Integrating Verification Components:
The Evidential Tool Bus

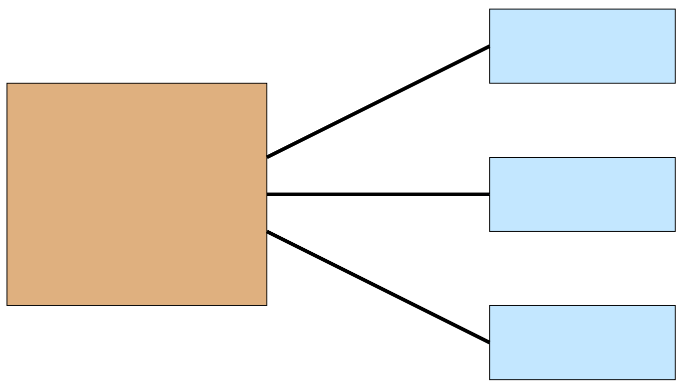
John Rushby

Computer Science Laboratory
SRI International
Menlo Park, California, USA

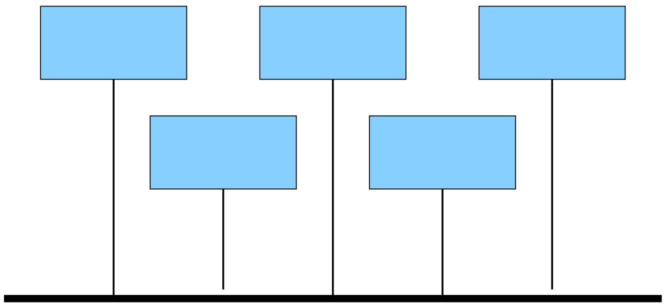
Integrating (Deductive) Verification Components

- In the beginning there was just (interactive) theorem proving
- Then there were VC generators, decision procedures, model checkers, abstract interpretation, predicate abstraction, fast SAT solvers,. . .
- Now there are systems that use several of these
  (SDV, Blast,. . .)
- And in 15 years time. . . ?
- We need an architecture that allows us to make opportunistic use of whatever is out there
  - And to assemble customized tool chains easily
- It should be robust to changes (in problems and tools)
- And should deliver evidence

Two Kinds of Architecture

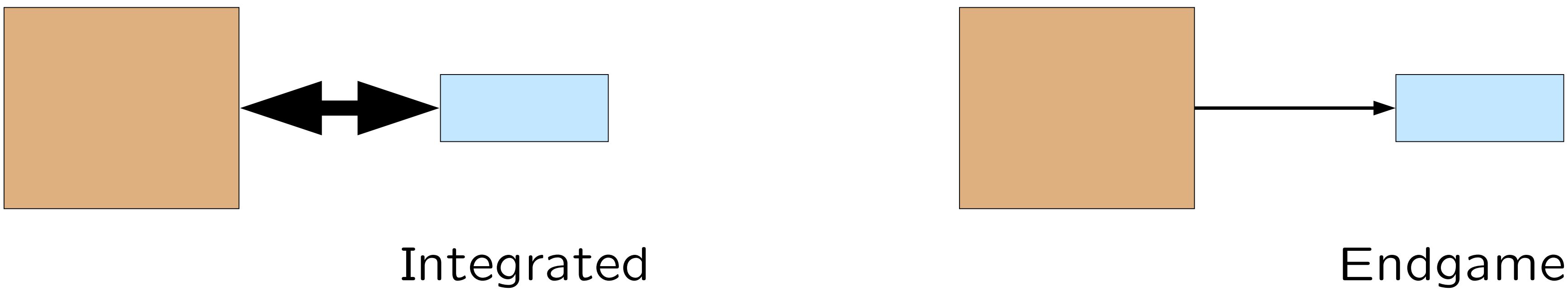


Backends



Bus

And Two Kinds of Backends



A Simple Case: Endgame Verifiers

- A higher level proof manager calls components (typically, decision procedures) to discharge subgoals
- Components return only `verified` or `unverified`
  - Embellishments: proof objects and counterexamples
- But the information returned on failure does not guide the higher-level proof search
  - Other than to cause it to try something else
  - Hence endgame verifiers

Endgame Verifier Examples

1979: Stanford Pascal Verifier and STP used decision procedures for combinations of theories including arithmetic (STP gave rise to Ehdm, then PVS)

