Unrestricting restrictions in ProVerif

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GT FMS

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Symbolic (Dolev-Yao) models

The attacker can…

- Read / Write
- Intercept

But they do not…

- Break cryptograhy
- Use side channels

Concurrent systems where dishonest parties have complete control over network communication ***but*** cryptography is idealised

Automated Verification

Proverif | **Two main verifiers** | **Tamarin**

Large class of cryptographic primitives

Reachability and equivalence properties

Unbounded number of sessions

Push-button

Almost no guidance

Interactive interface

Lemmas
Axioms
Restrictions

Lot of guidance

Less automated

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More guidance [BCC-S&P22]

Tamarin:

Interactive interface

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Less automated

More automation [CDDK-JCS22]

Lemmas / Axioms / Restrictions

Lemmas

Intermediary property useful to prove the main query

Proved by the tool

Axioms

Similarly to Lemmas but assumed by the tool

Restrictions

Restricts the search space of traces on which to prove the main query

Sometimes useful to avoid heavy encoding

Lemmas / Axioms / Restrictions in ProVerif [BCC22]

Already useful

```
axiom st:bitstring, x:bitstring, y:bitstring;
  event(precise(st,x)) && event(precise(st,y)) ==> x = y.
```

Basis of GSVerif tool

Allow to handle stateful protocols

Add precision to ProVerif

Instrumental in the verification of TLS-ECH, Voting protocols, ZCash

Lemmas / Axioms / Restrictions in ProVerif [BCC22]

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Lemmas are correspondence queries

Premise can be any predicate (events, attacker, mess, table, user-defined)

$$F_1 \wedge \ldots \wedge F_n \Rightarrow \phi$$

Disjunctions and conjunction of events, inequalities, equalities, and disequalities

$$\underbrace{\forall x_1, x_2, \ldots, x_k}_{\text{Variables in the premises}} . F_1 \wedge \ldots \wedge F_n \Rightarrow \underbrace{\exists y_1, \ldots, y_\ell}_{\text{Remaining variables in } \phi} . \phi$$

Lemmas / Axioms / Restrictions in ProVerif [BCC22]

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Semantics of restrictions enforce that events in the conclusion occur before at least one fact of the premise.

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Does not allow temporal variables

Conclusion cannot contain attacker, mess, table, or user defined predicate

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Allow to be more expressive in the order of events

```
axiom id:voter, v,v’:vote, i,j:time;
  event(hasVoted(id,v))@i && event(hasVoted(id,v’))@j ==> i = j.
```

Lemmas / Axioms / Restrictions in ProVerif

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Allow to be more expressive in the order of events

Allow to be more efficient in the application of the lemma

```
lemma i,j:nat;
  event(A(i)) && event(B(j)) && i < j ==> event(C(i,j)).
```

instead of

```
lemma i,j:nat;
  event(A(i)) && event(B(j)) ==>
     i >= j || ( i < j && event(C(i,j)) ).
```

Lemmas / Axioms / Restrictions in ProVerif

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Allow to be more expressive in the order of events

Allow to be more efficient in the application of the lemma

Avoid non-termination scenarios

```
lemma id:voter, v:vote, i,j:time;
  event(VoteCounted(id,v))@i ==> attacker(v)@j && i > j.
```

$$\text{s-event}(\text{VoteCounted}(id, v)) \wedge H \rightarrow \text{att}(\text{v})$$

Clause generated when the vote is revealed by the tally

Removed by application of the lemma

Lemmas / Axioms / Restrictions in ProVerif

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Semantics of restrictions enforce that events in the conclusion occur before at least one fact of the premise.

Allow to prove properties on complex data structure

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Improve precision

Allow to prove properties on complex data structure

Allow to prove liveness and accountability properties

Liveness properties [BDKK-EuroSnP17]

Local progress

Processes need to be reduced as far as possible, that is until they wait for a message

Resilient channels

Messages sent on resilient channel must be delivered

External non-determinism

Any process P + Q reduces to R if P or Q reduces to R.

