Symbolic Verification of Distance-bounding Protocols

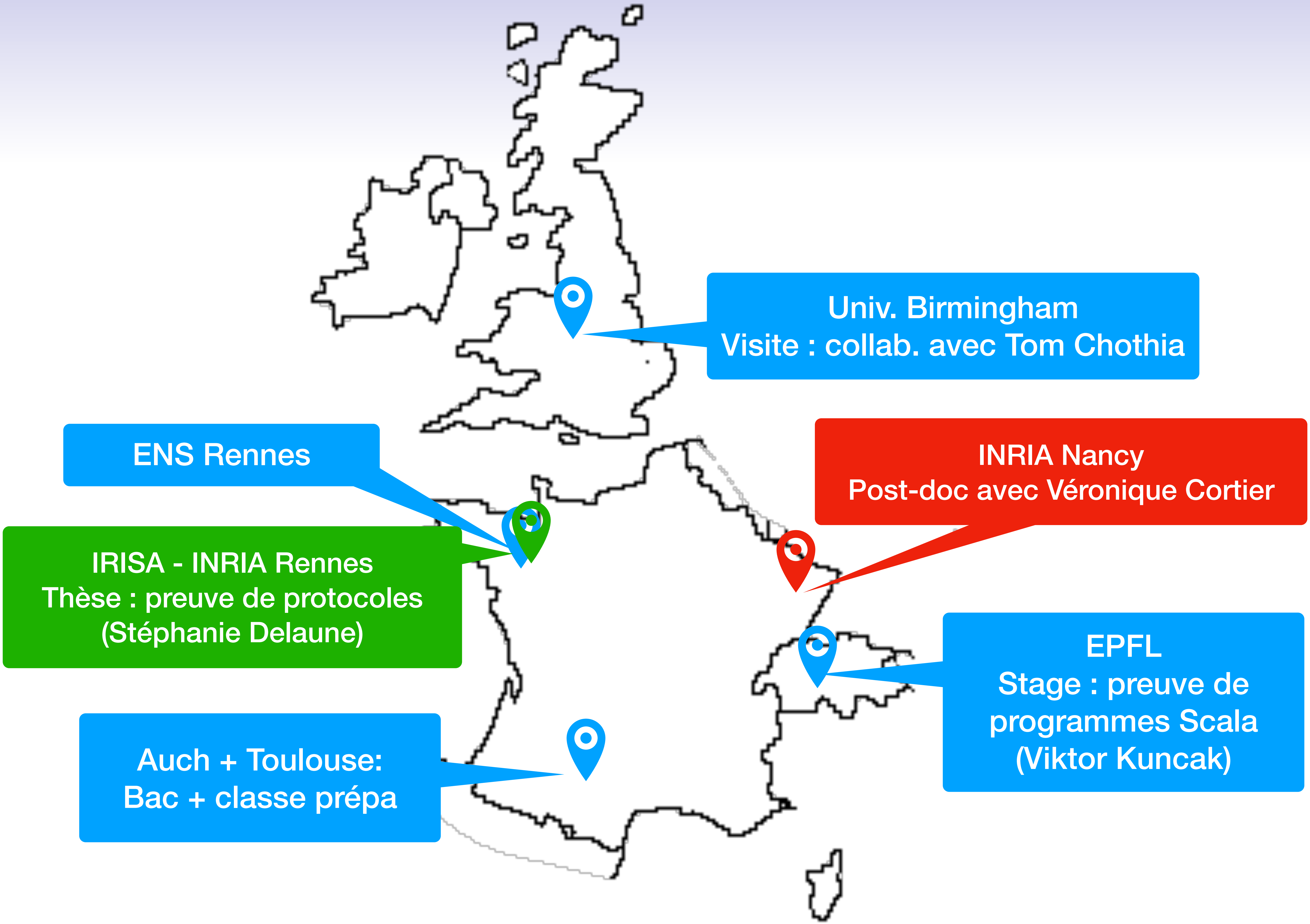
Application to payments protocols

Alexandre Debant

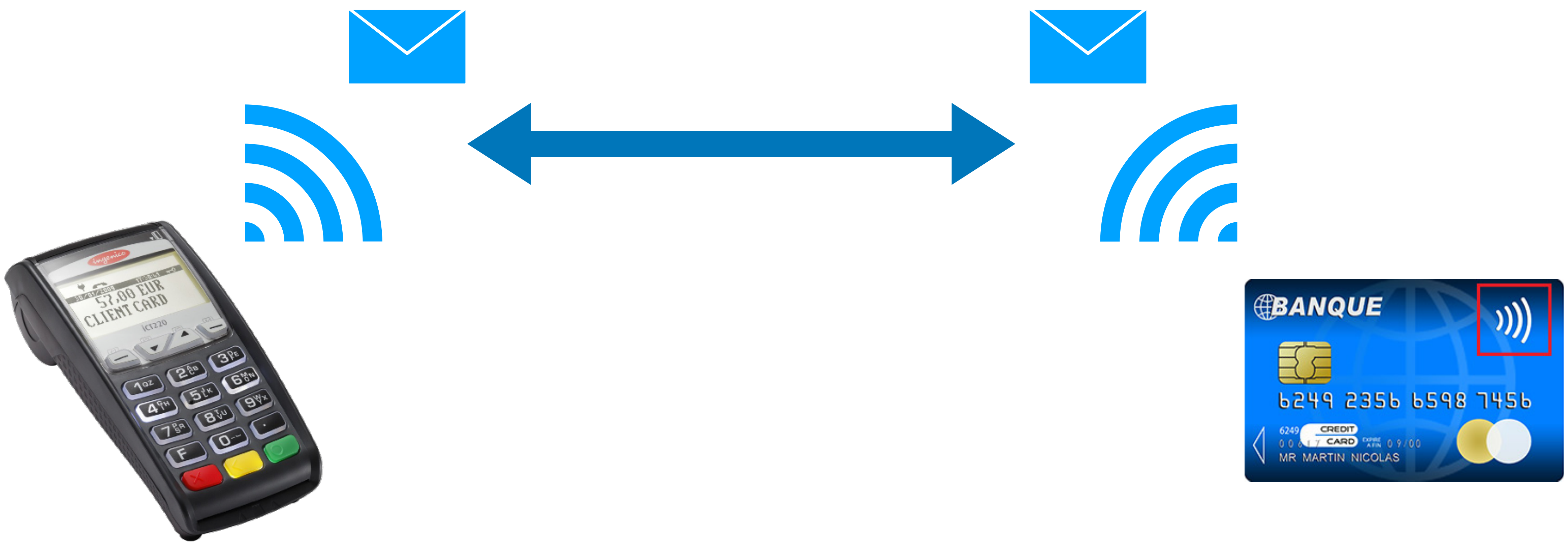
Université de Lorraine, CNRS, Inria, LORIA,

Seminar at LIRMM
February 12th 2021

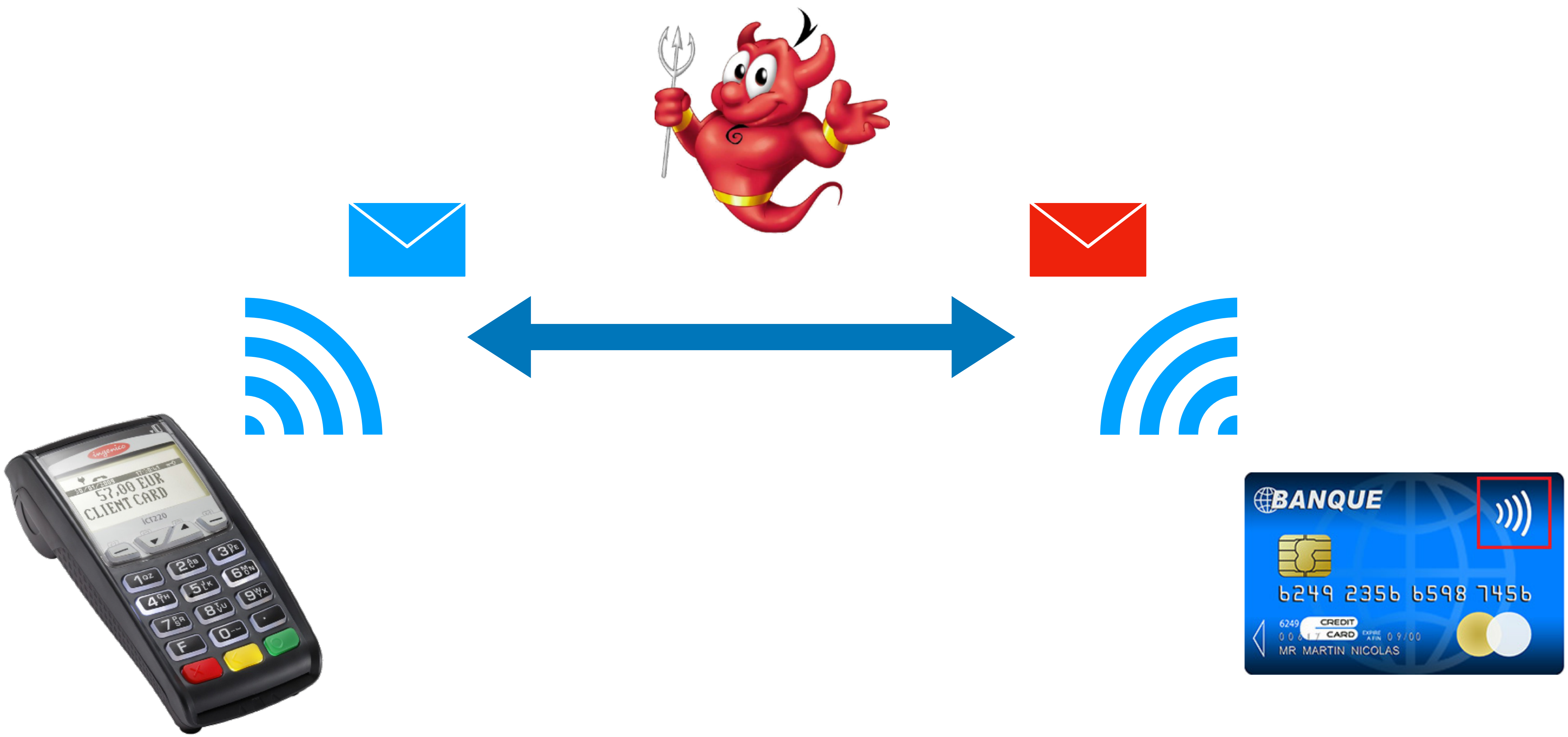
Laboratoire lorrain de recherche en informatique et ses applications


Univ. Birmingham
Visite : collab. avec Tom Chothia
ENS Rennes
INRIA Nancy
Post-doc avec Véronique Cortier
IRISA - INRIA Rennes
Thèse : preuve de protocoles
(Stéphanie Delaune)
EPFL
Stage : preuve de
programmes Scala
(Viktor Kuncak)
Auch + Toulouse:
Bac + classe prépa

Introduction



Introduction



Sensitive data
+ wireless communications $\Rightarrow$ **risks of attacks**

Many applications

Passport

Wi-Fi

Transport ticketing

Credit card

Many applications

that are insecure....

[Chothia *et al.* - 2010]

Passport

[Vanhoef *et al.* - 2017]

Wi-Fi

[Nohl *et al.* - 2008]

Transport ticketing

[Murdoch *et al.* - 2010]

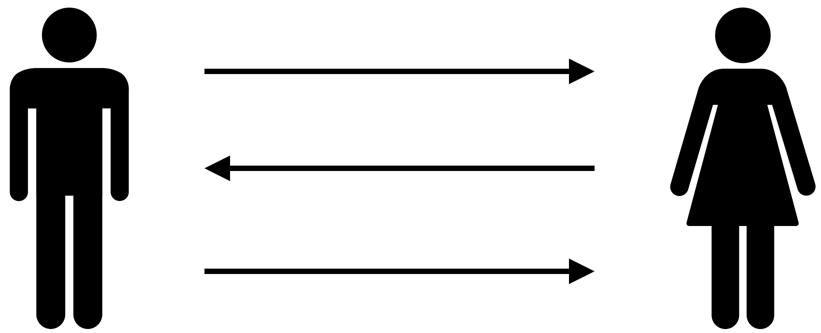
Credit card

Cryptographic protocols

Cryptographic primitives

- encryption/decryption
- digital signature
- hash function
- zero-knowledge proof

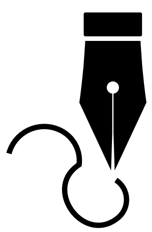
Protocols - how messages are exchanged?



Cryptographic protocols

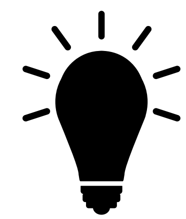
Cryptographic primitives

encryption/decryption



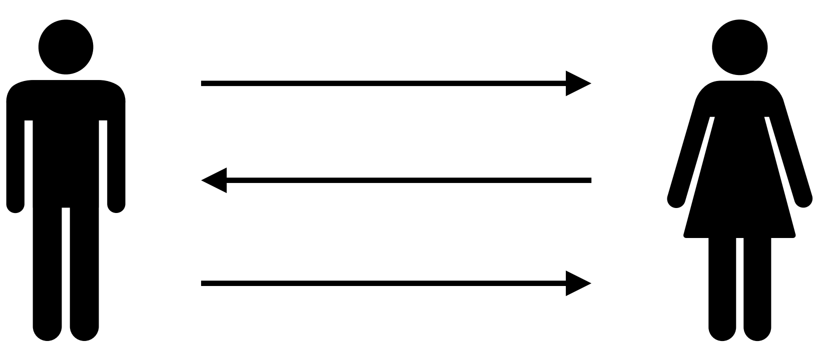
digital signature

hash function



zero-knowledge proof

Protocols - how messages are exchanged?



Cryptography is useless if misused!

Two major families of models…

… with some advantages and some drawbacks.

