Leapfrog: Certified Equivalence for Protocol Parsers

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Joint work with folks at Cornell

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John Sarracino

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Packet parsing

01000111011011110010

00000110001001101001

01100111001000000111

00100110010101100100

(and metadata)

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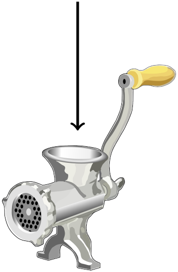

Packet parsing

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000001100010011010 01
011001110010000000111
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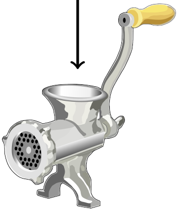

Success

```
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 bit<8> src;
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 bit<4> proto;
}
```
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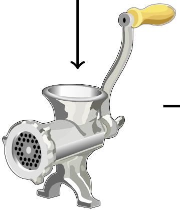
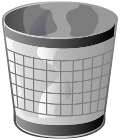


Error



A horror story

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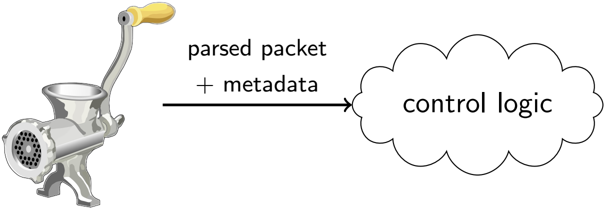

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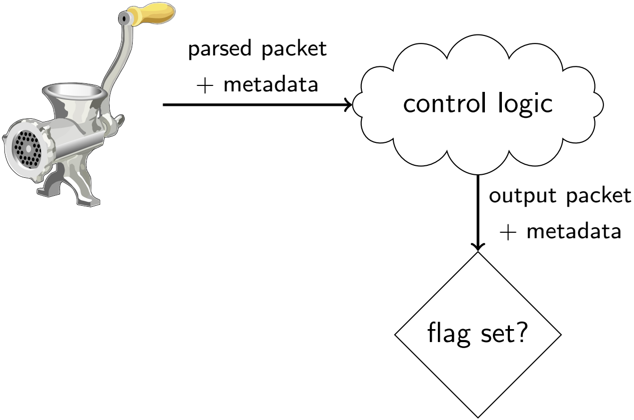

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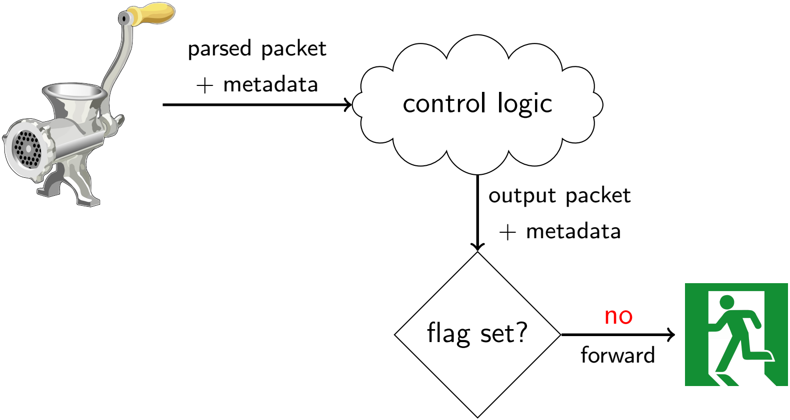

