

Analysis of Electronic Commerce Protocols in Algebraic Specification Languages *

Kazuhiro Ogata¹

In collaboration with *Kokichi Futatsugi*¹

¹ School of Information Science
Japan Advanced Institute of Science and Technology (JAIST)

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An Experience on Interactive Theorem Proving

- We tried verifying that an e-commerce protocol satisfied a property with **CafeOBJ**, an alg spec lang & system, which was used as an interactive theorem prover.
- In the course of the verification (in which a few different modles of the protocol were made), we happend to notice a counterexample showing that the protocol does not satisfy the property.

It took *a couple of weeks* for us to happen to notice it!

- We had wondered whether such a counterexample is able to be found systematically and quickly.

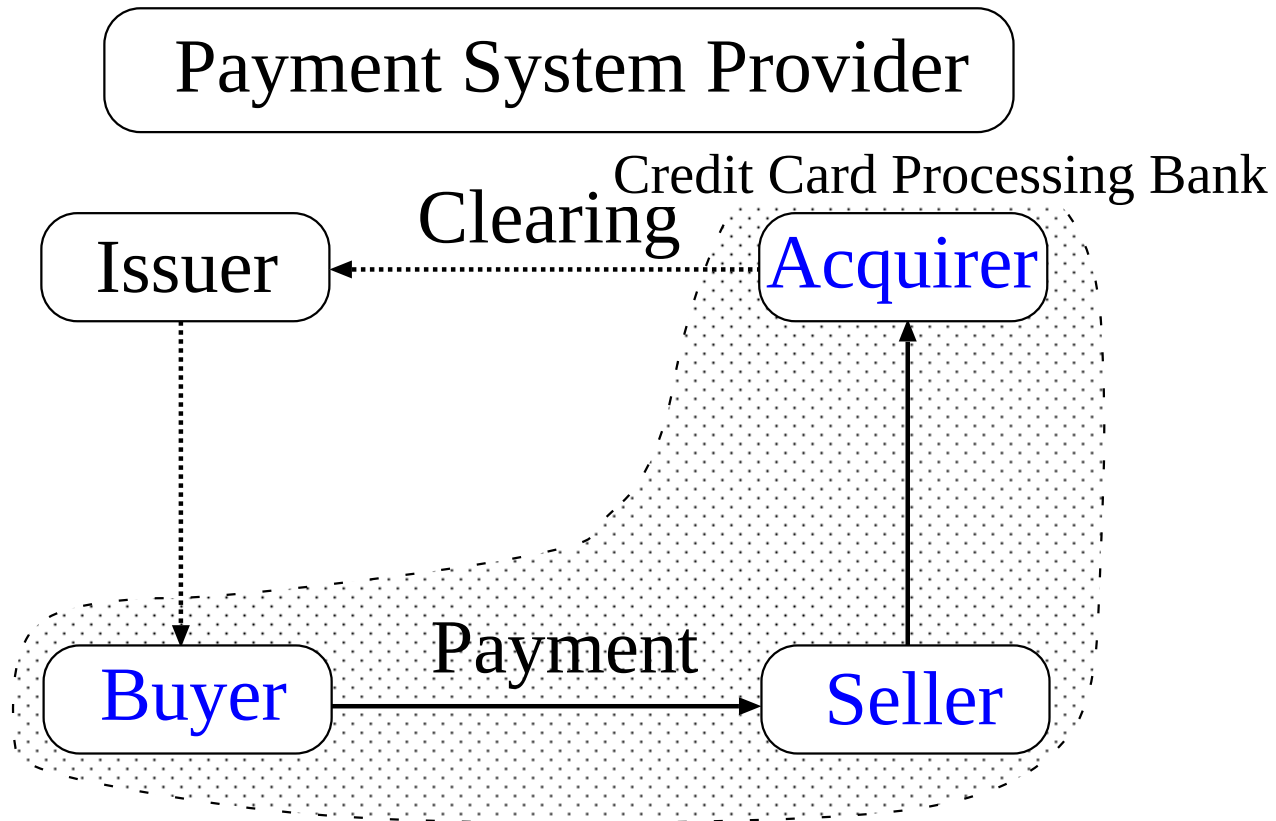
We conducted a case study in which the e-commerce protocol was *model checked* to find a counterexample showing that it does not satisfy the property.

