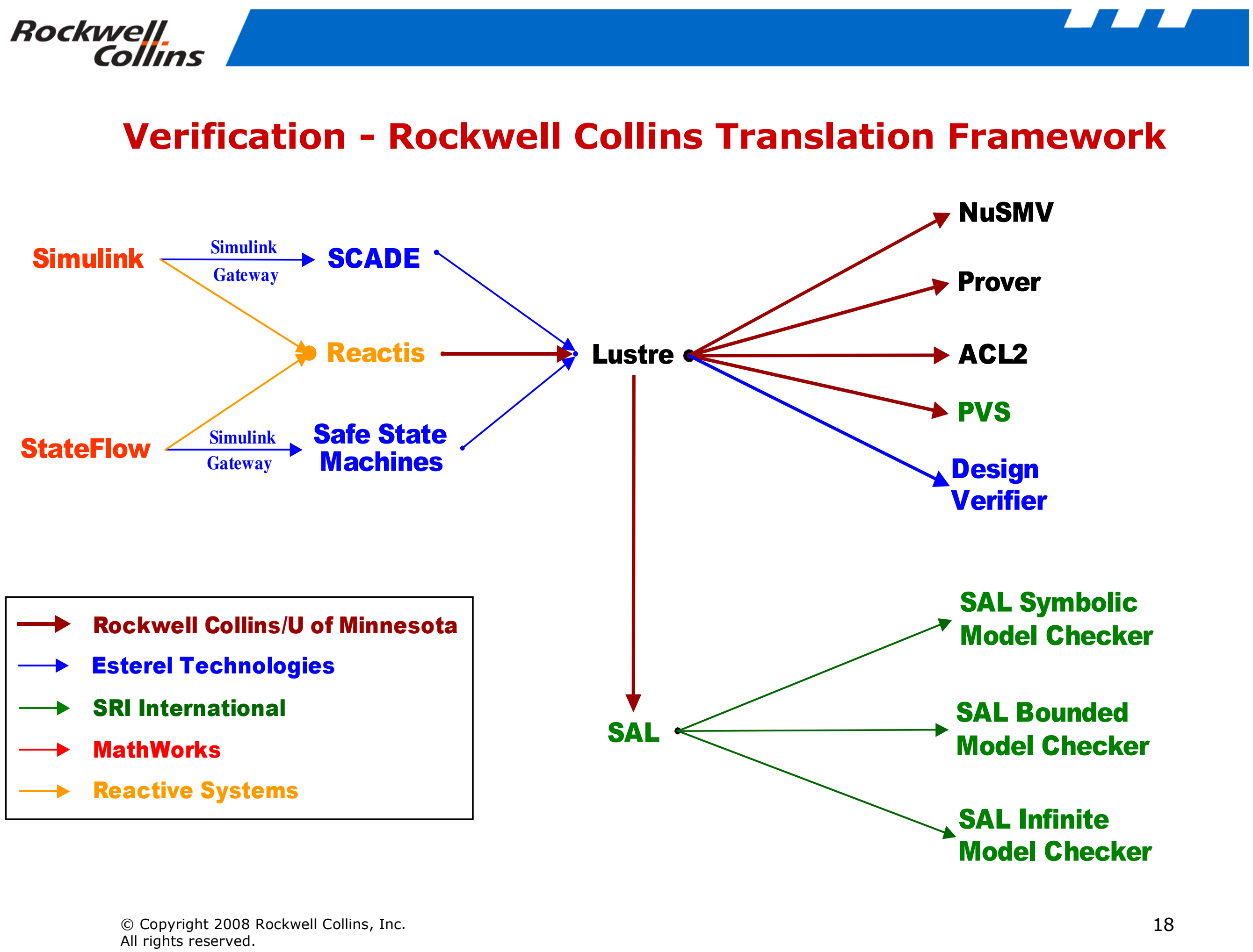
    - Also used for test case generation

  Infinite state: infinite bounded (SMT)

  Hybrid: hybrid abstraction (RAHD-like abstractor)

- Has its own language; type system is similar to PVS
- Intended as a target for translation from widely used languages—e.g., Simulink/Stateflow
    - Formal semantics for Stateflow and prototype translator, and cool method of test case generation (Hamon 2004)
    - Simulink Design Verifier is a standard Mathworks product: test generation, checking, verification (Hamon 2007)
        - ⋆ Uses an SMT-like solver (Prover) directly

Rockwell-Collins Simulink/Stateflow Toolchain



What's Wrong With All That?

