Verification by Theorem Proving

Issues and Challenges

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Verification by Theorem Proving

Issues and Challenges

When I wrote the abstract:

- ?
- ?
- ?
- ?
- ?
- ?

Verification by Theorem Proving

Issues and Challenges

Today's talk

- What is "verification by theorem proving"?
- Direct theorem proving versus embedded theorem proving
- Choice of logic, proof methodology, proof engines, middleware
- Debugging versus proof of correctness, proof as IP
- Theorem provers as tool implementation platforms
- Conclusions, opinions

What is verification by theorem proving

- Use of a theorem prover to aid verification.
  Here's an arbitrary selection of applications:

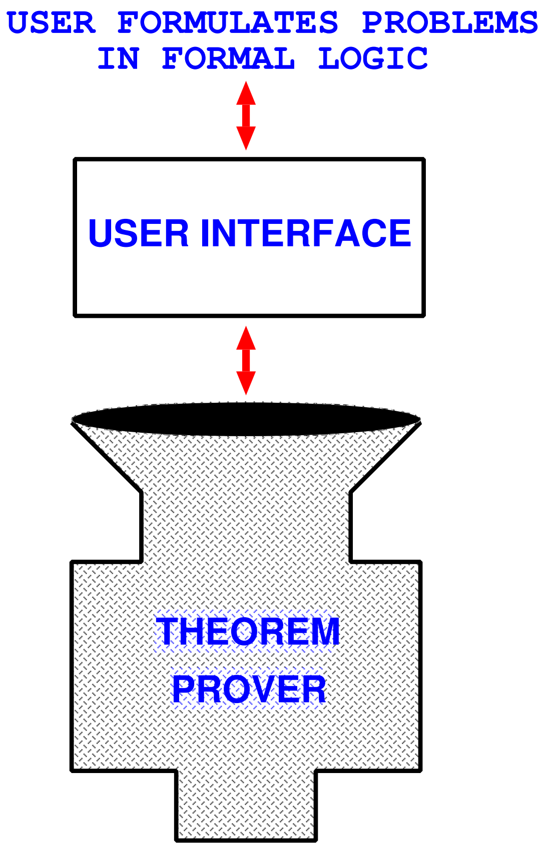
  parts of processors (e.g. pipelines, floating point units), whole processors, crypto hardware, security protocols, synchronization protocols, distributed algorithms, synthesis, system properties (e.g. separation), compilers, code transformation, high level code, machine code, proof carrying code, meta-theorems about property/hardware/software/design languages, flight control systems, railway signalling, . . .

- Broad interpretation of theorem proving includes most FV methods

Verification task	Theorem proving technique	Theorems proved
boolean equivalence	propositional algorithms (BDD, SAT etc)	$\vdash(B_1 = B_2)$
model checking	fixpoint calculation, automata algorithms etc	$\vdash(\mathcal{M} \models P)$
assertion checking	decision procedures, first-order methods	$\vdash f$
proof of correctness	induction, heuristic search, interactive proof	$\vdash \mathcal{F}$

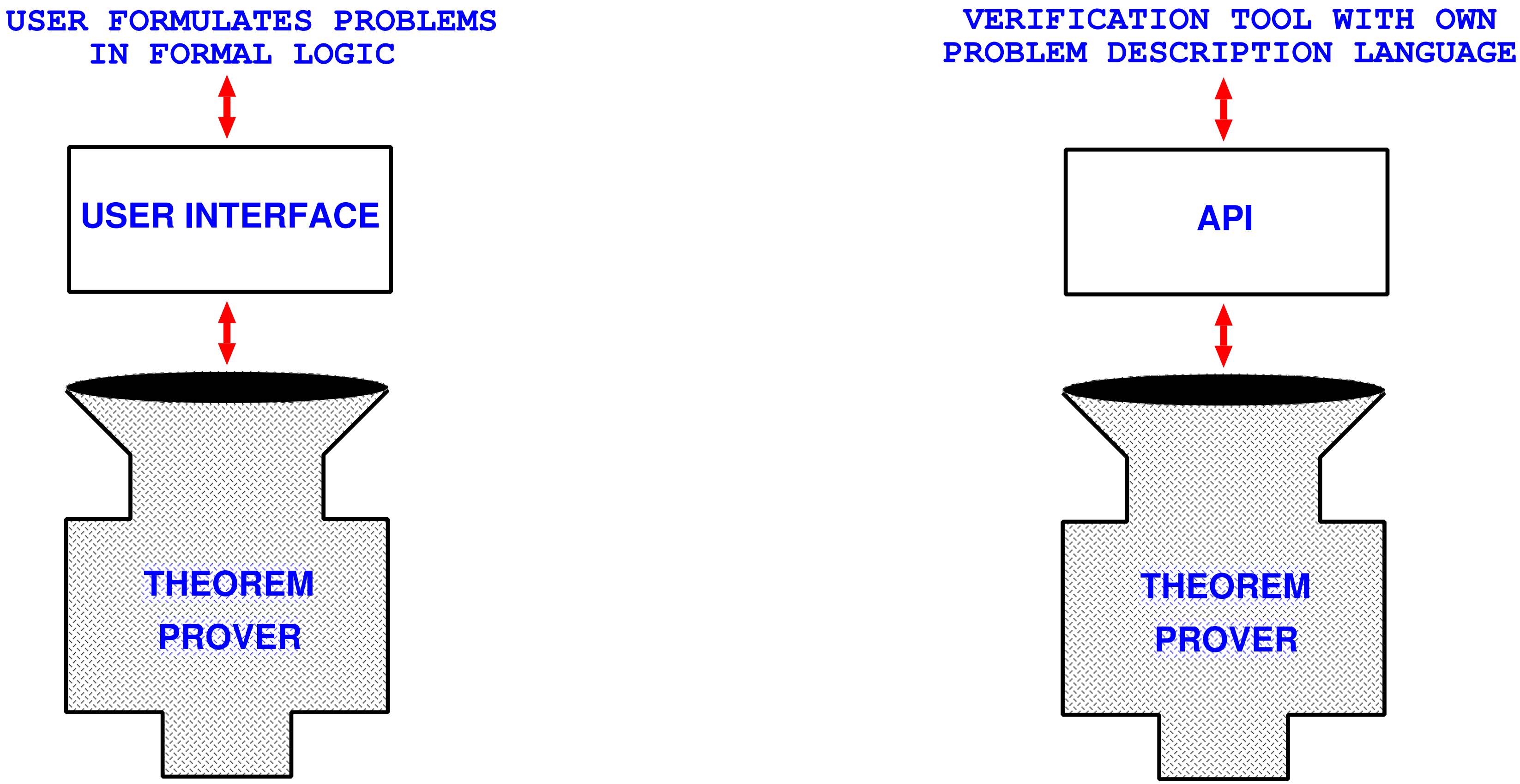
Direct versus embedded theorem proving

- Theorem prover can be used directly



Direct versus embedded theorem proving

- Theorem prover can be used directly . . . . or embedded in a tool



Direct and embedded theorem proving

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- Embedded proving common for verification

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  - substantial user guidance needed
  - e.g. processor proofs, verification of floating point algorithms
  - e.g. non verification proofs: Gödel's theorem, consistency of AC
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  - e.g. non verification proofs: Gödel's theorem, consistency of AC
- Embedded proving common for verification
  - can invoke automatic 'proof engines'
  - hides formal logic stuff
  - slot into standard design/verification flows

Direct theorem proving

- Need to formulate problems in logic
- Issue: how powerful should the logic be
- Need to drive the theorem prover to create proof
- Issue: design of user interface

Direct theorem proving

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  - can code in ‘raw logic’
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- Issue: design of user interface
  - fancy GUIs are good for beginners, but get in the way for experts
  - good for humans not necessarily good as API for tools

Recent quote from an EDA tool user group (ESNUG)

I don't know why tool vendors like GUIs so much.
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- This is not about theorem proving ....but maybe it applies?

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- Many provers support some kind of higher-order logic
  - because of types and support for functional programming
- Issue: should there be a standard logic?
  - lots of choices:
    - ∗ first order versus higher-order
    - ∗ classical versus constructive
    - ∗ typed versus untyped

Choice of logic and embedded proving

- Switching proof methodology harder than switching language

- Maybe choice of logic not really an issue

- Embedding prover in a verification tool hides logic from users

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- Embedding prover in a verification tool hides logic from users
  - but not from tool developers
  - tool developers are usually familiar with logic and semantics

Choice of theorem prover interaction method (1)

- Orthogonal choices:
  - top-down (backward or goal-directed) versus bottom-up (forward)
  - declarative versus imperative

Choice of theorem prover interaction method (1)

- Orthogonal choices:
  - top-down (backward or goal-directed) versus bottom-up (forward)
  - declarative versus imperative
- Top-down
  - also known as “backward” or “goal-directed” proof
  - split goal-to-be-proved into subgoals
  - split subgoals into sub-subgoals
  - proceed until subgoals are decidable
- Bottom-up
  - also known as “forward proof”
  - start from axioms
  - combine using rules of inference
  - eventually deduce goal to be proved

Choice of theorem prover interaction method (2)

- Orthogonal choices:
  - top-down (backward or goal-directed) versus bottom-up (forward)
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Choice of theorem prover interaction method (2)

- Orthogonal choices:
  - top-down (backward or goal-directed) versus bottom-up (forward)
  - declarative versus imperative
- Declarative: give a sequence lemmas or subgoals leading to conclusion
  - for top-down, something like:
    Goal follows if *goal-1* which follows if *goal-2* · · · which follows if *goal-n* which is trivial
  - for bottom-up, something like:
    Lemma-1 hence *Lemma-2* hence · · · hence *Theorem*
  - pioneered by Mizar proof checker; like textbook proofs; readable
  - good for checking proofs, less good for finding them
- Imperative: write a proof-generating program in a 'tactic language'
  - something like:
    apply induction then simplify and invoke resolution
  - typically unreadable prover-specific instructions
  - good for finding proofs and for programming verification algorithms

Choice of theorem prover interaction method (summary)

- Top-down versus bottom-up

- Declarative versus imperative

Choice of theorem prover interaction method (summary)