Computational models

+ messages are bitstrings, a general and powerful attacker
– tedious proofs, sometimes mechanized, but often hand-written

Symbolic models

– Some abstractions (messages, attacker…)
+ procedures and automated tools

Some results make a link between these two models
[Abadi & Rogaway - 2000]

Symbolic verification in a nutshell

Messages

- Function symbols: $\mathtt{enc}(x, k)$, $\mathtt{sign}(x, k)$, $\mathtt{h}(x)$,…
- Equations: $\mathtt{dec}(\mathtt{enc}(x, k), k) = x$

Protocols

- Process algebra, multiset rewriting rules, Horn clauses…

The attacker can…

read / overwrite messages

intercept / block messages

The attacker cannot…

break crypto

use side-channels

Symbolic verification in a nutshell

Messages

- Function symbols: $\mathtt{enc}(x,k)$, $\mathtt{sign}(x,k)$, $\mathtt{h}(x)$,…
- Equations: $\mathtt{dec}(\mathtt{enc}(x,k),k) = x$

Perfect cryptography

Protocols

- Process algebra, multiset rewriting rules, Horn clauses…

The attacker can…

read / overwrite messages

intercept / block messages

The attacker cannot…

break crypto

use side-channels

Existing verification tools

Bounded number of sessions

- decidable for classes of protocols
- tools implement decision procedures

DEEPSEC AKiSs

Existing verification tools

Bounded number of sessions

- decidable for classes of protocols
- tools implement decision procedures

DEEPSEC AKiSs

Unbounded number of sessions

- undecidable in general
- efficient tools in practice but:
  - do some approximations
  - may not terminate

ProVerif TAMARIN

Tamarin prover interactive mode

Existing verification tools

Bounded number of sessions

- decidable for classes of protocols
- tools implement decision procedures

DEEPSEC

AKiSs

Unbounded number of sessions

- undecidable in general
- efficient tools in practice but:
  - do some approximations
  - may not terminate

ProVerif

TAMARIN
Tamarin prover interactive mode

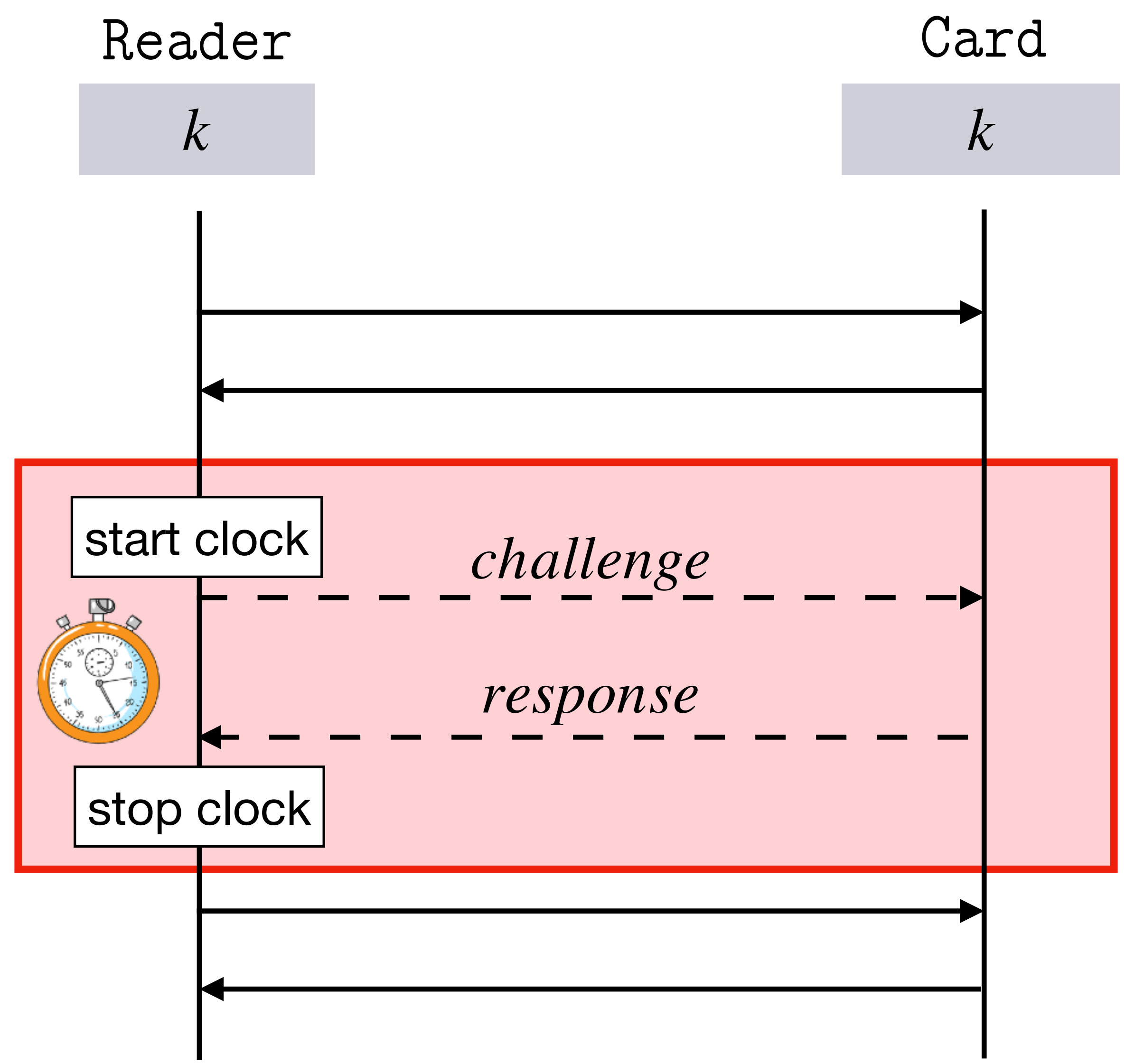
5G-AKA

Belenios e-voting

Proving the physical proximity

History of distance-bounding protocols

- First: Brands and Chaum protocol (1993)
- Today: more than 40 new protocols since 2003
- Application: in EMV's specification since 2016



Proving the physical proximity

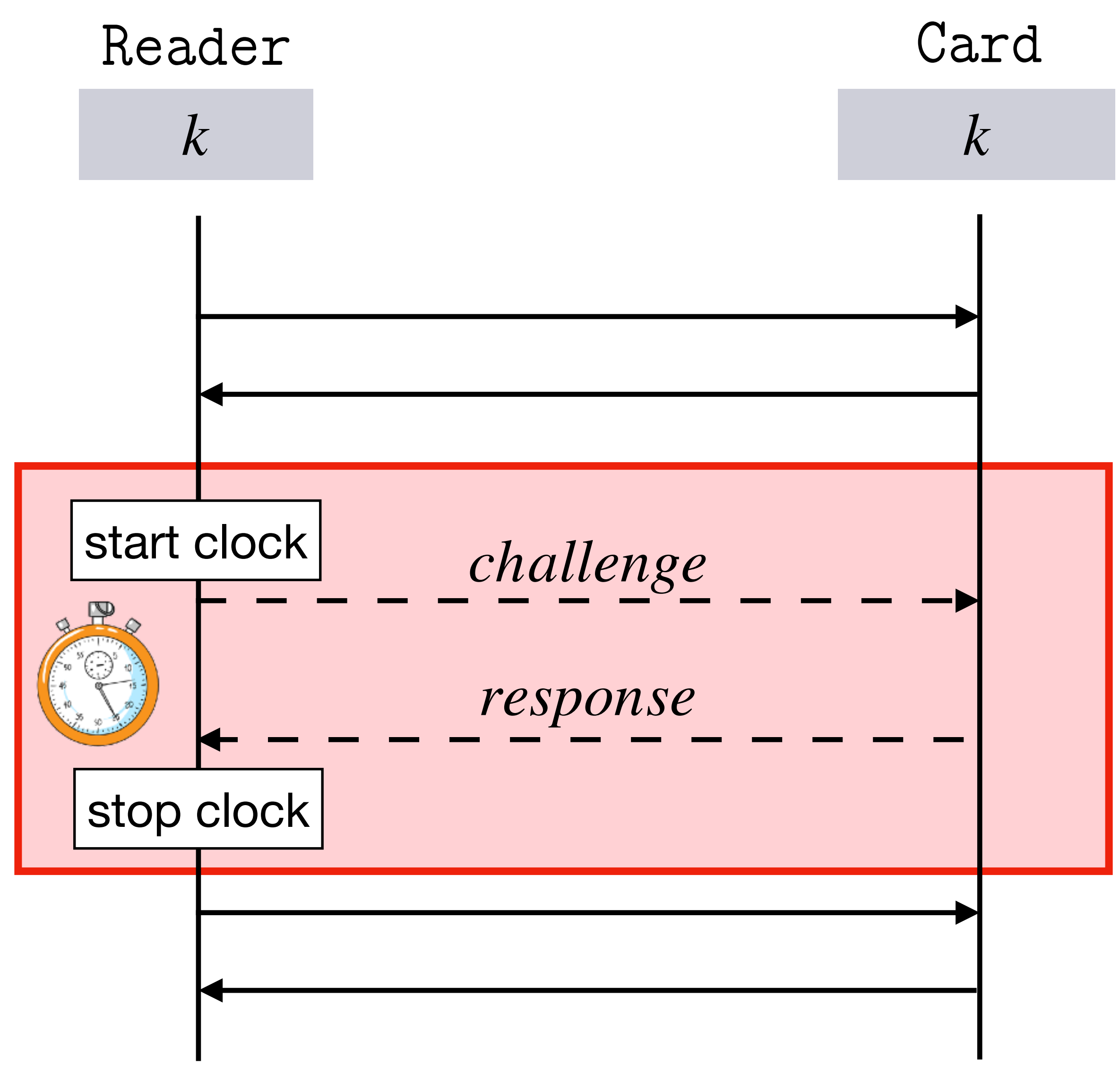
History of distance-bounding protocols

- First: Brands and Chaum protocol (1993)
- Today: more than 40 new protocols since 2003
- Application: in EMV's specification since 2016

Related work in symbolic verification

- Standard models and tools: do not model time and locations!
- Main specific models:
  - Meadows *et al.* (2007),
  - Basin *et al.* (2011)

➡ no automated verification procedure…



Proving the physical proximity

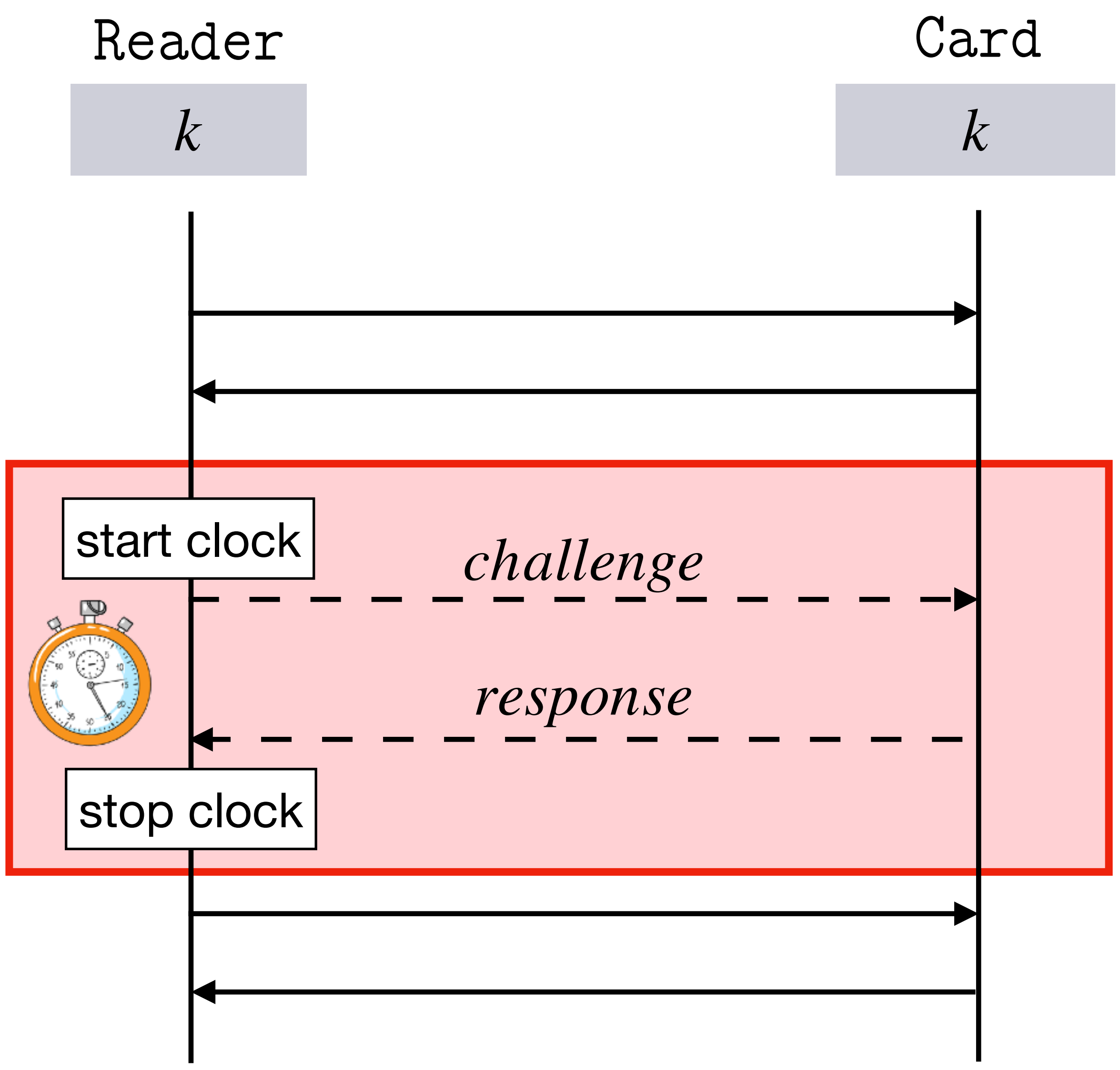
History of distance-bounding protocols

- First: Brands and Chaum protocol (1993)
- Today: more than 40 new protocols since 2003
- Application: in EMV's specification since 2016

Related work in symbolic verification

- Standard models and tools: do not model time and locations!
- Main specific models:
  - Meadows *et al.* (2007),
  - Basin *et al.* (2011)

➡ no automated verification procedure…



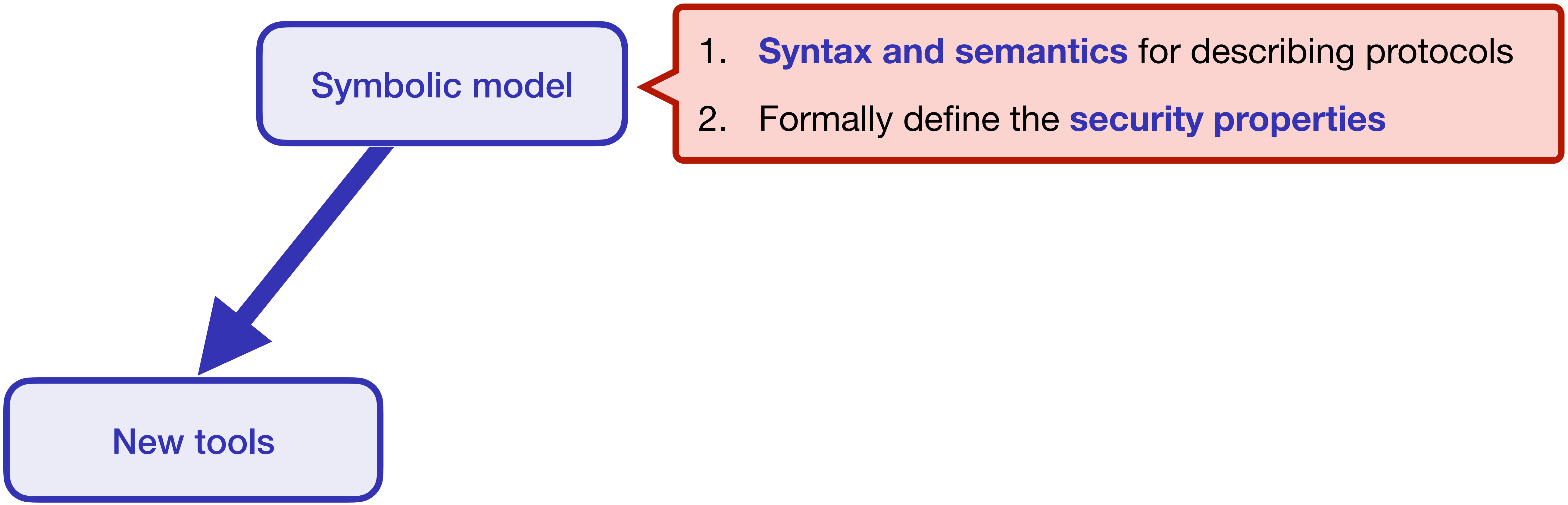
Can we design a framework that allows for a fully automated verification?

