Leapfrog: Certified Equivalence for Protocol Parsers

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Packet parsing

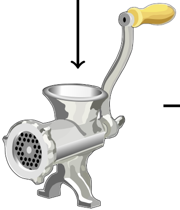
01000111011011110010
00000110001001101001
01100111001000000111
00100110010101100100

(and metadata)

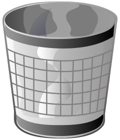
```
header baby_ip {
 bit<8> src;
 bit<8> dst;
 bit<4> proto;
}
```

(and metadata)

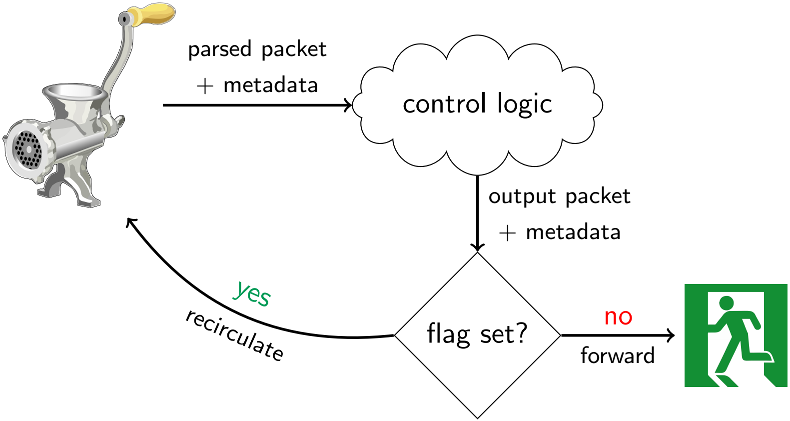
Success



Error



A horror story



Updating the parser

$\stackrel{?}{\approx}$

State of the art

Verification frameworks for parsers exist:

- `p4v` (Liu et al. 2018)
- Aquila (Tian et al. 2021)
- Neves et al. 2018

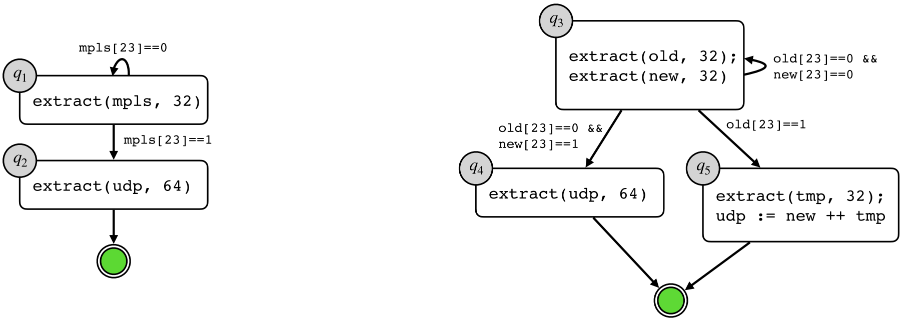
Great works. . . but room for improvement:

- Only functional properties are verified.
- No reusable certificate is produced.
- Rely on (trusted) verification to IR.

Contribution

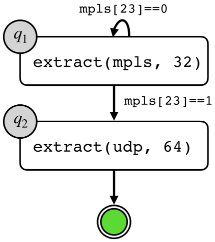
- P4 automata: a syntax and semantics for protocol parsers.
- Algorithm to check (hyperproperties like) language equivalence.
- Implementation of algorithm in Coq + SMT solver.
- Proof of soundness (in Coq) and completeness (on paper).

Running Example



Parameters: states Q, headers H, header sizes $\mathsf{sz} : H \to \mathbb{N}$.