All these properties can be enforced by "forward" restrictions

Liveness properties [BDKK-EuroS&P17]

External non-determinism

Any process P + Q reduces to R if P or Q reduces to R.

All these properties can be enforced by "forward" restrictions

$$P + Q$$

$$P = a; P'$$

translated into

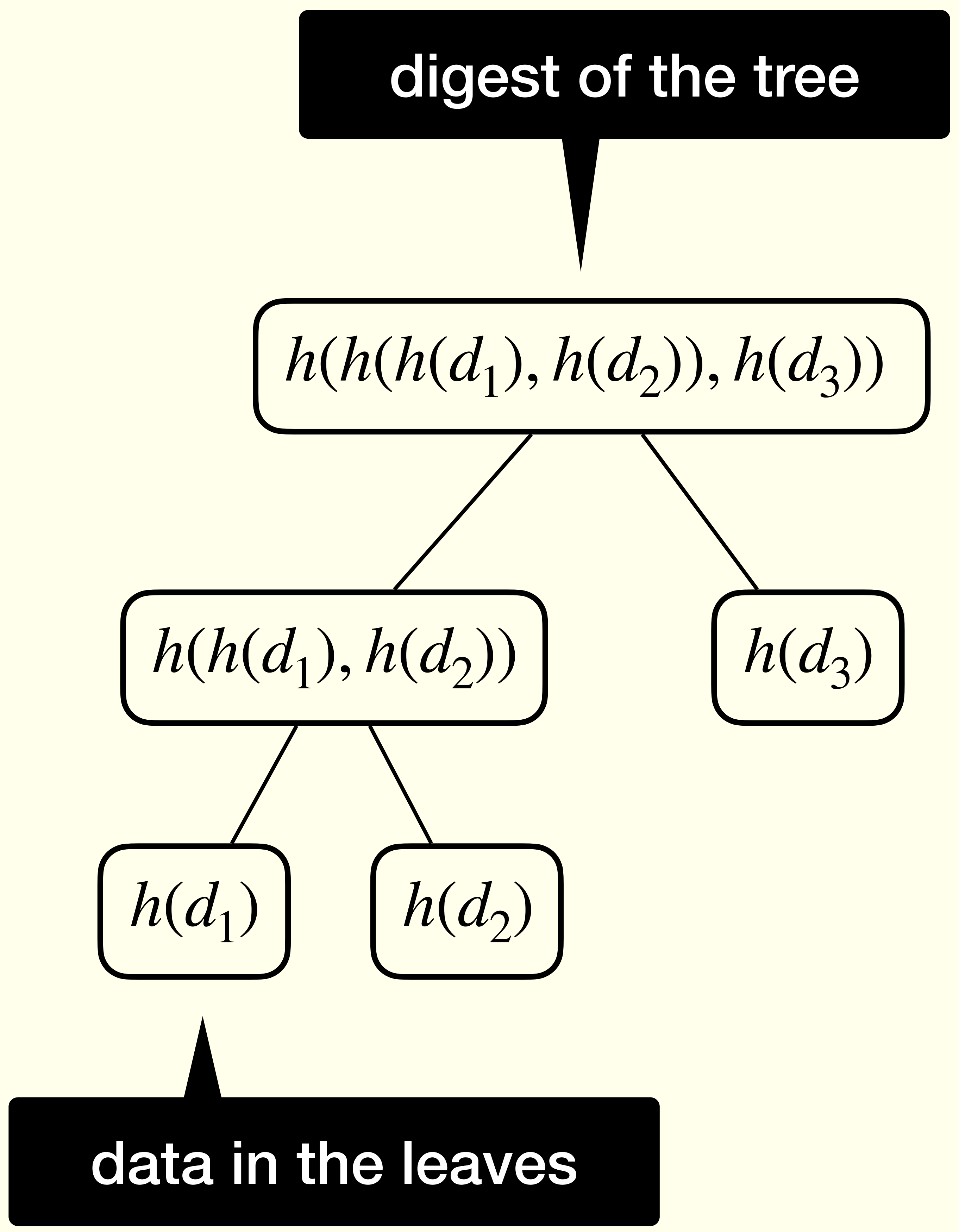
$$Q = b; Q'$$

$$\text{event } B; (\text{event } M; a; \text{event } E; P' \mid \text{event } M; b; \text{event } E; Q')$$

```
restriction
  event(B) ==> event(E);
  event(M)@i && event(M)@j ==> i = j.
```