The story of verification

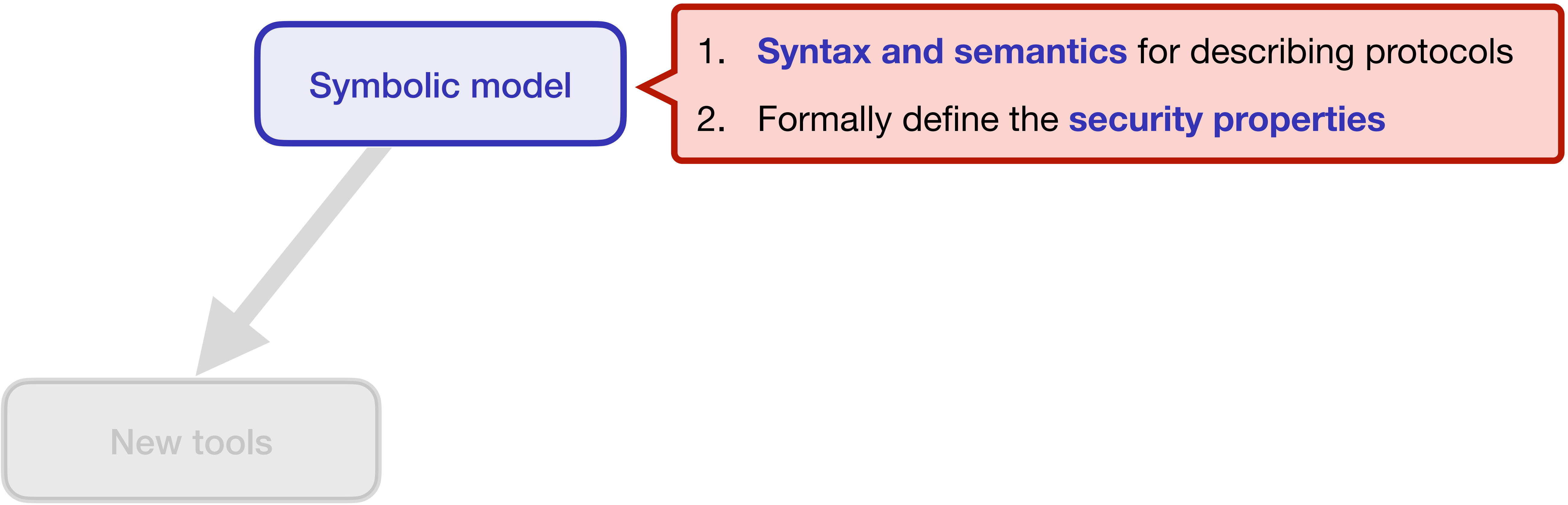
Symbolic model

1. **Syntax and semantics** for describing protocols
2. Formally define the **security properties**

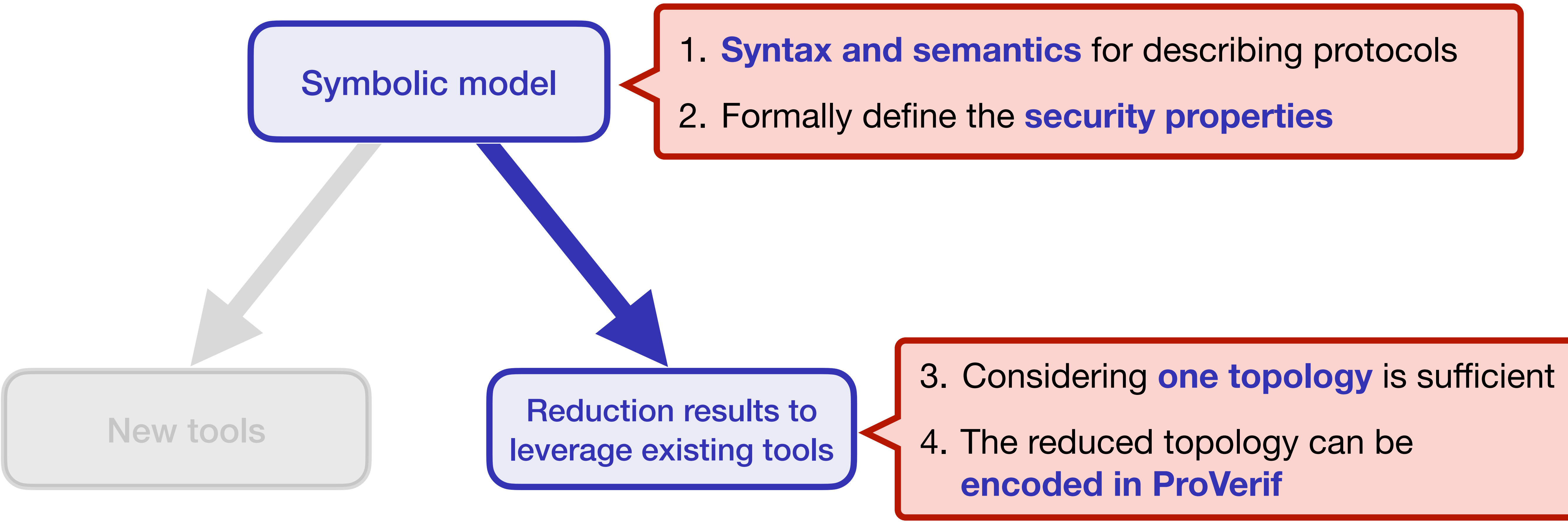
The story of verification



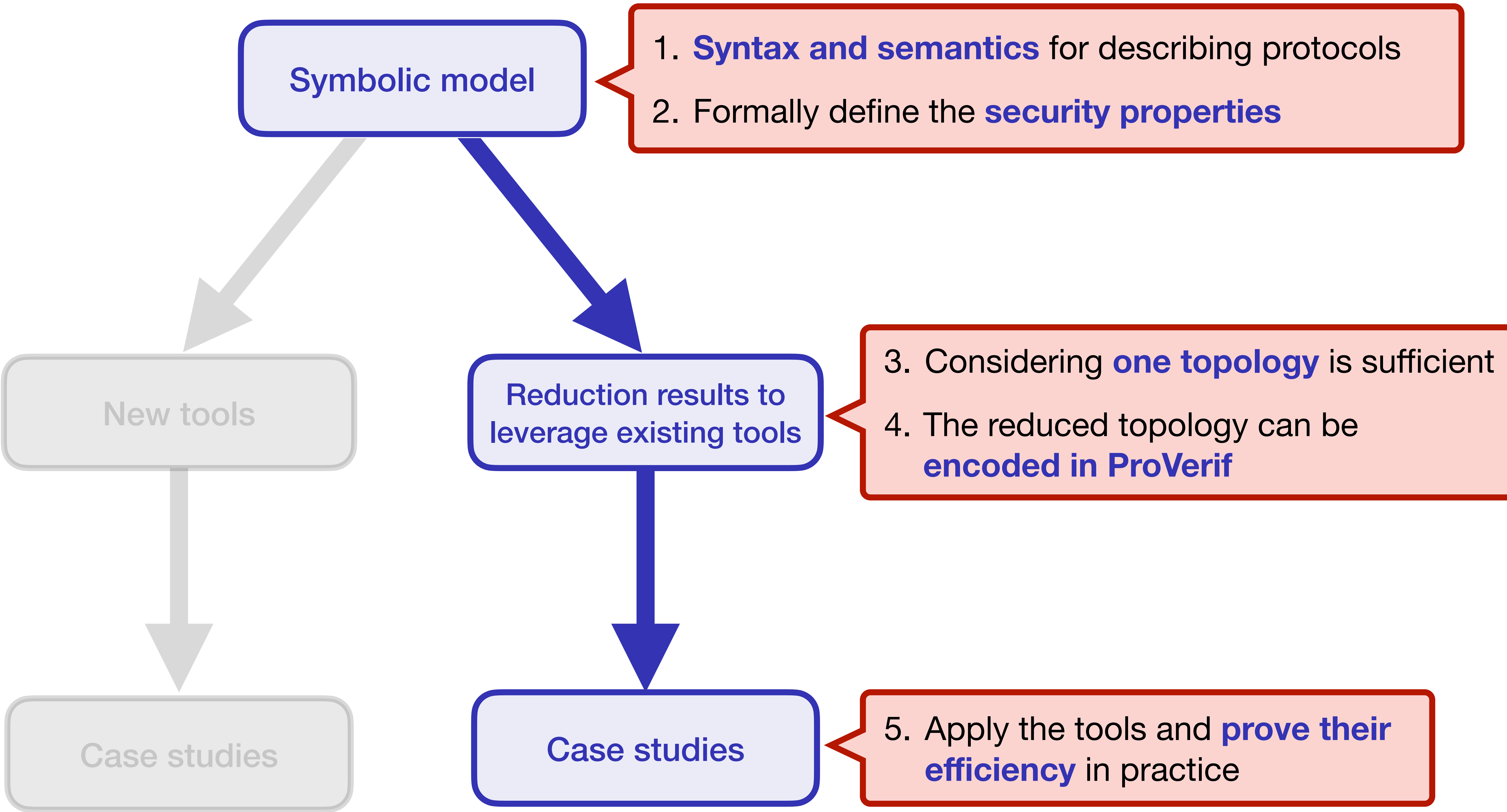
The story of verification



The story of verification



The story of verification

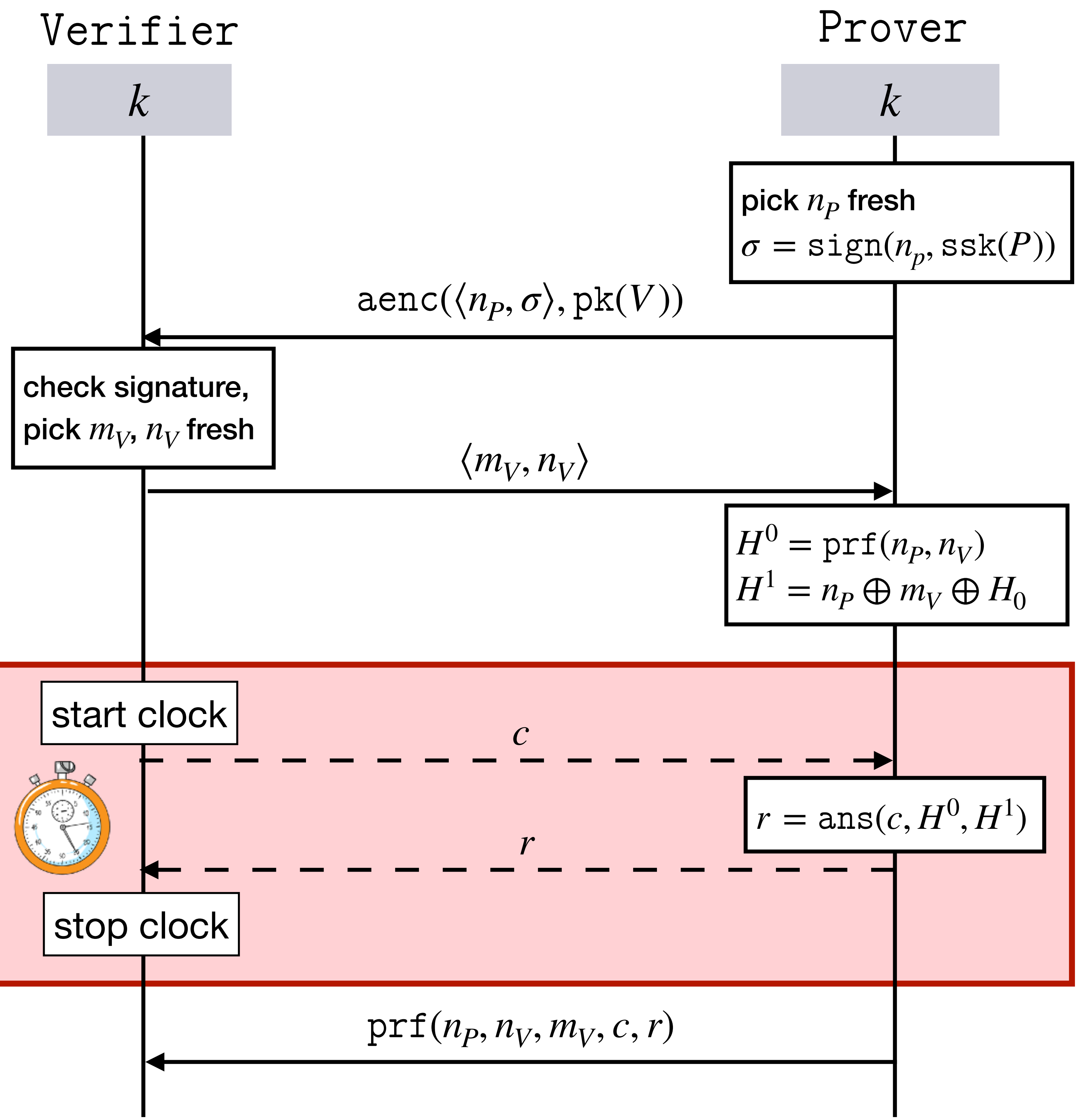


A symbolic model with time and locations

syntax and semantics

SPADE

[Bultel *et al.* - 2016]



Term algebra

Messages: terms built over a set of names $\mathcal{N}$ and a signature Σ given with either an equational theory E or a rewriting system.

