Automated Reasoning and Formal Verification

What is verification by automated reasoning?

Direct theorem proving versus embedded theorem proving

Examples (Fox, Hurd, Slind)

Theorem provers as tool implementation platforms

Debugging versus proof of correctness, proof as IP

Conclusions, opinions
Automated Reasoning and Formal Verification

- What is verification by automated reasoning?
- Direct theorem proving versus embedded theorem proving
- Examples (Fox, Hurd, Slind)
- Theorem provers as tool implementation platforms
- Debugging versus proof of correctness, proof as IP
- Conclusions, opinions
What is verification by automated reasoning

- 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

<table>
<thead>
<tr>
<th>Verification task</th>
<th>Theorem proving technique</th>
<th>Theorems proved</th>
</tr>
</thead>
<tbody>
<tr>
<td>boolean equivalence</td>
<td>propositional algorithms (BDD, SAT etc)</td>
<td>$\vdash (B_1 = B_2)$</td>
</tr>
<tr>
<td>model checking</td>
<td>fixpoint calculation, automata algorithms etc</td>
<td>$\vdash (M \models P)$</td>
</tr>
<tr>
<td>assertion checking</td>
<td>decision procedures, first-order methods</td>
<td>$\vdash f$</td>
</tr>
<tr>
<td>proof of correctness</td>
<td>induction, heuristic search, interactive proof</td>
<td>$\vdash \mathcal{F}$</td>
</tr>
</tbody>
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Theorem prover can be used directly

USER FORMULATES PROBLEMS
IN FORMAL LOGIC

USER INTERFACE

THEOREM PROVER
Direct versus embedded theorem proving

- Theorem prover can be used directly ............... or embedded in a tool
Direct and embedded theorem proving

- Direct proving mainly for traditional heroic proofs

- Embedded proving common for cool new verification applications
Direct and embedded theorem proving

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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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  - can invoke automatic ‘proof engines’
  - hides formal logic stuff
  - slot into standard design/verification flows
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- Example: ARM6 verification

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- Example: PSL/Sugar semantics directed tools
Proving processors correct

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  - academic processors:
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- But is it worthwhile?
Example: specification and verification of ARM6 (Anthony Fox, Cambridge)

- Implementations of all instructions of ARM6 formally verified

What have we learned?

What does ARM think?
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  - value of effective symbolic execution (already known by Boyer/Moore)
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- What does ARM think?
  - unimpressed by time taken
  - verification is debugging, not assurance

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Debugging versus assurance: opinions are divided

- Find bugs, not proofs

- Real value is assurance that there are no bugs
Debugging versus assurance: opinions are divided

▸ Find bugs, not proofs

  Proofs have low value. Counter-examples have very high value.
  Counter-example technologies have seen tremendous advances over last few years.
  Proof technologies have not made much progress.
  Design teams that try a revolutionary path (e.g., “proving correctness”) will miss
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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/0EG20030606S0017]
My opinions

▶ Finding bugs has immediate value
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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
  • reusable IP needs specifications with correctness assurance
From debugging to assurance

- Current debugging flow (functional)
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  - current testbench tools have some FV (property checking)
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  - move from coverage metrics to total coverage
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- How to combine debugging FV with assurance theorem proving?
Current research on theorem proving for FV

- Add checking and simulation to a theorem prover

- Add theorem proving to a model checker

- Build new verification platform

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Current research on theorem proving for FV

- Add checking and simulation to a theorem prover
  - start with user guided prover, add fast execution & model checking
  - efficiently decide properties in subset of a powerful logic
  - Examples: Acl2, PVS, HOL

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- Issues
  - security versus efficiency (assurance versus debugging)
  - programmability (ease-of-use versus flexibility and power)
Example: HOL4

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- Applications
  - fully expansive model checker (BDDs + SAT for refinements) – Amjad
  - puzzleTool: rewrite puzzle descriptions to QBFs, solve with BDDs
Example: executing the formal semantics of PSL/Sugar
(joint work with Joe Hurd & Konrad Slind)

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- Programming methodology, not new verification algorithms
  - EDA tools with theorem prover inside (c.f. PROSPER)
Use theorem proving to generate tools from semantics
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- Input ‘golden’ semantics from LRM
- Perform mechanised proof
- Generate tools
Compare with generating tools from syntax
Compare with generating tools from syntax

- Input a grammar
- Apply theory of formal languages
- Generate a parser
Accellera’s PSL (formerly IBM’s Sugar 2.0)

- PSL is a property specification language combining
  - boolean expressions (Verilog syntax)
  - patterns (Sequential Extended Regular Expressions SEREs)
  - LTL formulas (Foundation language FL)
  - CTL formulas (Optional Branching Extension OBE)