Roadmap

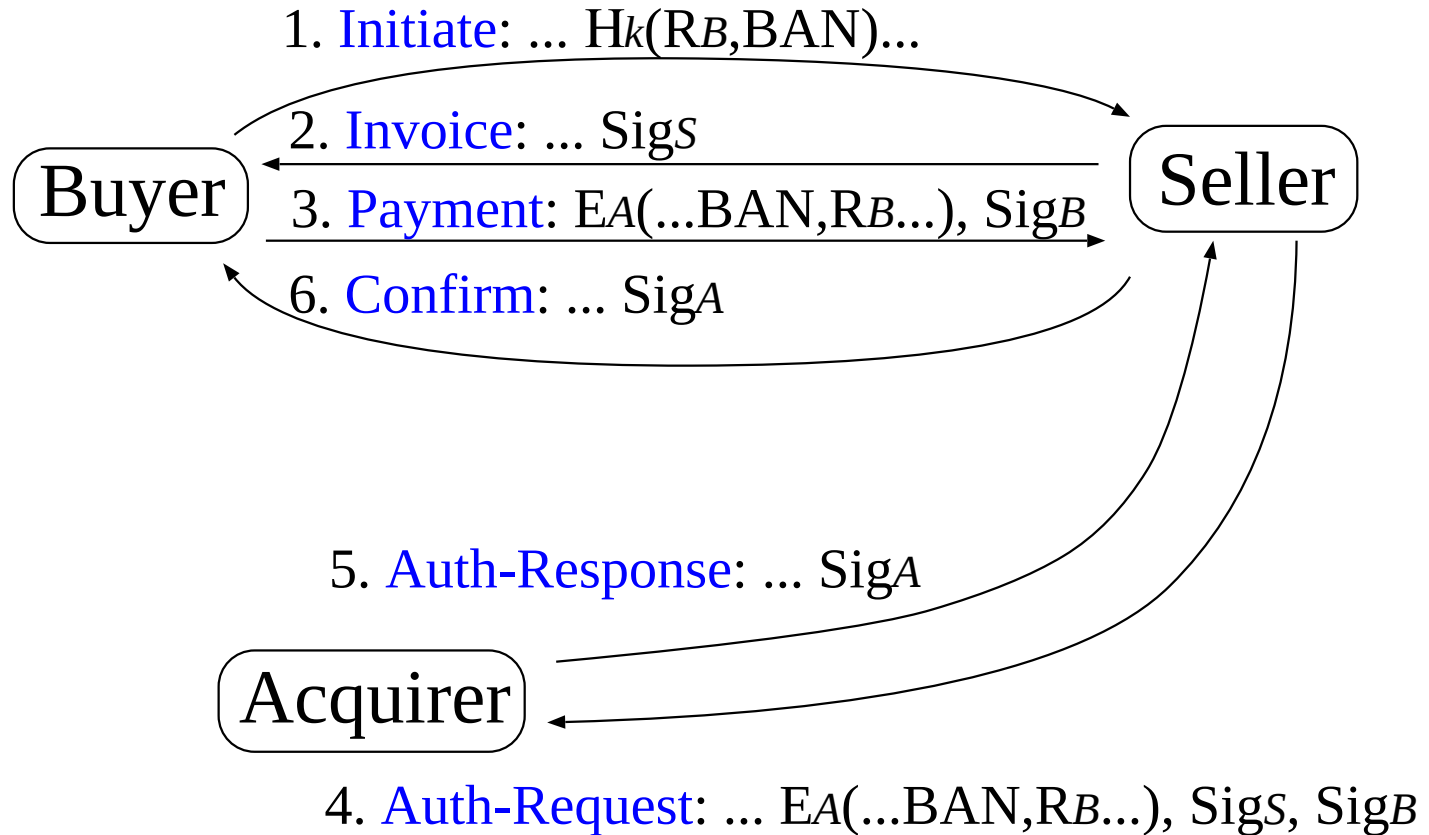
We report on the case study in which the e-commerce protocol was model checked to find a counterexample showing that it does not satisfy the property.

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Generic Model of Payment System