Example

- Function symbols: $\mathtt{aenc}, \mathtt{adec}, \mathtt{pk}, \mathtt{sk}, \mathtt{sign}, \mathtt{get\_message}, \mathtt{spk}, \mathtt{ssk}, \langle\cdot,\cdot\rangle, \mathtt{proj}_1, \mathtt{proj}_2$
- Rules:

$$\mathtt{adec}(\mathtt{aenc}(x, \mathtt{pk}(y)), \mathtt{sk}(y)) \to x \qquad \mathtt{proj}_1(\langle x, y\rangle) \to x$$

$$\mathtt{get\_message}(\mathtt{sign}(x, \mathtt{ssk}(y)), \mathtt{spk}(y)) \to x \qquad \mathtt{proj}_2(\langle x, y\rangle) \to y$$

$$\mathtt{eq}(x, x) \to ok$$

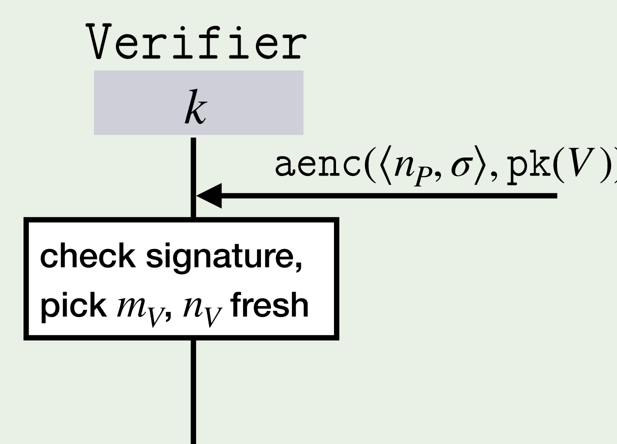
Running example

$V(v,p) = \mathtt{in}(x).$

$\quad \mathtt{let}\ u = \mathtt{adec}(x, \mathtt{sk}(v))\ \mathtt{in}$

$\quad \mathtt{let}\ x_{ok} = \mathtt{eq}(\mathtt{proj}_1(u), \mathtt{get\_message}(\mathtt{proj}_2(u), \mathtt{spk}(P)))\ \mathtt{in}$

$\quad \ldots$



Process algebra

The role of each agent is described by a process following the grammar:

P :=	0	null process
$\mid$	$\texttt{new}\ n\,.\,P$	name restriction
$\mid$	$\texttt{let}\ x = u\ \texttt{in}\ P$	conditional declaration
$\mid$	$\texttt{out}(u)\,.\,P$	output
$\mid$	$\texttt{in}(x)\,.\,P$	input

Process algebra

The role of each agent is described by a process following the grammar:

$P \ := \ 0$	null process
$\mid \ \ \mathtt{new}\ n\,.\,P$	name restriction
$\mid \ \ \mathtt{let}\ x = u\ \mathtt{in}\ P$	conditional declaration
$\mid \ \ \mathtt{out}(u)\,.\,P$	output
$\mid \ \ \mathtt{in}(x)\,.\,P$	input
$\mid \ \ \mathtt{in}^{<t}(x)\,.\,P$	guarded input
$\mid \ \ \mathtt{reset}\,.\,P$	personal clock reset

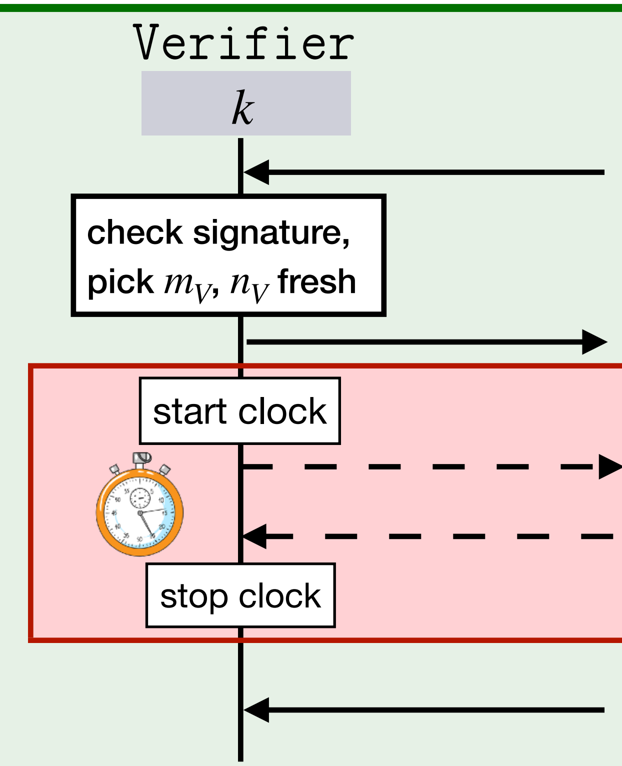
Process algebra

The role of each agent is described by a process following the grammar:

$P \ :=$	0	null process
$\mid$	$\texttt{new}\ n\,.\,P$	name restriction
$\mid$	$\texttt{let}\ x = u\ \texttt{in}\ P$	conditional declaration
$\mid$	$\texttt{out}(u)\,.\,P$	output
$\mid$	$\texttt{in}(x)\,.\,P$	input
$\mid$	$\texttt{in}^{<t}(x)\,.\,P$	guarded input
$\mid$	$\texttt{reset}\,.\,P$	personal clock reset

Running example

$$
\begin{aligned}
V(v,p) = {} & \texttt{in}(x)\,.\\
& \texttt{let}\ u = \texttt{adec}(x, \texttt{sk}(v))\ \texttt{in}\\
& \texttt{let}\ x_{ok} = \texttt{eq}(\texttt{proj}_1(u), \texttt{get\_message}(\texttt{proj}_2(u), \texttt{spk}(P))\ \texttt{in}\\
& \texttt{new}\ m_V\,.\,\texttt{new}\ n_V\,.\\
& \texttt{out}(\langle m_V, n_V\rangle)\,.\\
& \texttt{reset}\,.\,\texttt{new}\ c\,.\,\texttt{out}(c)\,.\,\texttt{in}^{<t}(y)\,.\\
& \texttt{in}(z)\,.\,\ldots
\end{aligned}
$$



Semantics

Physical restrictions

- locations: elements in $\mathbb{R}^3$, i.e. $\mathtt{Loc} : \mathscr{A} \to \mathbb{R}^3$
- distance: Euclidean norm between locations, i.e. $\mathtt{Dist}(a, b) = \dfrac{\|\mathtt{Loc}(a) - \mathtt{Loc}(b)\|}{c}$
- message transmission: a message takes time to reach its destination

Semantics

Physical restrictions

- locations: elements in $\mathbb{R}^3$, i.e. $\mathtt{Loc} : \mathscr{A} \to \mathbb{R}^3$
- distance: Euclidean norm between locations, i.e. $\mathtt{Dist}(a,b) = \dfrac{\|\mathtt{Loc}(a) - \mathtt{Loc}(b)\|}{c}$
- message transmission: a message takes time to reach its destination

System configuration $(\mathscr{P}, \Phi, t)$

- $\mathscr{P}$: multiset of processes which remain to execute, i.e.
- Φ: frame made of the output messages so far, i.e. $w \xrightarrow{a,t_a} u$
- t: current global time

Semantics

Physical restrictions

- locations: elements in $\mathbb{R}^3$, i.e. $\mathtt{Loc} : \mathscr{A} \rightarrow \mathbb{R}^3$
- distance: Euclidean norm between locations, i.e. $\mathtt{Dist}(a,b) = \dfrac{\|\mathtt{Loc}(a) - \mathtt{Loc}(b)\|}{c}$
- message transmission: a message takes time to reach its destination

System configuration $(\mathscr{P}, \Phi, t)$

- $\mathscr{P}$: multiset of processes which remain to execute, i.e.
- Φ: frame made of the output messages so far, i.e. $w \xrightarrow{a,t_a} u$
- t: current global time

Execution rules

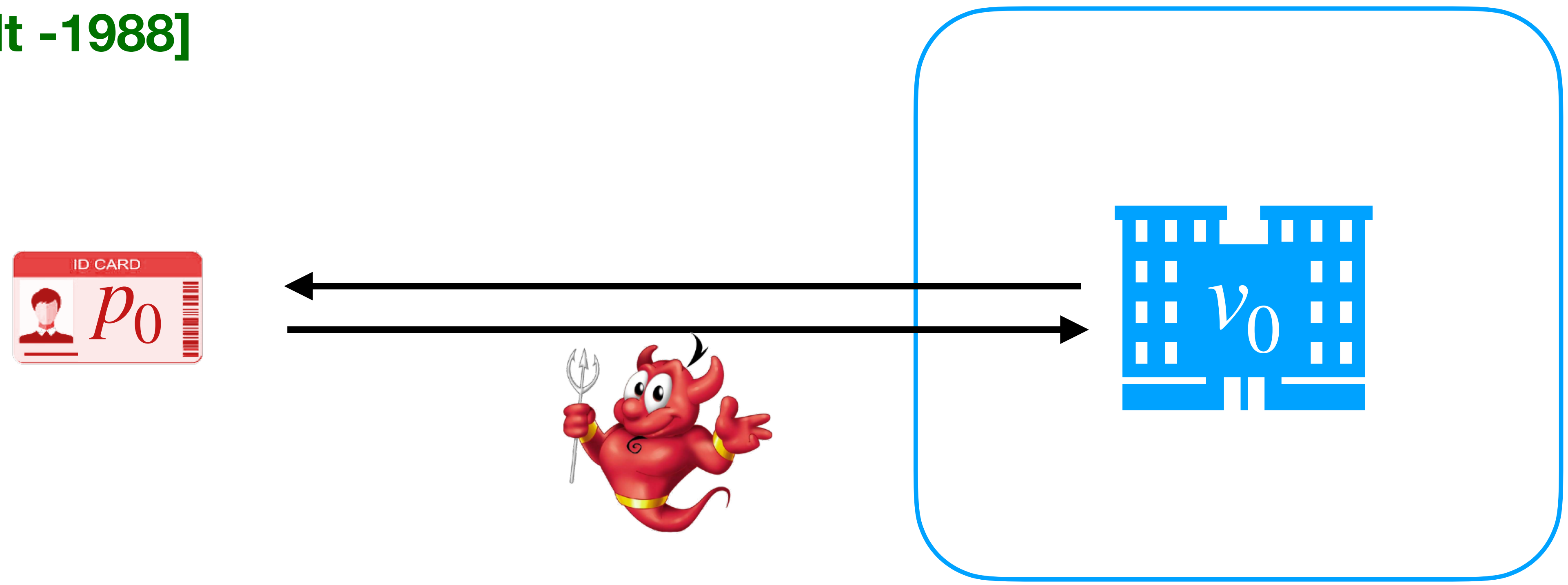
- *TIM*: $(\mathscr{P}, \Phi, t) \longrightarrow (\mathtt{Shift}(\mathscr{P}, \delta), \Phi, t + \delta)$ with $\delta > 0$
- *OUT*: $(\lfloor \mathtt{out}(u) \,.\, P \rfloor_a^{t_a} \uplus \mathscr{P}, \Phi, t) \xrightarrow{a,\mathtt{out}(u)} (\lfloor P \rfloor_a^{t_a} \uplus \mathscr{P}, \Phi \cup \{w \xrightarrow{a,t} u\}, t)$
- *IN*: $(\lfloor \mathtt{in}(x) \,.\, P \rfloor_a^{t_a} \uplus \mathscr{P}, \Phi, t) \xrightarrow{a,\mathtt{in}(u)} (\lfloor P\{x \mapsto u\} \rfloor_a^{t_a} \uplus \mathscr{P}, \Phi, t)$

  if u is deducible from Φ at time t
- ...

Distance fraud/hijacking attack

An honest verifier shall not authenticate a malicious and distant prover

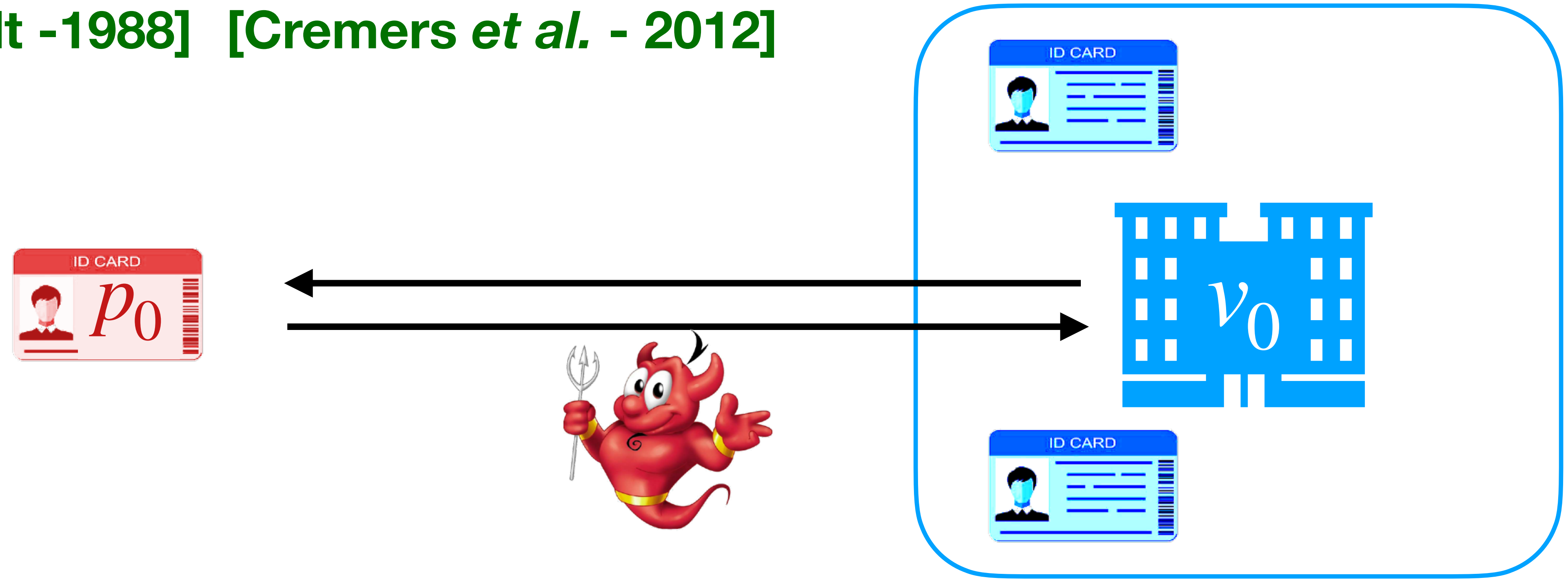
[Desmedt -1988]



Distance fraud/hijacking attack

An honest verifier shall not authenticate a malicious and distant prover even in the presence of honest participants in his vicinity.

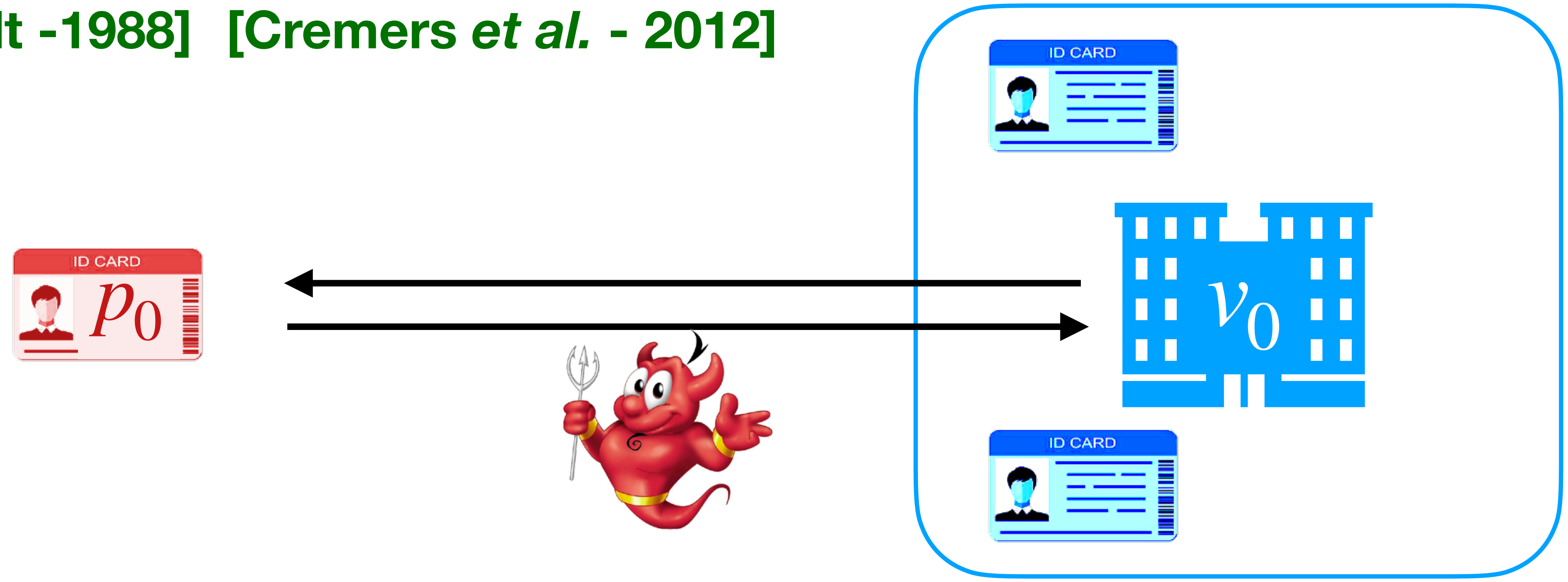
[Desmedt -1988] [Cremers *et al.* - 2012]



Distance fraud/hijacking attack

An honest verifier shall not authenticate a malicious and distant prover even in the presence of honest participants in his vicinity.