1995: PVS used a BDD-based symbolic model checker

2000: PVS used Mona for WS1S

Not only did theorem provers use model checkers as backends, some model checkers grew a front-end theorem prover

1998: Cadence SMV had a proof assistant that generated model checking subproblems by abstraction and composition

And some other systems used an entire interactive theorem prover for the endgame

1999: VSDITLU: used PVS backend to check side conditions on Symbolic Definite Integral Table Look-Up in Maple

Integrating Endgame Verifiers

It's pretty simple

- Provide higher level proof strategies that decompose proof goals into subgoals that can be steered towards the competence of the endgame verifier(s)
- Provide a recognizer for proof goals within the competence of an endgame verifier
- Provide glue code to translate suitable proof goals into the input of an endgame verifier and to interpret its output

Many classes of endgame verifiers are being honed through competition

- Improves performance (be careful)
- Standardizes interfaces
- FO provers, BDD packages, SAT solvers, SMT solvers

Evolution of Endgame Verifiers

Evolution of Endgame Verifiers

- One path grows the endgame verifier and specializes and shrinks the higher-level proof manager
- Example:
  - SAL language has a type system similar to PVS, but is specialized for specification of state machines
    (as transition relations)
  - The SAL infinite-state bounded model checker uses an SMT solver (ICS), so handles specifications over reals and integers, uninterpreted functions
  - Often used as a model checker (i.e., for refutation)
  - But can perform verification with a single higher level proof rule: k-induction (with lemmas)
  - Note that counterexamples help debug invariant

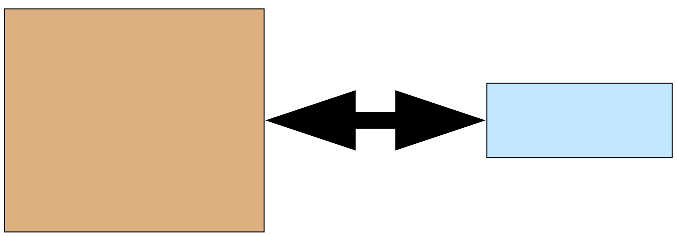
Performance of Evolved Endgame Verifiers

- Biphase Mark Protocol is an algorithm for asynchronous communication
  - Clocks at either end may be skewed and have different rates, jitter
  - So have to encode a clock in the data stream
  - Used in CDs, Ethernet
  - Verification identifies parameter values for which data is reliably transmitted
- Verified in ACL2 by J Moore (1994)
- Three different verifications used PVS
  - One by Groote and Vaandrager used PVS + UPPAAL
  - Required 37 invariants, 4,000 proof steps, hours of prover time to check

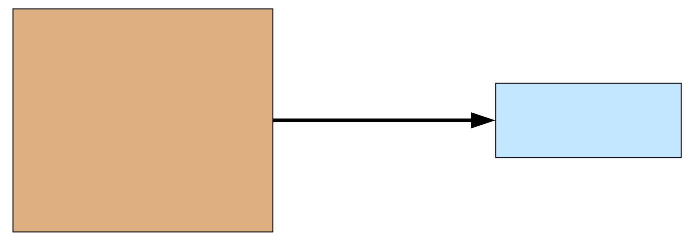
Performance of Evolved Endgame Verifiers (ctd.)

- Brown and Pike recently did it with `sal-inf-bmc`
  - Used timeout automata to model timed aspects
  - Statement of theorem discovered systematically using disjunctive invariants (7 disjuncts)
  - Three lemmas proved automatically with 1-induction,
  - Theorem proved automatically using 5-induction
  - Verification takes seconds to check
- Adapted verification to 8-N-1 protocol (used in UARTs)
  - Additional lemma proved with 13-induction
  - Theorem proved with 3-induction (7 disjuncts)