Overview of 3KP



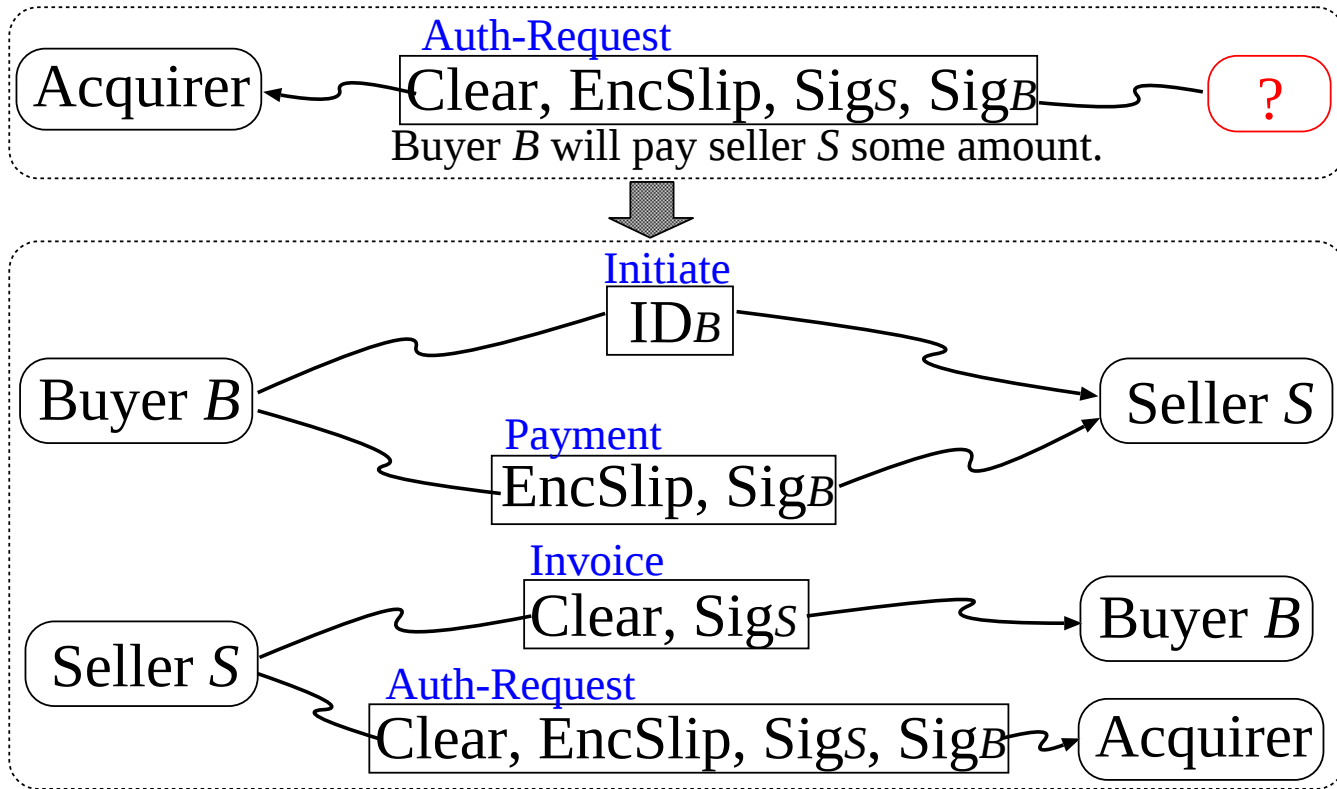
Traditional Description of 3KP

Initiate	$B \rightarrow S : ID_B$
Invoice	$S \rightarrow B : \text{Clear}, \text{Sig}_S$
Payment	$B \rightarrow S : \text{EncSlip}, \text{Sig}_B$
Auth-Request	$S \rightarrow A : \text{Clear}, \text{EncSlip}, \text{Sig}_S, \text{Sig}_B$
Auth-Response	$A \rightarrow S : \text{RESPCODE}, \text{Sig}_A$
Confirm	$S \rightarrow B : \text{RESPCODE}, \text{Sig}_A$

- $ID_B : \mathcal{H}_k(R_B, \text{BAN})$
- $\text{Common} : \text{PRICE}, ID_S, \text{NONCE}_S, ID_B$
- $\text{Clear} : ID_S, \text{NONCE}_S, \mathcal{H}(\text{Common})$
- $\text{Slip} : \text{PRICE}, \mathcal{H}(\text{Common}), \text{BAN}, R_B$
- $\text{EncSlip} : \mathcal{E}_A(\text{SLIP})$
- $\text{Sig}_A : \mathcal{S}_A(\text{RESPCODE}, \mathcal{H}(\text{Common}))$
- $\text{Sig}_S : \mathcal{S}_S(\mathcal{H}(\text{Common}))$
- $\text{Sig}_B : \mathcal{S}_B(\text{EncSlip}, \mathcal{H}(\text{Common}))$