[Desmedt -1988] [Cremers *et al.* - 2012]



Definition

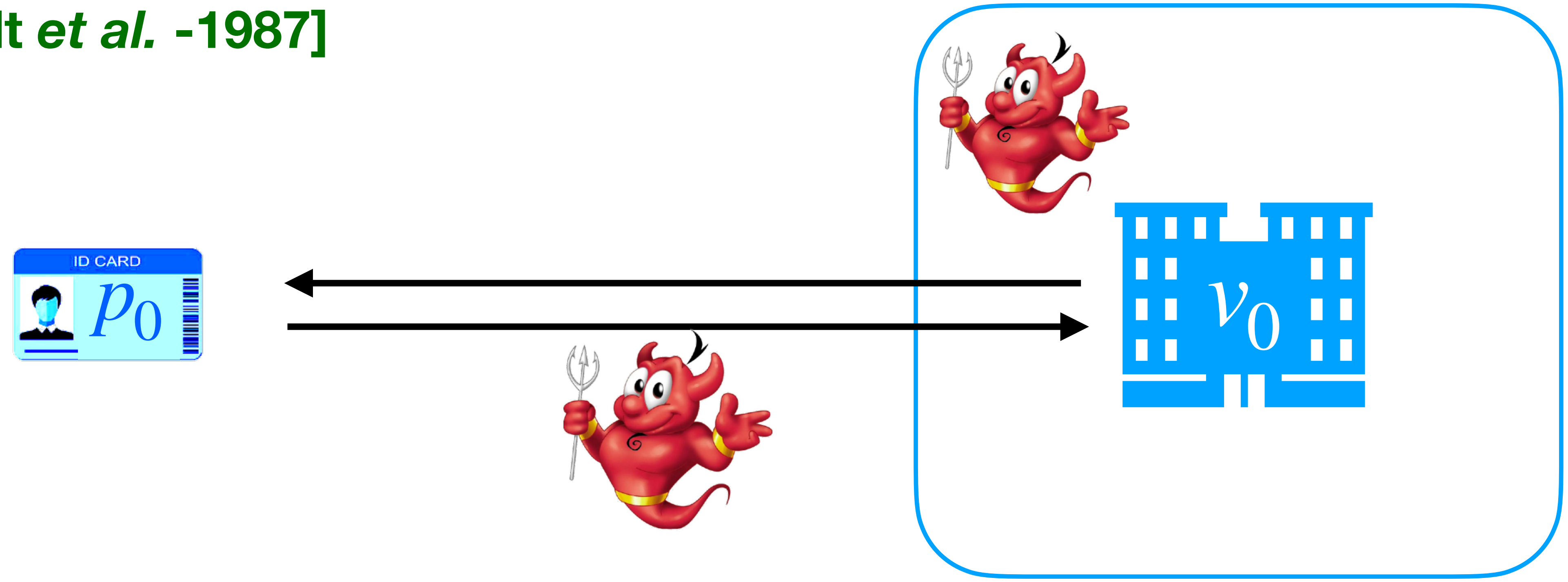
A protocol admits a distance hijacking attack if there exists a topology $\mathcal{T} \in \mathcal{C}_{\mathtt{DH}}$ and an initial configuration K such that:

$$K \longrightarrow (\lfloor \mathtt{end}(v_0, p_0) \rfloor_{v_0}^{t_{v_0}} \ ; \ \Phi \ ; \ t)$$

Mafia fraud (MiM attacks)

An honest verifier shall not authenticate an honest and distant prover even in presence of an attacker in his vicinity.

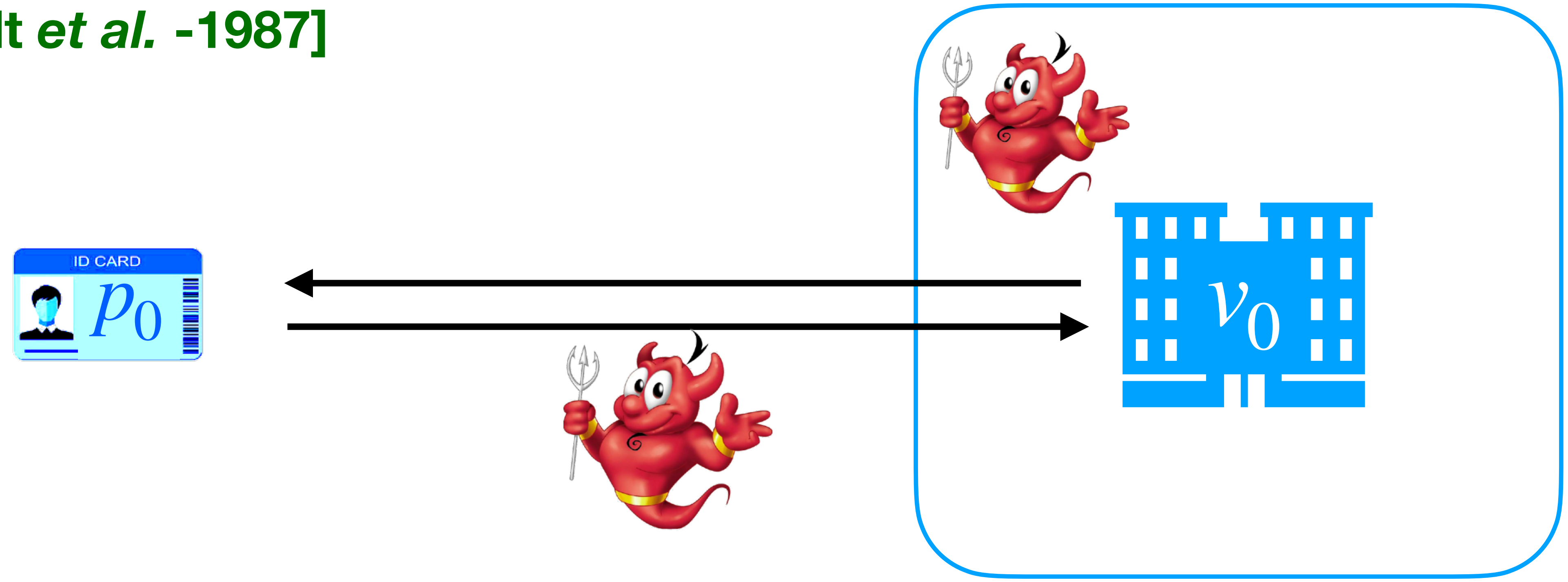
[Desmedt *et al.* -1987]



Mafia fraud (MiM attacks)

An honest verifier shall not authenticate an honest and distant prover even in presence of an attacker in his vicinity.

[Desmedt *et al.* -1987]



Definition

A protocol admits a mafia fraud if there exists a topology $\mathscr{T} \in \mathscr{C}_{\mathtt{MF}}$ and an initial configuration K such that:

$$K \longrightarrow (\lfloor \mathtt{end}(v_0, p_0) \rfloor_{v_0}^{t_{v_0}} \ ; \ \Phi \ ; \ t)$$

Some reduction results

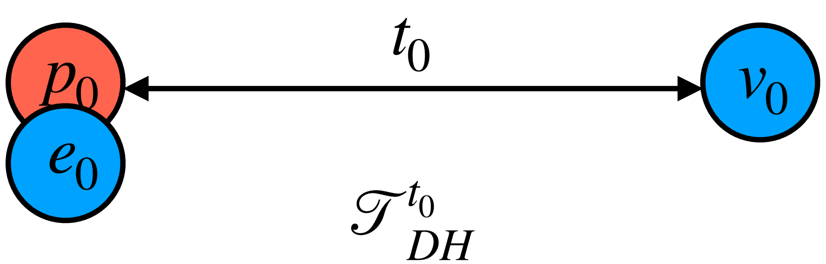
Topologies and time

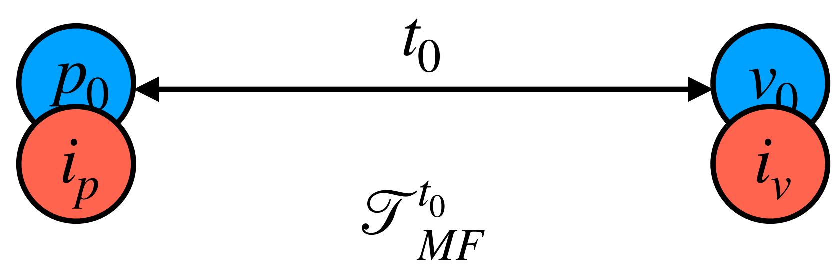
Main difficulties

1. An infinite number of topologies must be considered for each class of attacks

Main difficulties

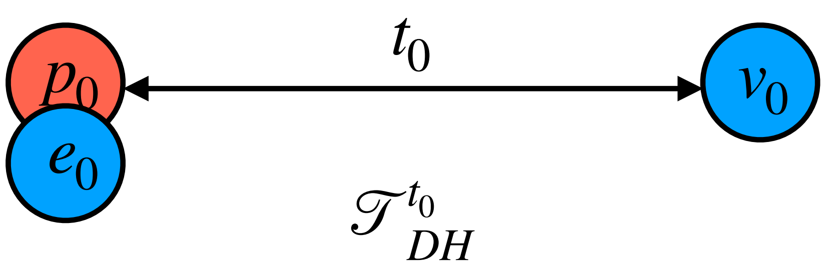
1. An infinite number of topologies must be considered for each class of attacks
   —> it is sufficient to focus on a unique topology for each class!

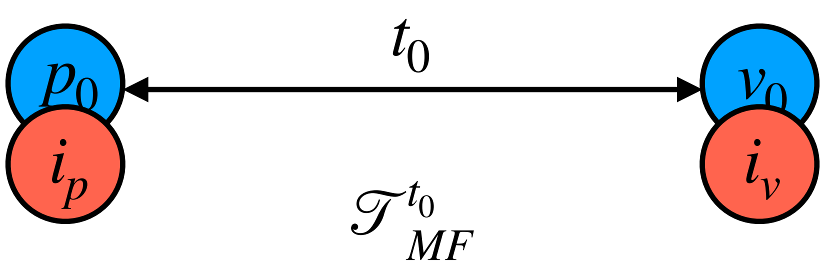




Main difficulties

1. An infinite number of topologies must be considered for each class of attacks
   —> it is sufficient to focus on a unique topology for each class!

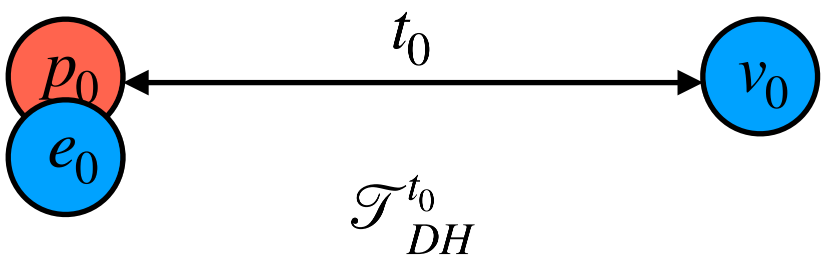


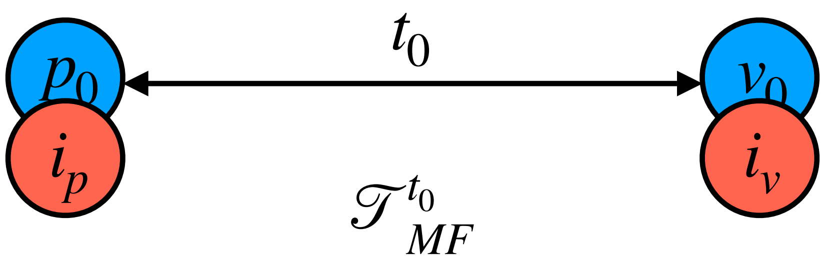


2. We must deal with time when conducting our analyses

Main difficulties

1. An infinite number of topologies must be considered for each class of attacks
   —> it is sufficient to focus on a unique topology for each class!



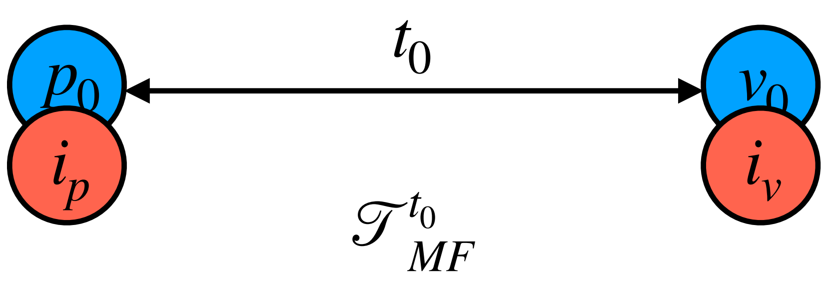


2. We must deal with time when conducting our analyses
   —> we can use ProVerif's phases to encode the topologies!

Mafia frauds

Theorem

A protocol admits a mafia fraud, if and only if, there is an attack in $\mathcal{T}^{t_0}_{MF}$.

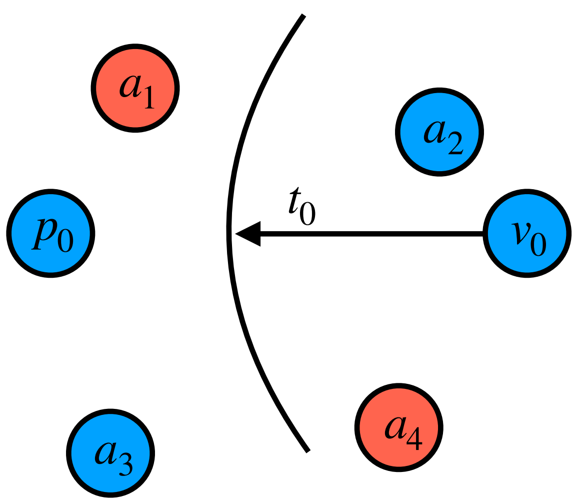


Mafia frauds

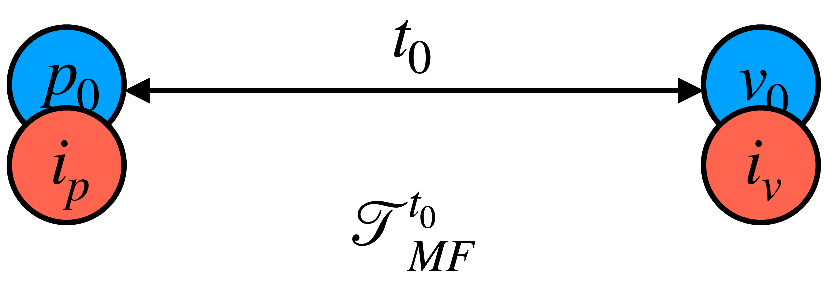
Theorem

A protocol admits a mafia fraud, if and only if, there is an attack in $\mathcal{T}^{t_0}_{MF}$.