Properties on complex data structures [CMR-EuroS&P23]

Merkle trees



Good to model ledgers

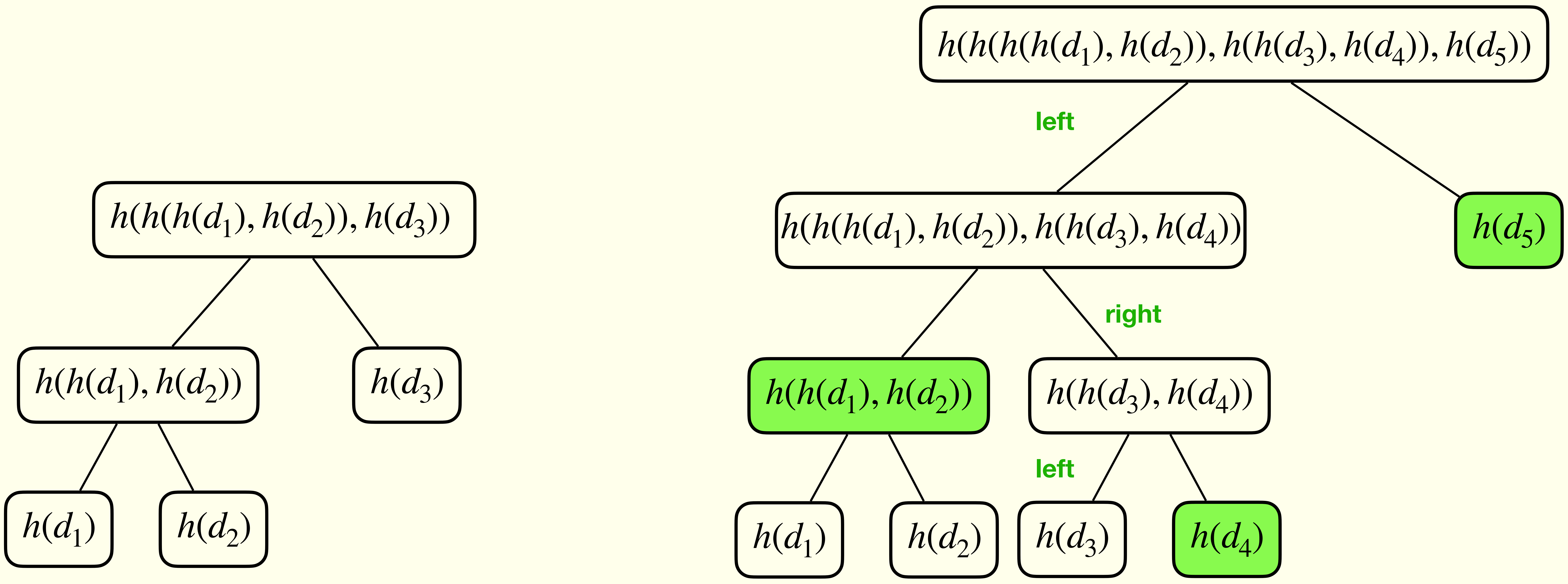
Append only structure

Proof of presence in O(log(n))

Proof of extension in O(log(n))

Properties on complex data structures [CMR-EuroS&P23]

Merkle trees



In green, proof of extension between the two trees

Properties on complex data structures [CMR-EuroS&P23]

