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An Overview of SAL

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Historical Context

- SAL is next in a succession of verification systems (deductively-based systems to support mechanized formal methods) developed at SRI: HDM, (STP), Ehdm, PVS, (InVeSt),. . .
- Each was more powerful, more cost-effective, and more widely-used than its predecessor
- Hope to achieve the same for SAL
- And maybe even to "get off the curve"
  (at least, for concurrent systems)
- PVS is a component of SAL

Back to Basics: Mathematics in Engineering

- Build mathematical models of a 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 (cf. CFD)
- Used in the design loop (exploration, debugging) as well as for verification
- Need to be sure that design is implemented correctly, and that environment and requirements models are "correct"
    - These are separate concerns

Formal Methods

- Same idea
- The applied math of Computer Science is formal logic
- So the models are formal specifications in some logical system: $\textit{environment} + \textit{design} \vdash \textit{requirements}$
- And calculation is mechanized by automated deduction: theorem proving, model checking, etc.
    - Undecidable in general; need human guidance
    - Decidable problems have much greater computational complexity than mechanizing continuous mathematics
- Must often trade off accuracy or completeness of the model for tractability and automation of calculation
    - E.g., downscale with a machete to allow model checking

Formal Methods for Assurance and Certification

- Formal calculations can cover all modeled behaviors, even if numerous or infinite (the power of symbolic reasoning)
  - Whereas complete testing is infeasible
  - And incomplete testing is unreliable
- Want highly accurate models, so that formal calculations support strong claims
- 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

Adoption of Formal Methods for Assurance

- Must use accurate models
- Whose analysis generally requires interactive theorem proving
  - Automatic (heuristic) theorem proving seldom succeeds
    (so human guidance is provided indirectly)
- Driving a theorem prover is a specialized skill
- Often more about the prover than the design being examined
  - (Most) engineers will not do it
- FM may provide improved assurance, but at additional cost
  (unless there is regulatory relief on other processes)
- Provides few other benefits (so not used in the design loop)
  - Difficult to distinguish causes of failure:
    flawed proof, or flawed design?
- Overall: a difficult sale