Sketch of proof:



An attack trace in an **arbitrary** topology

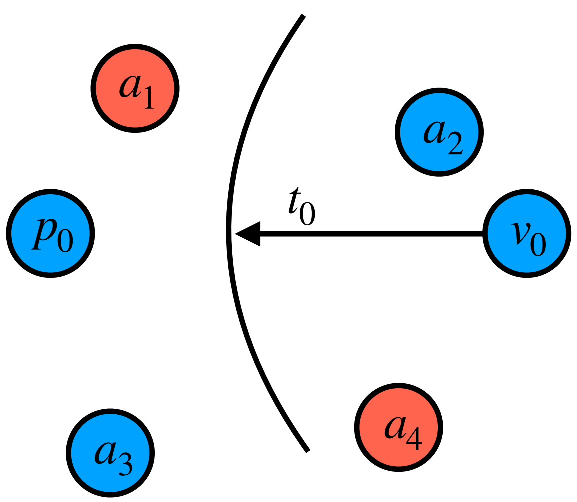


Mafia frauds

Theorem

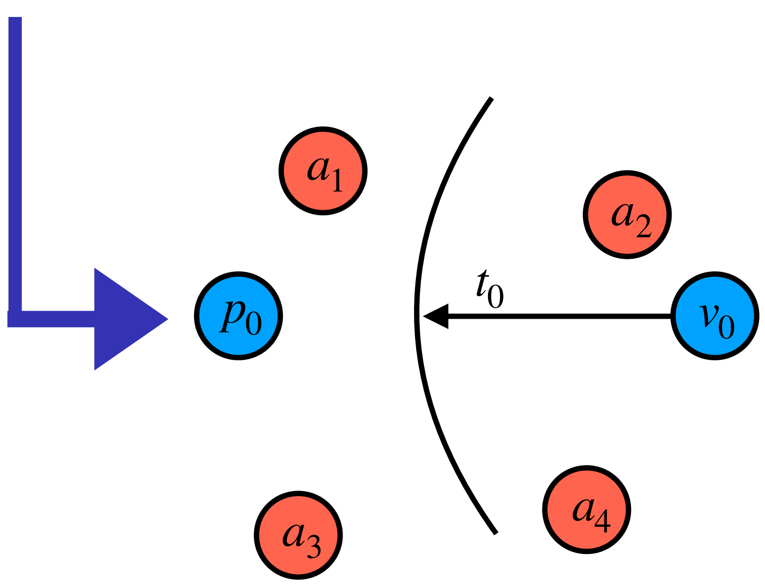
A protocol admits a mafia fraud, **if and only if**, there is an attack in $\mathscr{T}^{t_0}_{MF}$.

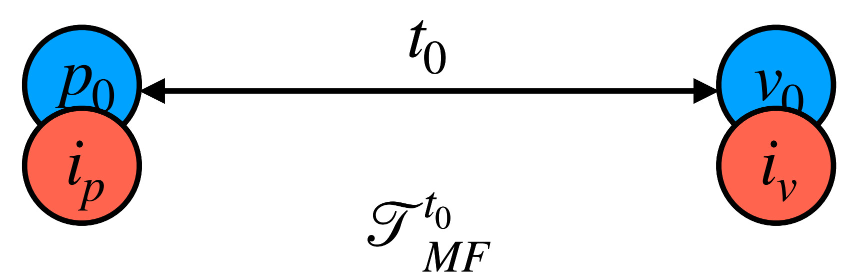
Sketch of proof:



An attack trace in an **arbitrary** topology

Assume everyone **malicious**



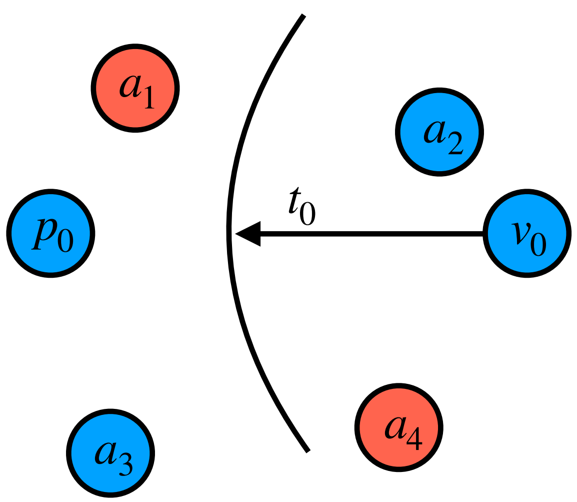


Mafia frauds

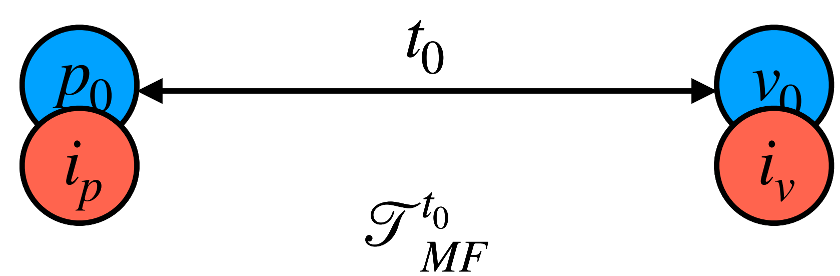
Theorem

A protocol admits a mafia fraud, if and only if, there is an attack in $\mathscr{T}^{t_0}_{MF}$.

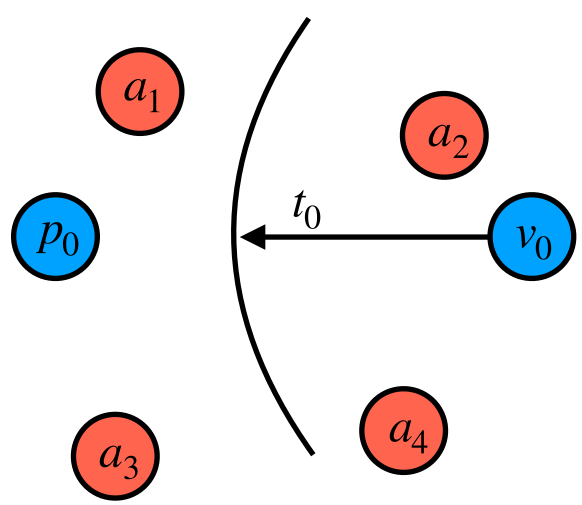
Sketch of proof:



An attack trace in an **arbitrary** topology

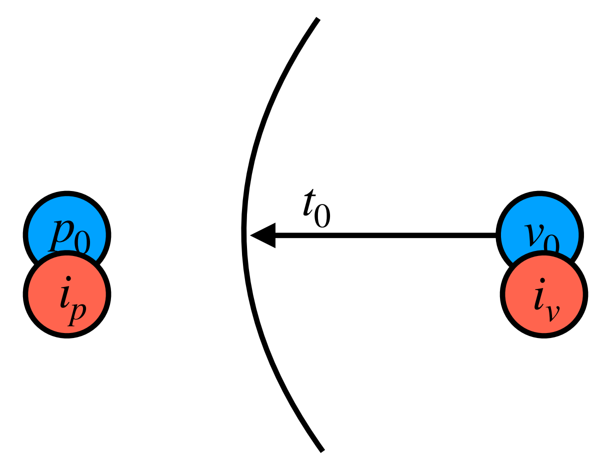


Assume everyone **malicious**



[Nigam *et al.* - 2016]

Place malicious agents **ideally**

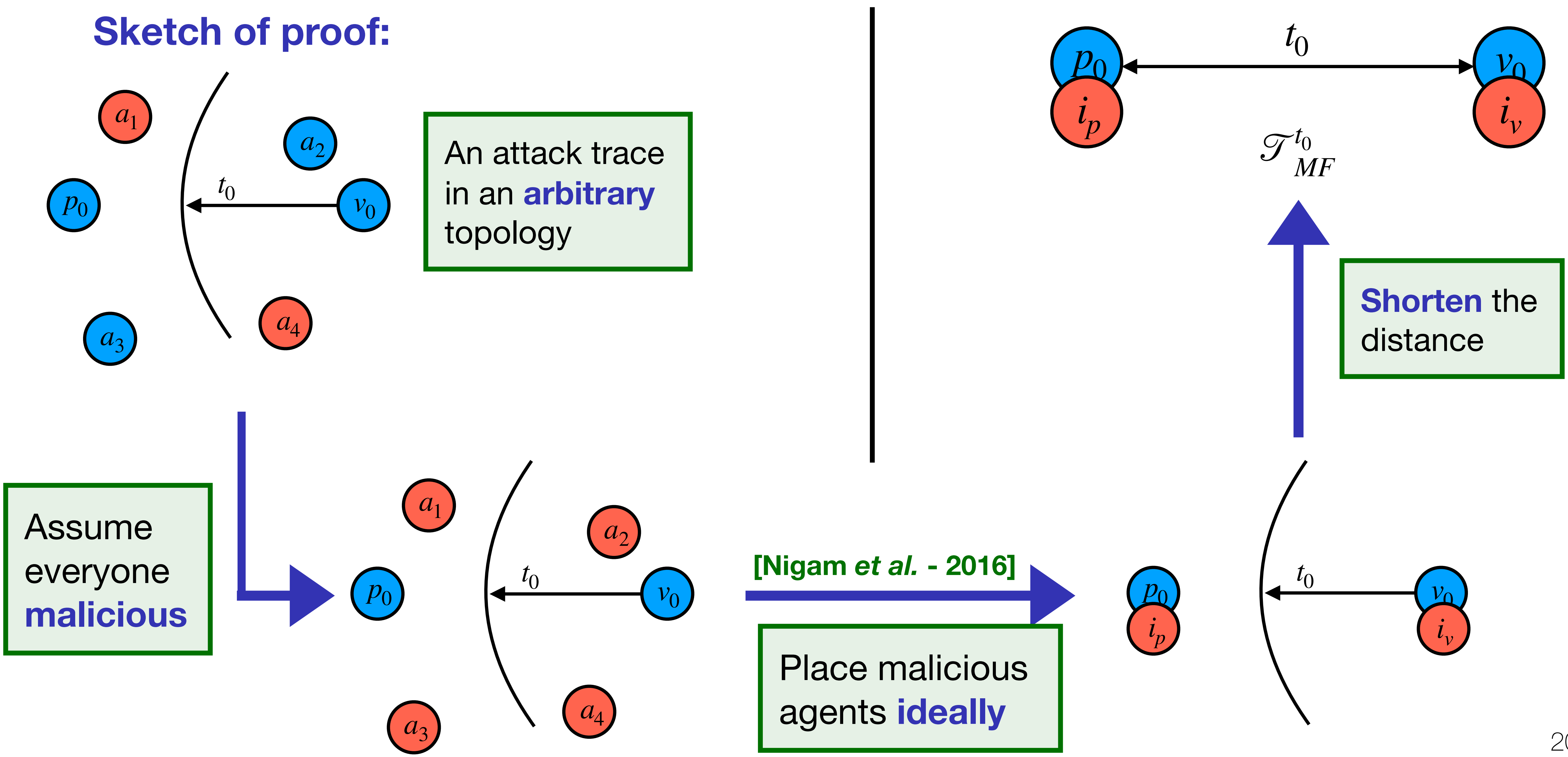


Mafia frauds

Theorem

A protocol admits a mafia fraud, if and only if, there is an attack in $\mathcal{T}^{t_0}_{MF}$.

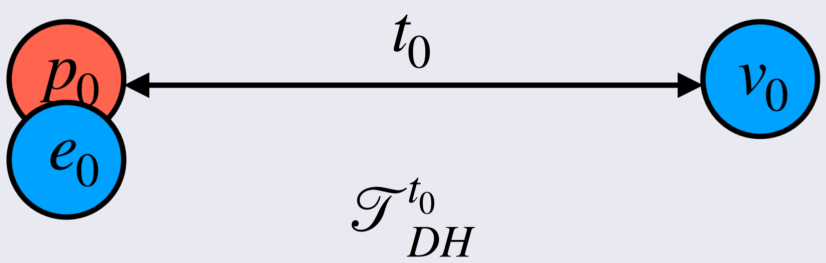
Sketch of proof:



Distance hijacking attacks

Theorem

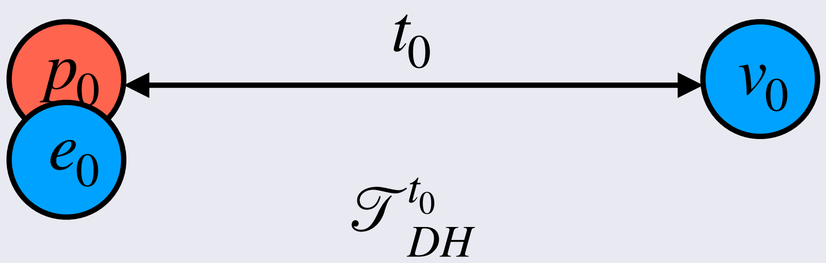
If $\mathscr{P}_{\texttt{db}}$ admits a distance hijacking attack, then $\overline{\mathscr{P}_{\texttt{db}}}$ admits an attack in $\mathscr{T}^{t_0}_{DH}$.



Distance hijacking attacks

Theorem

If $\mathscr{P}_{\texttt{db}}$ admits a distance hijacking attack, then $\overline{\mathscr{P}_{\texttt{db}}}$ admits an attack in $\mathscr{T}^{t_0}_{DH}$.

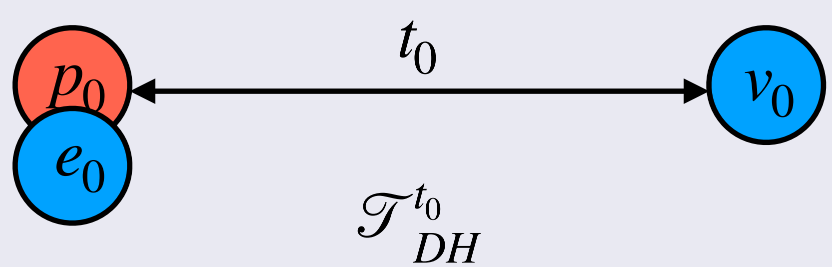


Remark: the previous proof does not apply!