- Top-down versus bottom-up
  - top-down better for direct proof
  - bottom-up good for ‘fine grain’ proof scripts (cf. machine code)
  - LCF-like systems synthesise forward proofs via backward scripts

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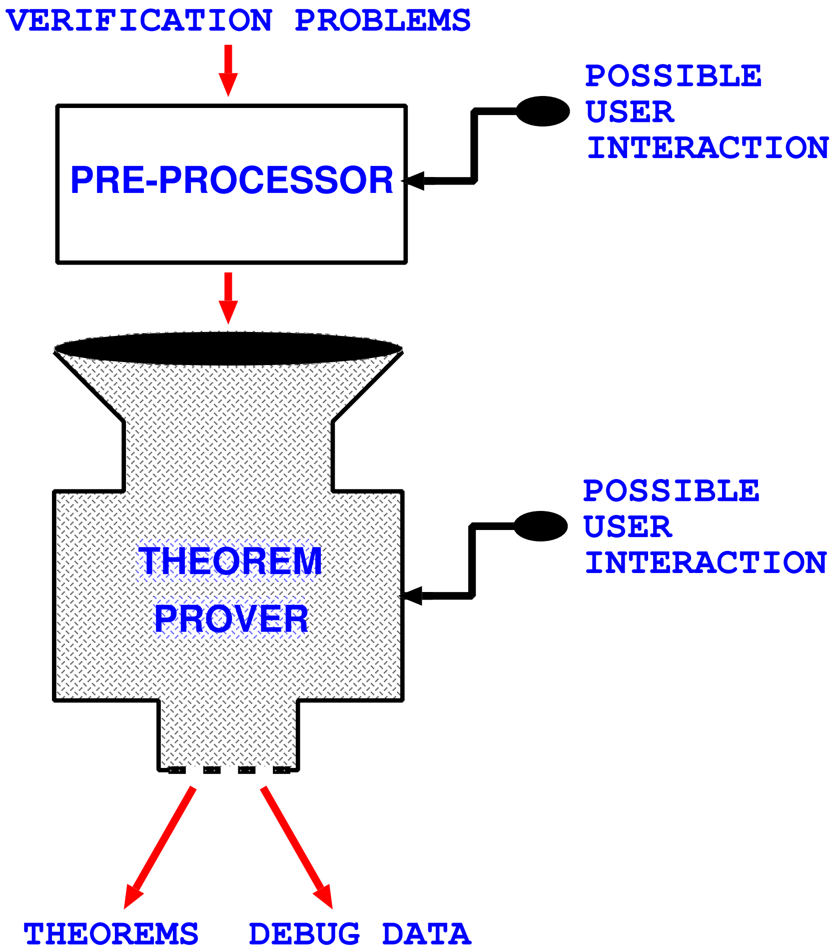
A common verification scenario



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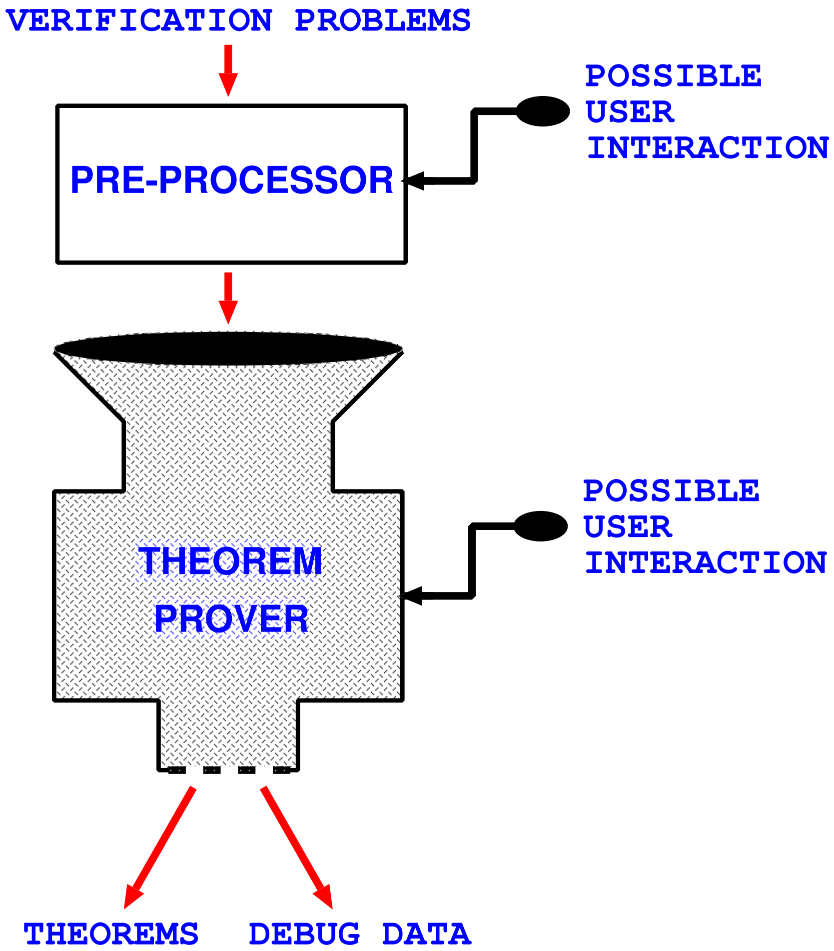

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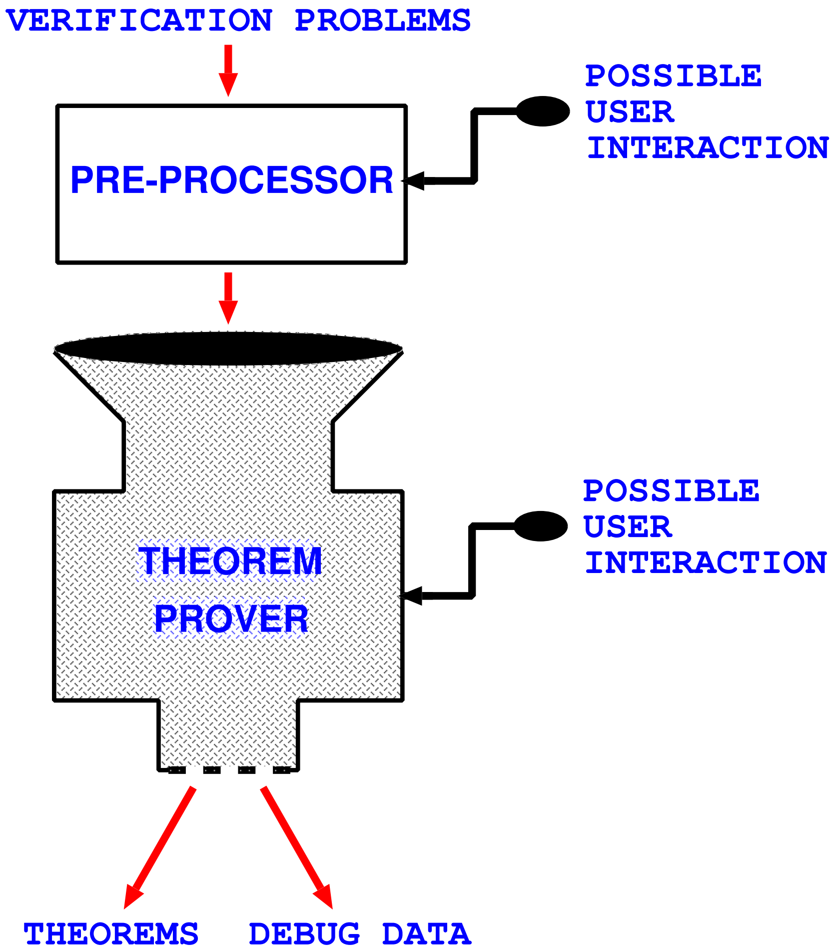

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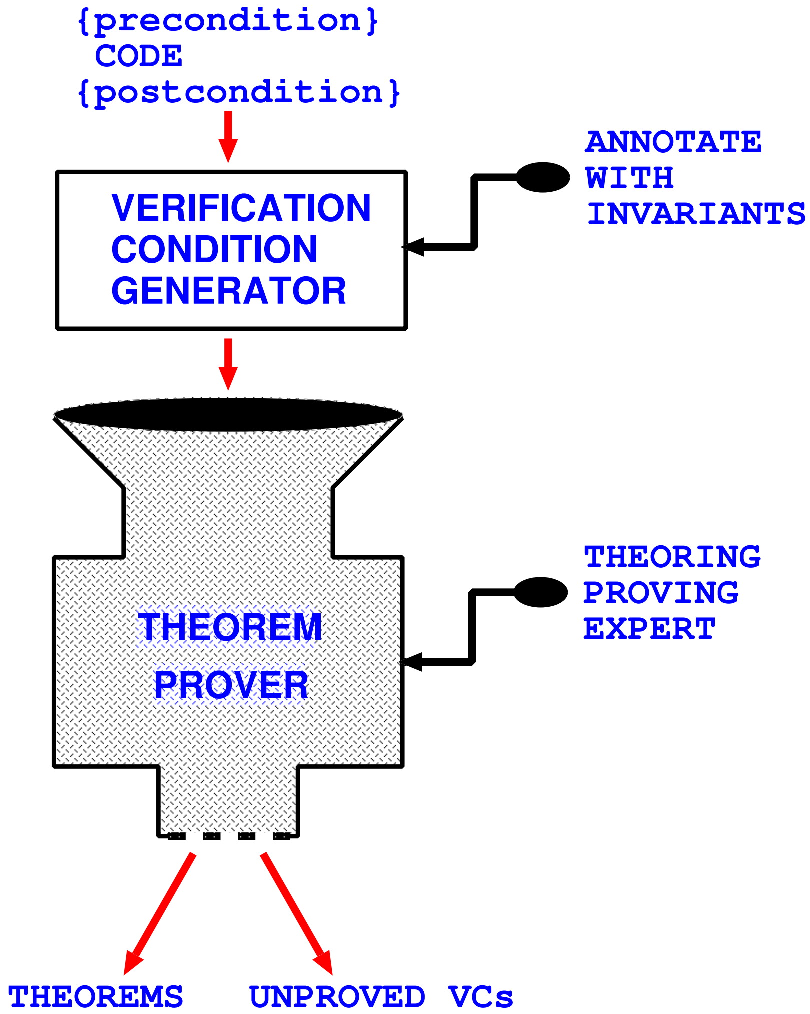
- Ideally no user interaction
- Pre-processor may need extra input (e.g. pragmas, annotations)
- Prover may need lots of help