Defining verification predicates through Horn clauses

```
(* Proof of presence *)

fun PP(list):proof_of_presence [data].

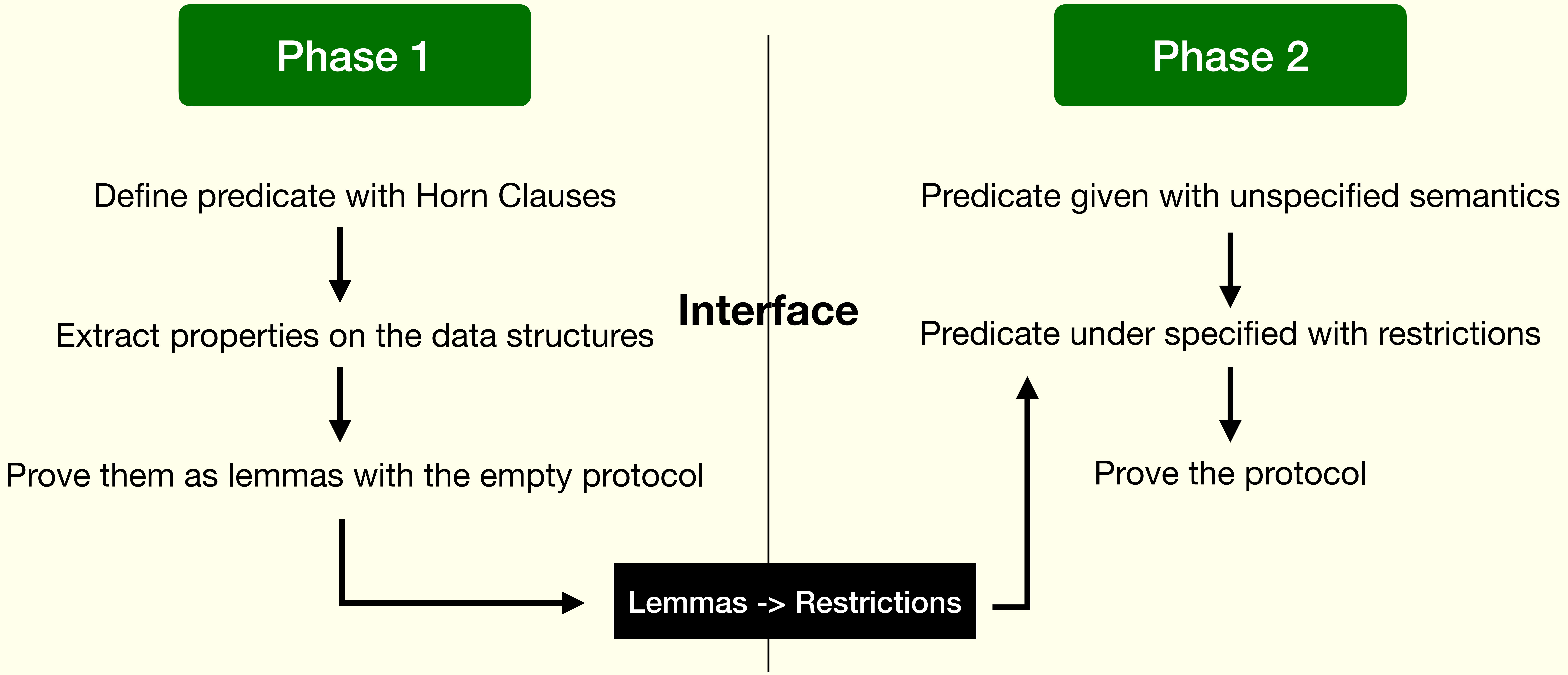
clauses
  forall x:bitstring;
    verify_pp(PP(nil),x,hash(leaf(x)));
  forall pl:list, x:bitstring, d_left,d_right:digest;
    verify_pp(PP(pl),x,d_left) ->
    verify_pp(PP(cons((left,d_right),pl)),x,hash(node(d_left,d_right)));
  forall pl:list, x:bitstring, d_left,d_right:digest;
    verify_pp(PP(pl),x,d_right) ->
    verify_pp(PP(cons((right,d_left),pl)),x,hash(node(d_left,d_right)))
.
```

Will often not terminate if these Horn clauses are given with the protocol

Properties on complex data structures [CMR-EuroS&P23]