- Deduction is no longer the hard part of verification

- Invariant generation is now the hard problem
  - Abstract interpretation (over logical lattices), templates (solve $\exists\forall$ problems), predicate/data abstraction, CEGAR and interpolants, van Eijk methods, dynamic analysis

- Verification is not the only task of interest
  - Debugging, test case generation, static analysis, abstraction, scheduling, plan generation, controller synthesis, approximate and maxSAT-like problems

- Users want direct access to components

So We Need to Link Tools

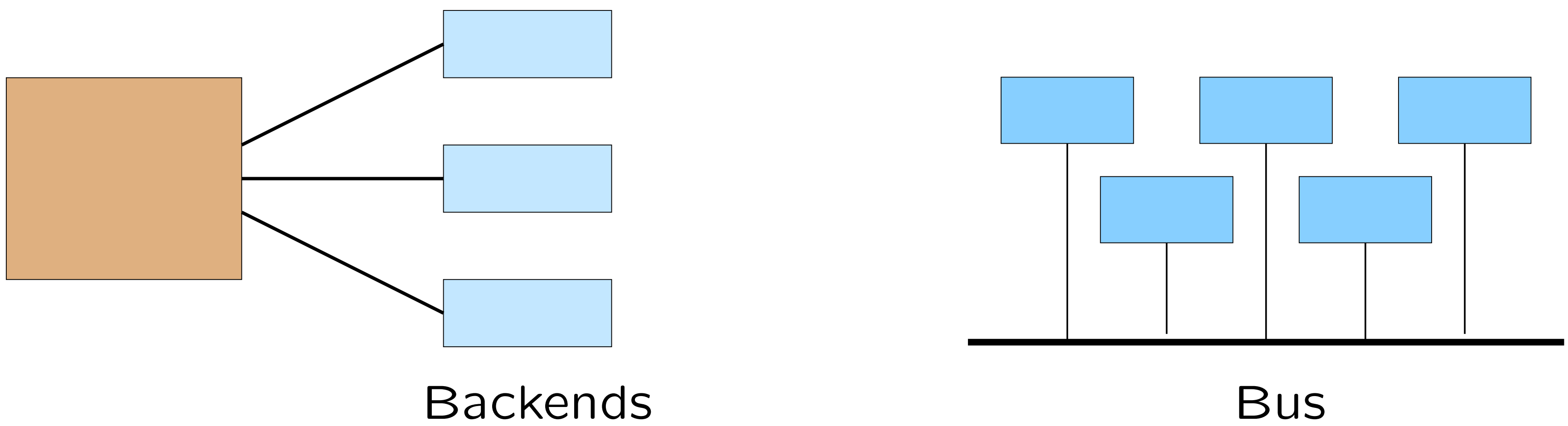
Desiderata:

- Make it worthwhile for people to open up their tools
  - Extract and package components
  - Make internal computations available
- Low cost of entry, network effect
- Allow tools to work together in ad-hoc combinations

Observation:

- Components return values other than (sub)proof outcomes
- E.g., Unsat cores, sets of predicates, counterexamples, invariants, abstractions
- i.e., heterogeneous functionality

Backends or Bus?