Recap: Two Kinds of Backends



Integrated



Endgame

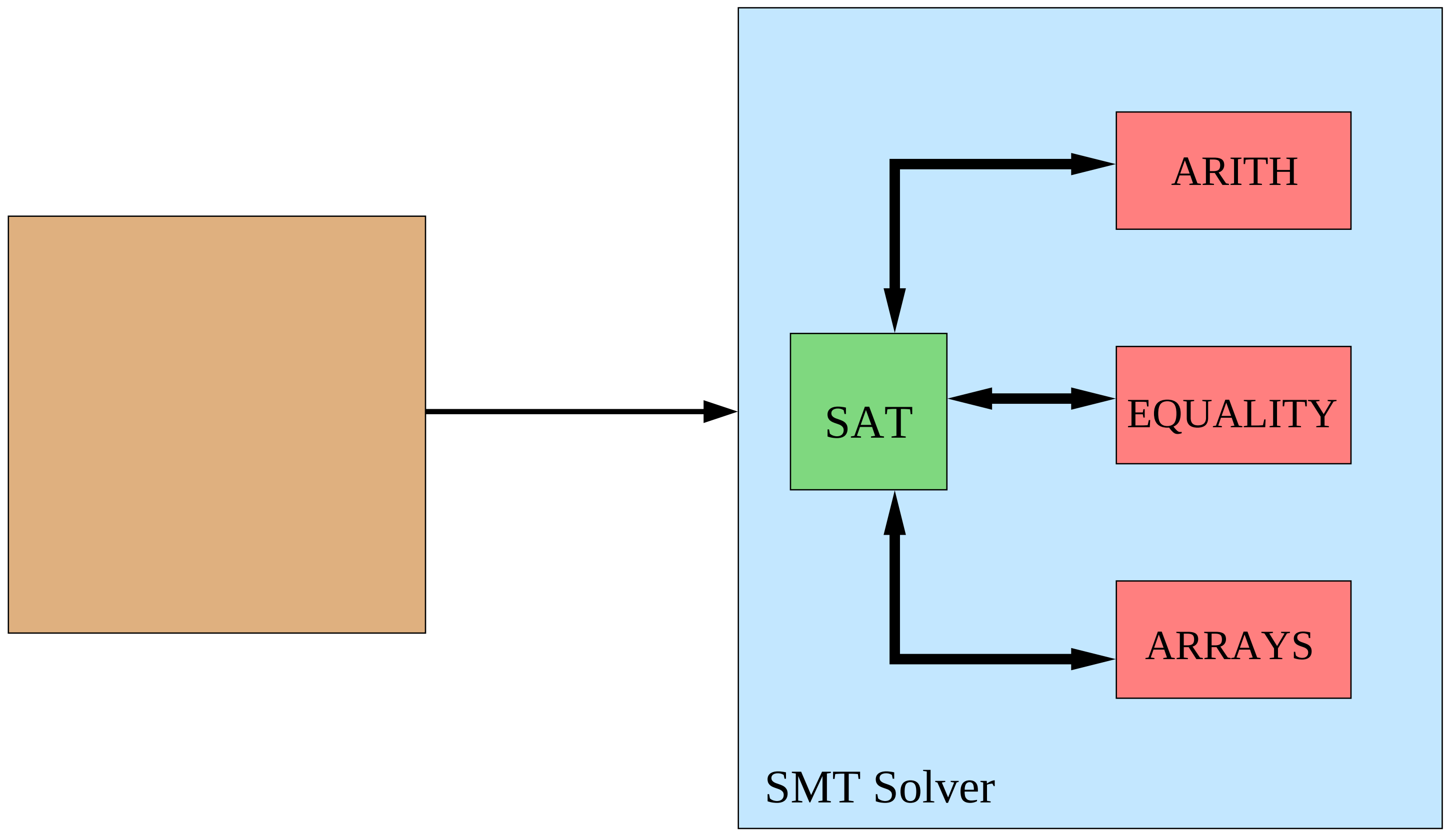
A Difficult Case: Tightly Integrated Components

- Endgame verifiers are easy to integrate because they do not interact with higher level proof search (nor with each other)
- In fact, they are barely integrated
- Classic Boyer-Moore 1986 paper describes tight integration of linear arithmetic decision procedure with Nqthm
  - Two pages of code for endgame decision procedure
  - Became 60 for integrated version
- PVS takes an intermediate path
  - Decision procedures are integrated with the rewriter
  - And used in simplification
- A tractable case is the integration of decision procedures with each other

