Leapfrog: Certified Equivalence for Protocol Parsers

Tobias Kappé

Open University of the Netherlands
ILLC, University of Amsterdam

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Joint work with folks at Cornell

Ryan Doenges

John Sarracino

Nate Foster

Greg Morrisett

Packet parsing

01000111011011110010

00000110001001101001

01100111001000000111

00100110010101100100

(and metadata)

Packet parsing

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00000110001001101001

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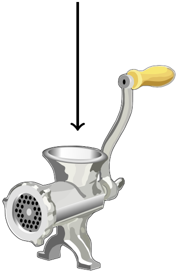

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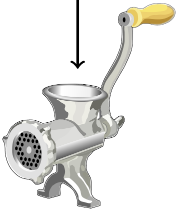

Success

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

(and metadata)

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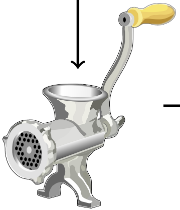
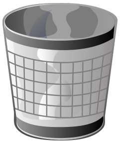


Success ← → Error



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(and metadata)

A horror story

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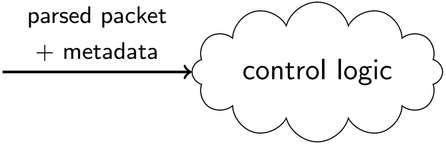

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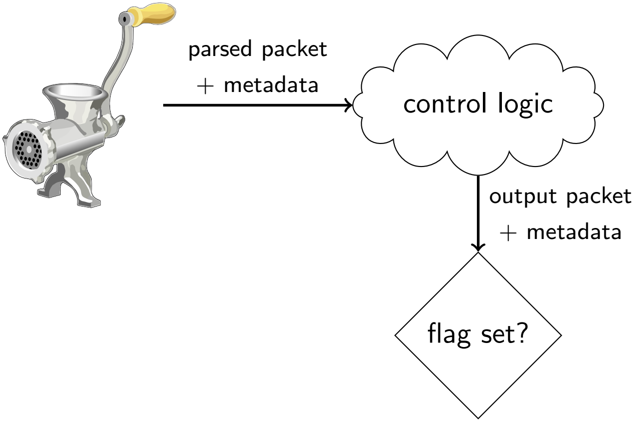

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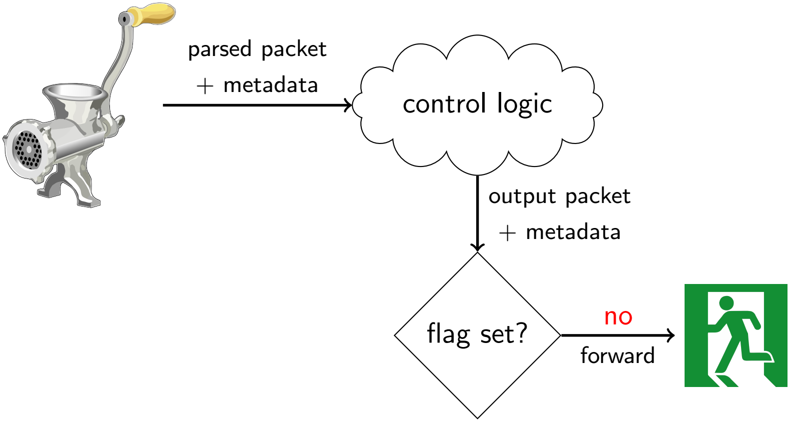

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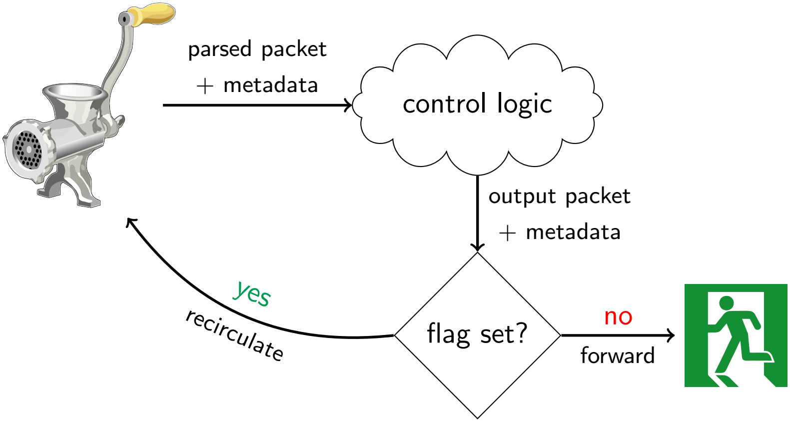