- Designed both for model checking and simulation testbenches

- Intended to be the industry standard
Generating PSL tools

Official semantics of PSL

HOL 4 THEOREM PROVER

TOOL1: evaluate properties on a specific path
TOOL2: compile properties to HDL checkers (Hurd)
TOOL3: model check OBE properties (Amjad’s PhD)

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**TOOL1: executing the semantics**

- By rewriting and evaluation (PSL in red, HOL in blue):
  
  ![Red and blue code snippets]
  
  `f`
**TOOL1: executing the semantics**

By rewriting and evaluation (PSL in red, HOL in blue):

\[ s_0 s_1 s_2 s_3 s_4 s_5 s_6 s_7 s_8 s_9 \models p \land \text{next}! f = s_0 \models p \land s_1 s_2 s_3 s_4 s_5 s_6 s_7 s_8 s_9 \models f \]

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- LRM semantics of the until-operator not directly executable
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- LRM semantics of the until-operator not directly executable
  \[ w \models [f_1 \ U \ f_2] = \exists k \in [0 \ .. \ |w|). w^k \models f_2 \land \forall j \in [0 \ .. \ k). w^j \models f_1 \]
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LRM semantics of the until-operator not directly executable
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Standard reformulation makes it directly executable
\[ \vdash w \models [f_1 U f_2] = |w| > 0 \land (w \models f_2 \lor w \models f_1 \land w^1 \models [f_1 U f_2]) \]
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  \[s_0 \models b_2 ∨\]
  \[s_0 \models b_1 ∧ (s_1 \models b_2 ∨ s_1 \models b_1 ∧\]
  \[(s_2 \models b_2 ∨ s_2 \models b_1 ∧ (s_3 \models b_2 ∨ s_3 \models b_1 ∧ s_4 \models b_2))\]}
Matching regular expressions by proof  

- PSL formulas may contain regular expressions
Matching regular expressions by proof

PSL formulas may contain regular expressions

Semantics of PSL regular expressions is self-explanatory

- \( (w \models b) = (|w| = 1) \land w_0 \models b) \land \)
- \( (w \models r_1; r_2) = \exists w_1w_2. (w = w_1w_2) \land w_1 \models r_1 \land w_2 \models r_2) \land \)
- \( (w \models r_1 : r_2) = \exists w_1w_2l. (w = w_1[l]w_2) \land w_1[l] \models r_1 \land [l]w_2 \models r_2) \land \)
- \( (w \models \{r_1\} | \{r_2\}) = w \models r_1 \lor w \models r_2) \land \)
- \( (w \models \{r_1\} \&\& \{r_2\}) = w \models r_1 \land w \models r_2) \land \)
- \( (w \models r[*]) = \exists wlist. (w = Concat wlist) \land Every(\lambda w. w \models r)wlist) \land \)
Matching regular expressions by proof

- PSL formulas may contain regular expressions
- Semantics of PSL regular expressions is self-explanatory

\[ (w \models b) = (|w| = 1) \land w_0 \models b \] \land

\[ (w \models r_1; r_2) = \exists w_1w_2. (w = w_1w_2) \land w_1 \models r_1 \land w_2 \models r_2 \] \land

\[ (w \models r_1 : r_2) = \exists w_1w_2l. (w = w_1[l]w_2) \land w_1[l] \models r_1 \land [l]w_2 \models r_2 \] \land

\[ (w \models \{r_1\} | \{r_2\}) = w \models r_1 \lor w \models r_2 \] \land

\[ (w \models \{r_1\} \& \& \{r_2\}) = w \models r_1 \land w \models r_2 \] \land

\[ (w \models r[*]) = \exists wlist. (w = \text{Concat} wlist) \land \text{Every}(\lambda w. w \models r)wlist \]

- Make executable by proving
Matching regular expressions by proof (Hurd)

- PSL formulas may contain regular expressions
- Semantics of PSL regular expressions is self-explanatory

\[
\begin{align*}
(w \models b) &= (|w| = 1) \land w_0 \models b) \\
(w \models r_1; r_2) &= \exists w_1w_2. (w = w_1w_2) \land w_1 \models r_1 \land w_2 \models r_2) \\
(w \models r_1 : r_2) &= \exists w_1w_2l. (w = w_1[l]w_2) \land w_1[l] \models r_1 \land [l]w_2 \models r_2) \\
(w \models \{r_1\} | \{r_2\}) &= w \models r_1 \lor w \models r_2) \\
(w \models \{r_1\} \&\& \{r_2\}) &= w \models r_1 \land w \models r_2) \\
(w \models r[^*]) &= \exists wlist. (w = \text{Concat } wlist) \land \text{Every}(\lambda w. w \models r) wlist)
\end{align*}
\]

- Make executable by proving
  \[\vdash \forall w r. w \models r = \text{Match } r w\]

where:
  - \text{Match} is an executable matcher for regular expressions
Example formula with regular expression: $\{ r \}(f)$ (Hurd)