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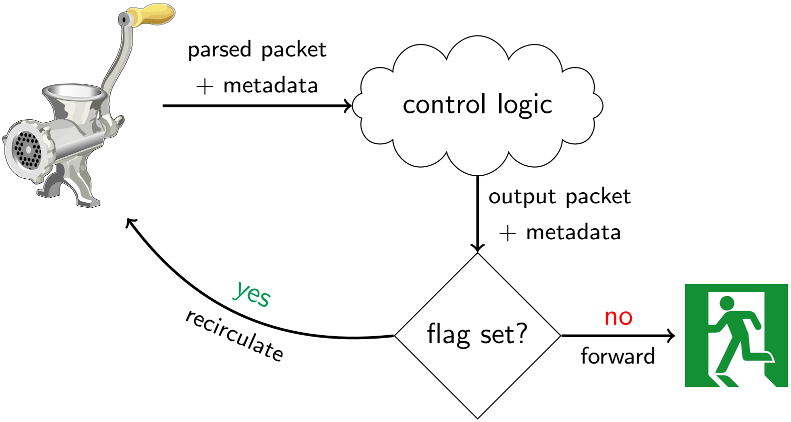

State of the art

Verification frameworks for parsers exist:

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- No reusable certificate is produced.
- Rely on (trusted) verification to IR.

Comparing parsers

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$$\stackrel{?}{\approx}$$

Contribution

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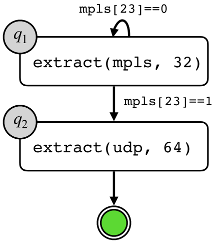
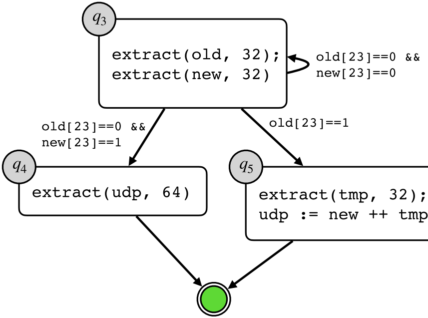
- Algorithm to check (hyperproperties like) language equivalence.
- Implementation of algorithm in Coq + SMT solver.
- Proof of soundness (in Coq) and completeness (on paper).

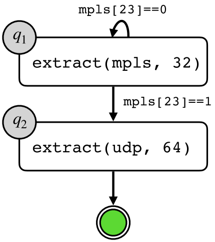
Running Example





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

Semantics



$$c = \langle q_1, s, \epsilon \rangle$$

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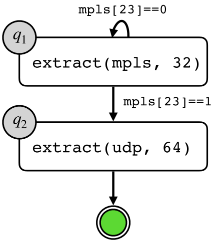
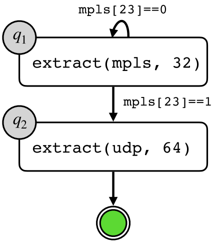


$$c = \langle q_1, s, 0 \rangle$$

Semantics



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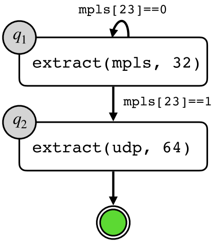

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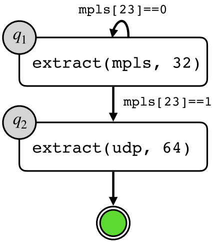

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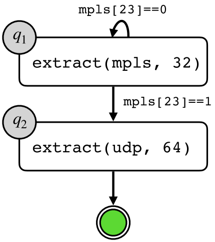

$$c = \langle q_1, s[01 \cdots 0/\texttt{mpls}], 01 \cdots 0 \rangle$$

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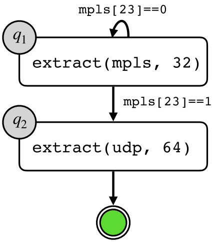

$$c = \langle q_2, s[01\cdots 0/\texttt{mpls}], 01\cdots 0\rangle$$

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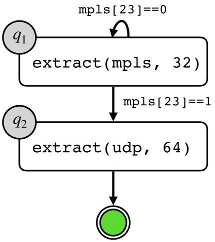

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Formalization

Every P4 automaton gives rise to a DFA $\langle C, \delta, F \rangle$.

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Definition (Bisimulation)

A binary relation R is a *bisimulation* if for all $c_1 \; R \; c_2$,

1. $c_1 \in F$ if and only if $c_2 \in F$
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Definition (Equivalence)

P_1 and P_2 are *equivalent* if there exists a bisimulation that relates their start states.