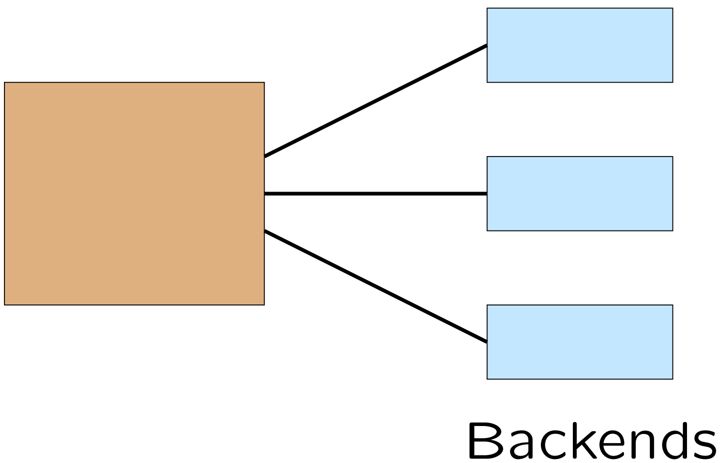
Integrated Decision Procedures and SMT Solvers

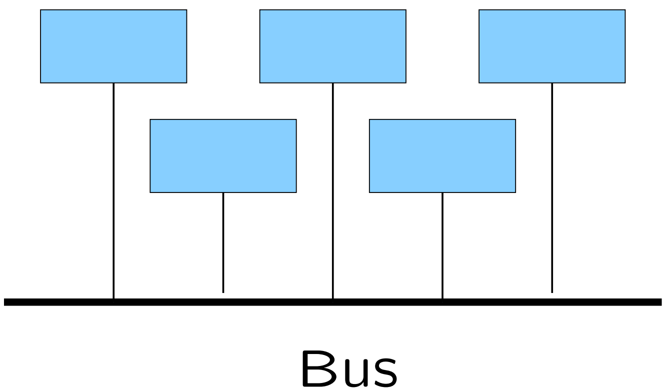
- Long line of research on integrating decision procedures for separate theories so they decide the combined theory
  - Starts with Nelson-Oppen and Shostak methods
  - Activity continues today: theory, presentation, verification, and pragmatics
- Recently extended through integration with SAT solving to yield SMT solvers
  - Interactions are intense (millions per verification)
  - Information from decision procedures must be used efficiently to prune SAT search
  - Impacts design of individual decision procedures
  - Engineering choices explored through benchmarking and competition
- Homogeneous integration: not quite solved, but on the way

SMT Solver Backend



Recap: Two Kinds of Architecture





A New Case: Integration of Heterogeneous Components

- Modern formal methods tools do more than verification
- They also do refutation (bug finding)
- And test-case generation
- And controller synthesis
- And construction of abstractions
- And generation of invariants
- And ...
- Observe that these tools can return objects other than verification outcomes
  - Counterexamples, test cases, abstractions, invariants
  - Hence, heterogeneous

Integration of Heterogeneous Components

- The tools that perform these computations can be used in opportunistic combination
  - E.g., use static analysis and model checking to find bugs before attempting verification
- And can use each other as (scripted) components
  - E.g., use a model checker in test case generation
- And can be used in integrated combinations
  - E.g., software model checkers generally have a C front end with CFG analyzer, a predicate abstractor (which uses decision procedures and possibly a model checker), a model checker and counterexample generator, a counterexample concretizer and refinement generator (using Craig interpolation), and a control loop around the whole lot

Customized (Re)integration

- LAST (Xia, DiVito, Muñoz) generates MC/DC tests for avionics code involving nonlinear arithmetic (with floating point numbers, trigonometric functions etc.)
- It's built on Blast (Henzinger et al)
- But extends it to handle nonlinear arithmetic using RealPaver (a numerical nonlinear constraint unsatisfiability checker)
  - Added 1,000 lines to CIL front end for MC/DC
  - Added 2,000 lines to RealPaver to integrate with CVC-Lite (Nelson-Oppen style)
  - Changed 2,000 lines in Blast to tie it all together
- Applied it to Boeing autopilot simulator
  - Modules with upto 1,000 lines of C
  - 220 decisions

Generated tests to (almost) full MC/DC coverage in minutes

A Tool Bus

- How can we construct these customized combinations and integrations easily and rapidly?
- The integrations are coarse-grained (hundreds, not millions of interactions per analysis), so they do not need to share state
- So we could take the outputs of one tool, massage it suitably and pass it to another and so on
- A combination of XML descriptions, translations, and a scripting language could probably do it
- Suitably engineered, we could call it a tool bus

But . . .