- Called “suffix implication”, semantics is:

$$w \models \{ r \}(f) = \forall j \in [0 .. |w|). w^{0,j} \models r \Rightarrow w^j \models f$$
Example formula with regular expression: $\{ r \}(f)$ (Hurd)

- Called “suffix implication”, semantics is:

  $w \models \{ r \}(f) = \forall j \in [0..|w|). w^{0,j} \models r \Rightarrow w^j \models f$

- Define an efficient executable function $\text{Check}$ so that, for example:

  $\text{Check } r f [x_0; x_1; x_2; x_3] =$

  $(\text{Match } r [x_0] \Rightarrow f[x_0; x_1; x_2; x_3]) \land$

  $(\text{Match } r [x_0; x_1] \Rightarrow f[x_1; x_2; x_3]) \land$

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  (\text{Match } r \ [x_0] \Rightarrow f[x_0; \ x_1; \ x_2; \ x_3]) \land \\
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  (\text{Match } r \ [x_0; \ x_1; \ x_2; \ x_3] \Rightarrow f[x_3])
  \]

- Then prove:
  
  $$\vdash \forall w \ r \ f. \ w \models \{r\}(f) = \text{Check } r \ (\lambda x. \ x \models f) \ w$$
Example formula with regular expression: \(\{r\}(f)\) (Hurd)

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  \[ w \models \{r\}(f) = \forall j \in [0..|w|). \ w^{0,j} \models r \Rightarrow w^j \models f \]

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- Then prove
  \[
  \vdash \forall w \ r \ f. \ w \models \{r\}(f) = \text{Check } r (\lambda x. x \models f) \ w
  \]

- Rewrite with this, then execute
Example illustrating TOOL1

- PSL Reference Manual Example 2, page 45

<table>
<thead>
<tr>
<th>time</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>clk1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>a</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>b</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>c</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>clk2</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

- Define \( w \) to be this path, so \( w \) is:
  \[
  \{c,clk2}\{clk1\}\{\}\{clk1,a,clk2\}\{a\}\{clk1,a,b,c\}\{c,clk2\}\{clk1,b\}\{b\}\{clk1,clk2\}
  \]

- Can evaluate in SML, or via a command line wrapper

- Example: to evaluate \((c \&\& \text{next!(a until b)})@clk1\) at all times in \( w \):

  ```
  % pslcheck -all \n  -fl ' (c \&\& next!(a until b))@clk1' \n  -path '{c,clk2}{clk1}{\}{clk1,a,clk2}{a}{clk1,a,b,c}{c,clk2}{clk1,b}{b}{clk1,clk2}'
  >> > true at times 4,5,10
  ```
Uses of TOOL1 (calculating $w \models^T f$ from semantics)
Uses of TOOL1 (calculating $w \models^T f$ from semantics)

- Teaching and learning tool for exploring semantics
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- Checking one has the right property before using it in verification
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- Teaching and learning tool for exploring semantics
- Checking one has the right property before using it in verification
- Post simulation analysis (path is generated by simulator)
  - compare with “TransEDA VN-Property” property checker and analyzer
  - our tools much slower – but not necessary too slow!
  - guaranteed PSL compliant by construction: golden reference
Tools use standard algorithms

- **TOOL1**: semantic calculator

- **TOOL2**: checker compiler (Hurd)

- **TOOL3**: symbolic $\mu$-calculus model checker (Amjad)
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- **No** new algorithms, but **maybe** a new kind of logic programming
Summary

HOL 4THEOREM PROVER

Verication tools use theorem proving codederived (manually) from semantics by proof.

Correct by construction

PSL semantics will evolve for at least another year

Theorem prover as implementation platform prototyping standards compliant tools

Theorem proving is slow 

but not necessarily too slow

maybe OK for some industrial strength performance-non-critical tools

Mike Gordon, Strachey Lecture, 20 Jan 2004
Summary

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  - code derived (manually) from semantics by proof
  - tools use embedded theorem proving when they execute
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Future research idea: generating ESL design tools

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Generate bespoke verifier for XXX processor?

- input processor specification
- generate analysis tools for XXX-based ESL platform
- not performance critical, so implementation by deduction plausible
Could there be a market for ‘Proof IP’

- Already exists design IP and property IP
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- Design tweaks need verification tweaks
  - sell bespoke proof scripts to validate tweaks
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.
Future challenges

Long Live Theorem Proving!

I

Getting theorem proving into real verification owns

Intel, AMD can do it; tough for small companies

Proof engine deployment platform: Proof Studio.net

I

Continuing to advance state-of-the-art of theorem proving

Better integrate first order reasoning, equality & decision procedures

Go beyond first order automation

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More demonstrator projects

Hard to motivate as `proof of concept' established

Need more cost/benefit stories

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Make a market for specification and proof IP

Need a convincing `value proposition' and `ROI' story

THE END
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