Example 1


{precondition}
CODE
{postcondition}
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CONDITION
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ANNOTATE
WITH
INVARIANTS
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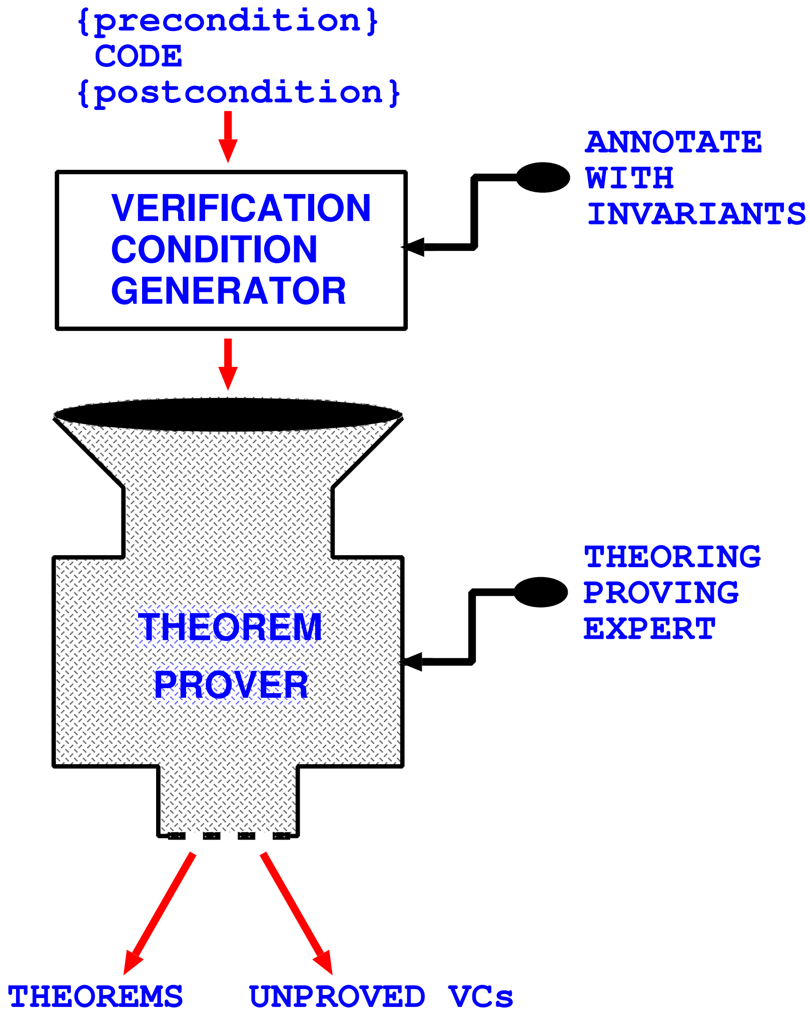

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  - user adds annotations
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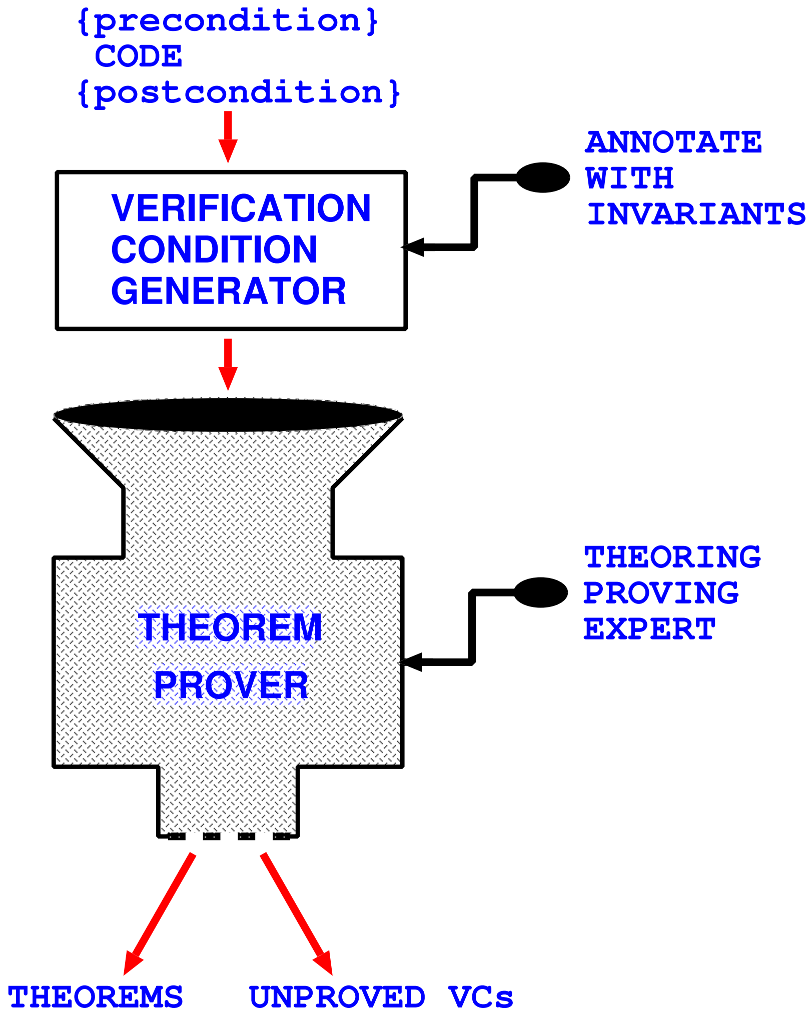

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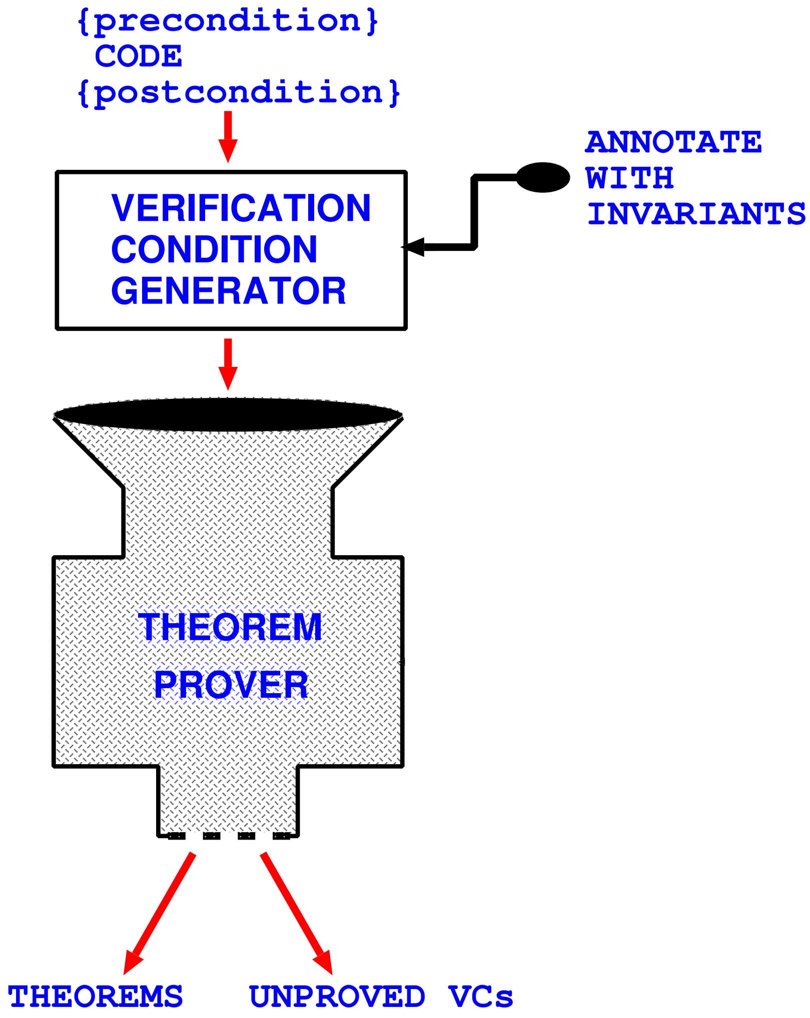

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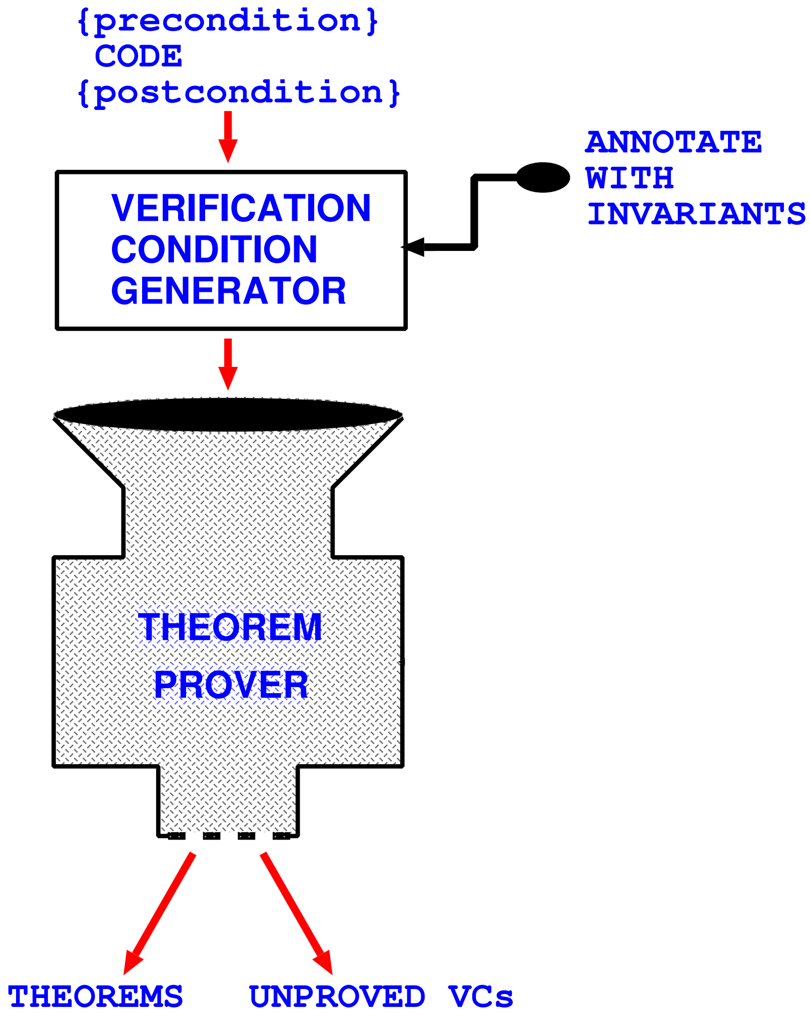