State of the art

Verification frameworks for parsers exist:

- `p4v` (Liu et al. 2018)
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- Only functional properties are verified.
- No reusable certificate is produced.
- Rely on (trusted) verification to IR.

Comparing parsers

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

Contribution

- P4 automata: a syntax and semantics for protocol parsers.

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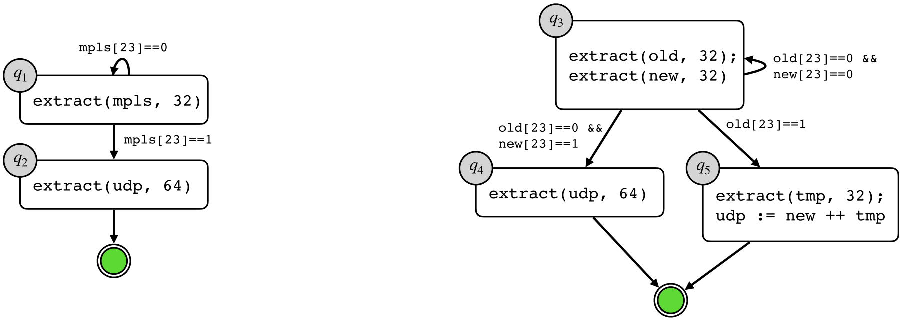
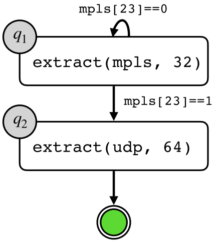
- Algorithm to check (hyperproperties like) language equivalence.
- Implementation of algorithm in Coq + SMT solver.
- Proof of soundness (in Coq) and completeness (on paper).

Running Example



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

Semantics



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

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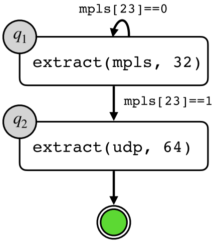
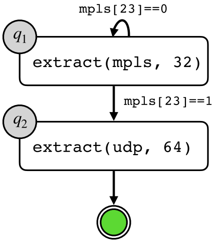


$$c = \langle q_1, s, 0 \rangle$$

Semantics



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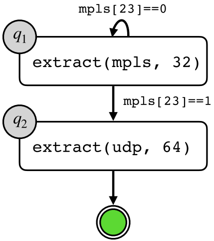

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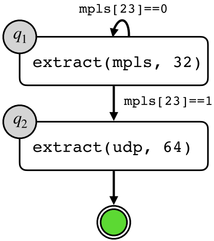

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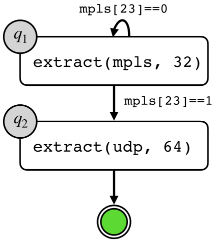

$$c = \langle q_1, s[01 \cdots 0/\texttt{mpls}], 01 \cdots 0 \rangle$$

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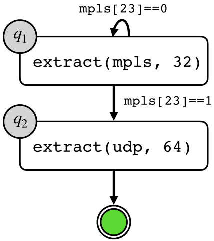

$$c = \langle q_2, s[01\cdots0/\texttt{mpls}], 01\cdots0\rangle$$

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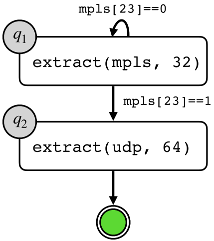

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Formalization

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 $c_2 \in F$
2. $\delta(c_1, b) \; R \; \delta(c_2, b)$ for all b

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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