- Heterogeneity argues against theorem prover backends
- Bus is a federation of equals; theorem prover is just another component

Interactions on A Tool Bus

- We need ways for one tool find another
- We need ways for one tool to invoke another
- We need ways for one tool to provide the right kind of input for another, and to understand its outputs
- This starts to look like Service-Oriented Architecture (SOA)
  - SOAP, WSDL, RDF, etc.
- Ugh! Want a higher-level, more declarative notation

Tool Bus Judgements

Propose that Tool Bus interactions take the form of judgments

- $T \vdash A$
- Tool instance T verifies assertion A
- Both the tool and the assertion can include variables

Query: ? $\vdash$ predicate-abstraction(?, B, ϕ)

Response:

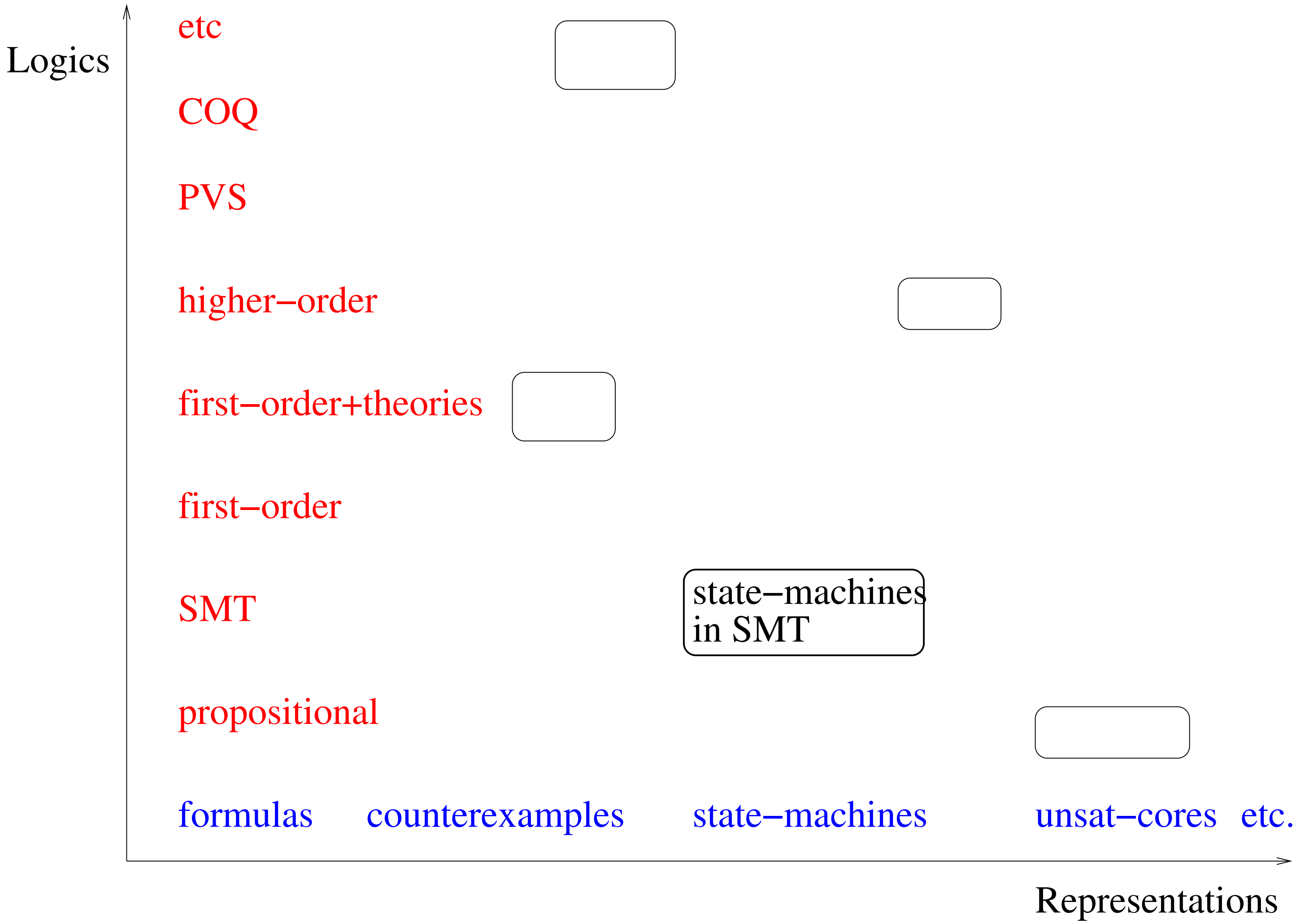
SAL-abstractor(. . .) $\vdash$ predicate-abstraction?(A, B, ϕ)

