Leapfrog: Certified Equivalence for Protocol Parsers

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Packet parsing

01000111011011110010
00000110001001101001
01100111001000000111
00100110010101100100
(and metadata)

header baby_ip {
  bit<8> src;
  bit<8> dst;
  bit<4> proto;
} (and metadata)

Success
Error
A horror story

parsed packet + metadata → control logic

output packet + metadata → flag set?

yes: recirculate

no: forward
Updating the parser

≈
State of the art

Verification frameworks for parsers exist:
>
▶ \textit{p4v} (Liu et al. 2018)
▶ Aquila (Tian et al. 2021)
▶ Neves et al. 2018

Great works... but room for improvement:
>
▶ Only functional properties are verified.
▶ No reusable certificate is produced.
▶ Rely on (trusted) verification to IR.
Contribution

- P4 automata: a syntax and semantics for protocol parsers.
- Algorithm to check (hyperproperties like) language equivalence.
- Implementation of algorithm in Coq + SMT solver.
- Proof of soundness (in Coq) and completeness (on paper).
Running Example

Parameters: states $Q$, headers $H$, header sizes $sz : H \to \mathbb{N}$. 
\[ c = \langle q_1 q_2, s[01\ldots0/mpls], \epsilon0\ldots0\epsilon \rangle \]
Challenge

Problem: $|\text{configurations}| \geq 10^{37}$ for reference MPLS parser.

Two-pronged solution:

- Symbolic representation + SMT solving.
- Up-to techniques to skip buffering.
Symbolic representation

First-order logic with semantics $\llbracket \phi \rrbracket \subseteq C \times C$.

Examples

- $\phi = q_1^<$ means “the left state is $q_1$”
- $\phi = 10^>$ means “the right buffer has 10 bits”
- mpl$\text{ls}^<$[24 : 24] = 1 means “the 24th bit of the mpl$\text{ls}$ header in the left store is 1”

If $\llbracket \phi \rrbracket$ is a bisimulation, then $\phi$ is a symbolic bisimulation.
Equivalence checking — intuition

$\phi_0 = \text{accept}< \iff \text{accept}>$

$\phi_1 = \text{WP}(\phi_0)$

$\phi_2 = \text{WP}(\phi_1)$

$\phi_0 \land \phi_1 \land \phi_2$
Equivalence checking — algorithm

\[ R \leftarrow \emptyset \]
\[ T \leftarrow \{ \text{accept} \leftarrow \text{accept} \} \]

while \( T \neq \emptyset \) do
\[ \text{pop } \psi \text{ from } T \]
\[ \text{if not } \land R \models \psi \text{ then} \]
\[ R \leftarrow R \cup \{ \psi \} \]
\[ T \leftarrow T \cup \text{WP(} \psi \text{)} \]

if \( \phi \models \land R \) then
\[ \text{return true} \]
else
\[ \text{return false} \]

Loop termination: either
\[ [\land R] \text{ shrinks; or} \]
\[ [\land R] \text{ stays the same, } T \text{ shrinks.} \]

Loop invariants:
\[ \text{If } c_1 \models [\land (R \cup T)] c_2, \text{ then} \]
\[ c_1 \in F \iff c_2 \in F. \]
\[ \text{If } c_1 \models [\land (R \cup T)] c_2, \text{ then} \]
\[ \delta(c_1, b) \models \land R \iff \delta(c_2, b). \]
\[ \text{If } \phi \text{ is a symbolic bisimulation,} \]
\[ \text{then } \phi \models \land (R \cup T). \]

After the loop, \( \land R \) is the \textit{weakest} symbolic bisimulation.
Unreachable pairs: left buffer 0, right buffer 13?

Buffering pairs: left buffer 7, right buffer 7?
Optimizations — Correctness

Compute *bisimulation with leaps* instead.

\[ \#(c_1, c_2) = \text{"no. of bits until next state change"} \]

\( R \) is a bisimulation with leaps if for all \( c_1 \ R c_2 \),

1. \( c_1 \in F \) if and only if \( c_2 \in F \)
2. \( \delta^*(c_1, w) \ R \delta^*(c_2, w) \) for all \( w \in \{0, 1\}^{\#(c_1, c_2)} \)

This is an up-to technique in disguise!