Challenge

Problem: $|C| \geq 10^{37}$ 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

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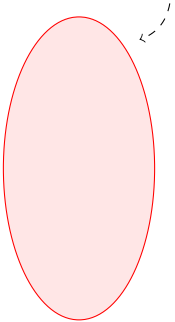
Definition (Symbolic bisimulation)

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

Equivalence checking — intuition

$$\phi_0 = \mathsf{accept}^< \iff \mathsf{accept}^>$$



ϕ_0

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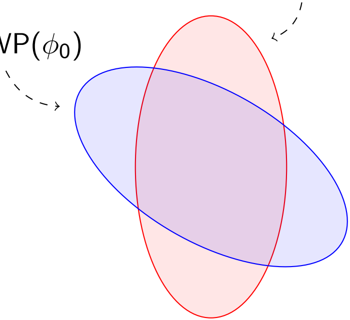

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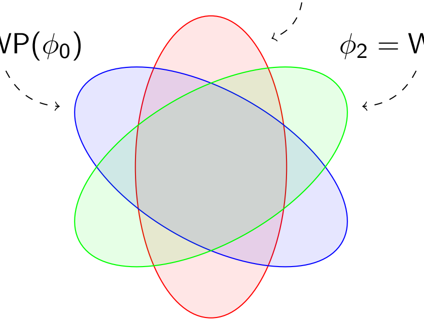

$\phi_0 \wedge \phi_1 \wedge \phi_2$

Equivalence checking — algorithm

$R \leftarrow \emptyset$
$T \leftarrow \{\text{accept}^{<} \iff \text{accept}^{>}\}$
while $T \neq \emptyset$ **do**
    pop ψ from T
    if not $\bigwedge R \models \psi$ **then**
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Loop termination: either

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

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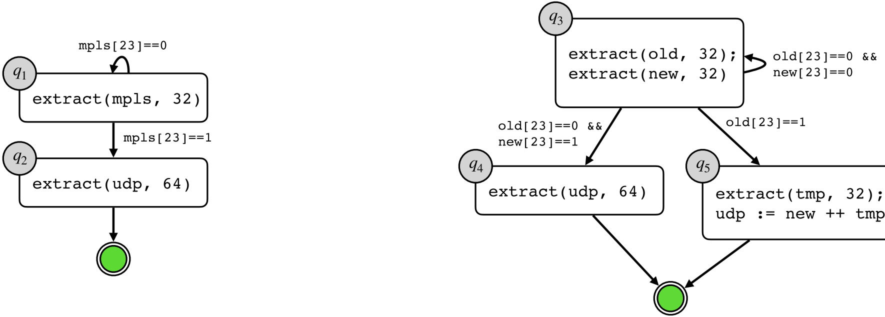
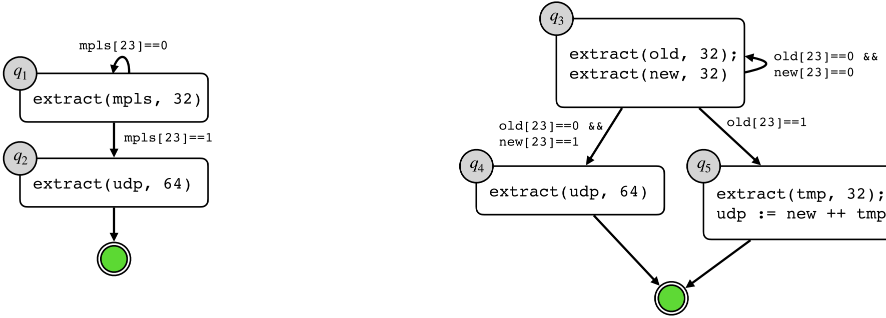


Optimizations — Pruning the bisimulation



Example (Unreachable pairs)

Left buffer 0, right buffer 13.