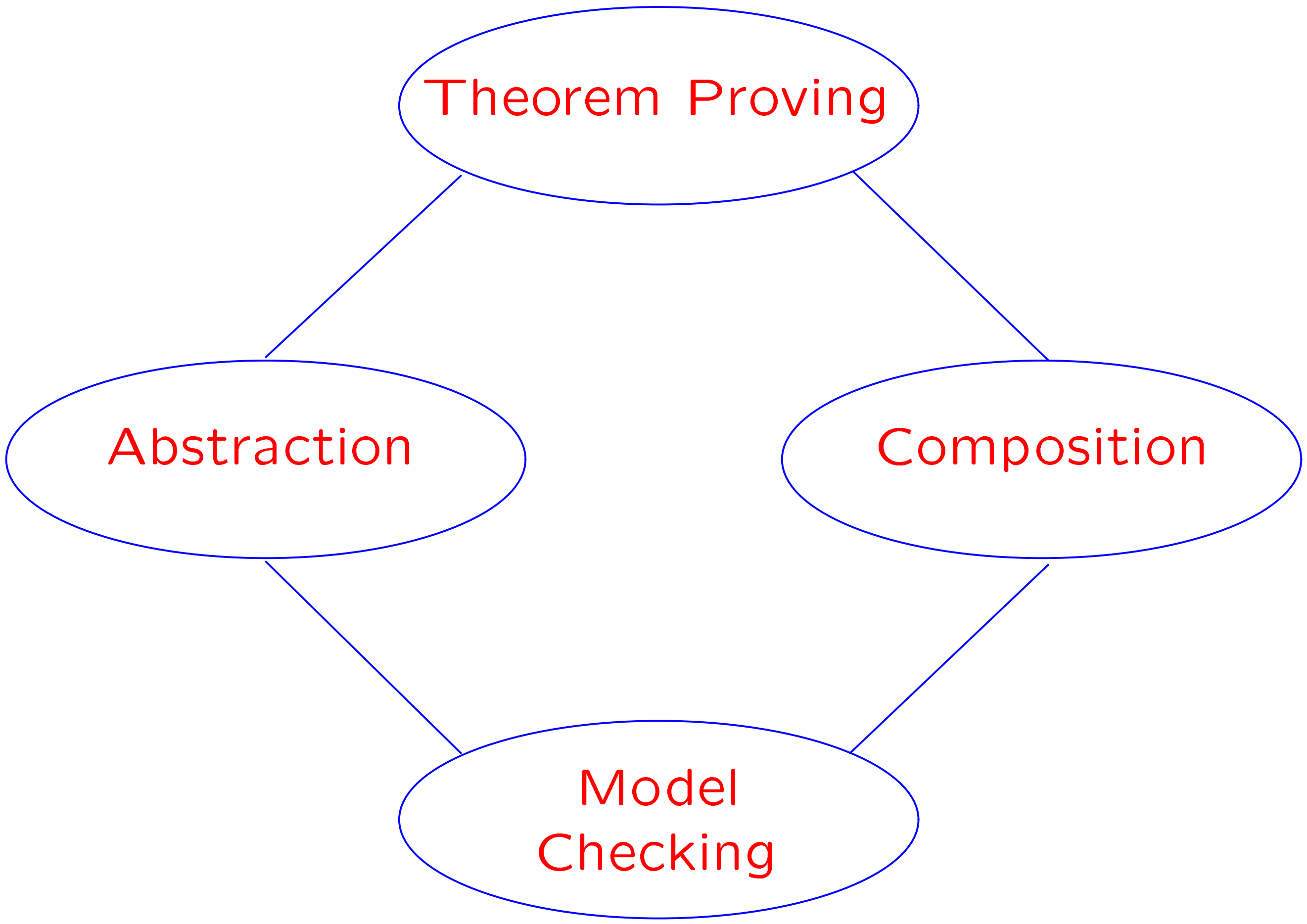
Adoption of Formal Methods Elsewhere

- Formal methods are quite widely adopted in certain industries (hardware, telecoms) for debugging (and design exploration)
- When the goal is debugging
  - Can use highly simplified or approximate models
  - So that highly automatic methods become available
    - ⋆ E.g., finite-state model checking
    - ⋆ Which also provides counterexamples
  - Interaction is through construction of the simplified models—this is like programming or design, and engineers don't mind doing it
- Large benefits in cost, reliability, and time to market
- But with simplified models, the failure to detect bugs does certify their absence—so no use for assurance

Overcoming Barriers to Adoption in Certification

- Methods must work for both debugging and assurance
  - Debugging provides the cost benefit
- Must be automated
  - Use model checking where possible
  - Theorem proving must be automatic
    - ⋆ Heavy use of decision procedures, quantifier elimination
    - ⋆ But also need heuristics, which will fail sometimes
    - ⋆ So need a framework in which a failed proof is not catastrophic
- Interaction must be through modeling
- Correctness-preserving abstraction is the key

Abstraction is the Bridge Between Deductive and Algorithmic Methods



Automated Abstraction

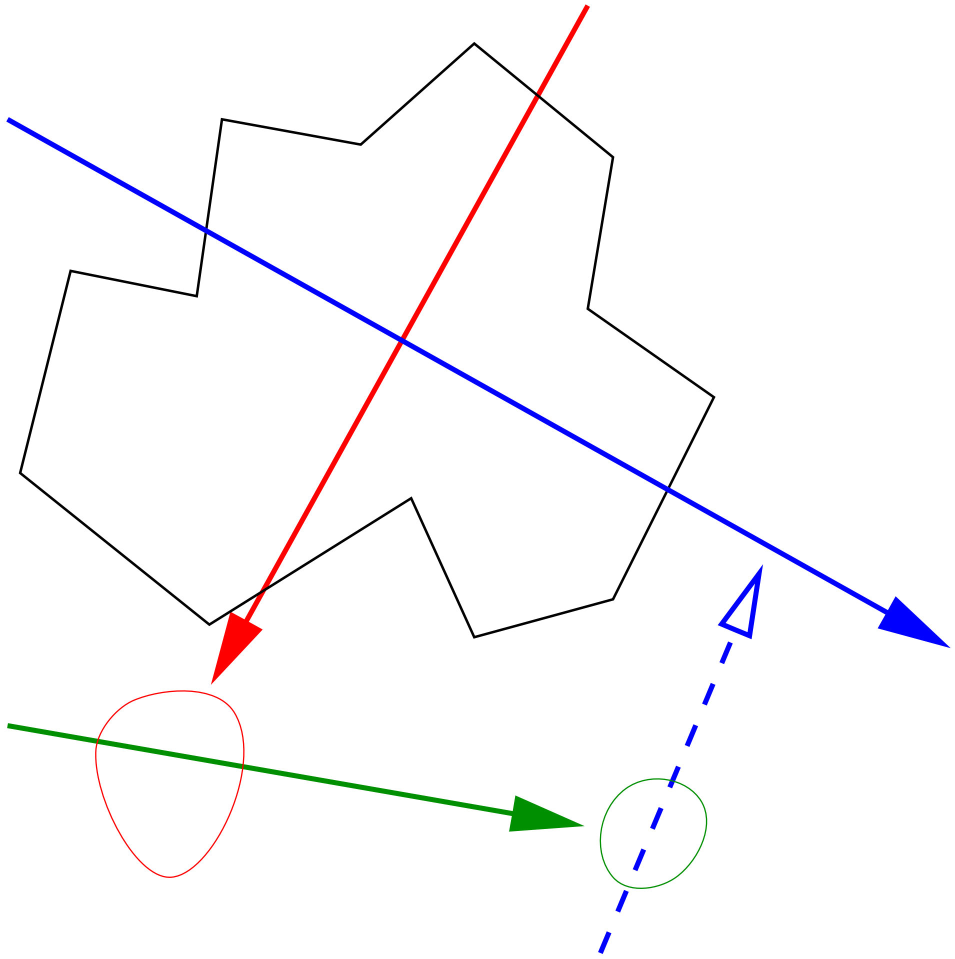
- Can often construct a simplified model that is faithful to the original (for a given property of interest)
  - The reduced model can by analyzed by model checking
  - And failure to detect bugs does certify their absence
- These reduced models can be constructed automatically by mechanized predicate abstraction (user suggests predicates)
  - The construction is done by trying to prove lots of little theorems (verification conditions)
    - ⋆ If a proof fails, reduced model will be more conservative, but is often still good enough
  - Already available in PVS as (abstract-and-mc)
- But 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 (another component of SAL)