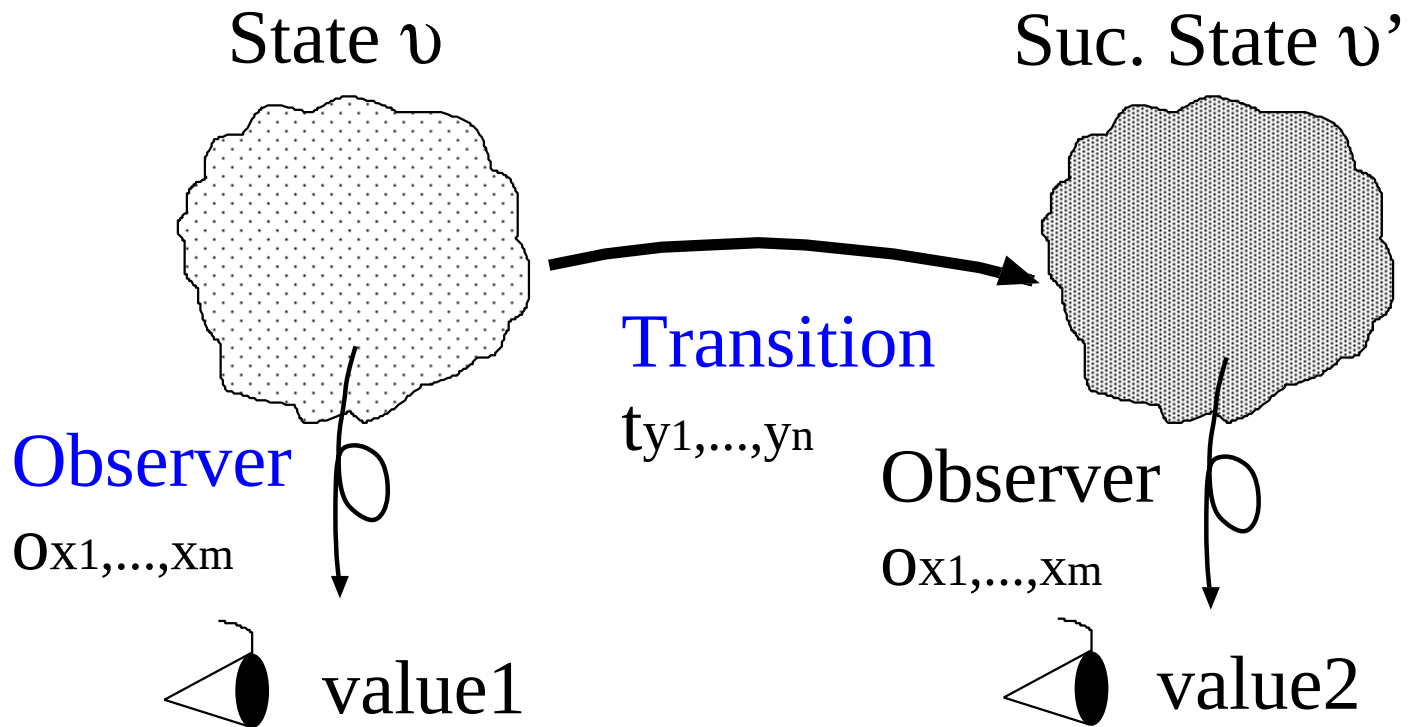
Payment Agreement Property

Whenever an acquirer authorizes a payment, both the buyer and seller concerned agree on it.



Informal Description of OTSs

OTSs are transition systems.



Definition of OTSs

Suppose a *universal state space* Υ and data types D_* used in OTSs.

An OTS $\mathcal{S}$ is $\langle \mathcal{O}, \mathcal{I}, \mathcal{T} \rangle$ such that

- $\mathcal{O}$: A finite set of observers.

Each *observer* is an indexed function $o_{x_1:D_{o1}, \dots, x_m:D_{om}} : \Upsilon \rightarrow D_o$.

- $\mathcal{I}$: The set of initial states such that $\mathcal{I} \subseteq \Upsilon$.

- $\mathcal{T}$: A finite set of transitions.

Each *transition* is an indexed function $t_{y_1:D_{t1}, \dots, y_n:D_{tn}} : \Upsilon \rightarrow \Upsilon$.

Each t has the condition c - t called the *effective condition*.

If c - $t_{y_1, \dots, y_n}(v)$ does not hold, then $t_{y_1, \dots, y_n}(v) =_{\mathcal{S}} v$.

Assumptions

- There exists **one genuine acquirer** (ga) who is known by every principal.
- Ciphertexts such as $\mathcal{E}_A(\text{SLIP})$ can be never decrypted and signatures such as $\mathcal{S}_A(\text{RESPCODE}, \mathcal{H}(\text{Common}))$ can be never made unless the corresponding private keys such as A 's private key are known.
- Secret information such as BANs is never guessable.
- There exists **the general intruder** who acts as a buyer (ib), a seller (is) and an acquirer (ia). What the intruder can do is
 - To look at every message in the network.
 - To glean the quantities obtained from such messages.
 - To fake messages based on the gleaned quantities.

Formalizing Quantities & Composite Fields

For example,

- Hban : Keyed hashed BANs. $\text{hban}(r, bn)$ denotes $\mathcal{H}_k(r, bn)$.
- Common : Commons. $\text{com}(p, s, n, hbn)$ denotes the Common that consists of p, s, n and hbn .
- Hcom : Hashed Commons. $\text{hcom}(c)$ denotes $\mathcal{H}(c)$.
- Eslip : EncSlips. $\text{esl}(a, sl)$ denotes $\mathcal{E}_a(sl)$.
- SigA : Acquirers' signatures. $\text{sig}_a(a, rc, hc)$ denotes $\mathcal{S}_a(rc, hc)$.

Formalizing Messages

Initiate – $\text{im}(b1, b, s, hbn)$

Invoice – $\text{vm}(s1, s, b, cl, gs)$

Invoice (cl, gs) that has been sent by $s1$ to b , but seems to have been sent by s , which may be different from $s1$.