- Tools operate by implicit invocation
- The responding tool constructs the witness, and returns the result or its handle, along with its own invocation

Arguments in Tool Bus Assertions

- These are formulas, counterexamples, sets of predicates, state machines, etc.
- Do we need a universal Tool Bus Language to specify all of these?
- Or are they opaque to the bus, interpreted only by the relevant tools?
- Propose that semantics are opaque, labeled by a Tool Bus Ontology
  - Two dimensions
    - ⋆ Logic (e.g., Yices)
    - ⋆ Representation (e.g., state machine)
- But syntax is registered (as XML, e.g., using RELAX NG)

Tool Bus Ontology



Tool Bus Operation

- The tool bus operates like a distributed Datalog framework, chaining forward and backward on queries and responses
- Similar to SRI AIC's Open Agent Architecture (OAA)
  - And maybe similar to MyGrid, Linda, TIB, . . . ?
- Can have hints, preferences etc.
- The bus needs to integrate with version management
- Tools can be local or remote
- Tools can run in parallel, in competition
- Some tools may be simple scripts

Tool Bus Scripts

- Example
  - If A is a finite state machine and P a safety property, then a model checker can verify P for A
  - If B is a conservative abstraction of B, then verification of B verifies A
  - If A is a state machine, and B is a predicate abstraction for A, then B is conservative for A
- How do we know this is sound?
- And that we can trust the computations performed by the components?

Trustworthy Software

- The World is not interested in software
- It's interested in (socio-technic) systems
- Formal analysis of software contributes only part of the evidence required for evaluation or certification of trustworthy systems
- Also need hazard analysis and its kin (FTA, FMEA, HAZOP), consideration of the environment, human factors etc.
- Modern treatment uses idea of a Safety or Assurance Case
  - Explicit claims, evidence, argument
- In critical systems, will often run multiple software channels: primary/backup or operational/monitor
- How much confidence do we need in a verified backup or monitor?