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!

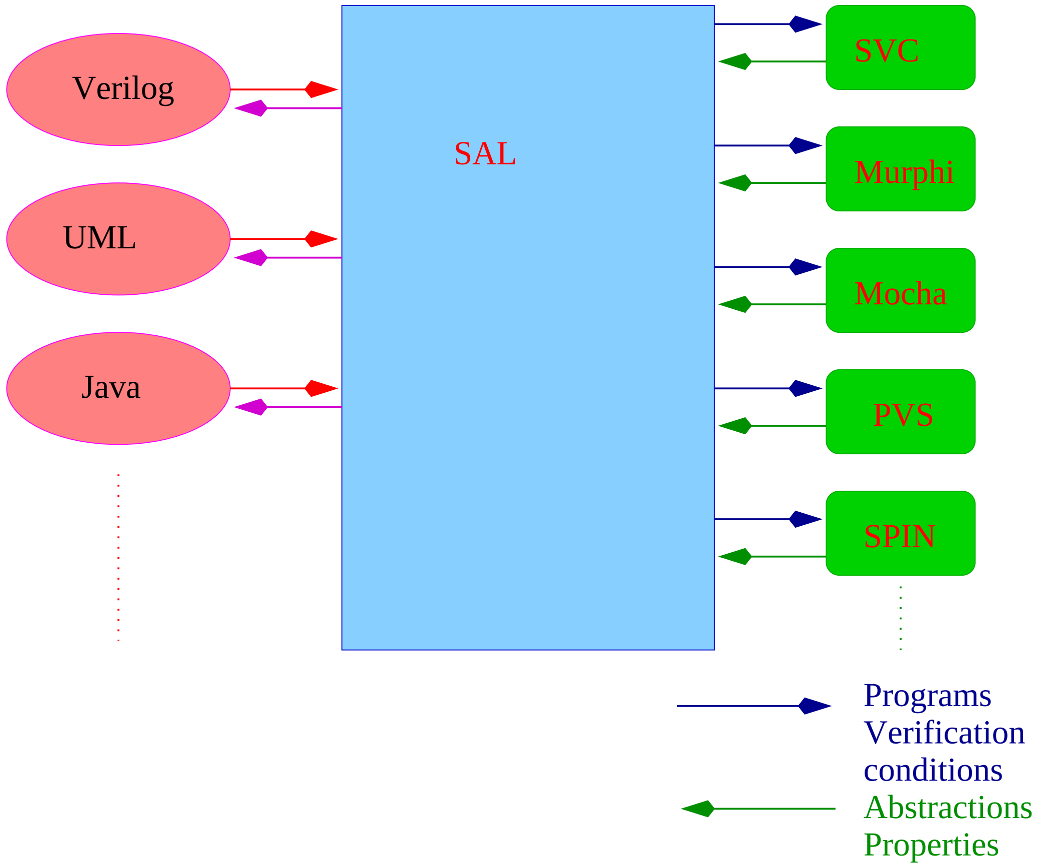
- Recast the goal as one of calculating and accumulating properties about a design (symbolic analysis)
- Rather than just verifying or refuting a specific property
- Properties convey information and insight, and provide leverage to construct new abstractions
  - And hence more properties
- Requires 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