Prove the protocol in two phases

Phase 2 proves the protocol for all implementations satisfying the interface



Properties on complex data structures [CMR-EuroS&P23]

Extract of the interface

```
(* Transitivity of proof of extension *)
lemma pe1,pe2,pe3:proof_of_extension, d1,d2,d3:digest;
  verify_pe(pe1,d1,d2) && verify_pe(pe2,d2,d3) ==> verify_pe(pe3,d1,d3)
.

(* Proofs of presence are stable by proofs of extension *)
lemma x:bitstring, pe:proof_of_extension, pp1,pp2:proof_of_presence,
d1,d2:digest;
  verify_pp(pp1,x,d1) && verify_pe(pe,d1,d2)  ==> verify_pp(pp2,x,d2)
.
```

Properties on complex data structures

Useful to model other predicates: is_subterm

In work with Véronique Cortier and Alexandre Debant on Election Verifiability

```
(* We do not implement the full subterm semantics but only a sufficient subset. *)

pred is_subterm(bitstring,bitstring).

clauses
  forall x,y:bitstring; is_subterm(x,hash((y,x)));
  forall x,y:bitstring; is_subterm(x,x);
  forall x,y,z:bitstring; is_subterm(x,y) -> is_subterm(x,hash((y,z)))
.
```

```
lemma x,y:bitstring, uuid:election_id,j1,j2,i1,i2:nat,
h1,h2,ballot1,ballot2:bitstring;
  event(Ballot_In_Bulletin_Board(uuid,j1,i1,ballot1,h1)) &&
  event(Ballot_In_Bulletin_Board(uuid,j2,i2,ballot2,h2)) && i1 <= i2 ==>
  is_subterm(ballot1,h2)
.
```

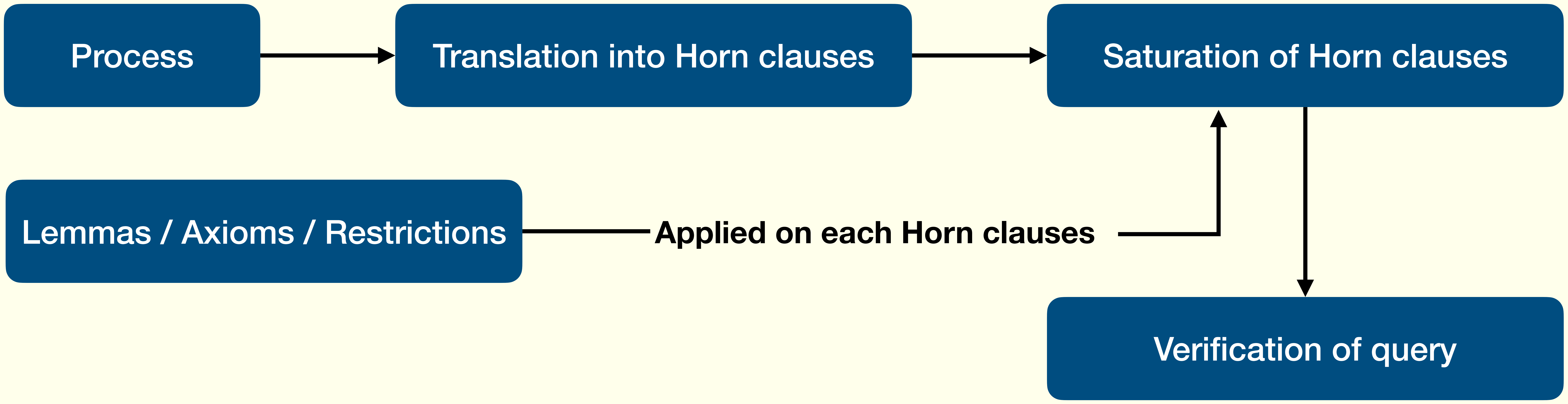
Lemmas / Axioms / Restrictions in ProVerif