- $\phi = q_1^<$ means "the left state is q_1"

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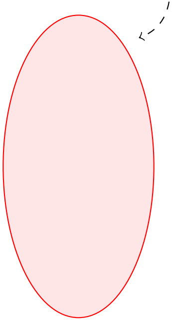
Definition (Symbolic bisimulation)

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

Equivalence checking — intuition

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



ϕ_0

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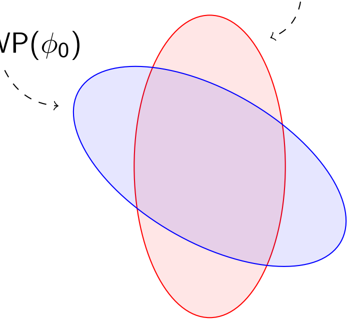
$$\phi_0 = \mathsf{accept}^< \iff \mathsf{accept}^>$$

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



$$\phi_0 \wedge \phi_1$$

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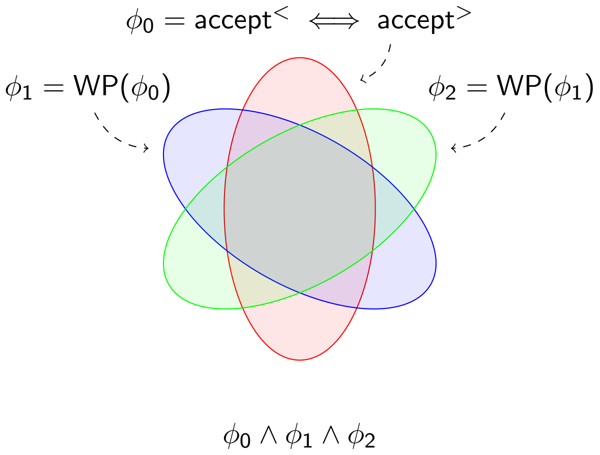

Equivalence checking — algorithm

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

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

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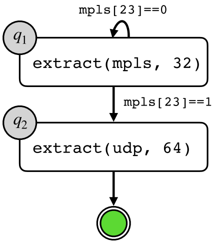
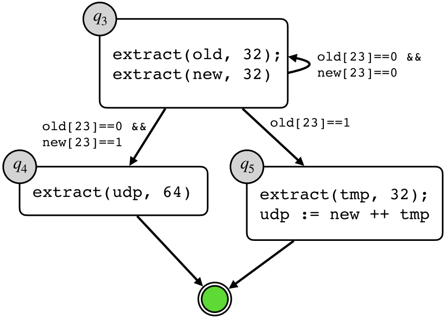
- If ϕ is a symbolic bisimulation, then $\phi \vDash \bigwedge(R \cup T)$.

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

Optimizations — Pruning the bisimulation





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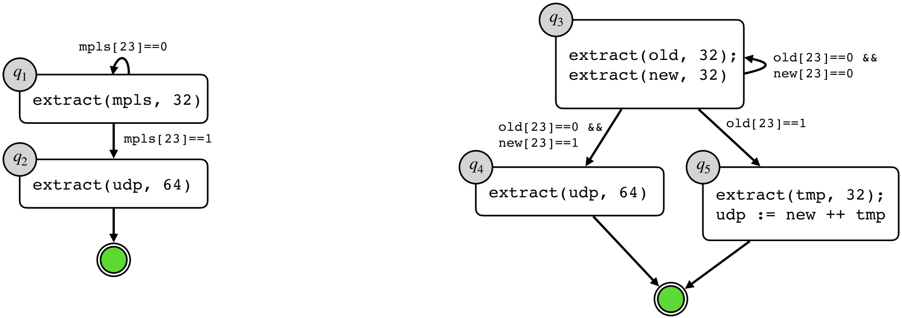

Example (Unreachable pairs)

Left buffer 0, right buffer 13.