Distance hijacking attacks

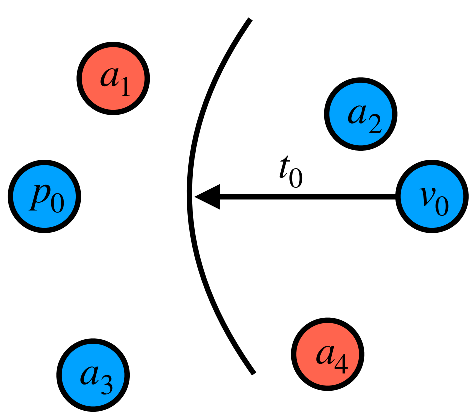
Theorem

If $\mathscr{P}_{\mathtt{db}}$ admits a distance hijacking attack, then $\overline{\mathscr{P}_{\mathtt{db}}}$ admits an attack in $\mathscr{T}^{t_0}_{DH}$.



Remark: the previous proof does not apply!

Sketch of proof:

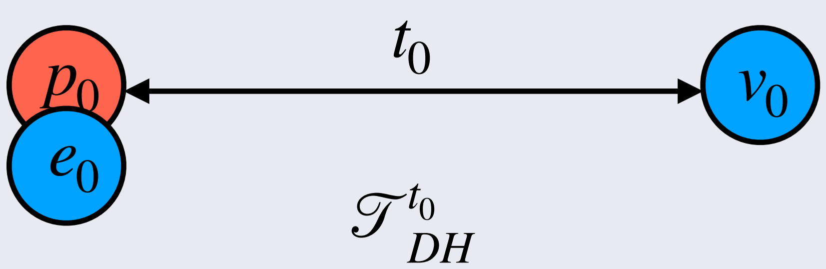


An attack trace in an **arbitrary** topology

Distance hijacking attacks

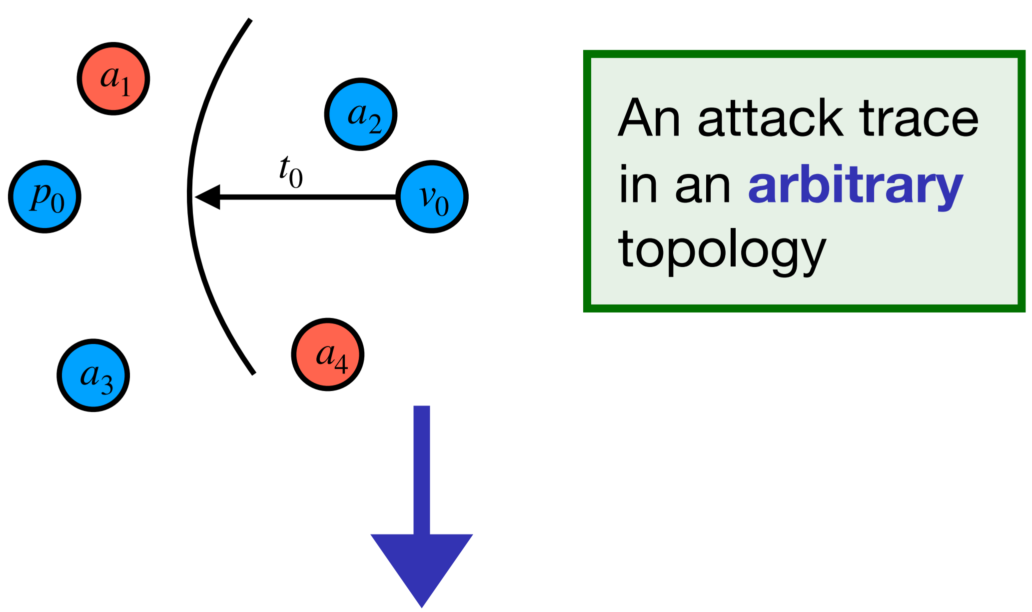
Theorem

If $\mathscr{P}_{\mathtt{db}}$ admits a distance hijacking attack, then $\overline{\mathscr{P}_{\mathtt{db}}}$ admits an attack in $\mathscr{T}_{DH}^{t_0}$.



Remark: the previous proof does not apply!

Sketch of proof:

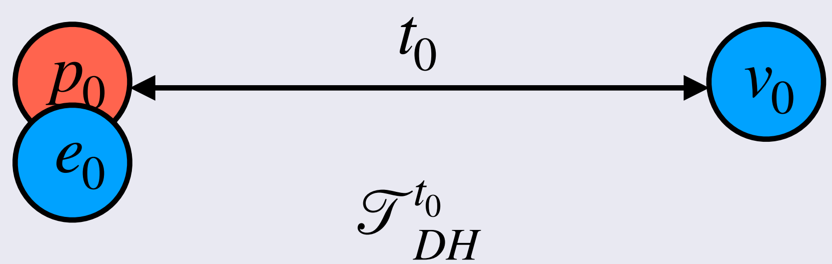


Untimed witness of attack

Distance hijacking attacks

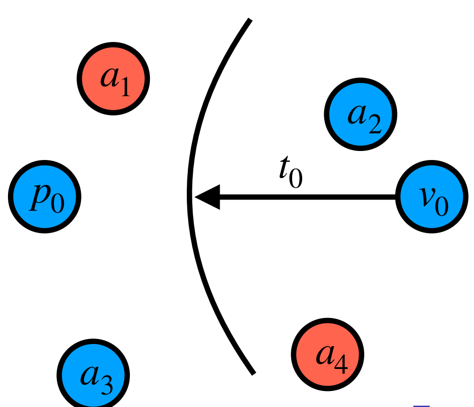
Theorem

If $\mathscr{P}_{\mathtt{db}}$ admits a distance hijacking attack, then $\overline{\mathscr{P}_{\mathtt{db}}}$ admits an attack in $\mathscr{T}^{t_0}_{DH}$.



Remark: the previous proof does not apply!

Sketch of proof:



An attack trace in an **arbitrary** topology

Untimed witness of attack

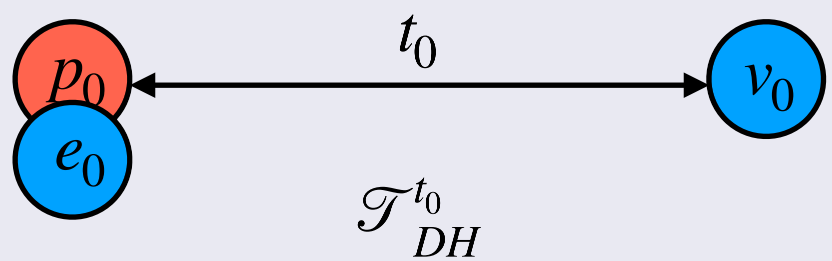
Action **re-ordering**

Untimed witness of attack

Distance hijacking attacks

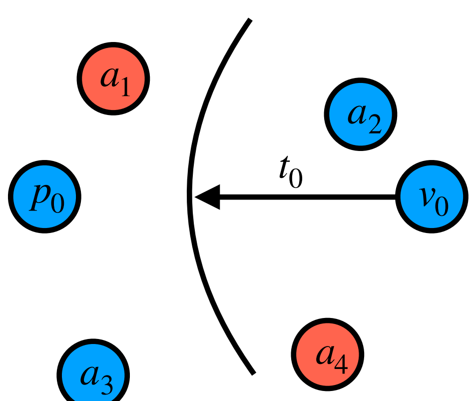
Theorem

If $\mathscr{P}_{\mathtt{db}}$ admits a distance hijacking attack, then $\overline{\mathscr{P}_{\mathtt{db}}}$ admits an attack in $\mathscr{T}^{t_0}_{DH}$.

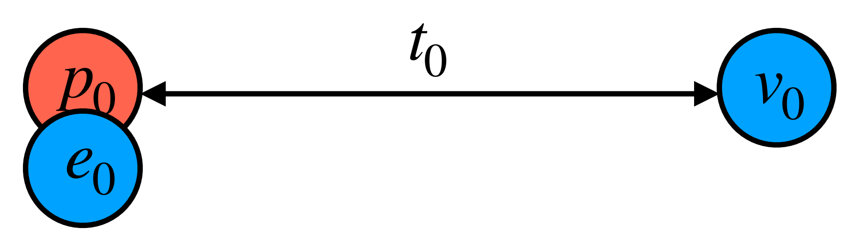


Remark: the previous proof does not apply!

Sketch of proof:



An attack trace in an **arbitrary** topology



Re-timing the witness

Action **re-ordering**

Untimed witness of attack → **Untimed witness of attack**

Getting rid of time

Even a single topology cannot be modeled into existing tools

Getting rid of time

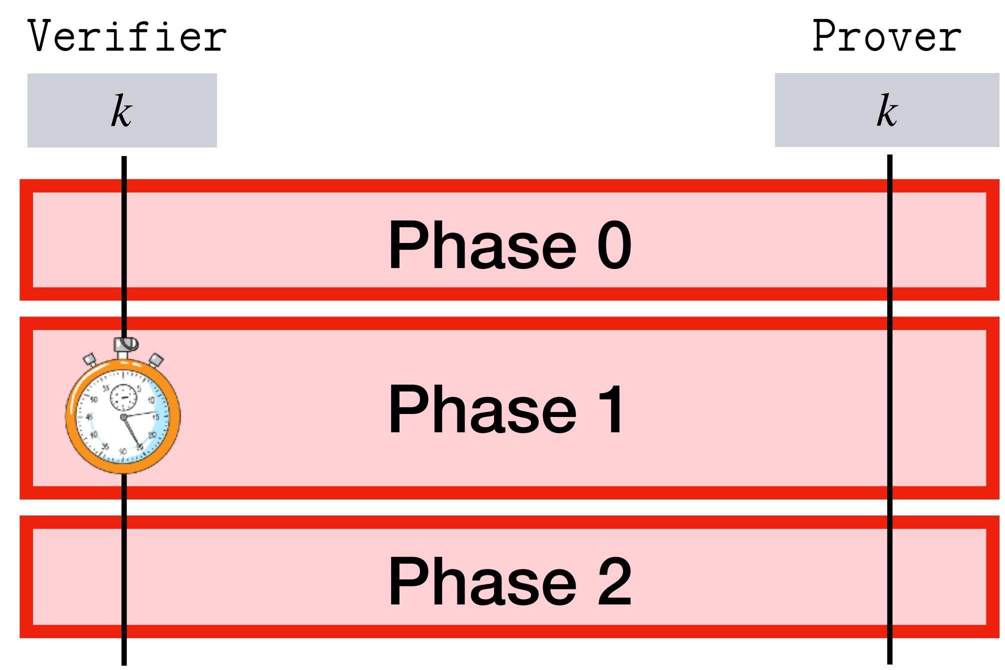
Even a single topology cannot be modeled into existing tools

Encoding the two topologies with phases
[Chothia *et al.* - 2015]

➡ it relies on the phases of ProVerif

- *Phase 0 $\longrightarrow$ slow initialization phase*
- *Phase 1 $\longrightarrow$ rapid phase*
- *Phase 2 $\longrightarrow$ slow verification phase*

➡ *Remote agents do not act in phase 1!*



Getting rid of time

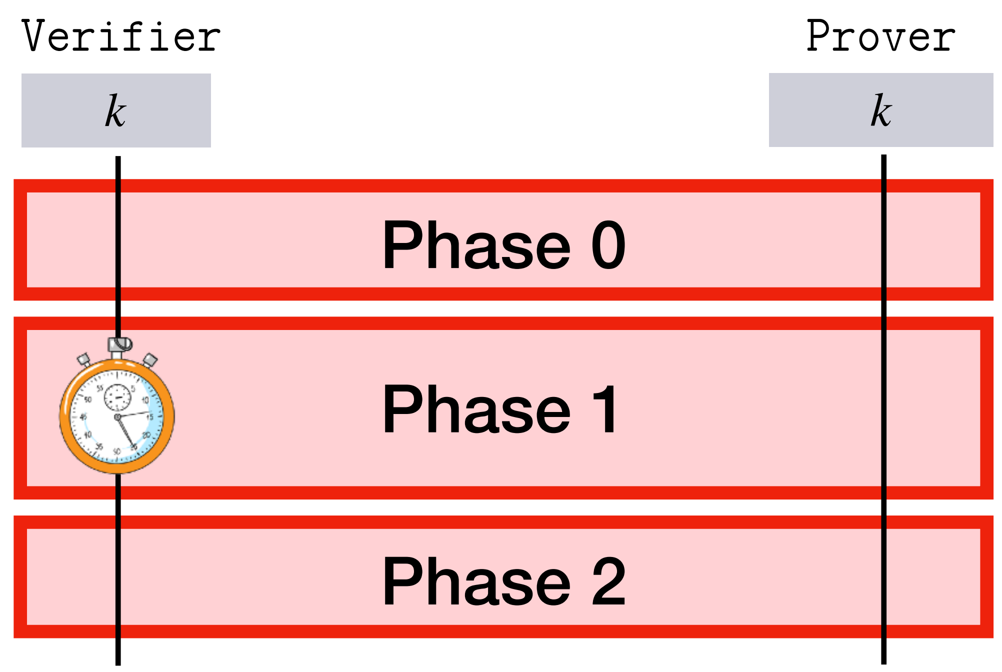
Even a single topology cannot be modeled into existing tools

Encoding the two topologies with phases
[Chothia *et al.* - 2015]

➡ it relies on the phases of ProVerif

- *Phase 0 ⟶ slow initialization phase*
- *Phase 1 ⟶ rapid phase*
- *Phase 2 ⟶ slow verification phase*

➡ *Remote agents do not act in phase 1!*



Proposition

If a protocol $\mathscr{P}_{\mathrm{db}}$ admits a mafia fraud (resp. distance hijacking, terrorist fraud) then $\mathtt{end}(v_0, p_0)$ is reachable in $\mathscr{F}(\mathscr{P}_{\mathrm{db}})$.