Does not allow temporal variables	**Allow to be more expressive in the order of events**
Does not allow disequalities and inequalities in the premises	**Allow to be more efficient in the application of the lemma**
Events in the conclusion do not restrict traces	**Avoid non-termination scenarios**
Conclusion cannot contain attacker, mess, table, or user defined predicate	**Improve precision**
	Allow to prove properties on complex data structure
Semantics of restrictions enforce that events in the conclusion occur before at least one fact of the premise.	**Allow to prove liveness and accountability properties**

Lemmas / Axioms / Restrictions in ProVerif (next release)

	Includes [CMR-EuroS&P23]
Allow temporal variables	**Allow to be more expressive in the order of events**
Allow disequalities and inequalities in the premises	**Allow to be more efficient in the application of the lemma**
Events in the conclusion restrict traces	**Avoid non-termination scenarios**
Conclusion can contain any predicate	**Improve precision**
	Allow to prove properties on complex data structure
No semantics constraints on the occurrence order of events in restrictions.	**Allow to prove liveness and accountability properties**

Under the hood: any predicate in query conclusion



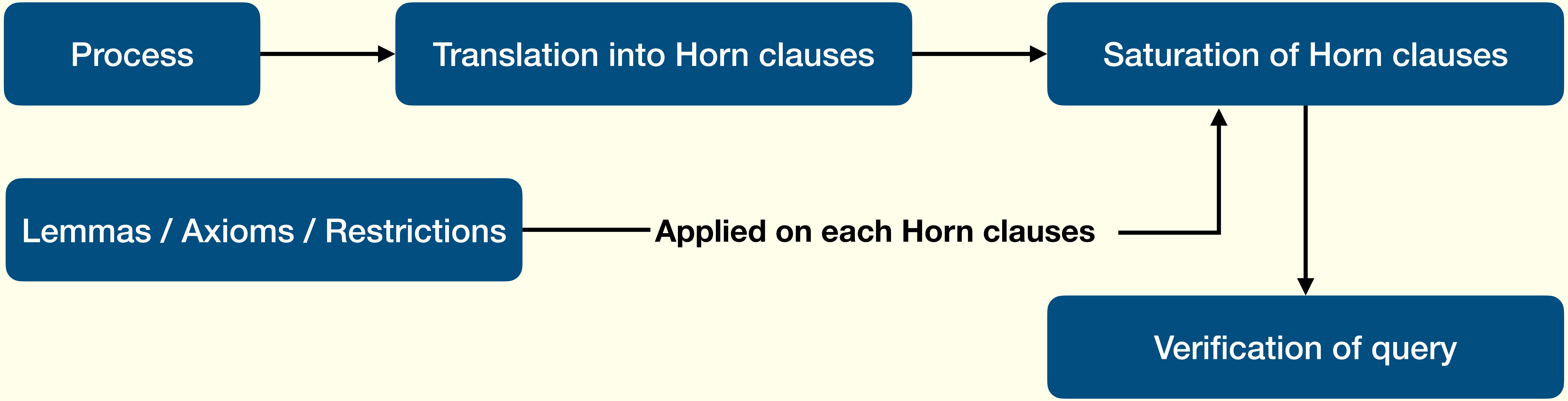
Lemma $F_1 \wedge F_2 \Rightarrow G_1 \wedge G_2 \wedge G_3$

Clause $H \rightarrow C$

If there is a substitution σ **such that** $F_1\sigma \wedge F_2\sigma \subseteq H$ **then**

$H \rightarrow C$ **is replaced by** $H \wedge G_1\sigma \wedge G_2\sigma \wedge G_3\sigma \rightarrow C$

Under the hood: any predicate in query conclusion



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$H \rightarrow C$ **is replaced by** $H \wedge G_1\sigma \wedge G_2\sigma \wedge G_3\sigma \rightarrow C$

Not always sound !

events ✓

attacker facts ✗

Under the hood: any predicate in query conclusion

Two predicates for events

s-event	*sure-event*: occurs only in hypotheses of Horn clauses
m-event	*may-event:* occurs only in conclusions of Horn clauses

Consequence: facts with s-event predicates are never resolved !

Applying a lemma is sound if no added facts can be resolved.