Payment – $\text{pm}(b1, b, s, esl, gb)$

Auth-Request – $\text{qm}(s1, s, a, esl, gb)$

Auth-Response – $\text{sm}(a1, a, s, cl, esl, gs, gb)$

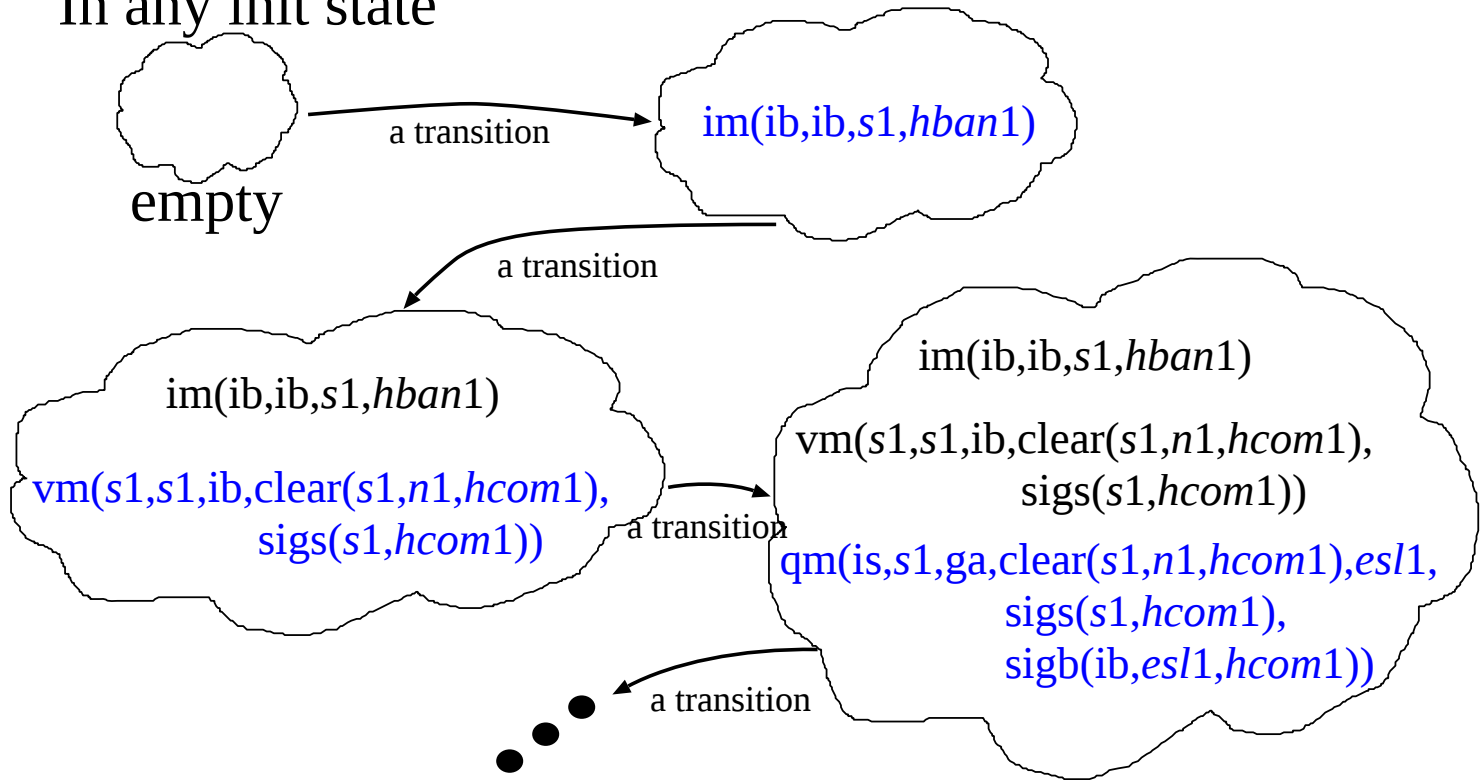
Confirm – $\text{cm}(s1, s, b, rc, ga)$

- 1st arg: *The principal who has actually sent the message.*
- 2nd arg: The principal who seems to have sent the message.
- 3rd arg: The principal who is supposed to receive the message.
- 4th arg and subsequent ones: The body of the message.

Formalizing Networks

The network is denoted by a collection of messages that has been sent.

In any init state



$\mathcal{S}_{3KP}$ (1)

$\mathcal{O}_{3KP}$ contains

- $\text{rand} : \Upsilon \rightarrow \text{Rand}$
- $\text{nonces} : \Upsilon \rightarrow \text{NonceBag}$
- $\text{bans} : \Upsilon \rightarrow \text{BanBag}$
- $\text{sigas} : \Upsilon \rightarrow \text{SigABag}$
- $\text{nonce} : \Upsilon \rightarrow \text{Nonce}$
- $\text{hbans} : \Upsilon \rightarrow \text{HbanBag}$
- $\text{rands} : \Upsilon \rightarrow \text{RandBag}$
- $\text{sigss} : \Upsilon \rightarrow \text{SigSBag}$
- $\text{nw} : \Upsilon \rightarrow \text{Network}$
- $\text{hcoms} : \Upsilon \rightarrow \text{HcomBag}$
- $\text{eslips} : \Upsilon \rightarrow \text{EsliPBag}$
- $\text{sigbs} : \Upsilon \rightarrow \text{SigSBag}$

The collections of gleaned quantities.