Semantics



$$c = \langle q_1 q_2, s[01 \cdots 0/\texttt{mpls}], \epsilon 01 \cdots 0 \epsilon \rangle$$

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

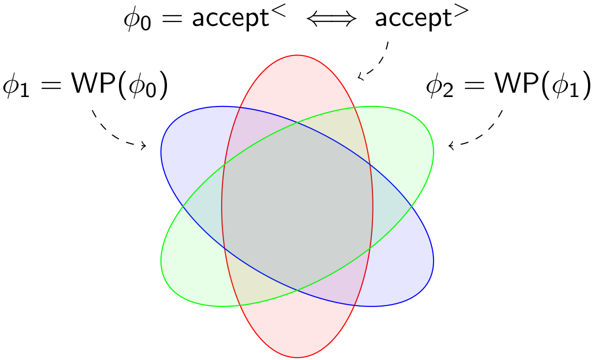
First-order logic with semantics $[\![\phi]\!] \subseteq C \times C$.

Examples

- $\phi = q_1^<$ means "the left state is q_1"
- $\phi = 10^>$ means "the right buffer has 10 bits"
- $\texttt{mpls}^<[24 : 24] = 1$ means "the 24th bit of the `mpls` header in the left store is 1"

If $[\![\phi]\!]$ is a bisimulation, then ϕ is a *symbolic bisimulation*.

Equivalence checking — intuition



$$\phi_0 \wedge \phi_1 \wedge \phi_2$$

Equivalence checking — algorithm

$R \leftarrow \emptyset$
$T \leftarrow \{\text{accept}^{<} \iff \text{accept}^{>}\}$
while $T \neq \emptyset$ **do**
  pop ψ from T
  if not $\bigwedge R \vDash \psi$ **then**
    $R \leftarrow R \cup \{\psi\}$
    $T \leftarrow T \cup \mathrm{WP}(\psi)$
if $\phi \vDash \bigwedge R$ **then**
  return true
else
  return false

Loop termination: either

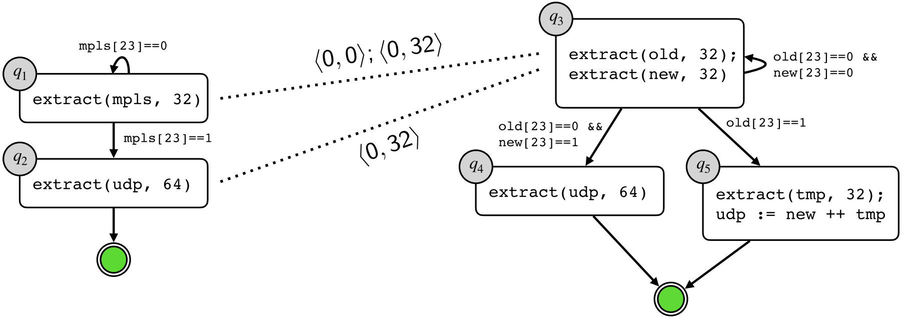
- $[\![\bigwedge R]\!]$ shrinks; or
- $[\![\bigwedge R]\!]$ stays the same, T shrinks.

Loop invariants:

- If $c_1 \; [\![\bigwedge(R \cup T)]\!] \; c_2$, then $c_1 \in F \iff c_2 \in F$.
- If $c_1 \; [\![\bigwedge(R \cup T)]\!] \; c_2$, then $\delta(c_1, b) \; [\![\bigwedge R]\!] \; \delta(c_2, b)$.
- If ϕ is a symbolic bisimulation, then $\phi \vDash \bigwedge(R \cup T)$.

After the loop, $\bigwedge R$ is the *weakest* symbolic bisimulation.

Optimizations — Pruning the bisimulation



Unreachable pairs: left buffer 0, right buffer 13?

Buffering pairs: left buffer 7, right buffer 7?

Optimizations — Correctness

Compute *bisimulation with leaps* instead.

$\sharp(c_1, c_2) =$ "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 $w \in \{0, 1\}^{\sharp(c_1, c_2)}$

This is an up-to technique in disguise!

Must adjust implementation of WP.