Under the hood: any predicate in query conclusion

Two predicates for events

s-event *sure-event*: occurs only in hypotheses of Horn clauses

m-event *may-event:* occurs only in conclusions of Horn clauses

Consequence: facts with s-event predicates are never resolved !

Applying a lemma is sound if no added facts can be resolved.

For every predicate, we consider a *blocking* predicate that cannot be resolved

Under the hood: any predicate in query conclusion

```
lemma id:voter, v:vote; event(VoteCounted(id,v)) ==> attacker(v).
```

Clause $\text{b-event}(\text{VoteCounted}(id, C_1)) \wedge H \rightarrow \text{att}(\text{C}_1)$

Under the hood: any predicate in query conclusion

```
lemma id:voter, v:vote; event(VoteCounted(id,v)) ==> attacker(v).
```

Clause $\text{b-event}(\text{VoteCounted}(id, C_1)) \wedge H \rightarrow \text{att}(\text{C}_1)$

After applying the lemma

$$\text{b-att}(C_1) \wedge \text{b-event}(\text{VoteCounted}(id, C_1)) \wedge H \rightarrow \text{att}(\text{C}_1)$$

Under the hood: any predicate in query conclusion

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After applying the lemma

$$\text{b-att}(C_1) \wedge \text{b-event}(\text{VoteCounted}(id, C_1)) \wedge H \rightarrow \text{att}(\mathrm{C}_1)$$

Transformation rules are adapted to take blocking predicate into account

The clause is removed by tautology

Under the hood: forward restriction

```
process event Send | (event Goal; event Received).
```

```
query event(Send) ==> event(Goal).
```

False

Under the hood: forward restriction

```
process event Send | (event Goal; event Received).
```

```
query event(Send) ==> event(Goal).
```

True

```
restriction event(Send) ==> event(Received).
```

But ProVerif can’t prove it… Why?

Under the hood: forward restriction

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process event Send | (event Goal; event Received).
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```
query event(Send) ==> event(Goal).
```

True

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```

But ProVerif can't prove it… Why?

Clauses generated:

$$\rightarrow \text{event}(\text{Send})$$

$$\text{b-event}(\text{Goal}) \rightarrow \text{event}(\text{Received})$$

$$\rightarrow \text{event}(\text{Goal})$$

Under the hood: forward restriction