For each $v_0 \in \mathcal{I}_{3KP}$,

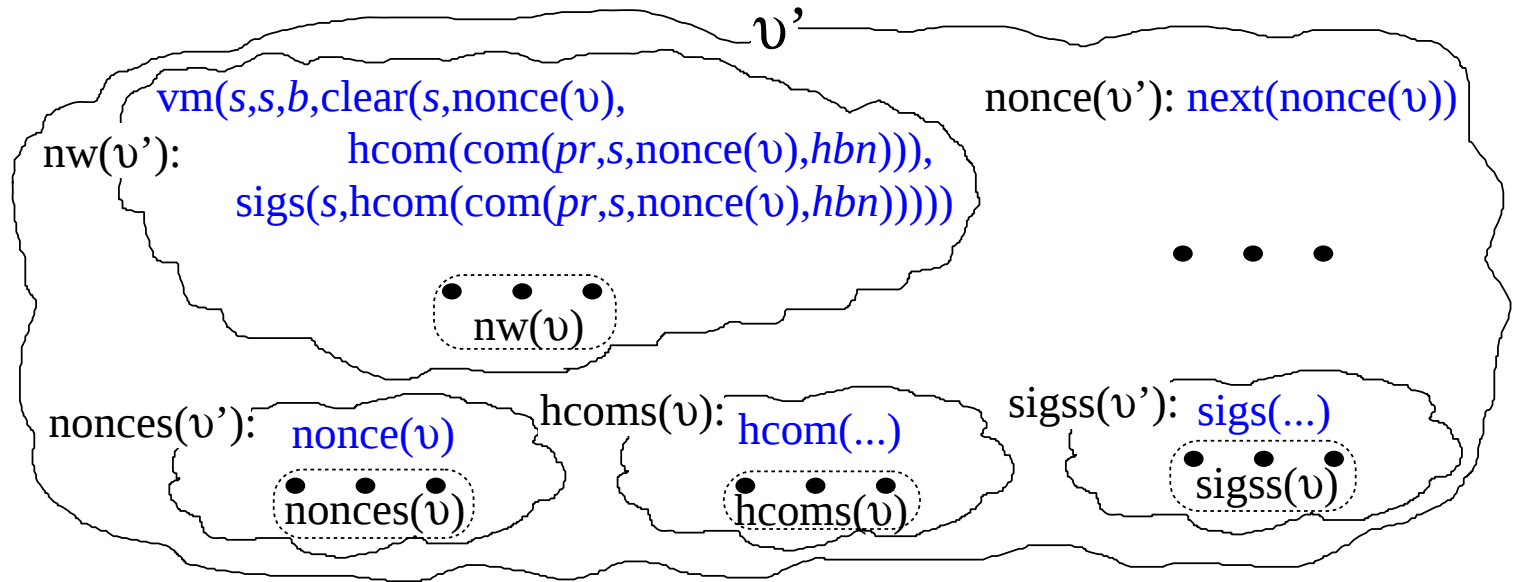
- $\text{rand}(v_0) = \text{seed}$
- $\text{nonces}(v_0) = \text{empty}$
- $\text{bans}(v_0) = \text{empty}$
- $\text{sigas}(v_0) = \text{empty}$
- $\text{nonce}(v_0) = \text{in}$
- $\text{hbans}(v_0) = \text{empty}$
- $\text{rands}(v_0) = \text{empty}$
- $\text{sigss}(v_0) = \text{empty}$
- $\text{nw}(v_0) = \text{empty}$
- $\text{hcoms}(v_0) = \text{empty}$
- $\text{eslips}(v_0) = \text{empty}$
- $\text{sigbs}(v_0) = \text{empty}$

$\mathcal{S}_{3KP}$ (2)

$\mathcal{T}_{3KP}$ contains 43 transitions: 6 for sending messages exactly following the protocol and 37 for faking messages based on the gleaned information.

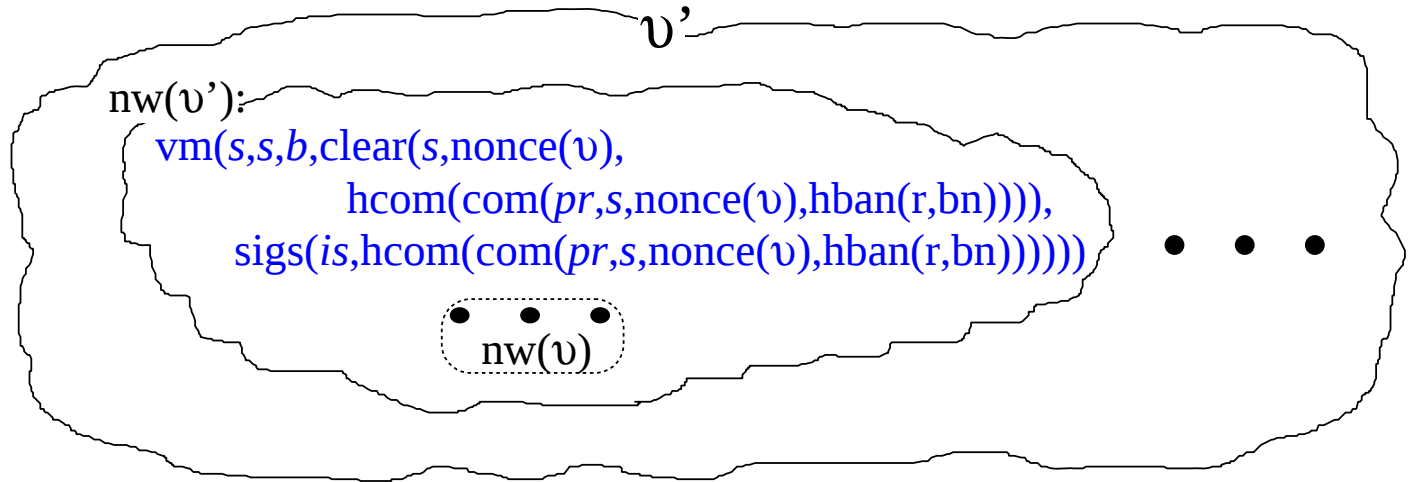
- $\text{sdvm}_{s,b,b1,hbn,pr} : \Upsilon \rightarrow \Upsilon$: Let v' be $\text{sdvm}_{s,b,b1,hbn,pr}(v)$.