Aside: Related Approaches

- Symbolic evaluation has some of the same benefits as integrated abstraction
  - Results of symbolic evaluation are considered in reviews (rather than have reviewers mentally execute the code)
  - Theorem proving is used to simplify expressions during evaluation
    - ⋆ Failure is not catastrophic
  - Used by Rockwell Collins for AAMP and JEM avionics and Java processors
- Domain-specific methods also seem viable (e.g., checkers for tabular specifications—lots of verification conditions) but these generally establish only weak properties
- PVS is being enhanced to do these better

SAL Architecture

The SAL Language serves as a hub



Not all of these boxes are populated yet

SAL Language

- A way to specify transition relations and their properties
- Developed in a loose collaboration with Stanford (David Dill), Berkeley (Tom Henzinger), and Verimag (Saddek Bensalem)
  - Still converging: slightly different versions at SRI and Stanford
  - InVeSt has adopted the SAL language
- Has definitions, guarded commands, modules, synchronous and asynchronous composition

Current Translators (Prototypes)

- SAL to PVS
- SAL to SMV
  - Validated by César Muñoz at ICASE on "autopilot" example (SPIN 99): as efficient as hand-written SMV
- SAL to Java (for animation)
- Verilog to SAL (under development by Vijay Ganesh)
- All implemented in Java: currently being reconfigured to drive all translators off a common grammar and abstract syntax

Other Components

- SAL typechecker nearing completion
  - Like PVS, uses theorem proving to discharge some extended typecheck conditions (e.g., absence of causal loops)
- Concretization of counterexamples and reachable statesets returned from SMV is being prototyped
- And experimental invariant generation/strengthening
  - Can do 2-process bakery automatically
- Efficient predicate abstraction available in PVS 2.3
- Goal is to have a coherent system available for distribution this year

Reading, Effectiveness

- Predicate abstraction in PVS
  - Abstract and Model Check While You Prove, by Hassen Saïdi and N. Shankar, CAV '99 (LNCS 1633)
  - A tutorial description using Bakery in PVS at `http://www.csl.sri.com/~rushby/movep2k.html`
  - Solves BRP automatically in a minute or so
- InVeSt (uses LCS, MONA)
  - Also solves BRP automatically in a minute or so, CAV 98, CAV 99

Related Systems

- David Dill's treatment
  - Variant on predicate abstraction; can do garbage collector automatically in an hour or so, CAV '99
- Ken McMillan's treatment
  - Lightweight theorem proving whose subgoals are discharged by model checking; can do Tomosulo automatically, CAV 00
- Bandera (Matt Dwyer, John Hatcliffe, Kansas State)
  - Uses abstract intepretation, works on Java, ICSE 00
- SLAM (Tom Ball, Sriram Rajamani, Microsoft Research)
  - Boolean programs, WAVE 00
- Veritech (Shmuel Katz, Orna Grumberg, The Technion)
  - Another intermediate rep'n; eclectic front and backends

Summary

Goals and mechanisms of SAL

- Serve the needs of both verification and refutation
- Analyses must be almost completely automatic
- With interactive guidance expressed in terms of the model, its predicates, and its properties
- Use iterated, integrated application of abstraction, invariant generation, theorem proving, model checking
  - Model checking good for global properties
  - Theorem proving good for propagating local properties
- Using (modified) off the shelf tools where possible
- Linked through the SAL intermediate language

Prospects for Formal methods in Certification

- Mechanized formal methods are feasible (and used today) for simple designs (e.g., nuclear shutdown), and for implementations (cf. B, SACRES)
- But the challenge is complex designs (e.g., fault tolerant, partitioning, IMA architectures)
- Though non-critical but "sensitive" systems could become a technology driver (cf. E-commerce)
- Combined methods based on automated abstraction seem the best (the only?) hope
  - Traditional (labor intensive) methods will be outpaced by the growth in critical systems
- Tool qualification will be an issue
  - Need independently checkable products (proof objects)

Excitement Grows As The Model Checker Is Applied To The Final Abstraction