```
process event Send | (event Goal; event Received).
```

```
query event(Send) ==> event(Goal).
```

True

```
restriction event(Send) ==> event(Received).
```

But ProVerif can't prove it… Why?

Clauses after saturation:

$$\text{b-event(Received)} \rightarrow \text{event(Send)}$$

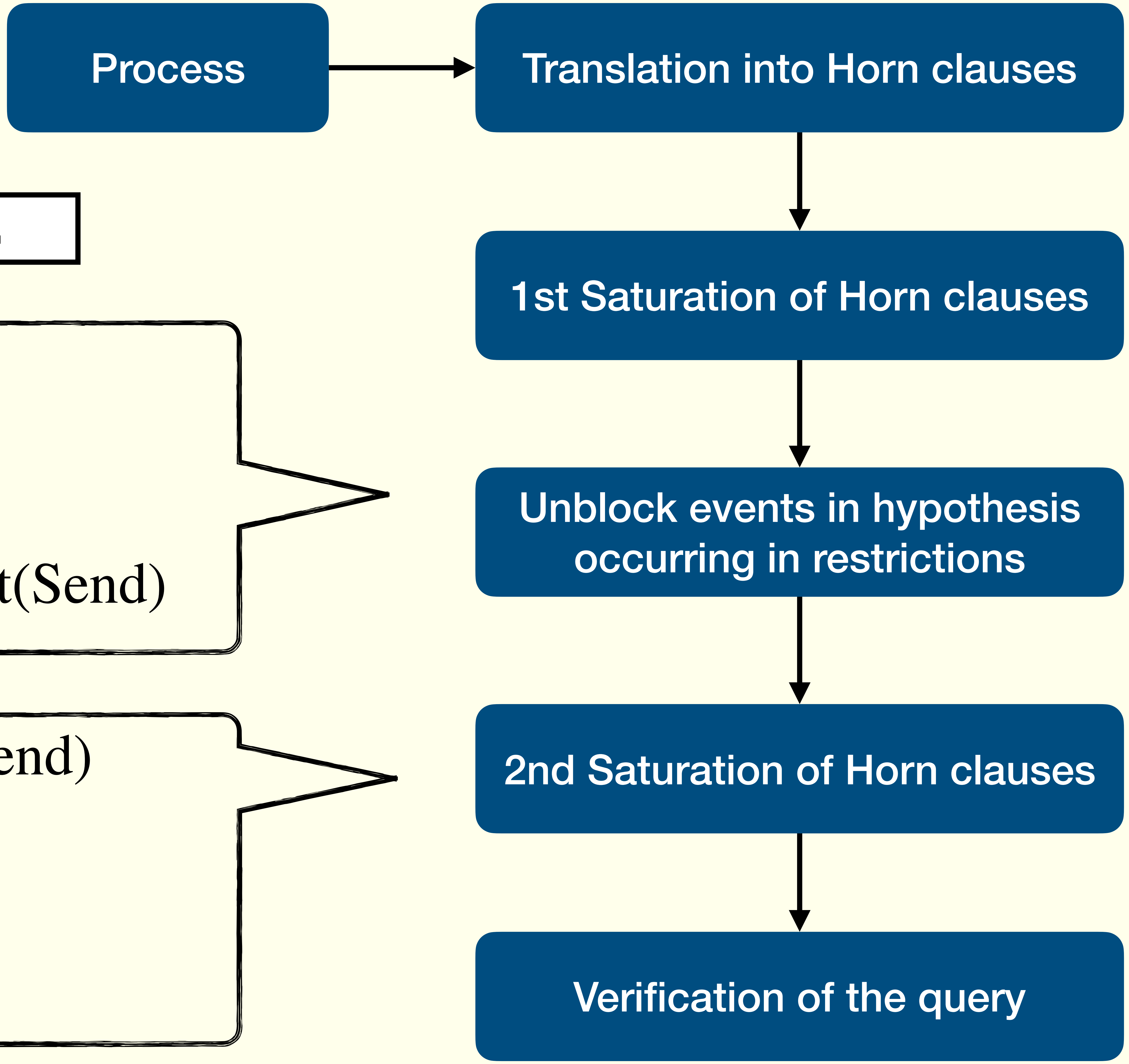
Hypothesis of the clause cannot show the execution of event Goal.

$$\text{b-event(Goal)} \rightarrow \text{event(Received)}$$

$$\rightarrow \text{event(Goal)}$$

Under the hood: forward restriction

Idea: Two rounds of saturation




```
restriction event(Send) ==> event(Received).
```

$\text{b-event}(\text{Received}) \rightarrow \text{event}(\text{Send})$

becomes

$\text{b-event}(\text{Received}) \wedge \text{event}(\text{Received}) \rightarrow \text{event}(\text{Send})$

$\text{b-event}(\text{Received}) \wedge \text{b-event}(\text{Goal}) \rightarrow \text{event}(\text{Send})$

$\text{b-event}(\text{Goal}) \rightarrow \text{event}(\text{Received})$

$\rightarrow \text{event}(\text{Goal})$

Timetable of ProVerif next releases

Available at

https://gitlab.inria.fr/bblanche/proverif

https://bblanche.gitlabpages.inria.fr/proverif/

Now	GT MFS 2023
2-3 months	Next release with unrestricted lemmas/axioms/restrictions
end of 2023	Memory optimisation (first prototype already developed)
mid 2024	ProVerif with DH, XOR, AC (early work with Caroline Fontaine)
??	Certificate generator and machine checked verifier
	Auto-detection of cycles with noselect suggestions
	Auto-detection of secrecy assumptions
	GSVerif integration
	MultiCore ProVerif
	Trace equivalence, simulation and bisimulation
	Algorithm optimisations (subsumption, redundancy, lemma applications, …)
	Symmetry-based query verification

Interns wanted!