- But we'd need to know the names and capabilities of the tools out there and explicitly to script the desired interactions
  - And we'd be vulnerable to change
- Whereas I would like to exploit whatever is out there
  - And in 15 years time there may be lots of things out there
- That is, I want the bus to operate declaratively
  - By implicit invocation
- And I want evidence that supports the overall analysis (i.e., the ingredients for a safety or assurance case)
- That is, I want a semantic integration

A Formal Tool Bus

- The data manipulated by tools on bus are formulas in logic
- In fact, they can be seen as formulas in a logic
  - The Formal Tool Bus Logic
  - Each tool operates on a sublogic
  - Syntactic differences masked with XML wrappers
- No point in limiting the expressiveness of the tool bus logic
  - Should be at least as expressive as PVS
    - ⋆ Higher order, with predicate, structural, and dependent subtypes, abstract data types, recursive and inductive definitions, parameterized theories, interpretations
  - With structured representations for important cases
    - ⋆ State machines (as in SAL), counterexamples, process algebras, temporal logics ...
    - ⋆ Handled directly by some tools, can be expanded to underlying semantics for others

Tool Bus Judgments

The tools on the bus evaluate and construct predicates over expressions in the logic—we call these judgments

Parser: A is the AST for string S

Prettyprinter: S is the concrete syntax for A

Typechecker: A is a well-typed formula

Finiteness checker: A is a formula over finite types

Abstractor to PL: A is a propositional abstraction for B

Predicate abstractor: A is an abstraction for formula B wrt. predicates ϕ

GDP: A is satisfiable

GDP: C is a context (state) representing input G

SMT: ρ is a satisfying assignment for A

Tool Bus Queries

- Tools publish their capabilities and the bus uses these to organize answers to queries

  Query: `well-typed?(A)`

  Response: `PVS-typechecker(...)  |- well-typed?(A)`

  The response includes the exact invocation of the tool concerned

- Queries can include variables

  Query: `predicate-abstraction?(a, B,` ϕ`)`

  Response:

  `SAL-abstractor(...) |-predicate-abstraction?(A, B,` ϕ`)`

  The tool invocation constructs the witness, and returns its handle A

Tool Bus Operation

- The tool bus operates like a distributed datalog framework, chaining on queries and responses
- Similar to SRI AIC's Open Agent Architecture
  - And maybe similar to MyGrid, Linda, . . . ?
- Can have hints, preferences etc.
- Tools can be local or remote
- Tools can run in parallel, in competition
- The bus needs to integrate with version management

Scripting

Three levels of scripting

Tools:

- Tools should be scriptable
- Better functionality, performance than wrappers
- E.g., SAL model checkers are Scheme scripts over an API
- Test generator is another script over the same API

Wrappers:

- Some functionality can be achieved by a little programming and maybe some tool invocation

Tool Bus:

- Scripts are chains of judgments

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 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?

An Evidential Tool Bus

- Each tool should deliver evidence for its judgments
  - Could be proof objects (independently checkable trail of basic deductions)
  - Could be reputation ("Proved by PVS")
  - Could be diversity ("using both ICS and CVC-Lite")
  - Could be declaration by user
    - "Because I say so"
    - "By operational experience"
    - "By testing"
- And the tool bus assembles these (on demand)
- And the inferences of its own scripts and operations
- To deliver evidence for overall analysis that can be considered in a safety or assurance case—hence evidential tool bus

The Evidential Tool Bus

- There should be only one evidential tool bus
- Just like only one WWW
- How to do it?
  - Standards committee?
  - Competition and cooperation!
- Probably not difficult to integrate multiple buses
  - Need agreement on ontologies
  - Fairly minimal glue code to link them together
- We'll be building one
  - Initially to integrate PVS and SAL
  - And to reconstruct Hybrid-SAL
- Will appreciate your input, and hope you'll like to use it, and to attach your tools

Thank you!

- And thanks to Bruno Dutertre, Grégoire Hamon, Leonardo de Moura, Sam Owre, Harald Rueß, Hassen Saïdi, N. Shankar, and Maria Sorea
- You can get our tools and papers from `http://fm.csl.sri.com`