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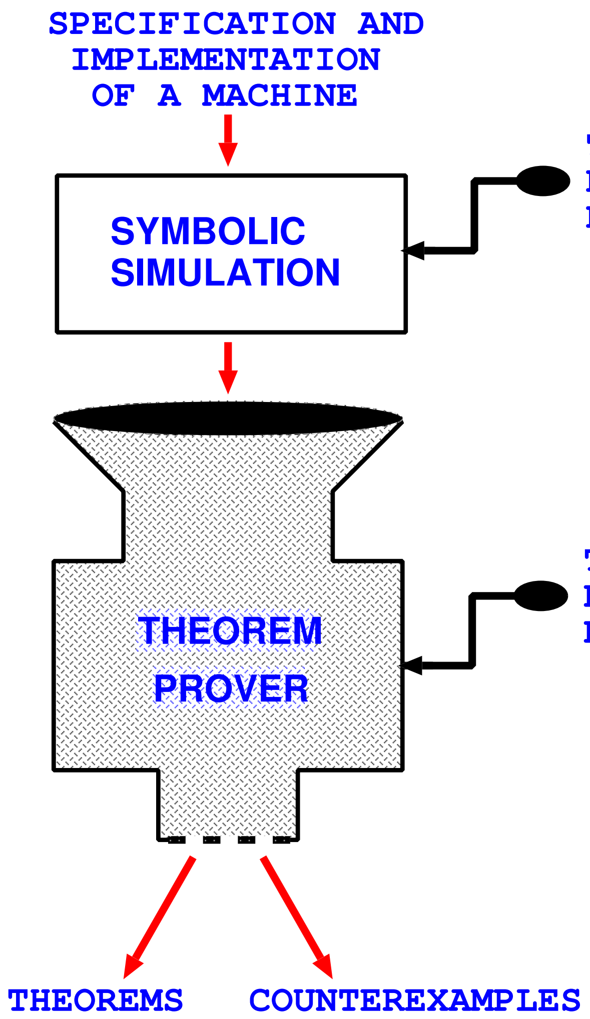
- Extended static checking (ESC)
- Maybe basis for deeper ABV?

Example 2


SPECIFICATION AND
IMPLEMENTATION
OF A MACHINE
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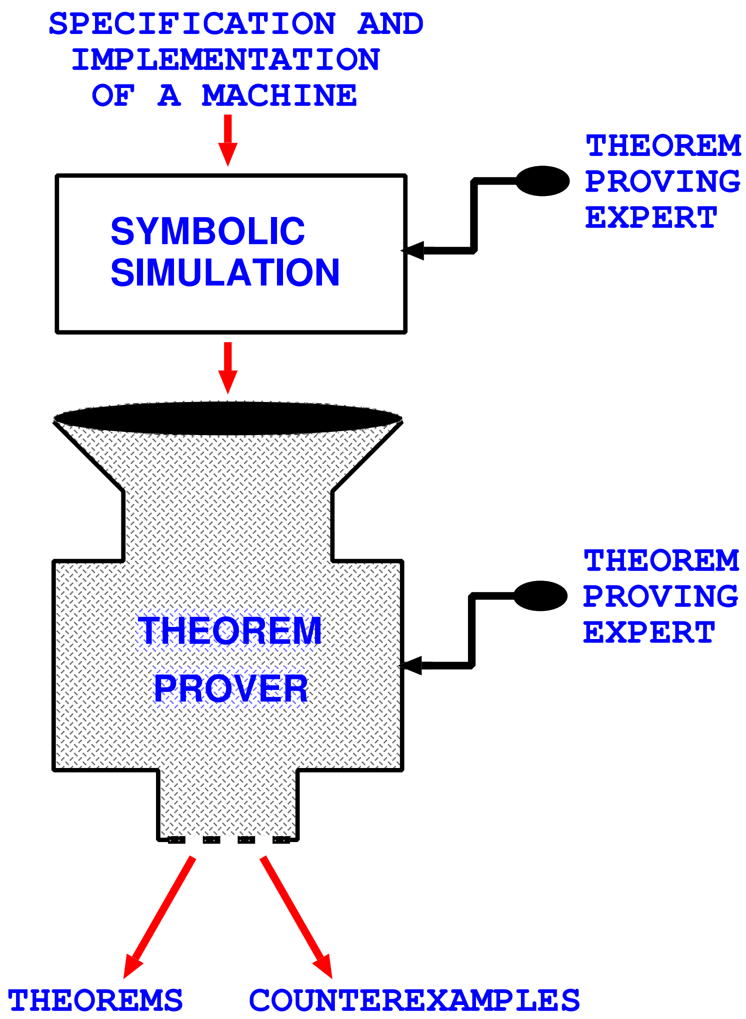

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  - specification transition function
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- Prove equivalence

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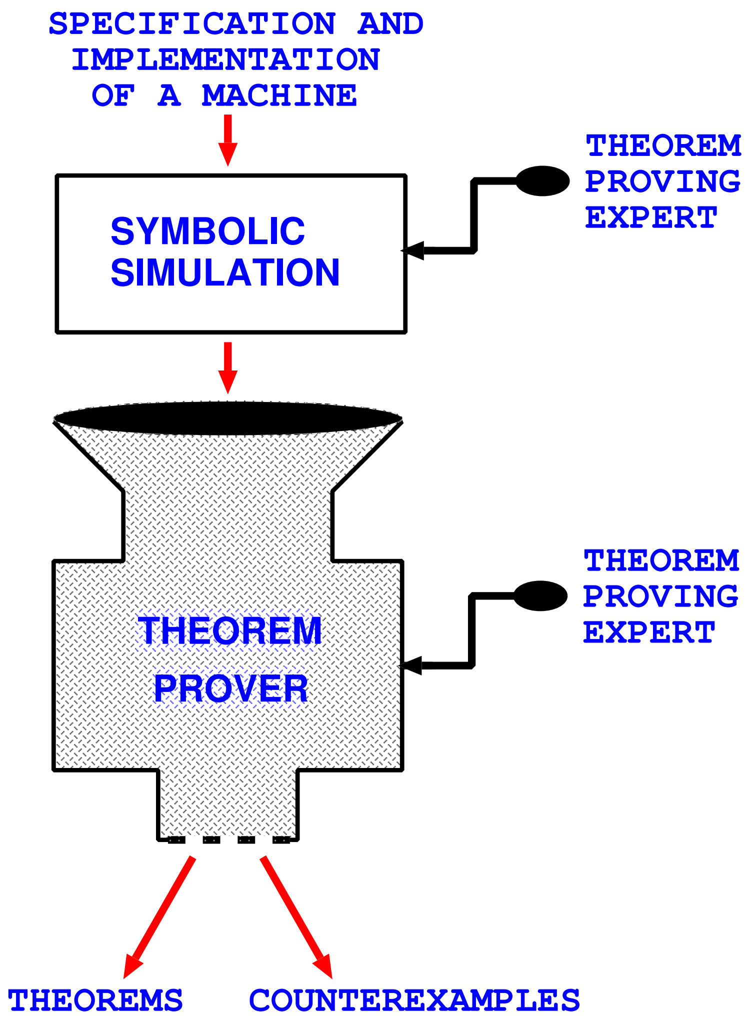

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  - ACL2, HOL, PVS
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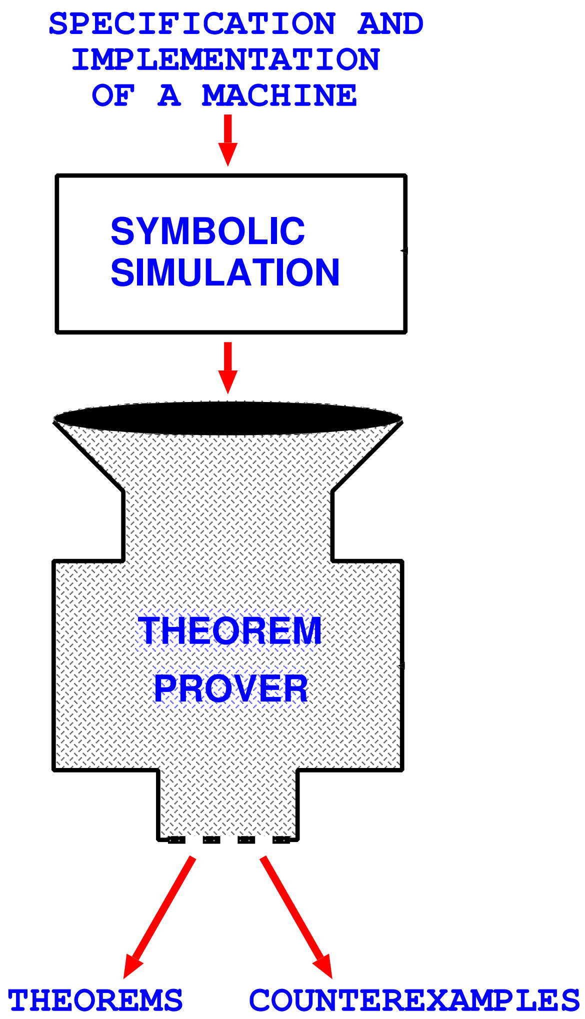