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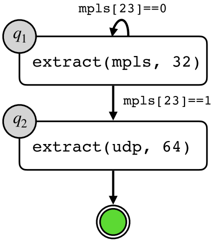

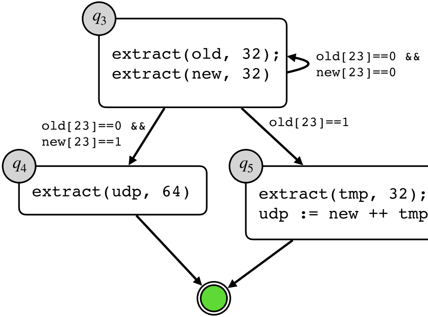

Example (Buffering pairs)

Left buffer 7, right buffer 7.

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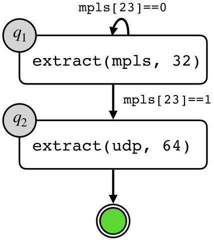

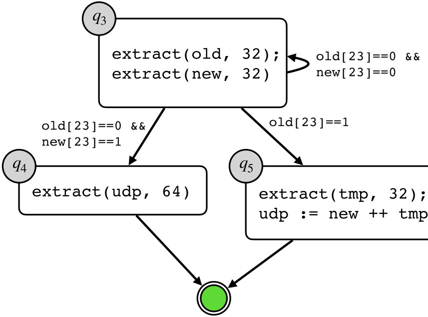

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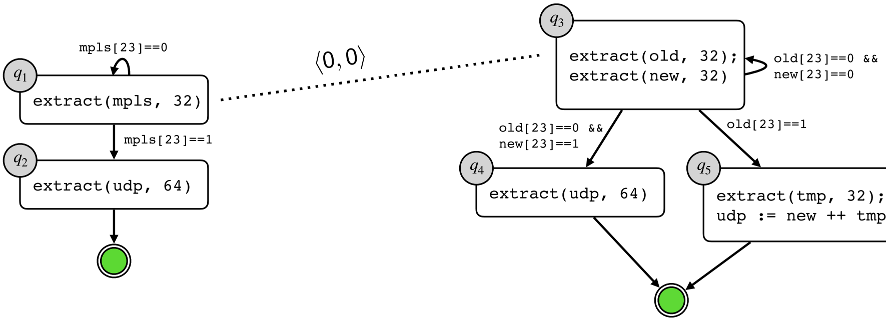

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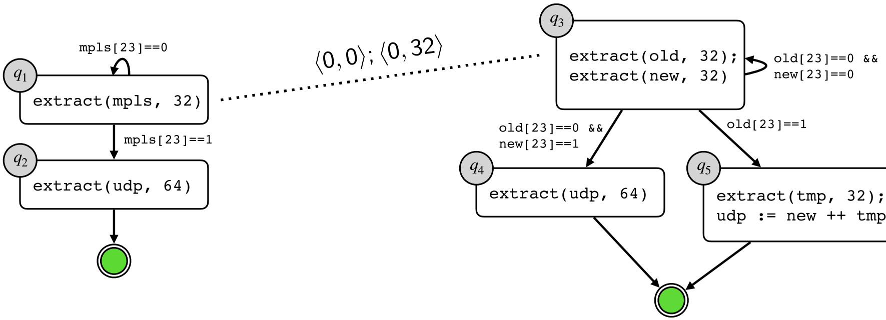

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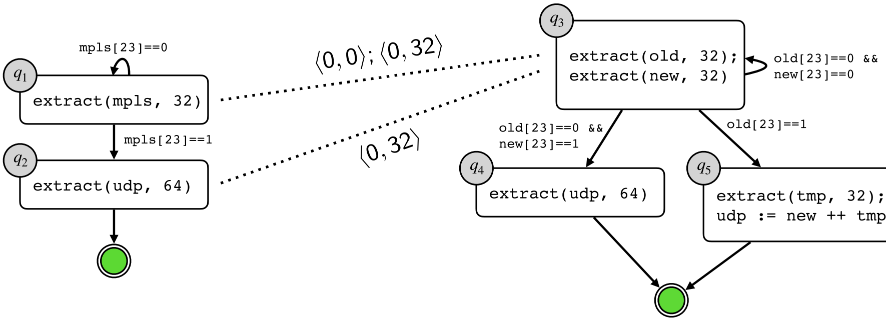

Optimizations — Correctness

Idea: 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 $c_1 \mathrel{R} c_2$,

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

This is an up-to technique in disguise!