$$\text{c-sdvm}_{s,b,b1,hbn,pr}(v) \triangleq \text{im}(b1, b, s, hbn) \in \text{nw}(v)$$



$\mathcal{S}_{3KP}$ (3)

- $\text{fkvm5}_{s,b,n,pr,r,bn} : \Upsilon \rightarrow \Upsilon$: Let v' be $\text{sdvm}_{s,b,b1,hbn,pr}(v)$.
 $\text{c-fkvm5}_{s,b,n,pr,r,bn} \triangleq n \in \text{nonces}(v) \wedge r \in \text{rands}(v) \wedge bn \in \text{bans}(v)$



Maude

- Data & state machines.
 - Data are specified in membership equational logic.
 - State machines are specified in rewriting logic.
- Fast rewrite engine & flexible meta-programming environment.
- Model checking facilities.

Inductive types can be used. Entire state spaces do not have to be finite.

- On-the-fly explicit state LTL model checker.
- Search command.

Even reachable state spaces do not have to be finite; BMC can be performed.

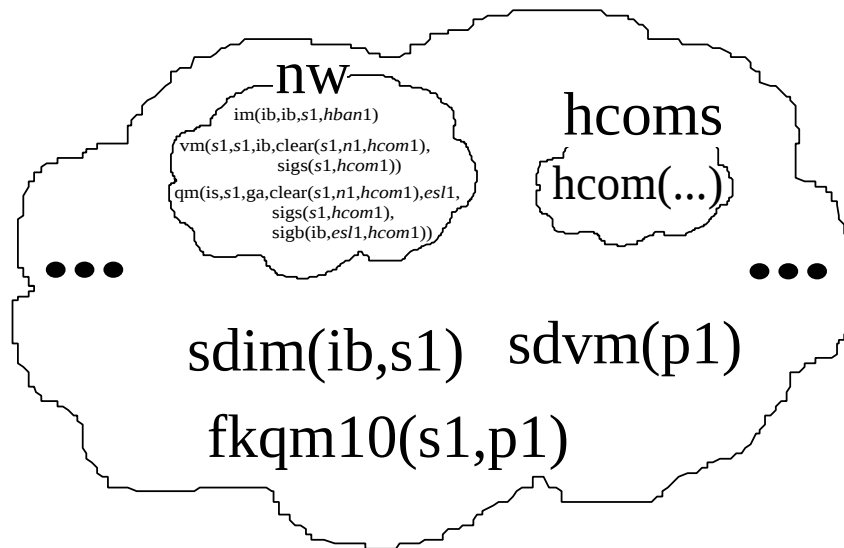
It can be used to find counterexamples showing that state machines do not satisfy invariant properties.

Overview of Specification

Observers & transitions are denoted by operators. For example,

```
op nw : _ : Network -> Observer .
op sdvm : Price -> Transition .
```

States are denoted by collections of terms whose sorts are **Observer** or **Transition**.



Definitions of Transitions

Transitions are defined in rewriting rules that change collections of terms whose sorts are **Observers** or **Transitions**.

For example, the rule defining $\text{sdvm}_{s,b,b1,hbn,pr} : \Upsilon \rightarrow \Upsilon$:

```

rl [rule-sdvm] : sdvm(PR) (nonce : N) (nw : (im(B1,B,S,HBN) NW))
  (nonces : Ns) (hcoms : HCs) (sigss : GSs)
=> sdvm(PR) (nonce : next(N))
    (nw : (vm(S,S,B,clear(S,N,hcom(com(PR,S,N,HBN))),
              sigs(S,hcom(com(PR,S,N,HBN))))
            im(B1,B,S,HBN) NW))
    (nonces : (N Ns)) (hcoms : (hcom(com(PR,S,N,HBN)) HCs))
    (sigss : (sigs(S,hcom(com(PR,S,N,HBN))) GSs)) .