Must adjust implementation of WP.
Implementation — Side-stepping the termination checker
Algorithm state as proof rules:

\[
\phi \models \bigwedge R \quad \text{CLOSE} \quad \bigwedge R \models \psi \quad \text{pre\_bisim} \phi \ R \ T \quad \text{SKIP} \\
\bigwedge R \not\models \psi \quad \text{pre\_bisim} \phi \ (\psi :: T) \quad \text{EXTEND}
\]

**Lemma (Soundness)**

*If \(\text{pre\_bisim} \phi \ [] \ I\), then all pairs in \([\phi]\) are bisimilar.*

**Workflow:** proof search for \(\text{pre\_bisim}\), applying exactly one of these three rules.
Implementation — Talk to SMT solver
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In theory:

- If $T$ is empty, apply Done.
- If $\bigwedge R \models \psi$, apply Skip.
- If $\bigwedge R \not\models \psi$, apply Extend.

In practice:

- Massage entailment into fully quantified boolean formula.
- Custom plugin pretty-prints to SMT-LIB 2.0, asks solver.
- If SAT, admit $\bigwedge R \models \psi$ and apply Skip.
- If UNSAT, admit $\bigwedge R \not\models \psi$ and apply Extend.
Implementation — Talk to SMT solver

Existing tools (Armand et al. 2011; Czajka and Kaliszyk 2018):
  ▶ Encode goal to SMT, translate result to Coq proof.
  ▶ No support for fully quantified boolean formulas.
  ▶ Very little control over eventual SMT query.

```
interp (R |= phi)
< vm_compute.
forall (x: bitvec n) (y: bitvec m), ...
< hammer.
Tactic failure: cannot solve this goal.
```
Our approach:

- Series of verified simplifications in Gallina.
- Eventual goal is translated almost literally into SMT query.
- No back-translation — have to trust solver (for now).

```lean
interp (R |= phi)
< apply compile_formula.
interp' (compile (R |= phi))
< cbn compile.
interp' (FForall (FExists (...)))
< verify_interp; admit.
```
Ceci n’est pas une diapo vide.
Implementation — Trusted computing base
Evaluation — Microbenchmarks

Automatically verifies common transformations:

- Speculative extraction / vectorization.
- Common prefix factorization
- General versus specialized TLV parsing.
- Early versus late filtering.

Extends to certain hyperproperties:

- Independence of initial header store.
- Correspondence between final stores.
**Evaluation — Applicability study**

parser-gen (Gibb et al. 2013) compiles parser to optimized implementation.

- Benchmarks: about 30 states each, *huge* store datastructure.
- Leapfrog can validate equivalence of input to output.

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**Match:** \([ff, 00, 00, ff, 00, f0, 00, 00, 00, 00]\) \([04, 00, 00, 00, 00, 00, 00, 00, 00, 00]\) \([01, 00, 00, 00, 00, 00, 00, 00, 00, 00]\) \([ff, 00, 00, ff, 00, f0, 00, 00, 00, 00]\) \([ff, 00, 00, ff, 00, f0, 00, 00, 00, 00]\)

**Next-State:** 3/255  \(\text{Adv: } 14\)  \(\text{Next-Lookup: } [0, 0, 0, 0]\)

**Next-State:** 4/255  \(\text{Adv: } 16\)  \(\text{Next-Lookup: } [0, 2, 4, 6]\)

**Next-State:** 1/255  \(\text{Adv: } 6\)  \(\text{Next-Lookup: } [0, 0, 0, 0]\)

**Next-State:** 1/255  \(\text{Adv: } 2\)  \(\text{Next-Lookup: } [0, 0, 0, 0]\)
Lessons learned

- Finite automata can go the distance.
- Up-to techniques can be specialized.
- Programming in Coq is fun.

http://langsec.org/occupy/
References


M. C. Neves et al. (2018). “Verification of P4 programs in feasible time using assertions”. In: CoNEXT, pp. 73–85. DOI: 10.1145/3281411.3281421.