Note: requires adjusting implementation of WP.

Implementation

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 `pre_bisim` ϕ `[]` 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 $\bigwedge R \vDash \psi$, apply `Skip`.
- If $\bigwedge R \nvDash \psi$, 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 $\bigwedge R \vDash \psi$ and apply `Skip`.
- If `UNSAT`, admit $\bigwedge R \nvDash \psi$ and apply `Extend`.

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Existing tools (Armand et al. 2011; Czajka and Kaliszyk 2018):

- Encode goal in SMT, translate result to Coq proof.
- No support for fully quantified boolean formulas.
- Very little control over eventual SMT query.

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forall (x: bitvec n) (y: bitvec m), ...
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< hammer.
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forall (x: bitvec n) (y: bitvec m), ...
< hammer.
Tactic failure: cannot solve this goal.
```

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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).

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interp (R |= phi)
< apply compile_formula.
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interp' (compile (R |= phi))
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```

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 (...))
```

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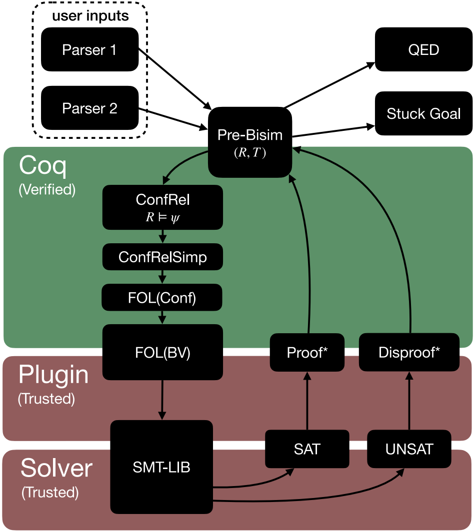
```
interp (R |= phi)
< apply compile_formula.
interp' (compile (R |= phi))
< cbn compile.
interp' (FForall (FExists (...))
< verify_interp; admit.
```

Implementation — Demo

Ceci n'est pas une diapo vide.

Implementation — Trusted computing base



Evaluation — Benchmarks

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 — Benchmarks

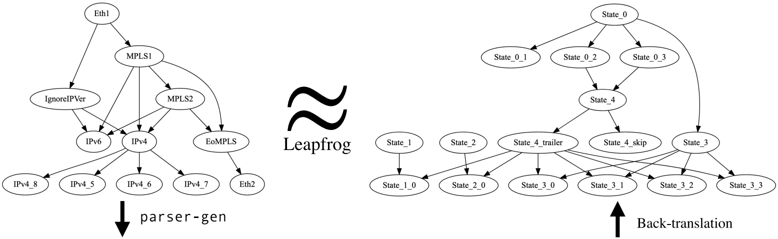
Leapfrog verifies many interesting properties of protocol parsers.

	Name	**States**	**Branched (bits)**	**Total (bits)**	**Time (min)**
Utility	St. rearrangement	5	8	136	0.12
	Variable-length	30	64	632	953.42
	Initialization	10	10	320	15.95
	Speculation	5	2	160	4.12
	Relational	6	64	1056	1.68
	Filtering	6	64	1056	1.18
Applicability	Edge	28	52	3184	528.38
	Service Provider	22	50	2536	1244.5
	Datacenter	30	242	2944	1387.95
	Enterprise	22	176	2144	217.93
	Tr. Validation	30	56	3148	746.2

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/

Thank you!

Questions?

For your convenience:

- https://kap.pe/papers
- https://kap.pe/slides

References

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