A comprehensive case studies analysis

Application to

distance-bounding protocols

Case studies analyses

Corpus +25 protocols

Tool ProVerif (slightly modified for distance hijacking attacks)

Abstractions

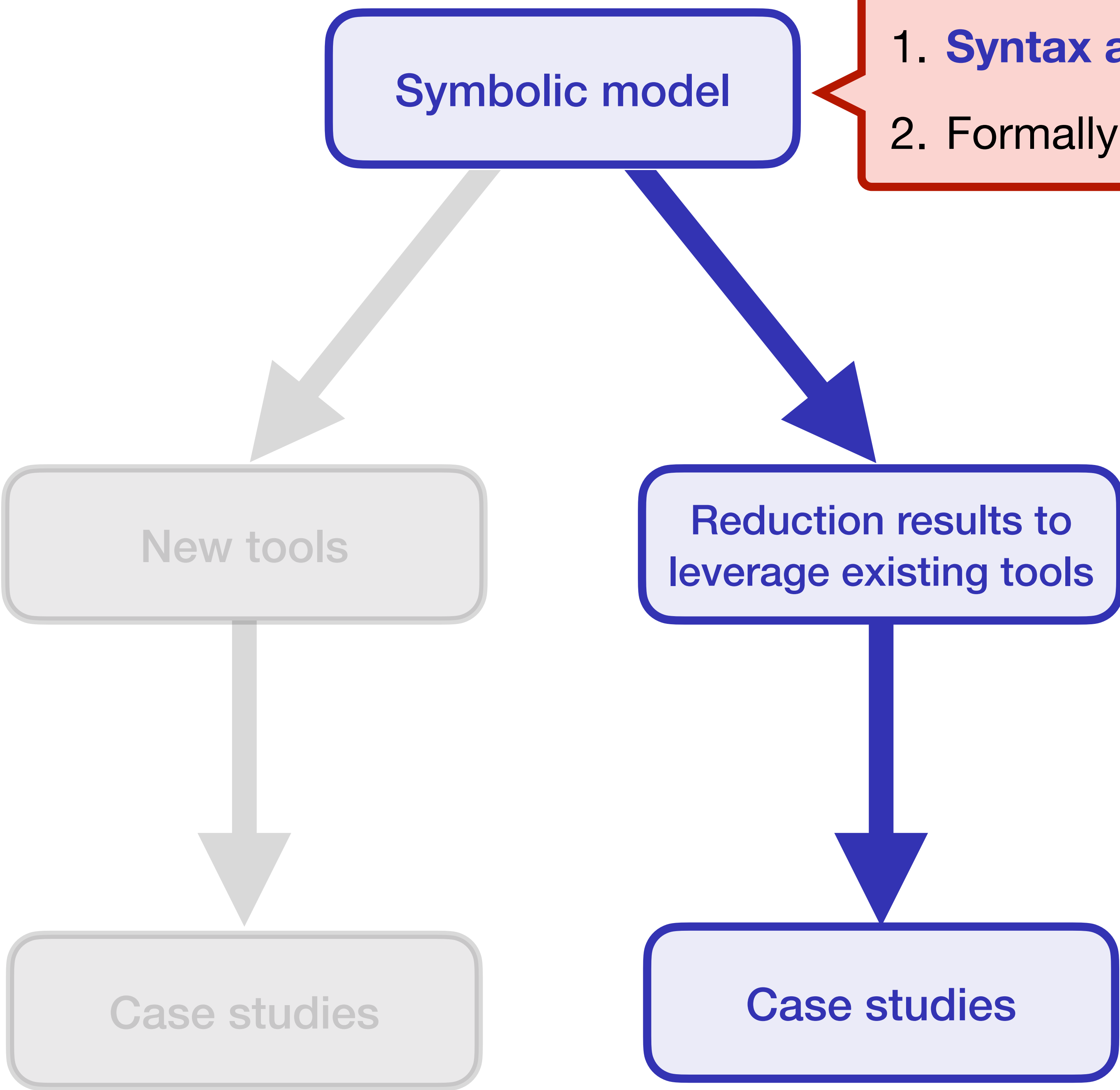
- rapid phase collapsed in a single round-trip — model limitation
- weak exclusive-OR — tool limitation

Application to real-world protocols

Protocols	Mafia fraud	Distance hijacking	Terrorist fraud
MasterCard RRP	✓	✗	✗
PaySafe	✓	✗	✗
MIFARE Plus	✓	✗	✗

Conclusion

Finally we have…

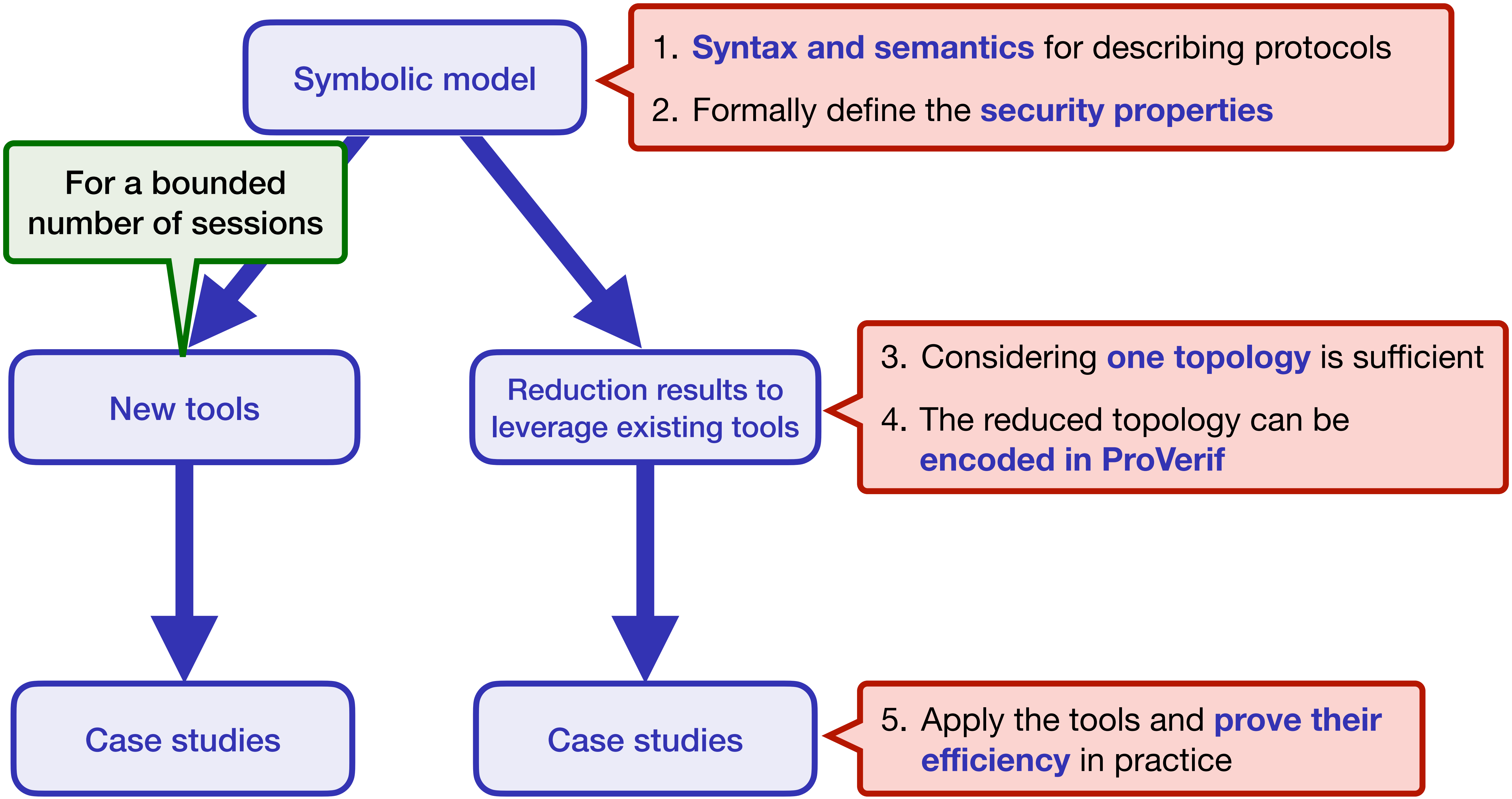


1. **Syntax and semantics** for describing protocols
2. Formally define the **security properties**

3. Considering **one topology** is sufficient
4. The reduced topology can be **encoded in ProVerif**

5. Apply the tools and **prove their efficiency** in practice

Finally we have…

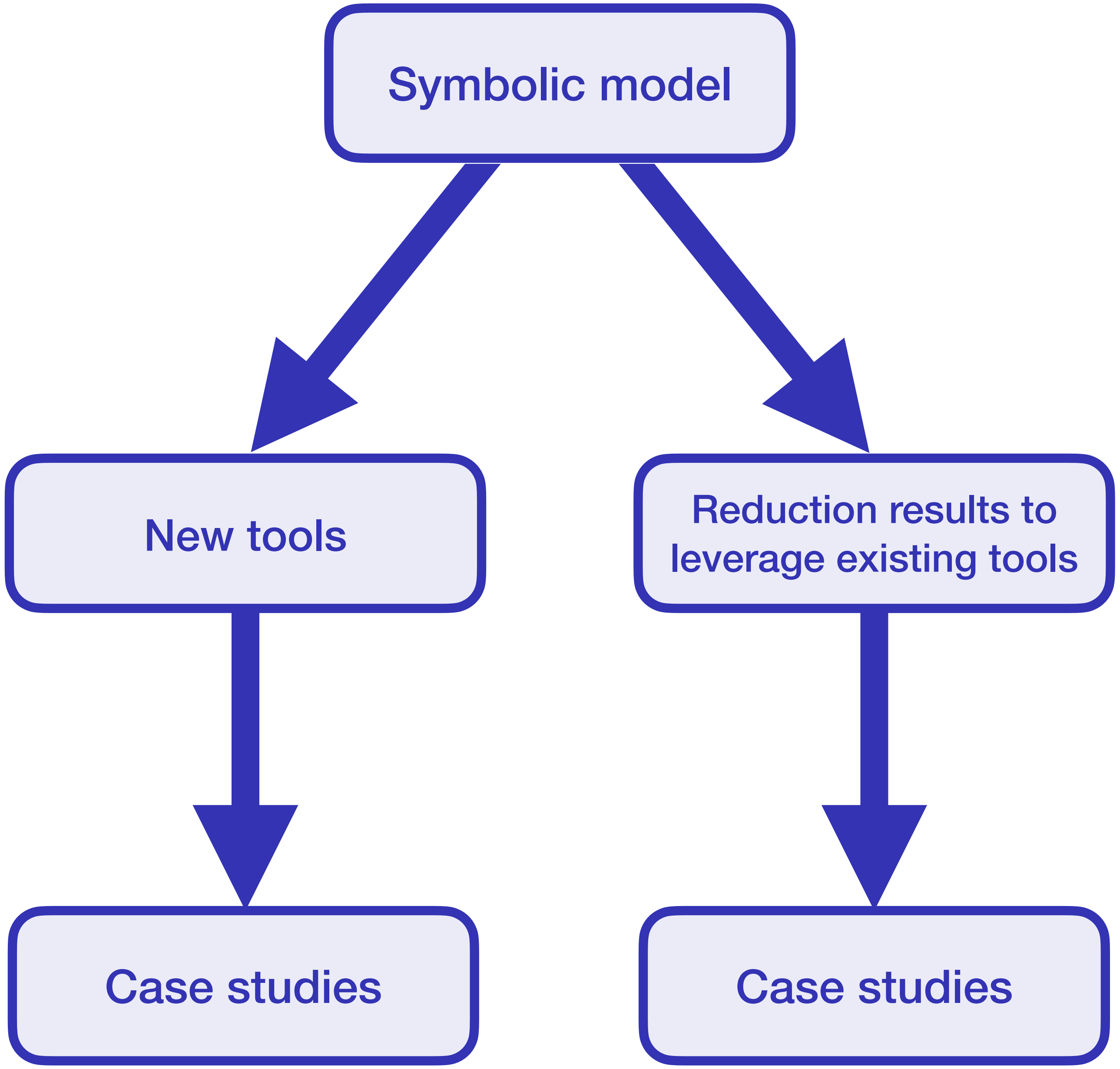


Future work

Remove hypotheses in the theorems

Make the existing tools support exclusive-OR

- extend ProVerif's procedure
- improve automation for Tamarin



Future work

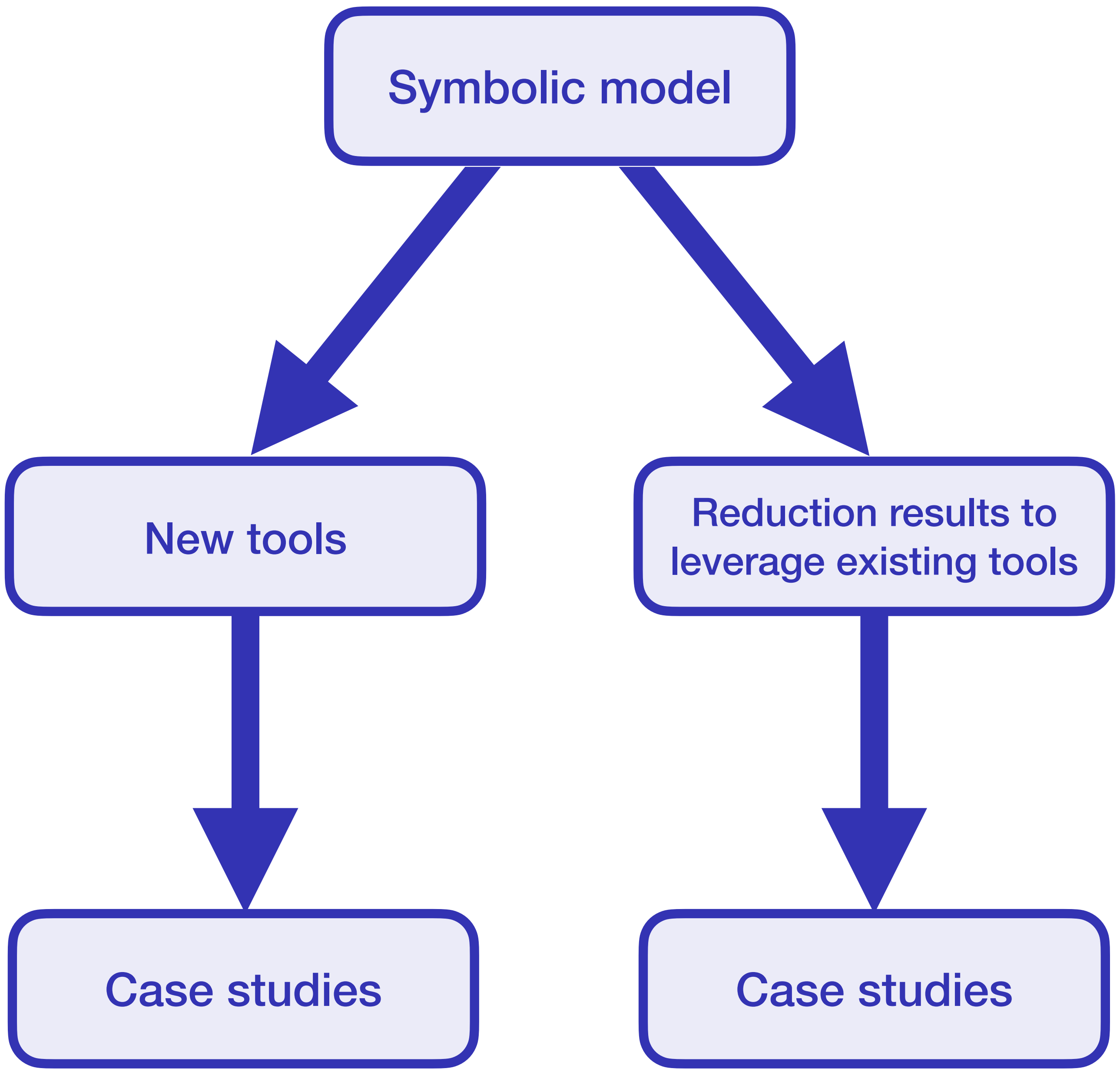
Remove hypotheses in the theorems

Make the existing tools support exclusive-OR

- extend ProVerif's procedure
- improve automation for Tamarin

Improve the model of time

- consider computation time
- design procedures for unbounded #sessions



Future work

Remove hypotheses in the theorems

Make the existing tools support exclusive-OR

- extend ProVerif's procedure
- improve automation for Tamarin

Improve the model of time

- consider computation time
- design procedures for unbounded #sessions

Model bit-level operations

- consider probabilistic processes and properties
- model messages with bitstrings