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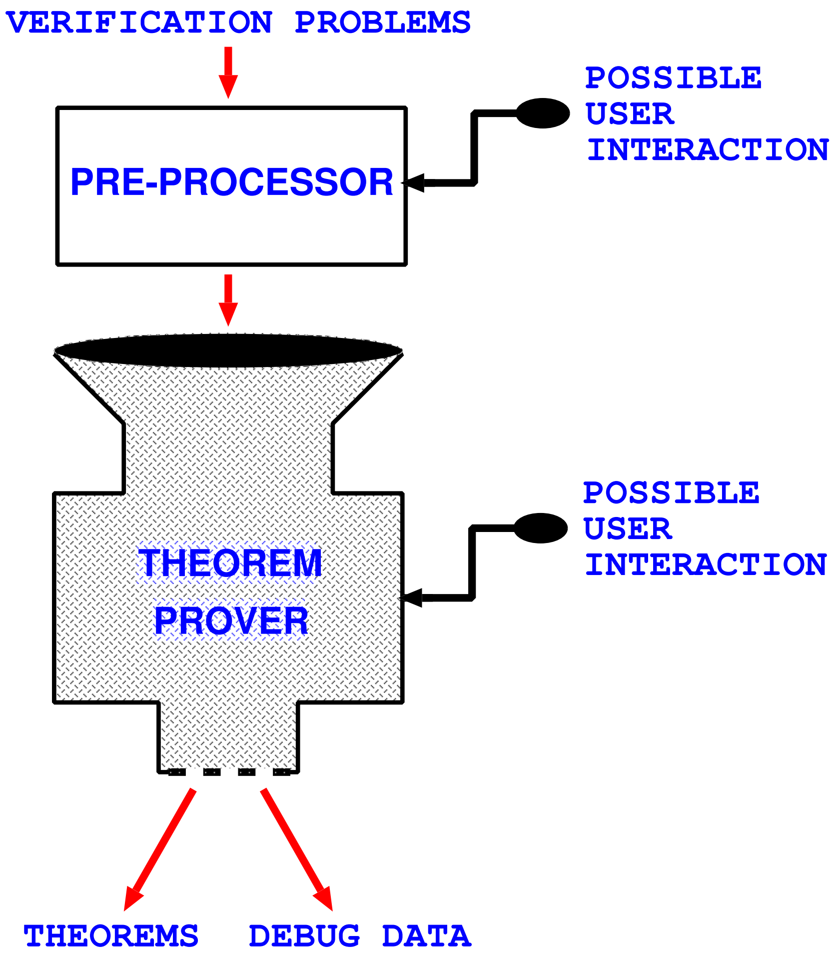
- Year long processor verifications
  - ACL2, HOL, PVS
  - symbolic simulation by proof
- Automatic pipeline verification
  - e.g. Burch and Dill
  - symbolic simulation not by proof

Methodology issues



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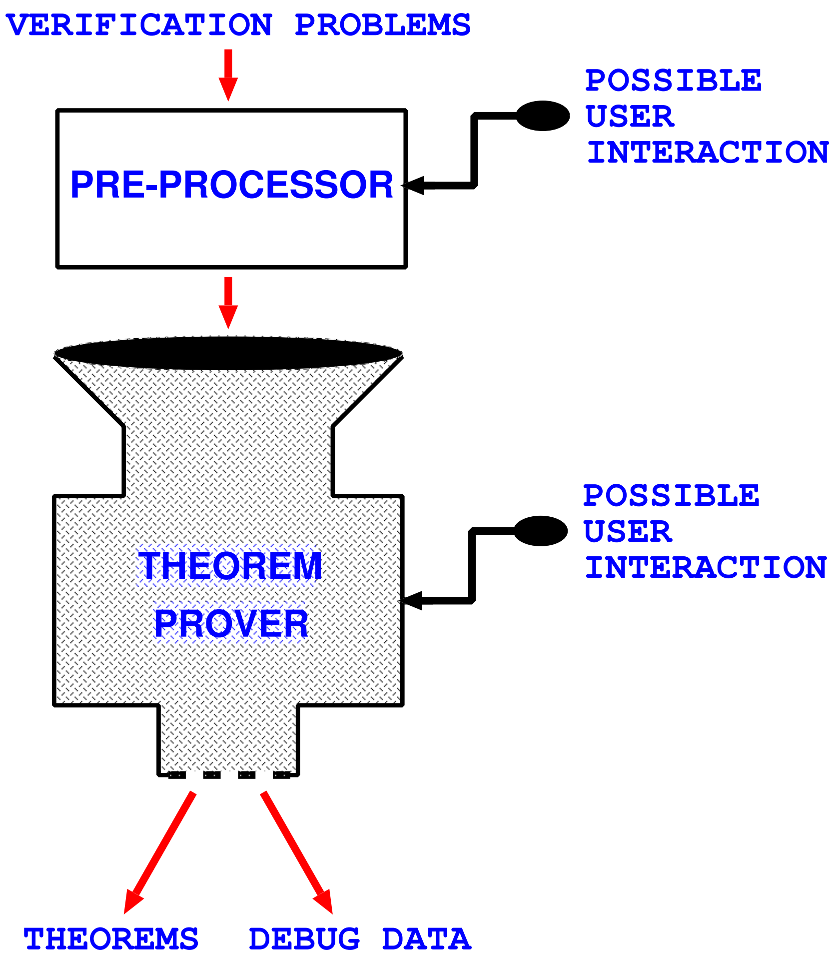

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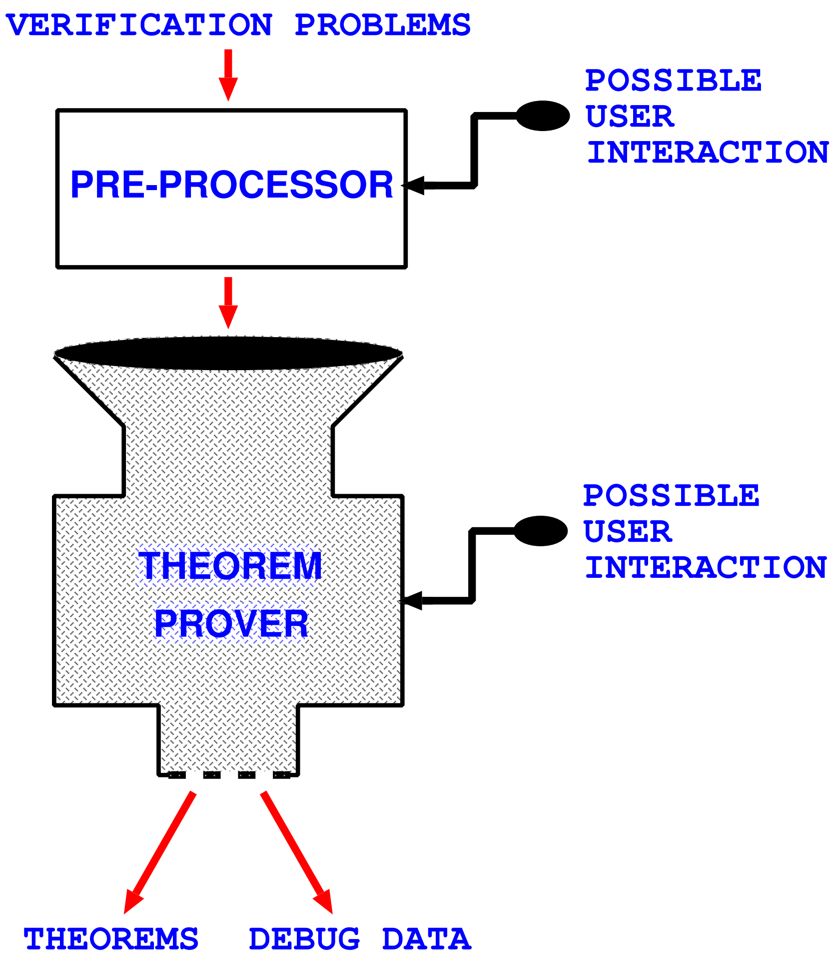
- How is pre-processing implemented?
- What kind of theorem prover?
- How are bits glued together?

Methodology issues: Extreme 1



- What problem description language?
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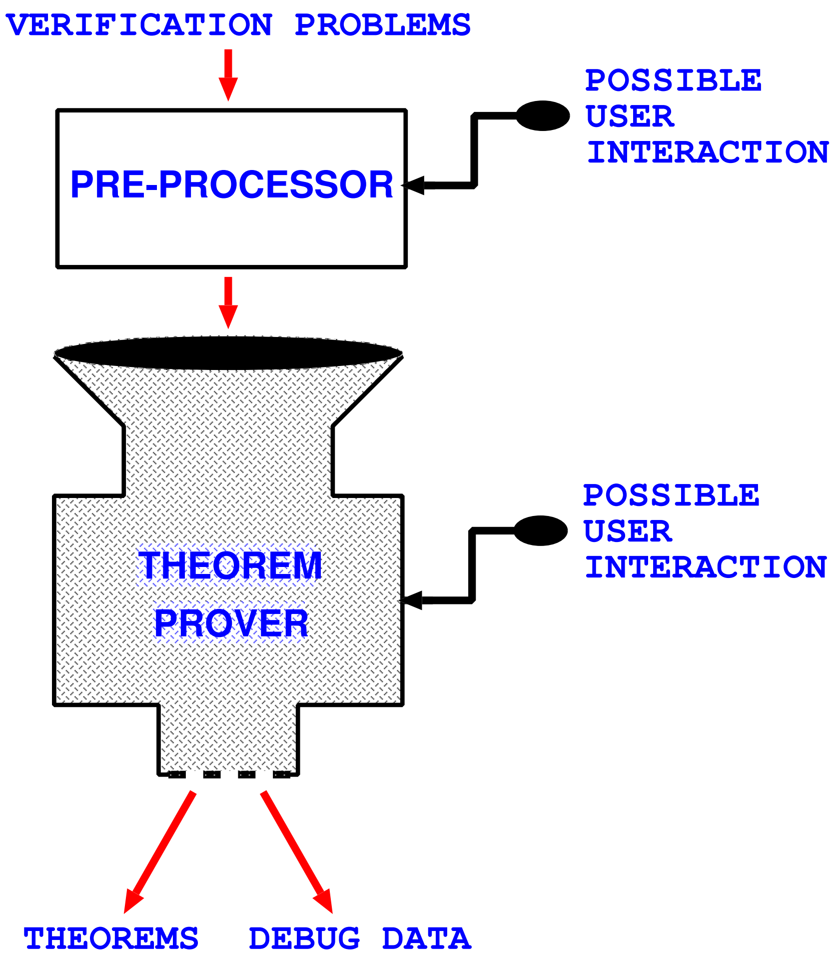
Methodology issues: ~~Extreme 1~~ Extreme 2