Implementation — Side-stepping the termination checker

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Algorithm state as proof rules:

$$\frac{\phi \vDash \bigwedge R}{\texttt{pre\_bisim}\ \phi\ R\ []}\ \textsc{close} \qquad \frac{\bigwedge R \vDash \psi \qquad \texttt{pre\_bisim}\ \phi\ R\ T}{\texttt{pre\_bisim}\ \phi\ R\ (\psi :: T)}\ \textsc{Skip}$$

$$\frac{\bigwedge R \nvDash \psi \qquad \texttt{pre\_bisim}\ \phi\ (\psi :: R)\ (T; \mathsf{WP}(\psi))}{\texttt{pre\_bisim}\ \phi\ R\ (\psi :: T)}\ \textsc{Extend}$$

Lemma (Soundness)

If $\texttt{pre\_bisim}\ \phi\ []\ I$*, then all pairs in* $[\![\phi]\!]$ *are bisimilar.*

Workflow: proof search for `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.
```

Implementation — Talk to SMT solver

Our approach:

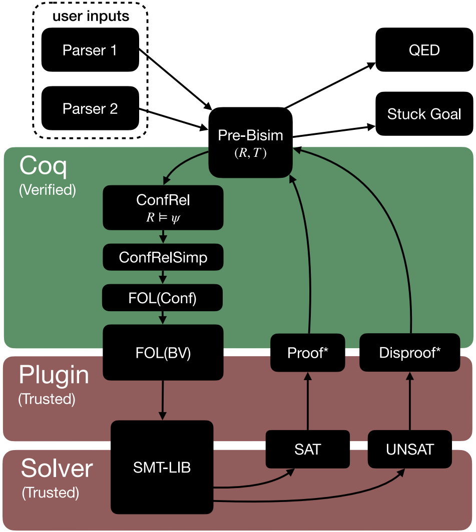
- Series of verified simplifications in Gallina.
- Eventual goal is translated almost literally into SMT query.
- No back-translation — have to trust solver (for now).

```
interp (R |= phi)
< apply compile_formula.
interp' (compile (R |= phi))
< cbn compile.
interp' (FForall (FExists (...))
< verify_interp; admit.
```

Implementation — Demo

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.

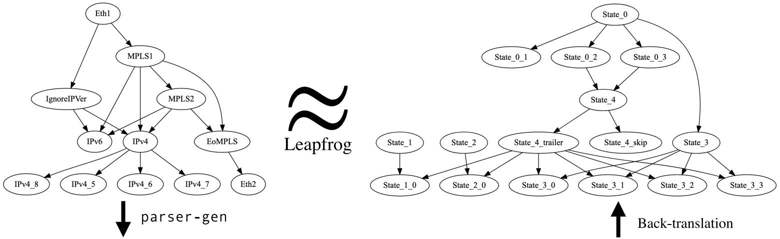
Extends to certain hyperproperties:

- 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.




```
Match: ([ff, 00, 00, ff, ff, 00, 00, 00, 00], [00, 00, 00, 08, 00, 00, 00, 00, 00])  Next-State: 3/255   Adv:  14  Next-Lookup: [0, 0, 0, 0]
Match: ([ff, 00, 00, ff, ff, 00, 00, 00, 00], [00, 00, 00, 88, 47, 00, 00, 00, 00])  Next-State: 4/255   Adv:  16  Next-Lookup: [0, 2, 4, 6]
Match: ([ff, 01, 00, 00, 00, 01, 00, f0, 00], [04, 00, 00, 00, 00, 01, 00, 00, 00])  Next-State: 1/255   Adv:   6  Next-Lookup: [0, 0, 0, 0]
Match: ([ff, 01, 00, f0, 00, 00, 00, 00, 00], [04, 01, 00, 00, 00, 00, 00, 00, 00])  Next-State: 1/255   Adv:   2  Next-Lookup: [0, 0, 0, 0]
...
Match: ([ff, 00, 00, 00, 00, 00, 00, 00, 00], [04, 00, 00, 00, 00, 00, 00, 00, 00])  Next-State: 255/255 Adv:  2   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

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