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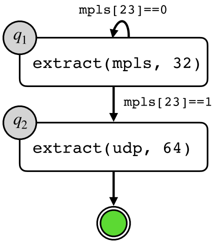

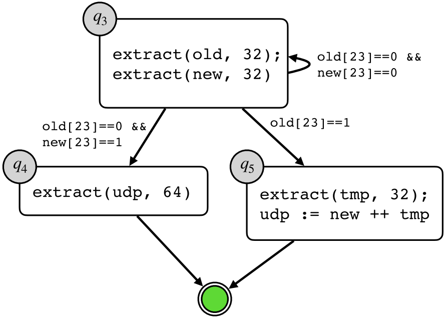

Example (Buffering pairs)

Left buffer 7, right buffer 7.

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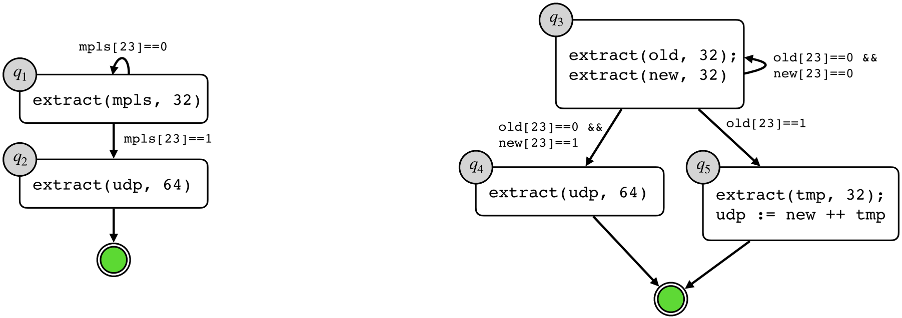

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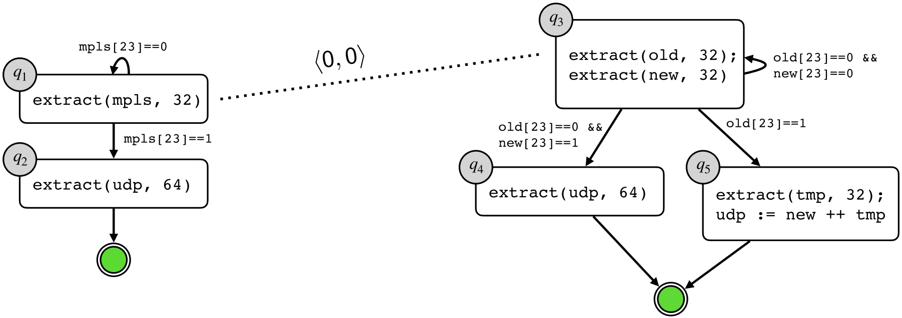

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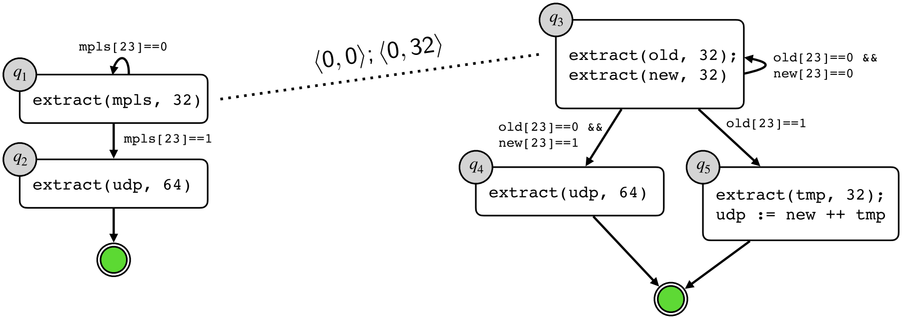

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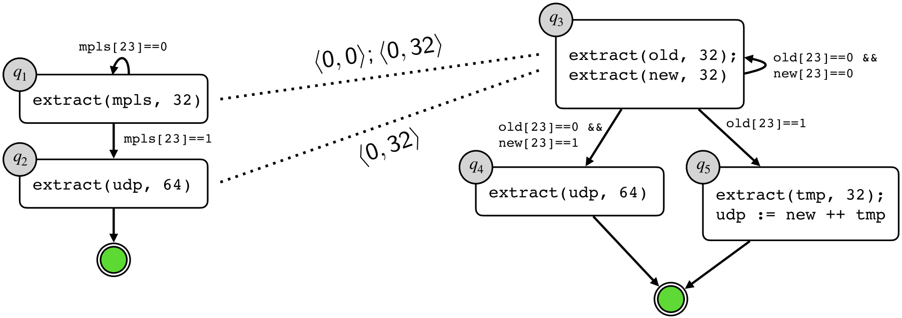

Optimizations — Correctness

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 $c_1 \; R \; c_2$,

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!