- What problem description language?
  - ~~problem specific language~~
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  - ~~pre-processing is YACC~~
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- What kind of theorem prover?
  - ~~problem specific algorithm~~
  - general purpose prover
- How are bits glued together?
  - ~~glue is scripting in C, Perl etc.~~
  - glue is formal proof

Issues

- What problem description language?
- Is pre-processing formal?
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Issues .... Extreme 1

- Extreme 1
  - efficient, scary

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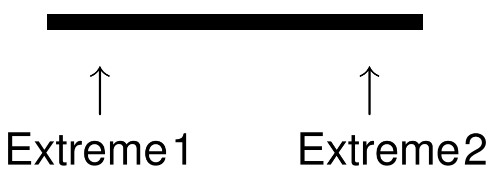
Issues .... Extreme 1 .... Extreme 2

- Extreme 1
  - efficient, scary
- Extreme 2
  - inefficient, reassuring
- Spectrum:



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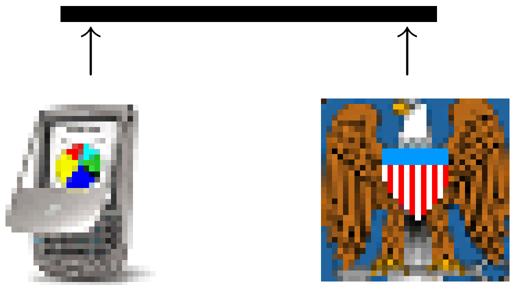

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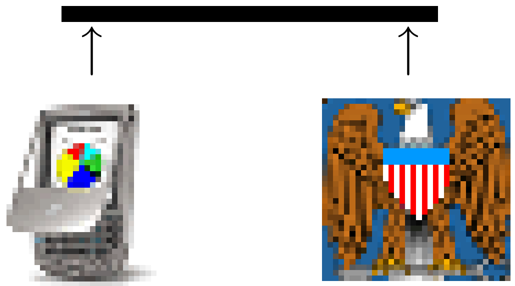

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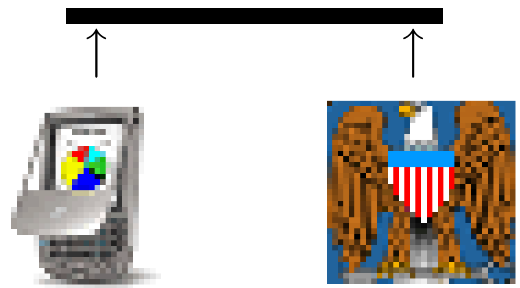

- Would like IDE to help manage programming across spectrum
  - IDE: Integrated Development Environment
  - provides proof engine components
  - and ways of linking them

Proof engines one might want to combine

- Little engines of proof . . . . (*cf.* Shankar, FLoC'02)
  - automatic
- Medium engines of proof
  - mainly automatic, lightweight user guidance
- Big engines of proof
  - user guided, but may have automatic tools (smaller engines)

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    - model checkers with lightweight proof (SMV, Forte)
    - first-order provers (SVC/CVC, EVC, Gandalf, Otter, SPASS, INKA, Vampire)
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- Big engines of proof
  - user guided, but may have automatic tools (smaller engines)
    - specific applications (LAMBDA, STeP)
    - general (PVS, Isabelle, HOL, ProofPower, Acl2, Nuprl, OMEGA, Eves, IMPS, Coq)

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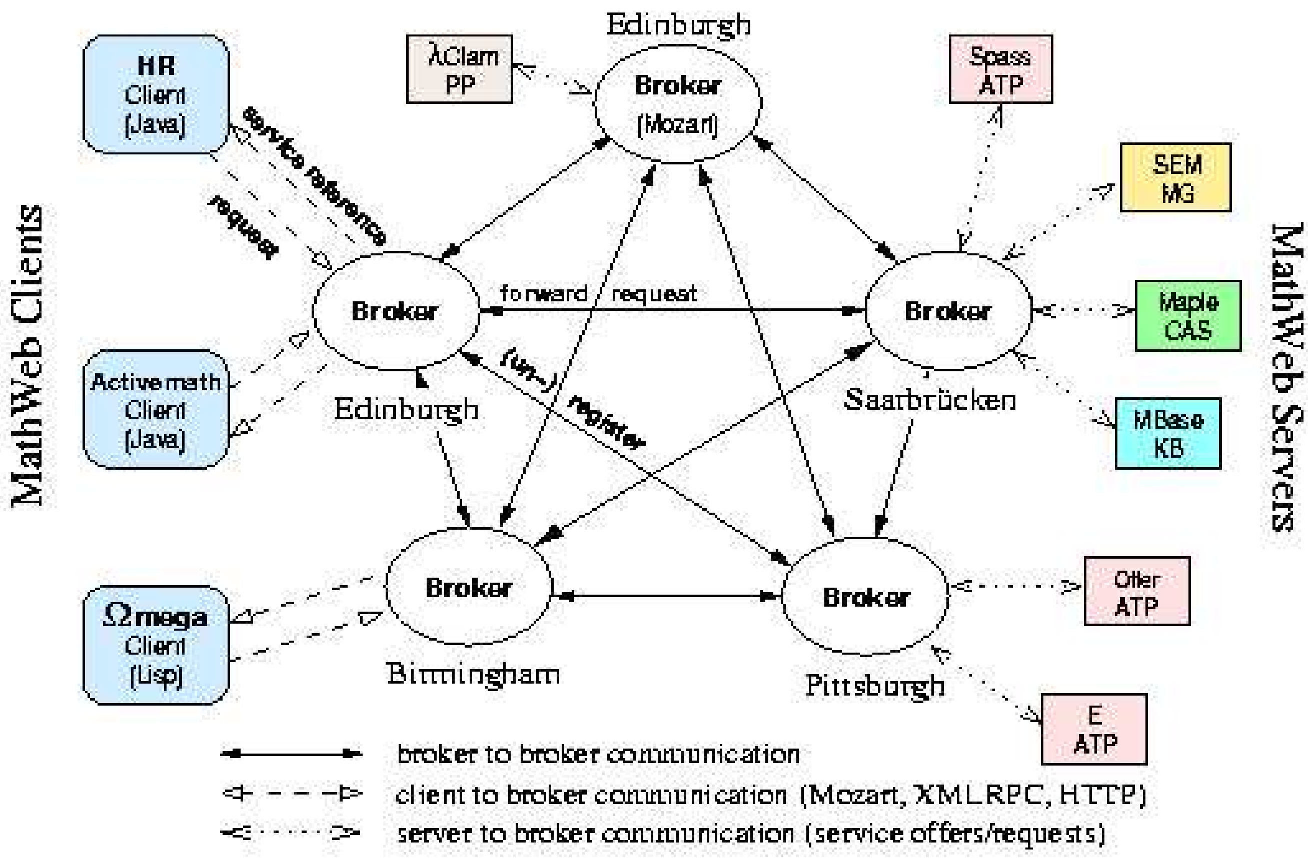
    - maybe using efficient representations (e.g. BDD operations)

MathWeb (http://www.mathweb.org/mathweb/demo.html)



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Debugging versus correctness

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    - that was 1990s, is practical now . . . . though expensive

Opinions are divided: recent quotes found on the web

- Find bugs, not proofs

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  ... senior staff engineer at XXXX, said formal verification has two possible applications finding bugs in RTL code, and gaining assurance of zero bugs prior to tapeout. "What we've found at XXXX, although we do find bugs, is that the real value of formal verification is the assurance," ...
  [http://www.eedesign.com/story/OEG20030606S0017]

My opinions

- Counter-example technologies are a stepping stone
- Finding bugs has immediate value, but proof can deliver much more
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- Full correctness assurance is possible now, and the cost is falling!
  - theorem proving methods getting better and better
  - computers faster and cheaper, so deep proof search more practical
  - components need specifications and correct implementations

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- Already exists design IP and property IP
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- Could also produce custom theorem proving environments
  - synthesise processor & hardware/software FV tools from specification
  - generate bespoke ESL/co-design theorem proving environments

Quote from the web – Proof IP?

PRODUCT OVERVIEW

XXXX: Conquers Toughest Verification Challenges with 100% Formal Proof

⋮

XXXX Pre-Built Proof Kits are available for a long list of industry standard interfaces. Pre-Built Proof Kits contain all the necessary spec-level requirements to prove interface compliance, delivering immediate benefits to users.

⋮

Conclusions

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THE END

Emergency slides for if I finish too early!