```

Search Command to Find a Counterexample

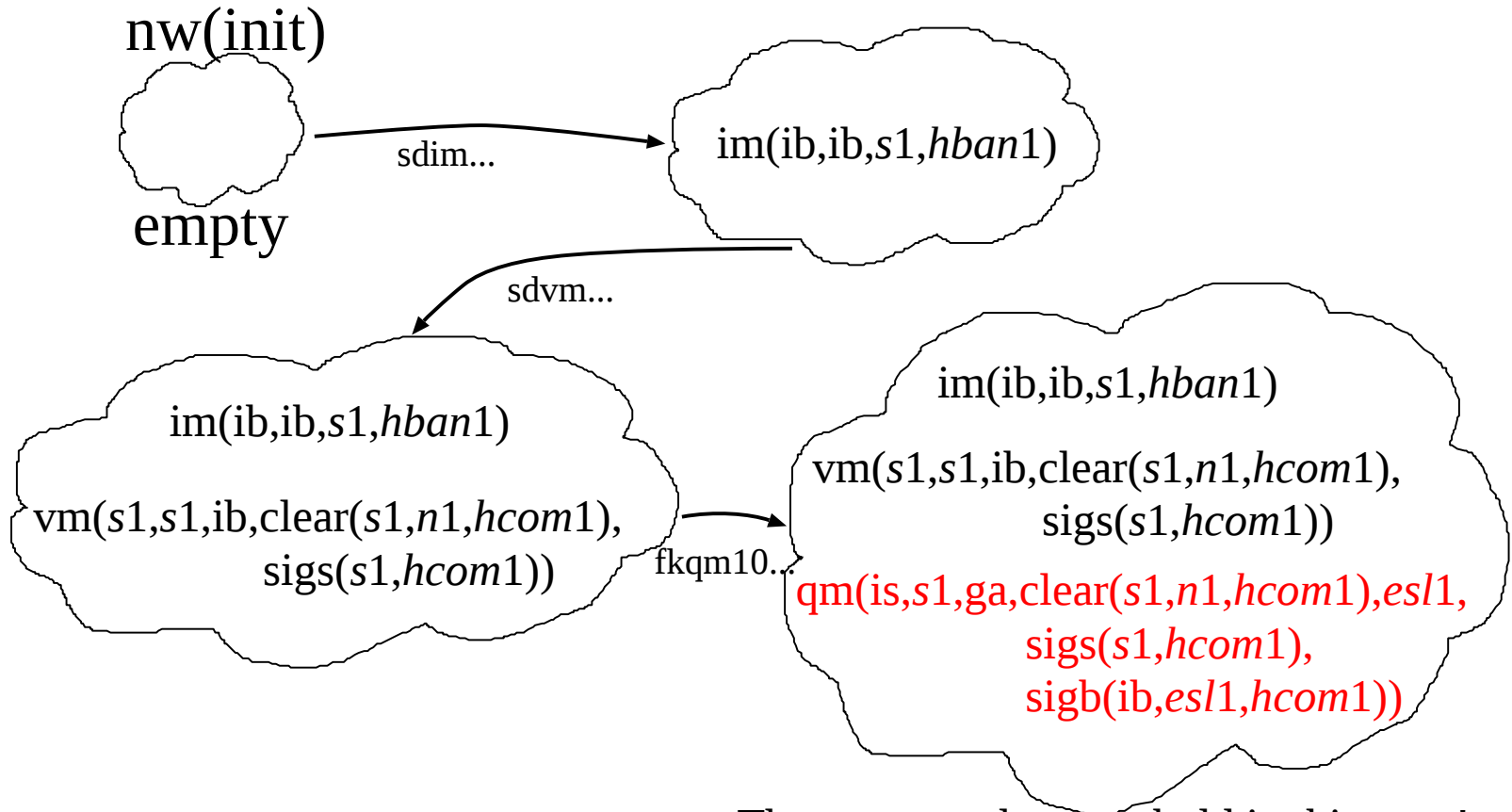
The search command to find a counterexample showing that $\mathcal{S}_{3KP}$ does not satisfy the payment agreement property looks like

```
search [1,10] init =>* (nw : (qm(S1,S,ga,...) NW)) Prot  
  such that not (not(S == is and B == ib) implies  
    im(B,B,S,...) \in NW and vm(S,S,B,...) \in NW and  
    pm(B,B,S,...) \in NW and qm(S,S,ga,...) \in NW) .
```

The constant `init` represents an initial state where there are one seller, one buyer, the genuine acquirer and the intruder.

[Watch a demo!](#)

Counterexample



The property does not hold in this state!

Summary

- We reported on the case study showing that 3KP does not satisfy the payment agreement property by model checking $\mathcal{S}_{3KP}$ with Maude.
- It took about 170ms for the search command to find the counterexample, while it took a couple of weeks for us to happen to find it.

Future & Ongoing Work

- What if the bounded reachable state space of $\mathcal{S}_{3KP}$ whose depths are at most 3 was too large to be traversed within a reasonable time?

We have shown that mathematical induction can alleviate the problem
– *Induction-Guided Falsification* (*IGF*).

- We have been developing a methodology that uses a model checker to support interactive theorem proving.

The methodology needs some tools, one of which is a translator from CafeOBJ specifications of OTSs into Maude specifications of OTSs.

We have been redesigning the translator for larger examples.

- *Creme*, an automatic invariant prover, will be used to verify that the modified 3KP satisfies the property.