Note: requires adjusting implementation of WP.

Implementation

Implementation — Side-stepping the termination checker

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Algorithm state as proof rules:

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

$$\frac{\bigwedge R \not\models \psi \qquad \texttt{pre\_bisim}\ \phi\ (\psi :: R)\ (T; \mathsf{WP}(\psi))}{\texttt{pre\_bisim}\ \phi\ R\ (\psi :: T)}\ \textsc{Extend}$$

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`.

Implementation — Talk to SMT solver

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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interp (R |= phi)
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interp (R |= phi)
< vm_compute.
forall (x: bitvec n) (y: bitvec m), ...
```

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interp (R |= phi)
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forall (x: bitvec n) (y: bitvec m), ...
< hammer.
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interp (R |= phi)
< vm_compute.
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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interp' (compile (R |= phi))
< cbn compile.
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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).

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

Implementation — Talk to SMT solver

Our approach:

- Series of verified simplifications in Gallina.
- Eventual goal is translated almost literally into SMT query.
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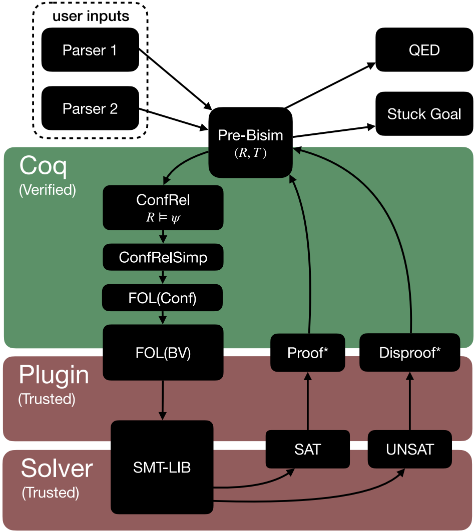
```
interp (R |= phi)
< apply compile_formula.
interp' (compile (R |= phi))
< cbn compile.
interp' (FForall (FExists (...))
< verify_interp; admit.
```

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

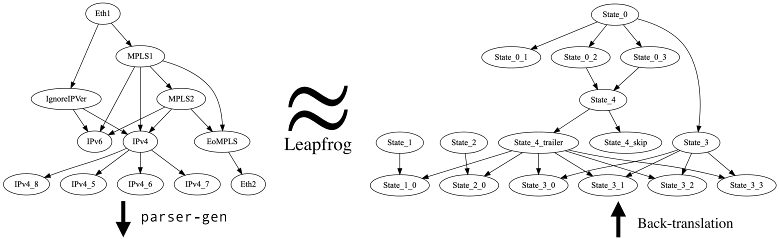
Leapfrog verifies many interesting properties of protocol parsers.

	Name	**States**	**Branched** (bits)	**Total** (bits)	**Time** (min)	**Mem.** (GB)
Utility	St. rearrangement	5	8	136	0.12	0.66
	Variable-length	30	64	632	953.42	405.64
	Initialization	10	10	320	15.95	13.71
	Speculation	5	2	160	4.12	3.16
	Relational	6	64	1056	1.68	2.07
	Filtering	6	64	1056	1.18	1.71
Applicability	Edge	28	52	3184	528.38	251.26
	Service Provider	22	50	2536	1244.5	499.80*
	Datacenter	30	242	2944	1387.95	404.50
	Enterprise	22	176	2144	217.93	66.13
	Tr. Validation	30	56	3148	746.2	350.48

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.

For your convenience:

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

`http://langsec.org/occupy/`

References

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