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- Some applications and spinoff from theorem proving research
-

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- Some applications and spinoff from theorem proving research
- Quotes from the web

Two applications of theorem proving research

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- Features of these examples

- Opinion

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  - need more wacky blue sky research, AI etc.
  - essential investment for long term innovation

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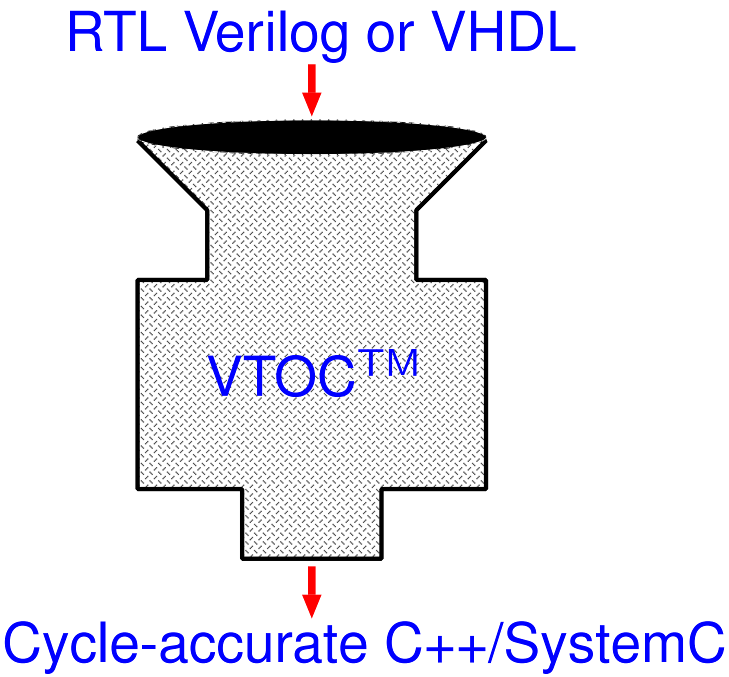

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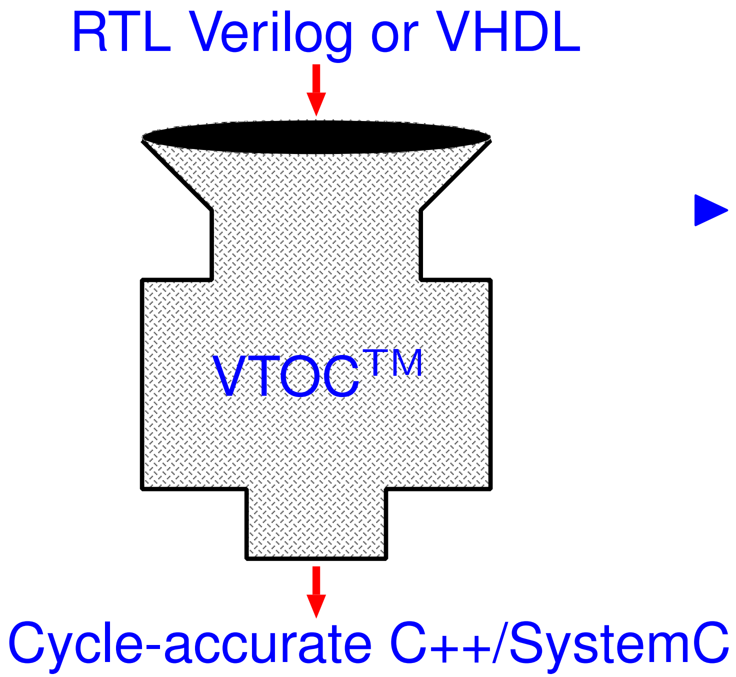

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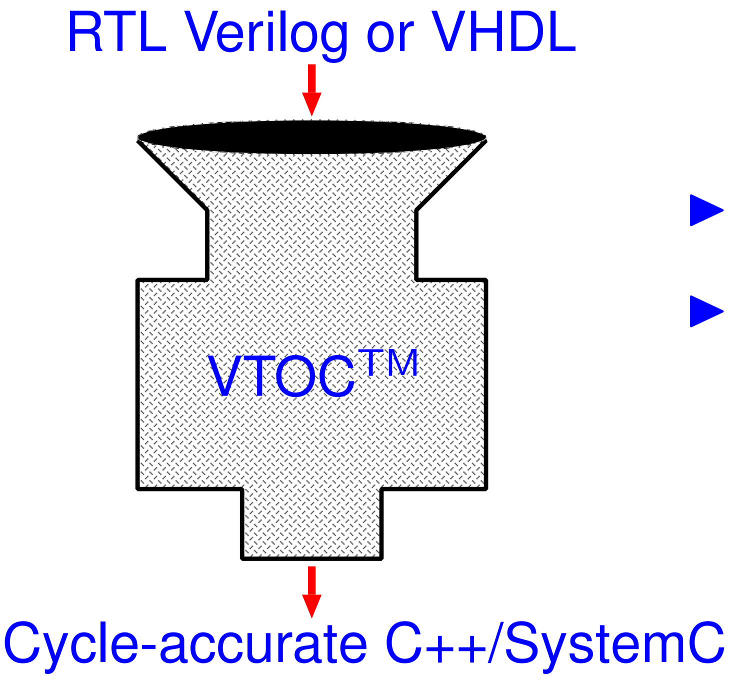

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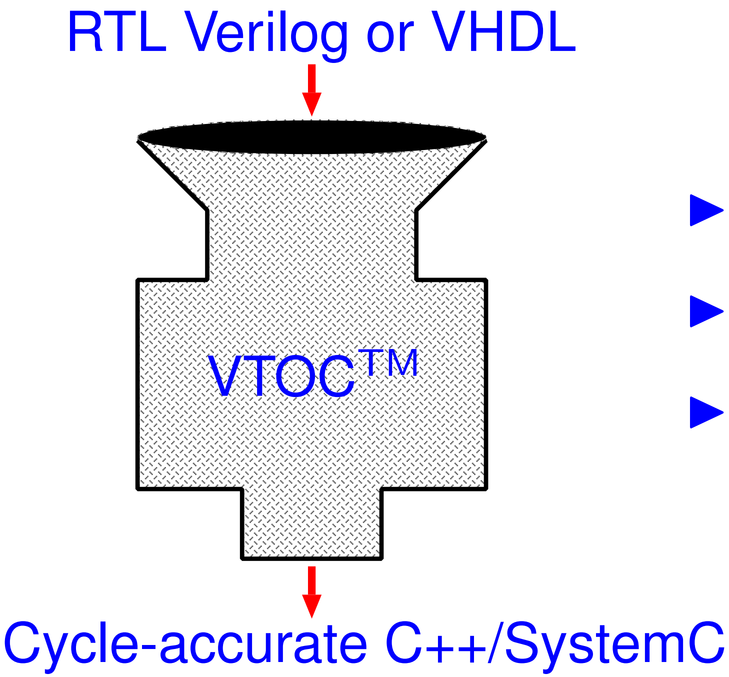

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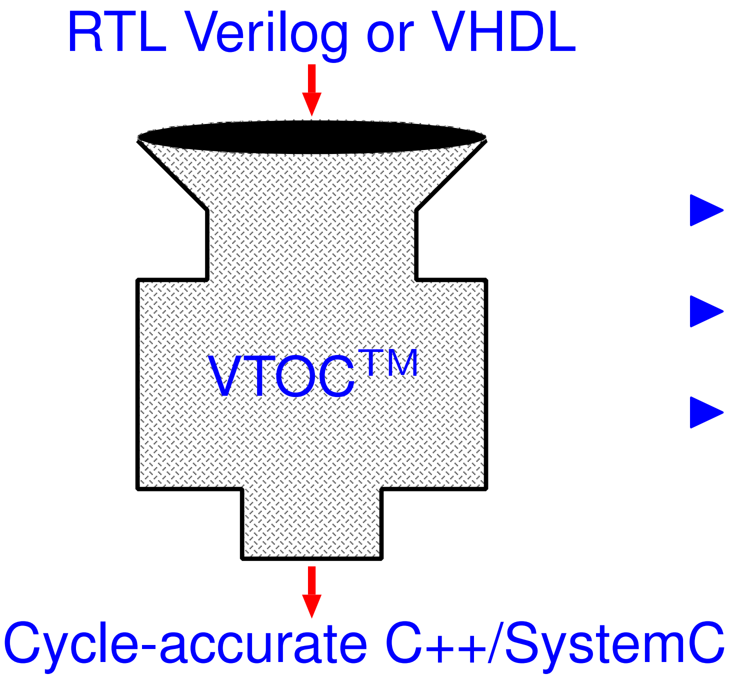

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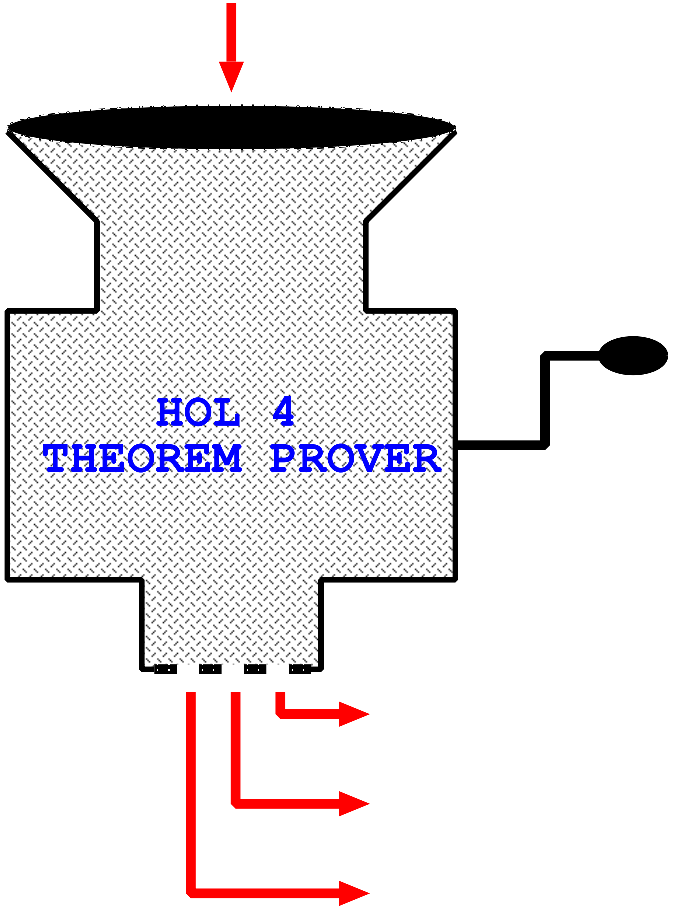
- Moral
  - 'blue sky' research can have unexpected applications
  - a cliché, but still worth repeating