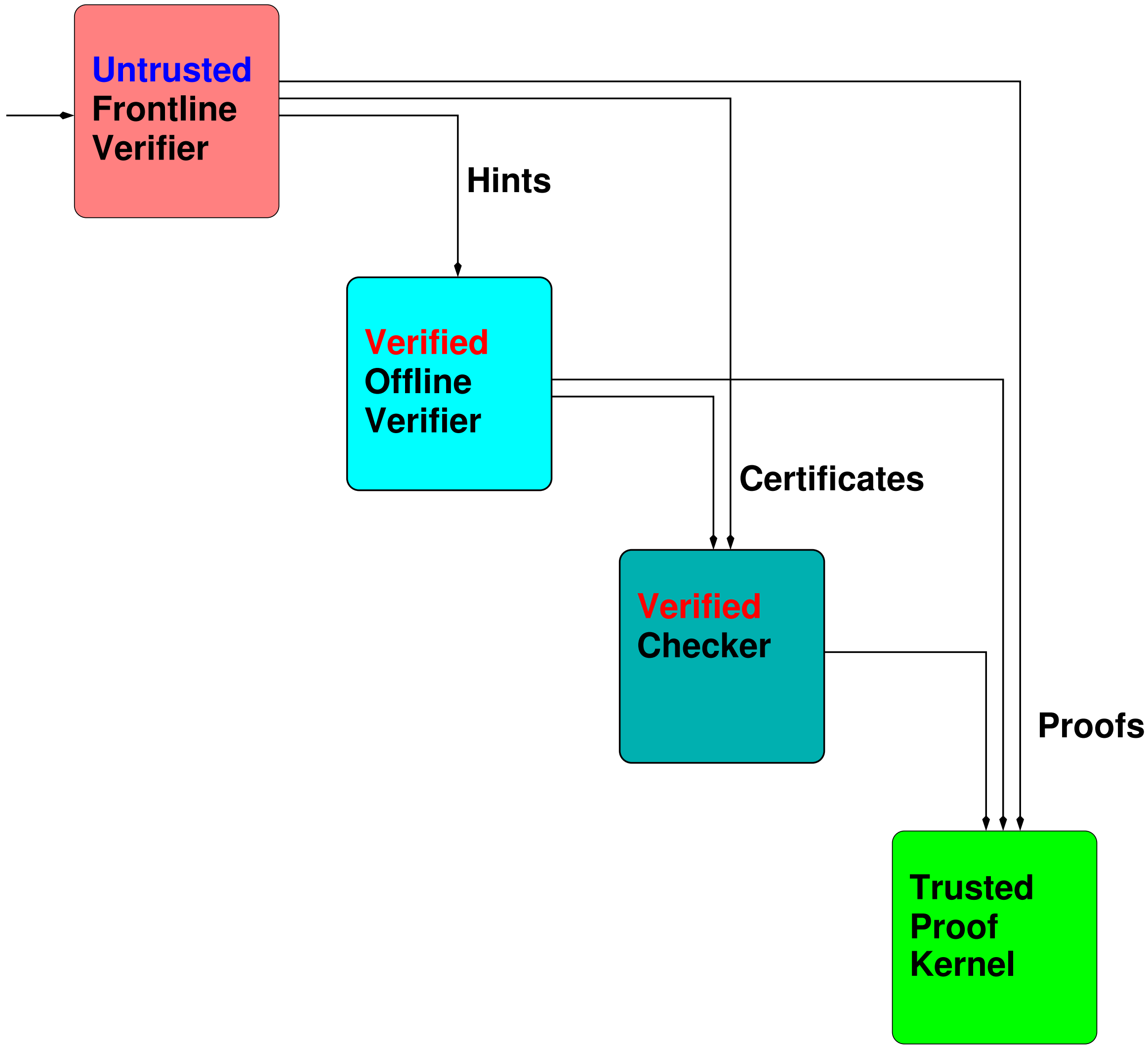
Confidence in Verification

- By consideration of aleatory uncertainty, Littlewood (2008) shows that failures of a reliable (tested) channel A and a possibly perfect (verified) channel B are conditionally independent
- Hence P(failure) $= pfd_A \times pnp_B$
- We have epistemic uncertainty about these parameters, but can estimate
- P(failure) $= C + pfd*_A \times pnp*_B$
  - Where C estimates common mode failures across testing and verification (e.g., misunderstood requirements)
  - $pfd*_A$ is estimated failure rate of tested channel
  - And $pnp*_B$ is estimated probability of unsound verification
- Modest confidence in verification (e.g., $1 - 10^{-4}$) is adequate

Sound Deduction

- Most failures in verification are due to incorrect formalization, bugs in language processing (e.g., typechecking errors), translation errors
- Very few (if any) can be traced to unsound deduction
- But a verification will certainly fail if your tools and deductive components lack the power to complete it
- We need ways to guarantee soundness that do not compromise deductive power
- Many options: trusted core, proof generation and verified checker, computational reflection, diverse verifiers
- Our preference is for verified checkers that are rather powerful, driven by compact hints, or certificates

Verified Reference Kernels



Shankar and Marc Vaucher have verified a modern SAT solver that is executable (modulo lacunae in the PVS evaluator)

An Evidential Tool Bus

- Each tool should deliver evidence for its judgments
  - Could be hints and certificates for a reference kernel
  - Could be reputation ("Proved by PVS")
  - Could be diversity ("using both Yices and Z3")
  - Could be declaration by user
    - ⋆ "By testing," or "Because I say so"
- A full judgment is $T \vdash E : A$, which is the claim that tool instance T provides evidence E for assertion A
- And the tool bus assembles these (on demand)
- Can chain on the evidence component
- To construct evidence for overall analysis for use in an assurance case—hence evidential tool bus
- In fact, an evidential tool bus could be (part of) ideal support environment for assurance cases

Summary

- We've built and used powerful tools
- And linked them with backends and frontends
- But what The World wants are components
- Individual components must be tightly integrated
  (e.g., SMT solvers may do 10^{12} internal interactions)
- But separate components can be loosely integrated
- And this should be done as peers on a bus
- Proposed a fairly specific outline for an Evidential Tool Bus
- We have a built prototype
  - Too heavyweight: used OAA, toolbus metalogic
- Now starting the second iteration
- Please join in