Generating tools for PSL

Official semantics of PSL



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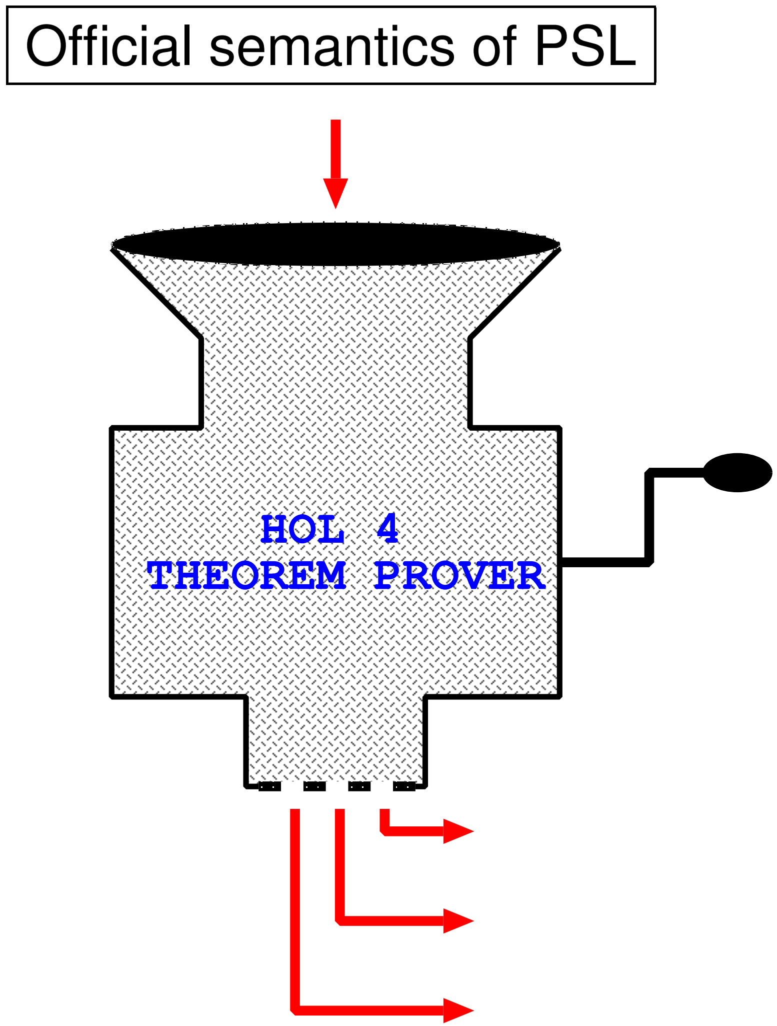

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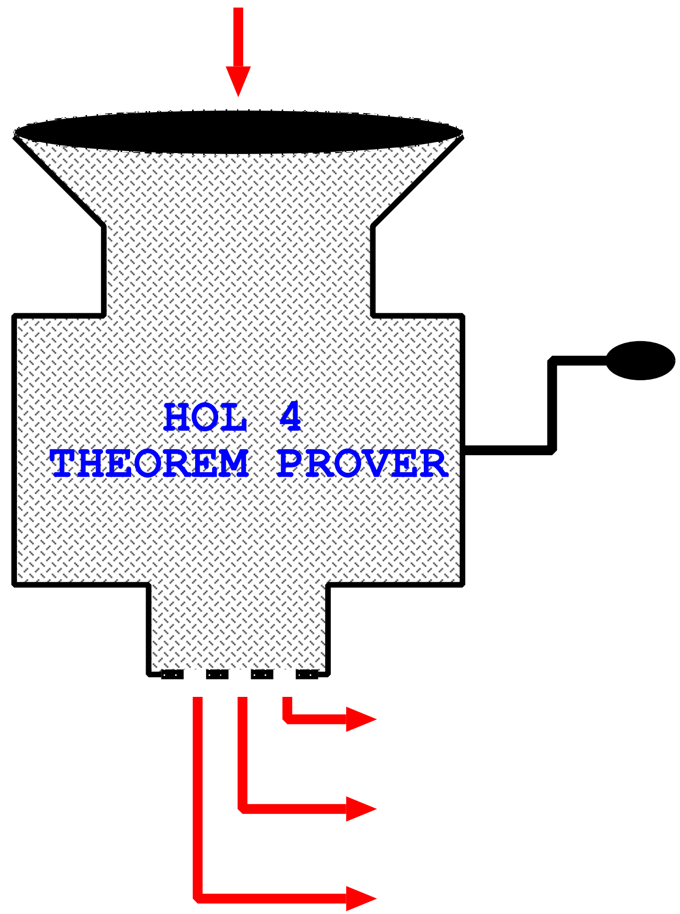

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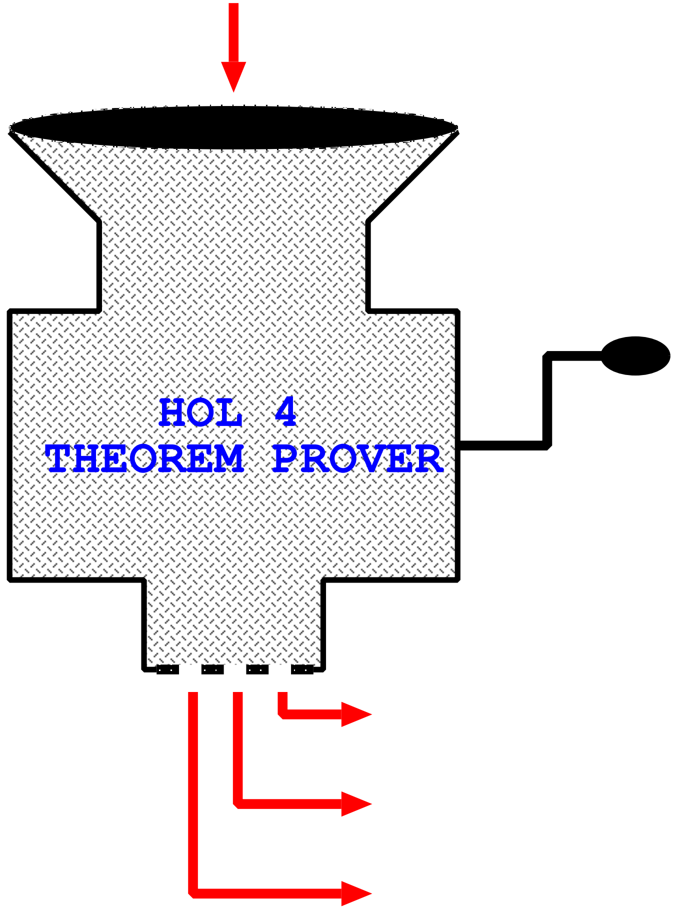

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Generating tools for PSL . . . . Gordon, Hurd, Slind, CHARME 2003

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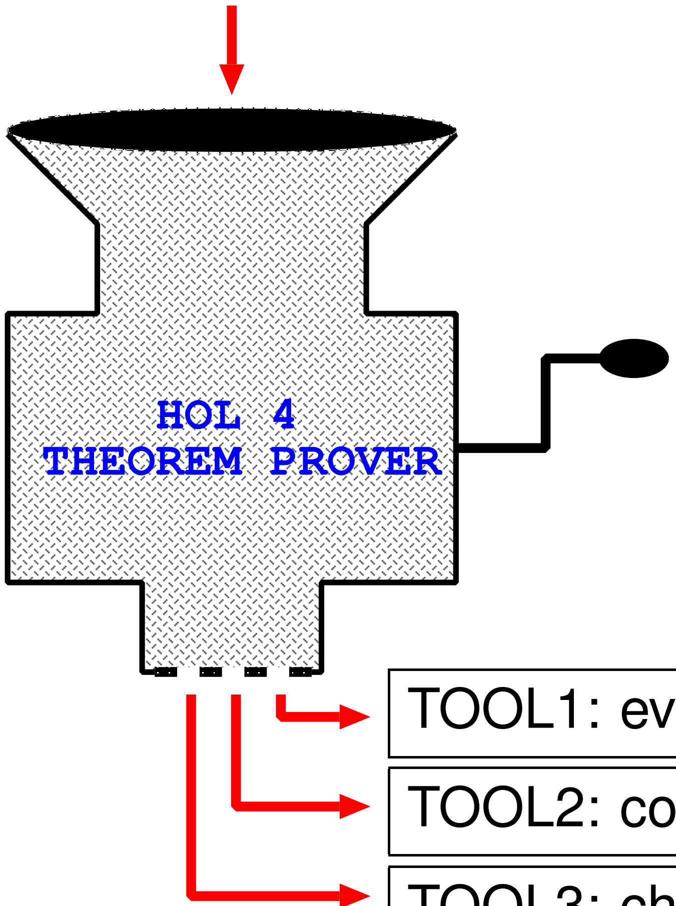

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TOOL1: evaluate LTL properties on a specific path

TOOL2: compile properties to HDL checkers (idea from FoCs)

TOOL3: check CTL properties against a model (Amjad’s PhD)

From the web

With re-spin costs of $1 Million or more, and time-to-market a driving concern, how can you be sure that your design is 100% Bug-Free? XXXX™ provides 100% Formal Proof that your design matches Spec-Level Design Requirements ensuring that your design will be right the first time.

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- Reminds me of *Viper*!

More quotes from the web

. . . a bug which costs $1 to fix on the programmer's desktop costs $100 to fix once it is incorporated into a complete program, and many thousands of dollars if it is identified only after the software has been deployed in the field.

. . . .

However, though formal-methods research may have failed to deliver on the promises of the 1960s, it has still produced a collection of useful techniques. A number of firms are now creating software tools that can allow such techniques to be applied more widely by programmers who are not versed in such formal methods.

The trick is to integrate them into the software systems, called integrated development environments, that are used to create and manage code.

[`http://www.economist.com/science/tq/displayStory.cfm?story_id=1841081`]

THE END

THE END .... really!