Symbolic Verification of Distance-bounding Protocols

Application to payments protocols

Alexandre Debant[1], Stéphanie Delaune[2], Cyrille Wiedling[3]

[1]Université de Lorraine, CNRS, Inria, LORIA,
[2]Univ Rennes, CNRS, IRISA,
[3]DGA-MI, Bruz

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Introduction

Scenario

Eve, a dishonest agent, wants to buy an item but without paying it!

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Existing solutions

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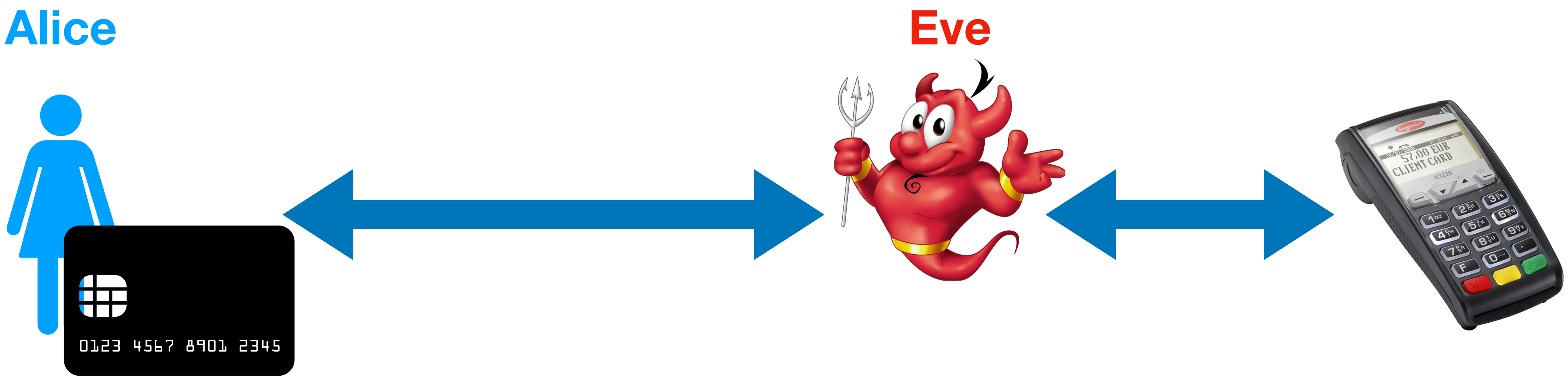
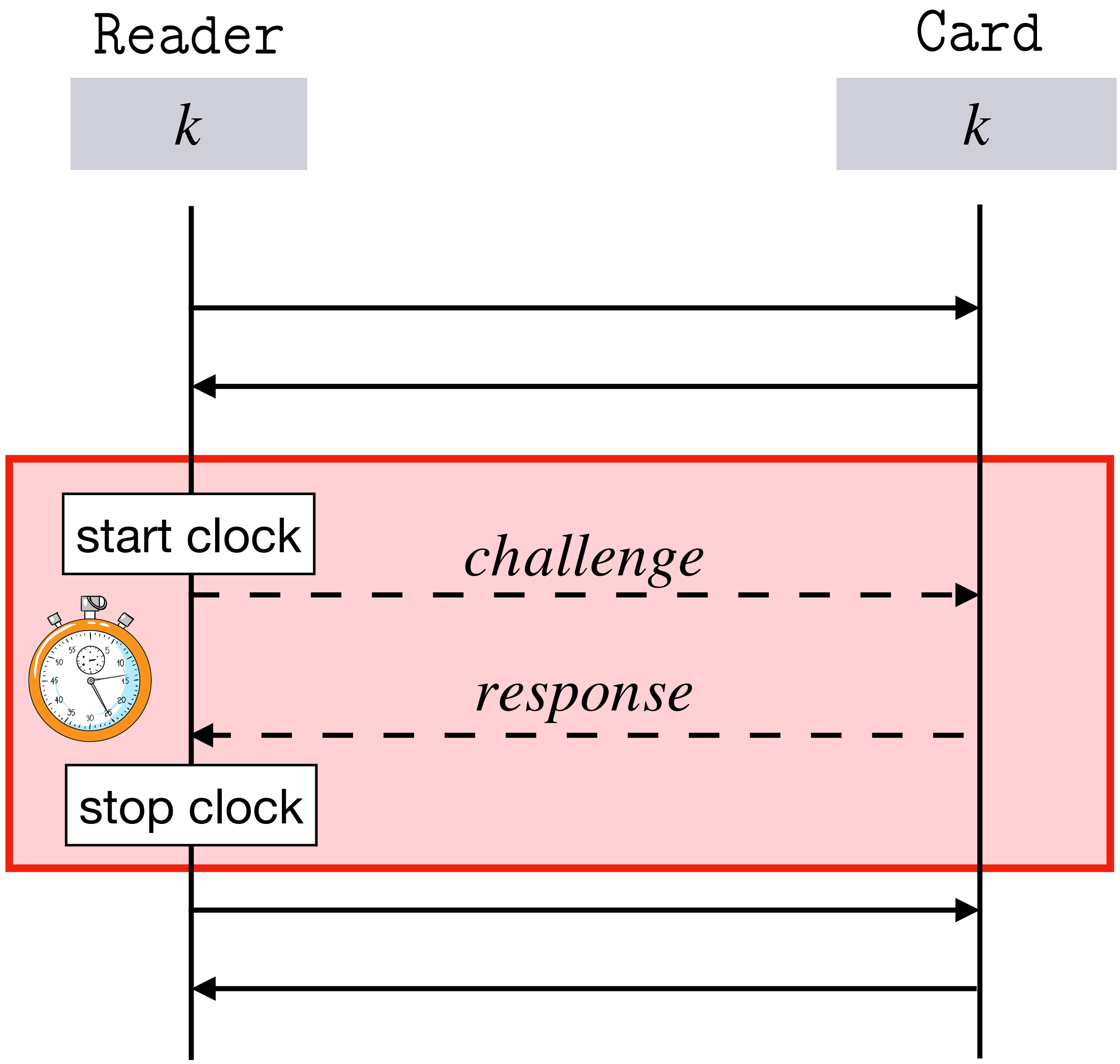
- Steal the item…
- Steal a credit card: by-pass the PIN code, pay on the Internet, contactlessly…
- Abuse a victim by relaying messages using the contactless technology



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



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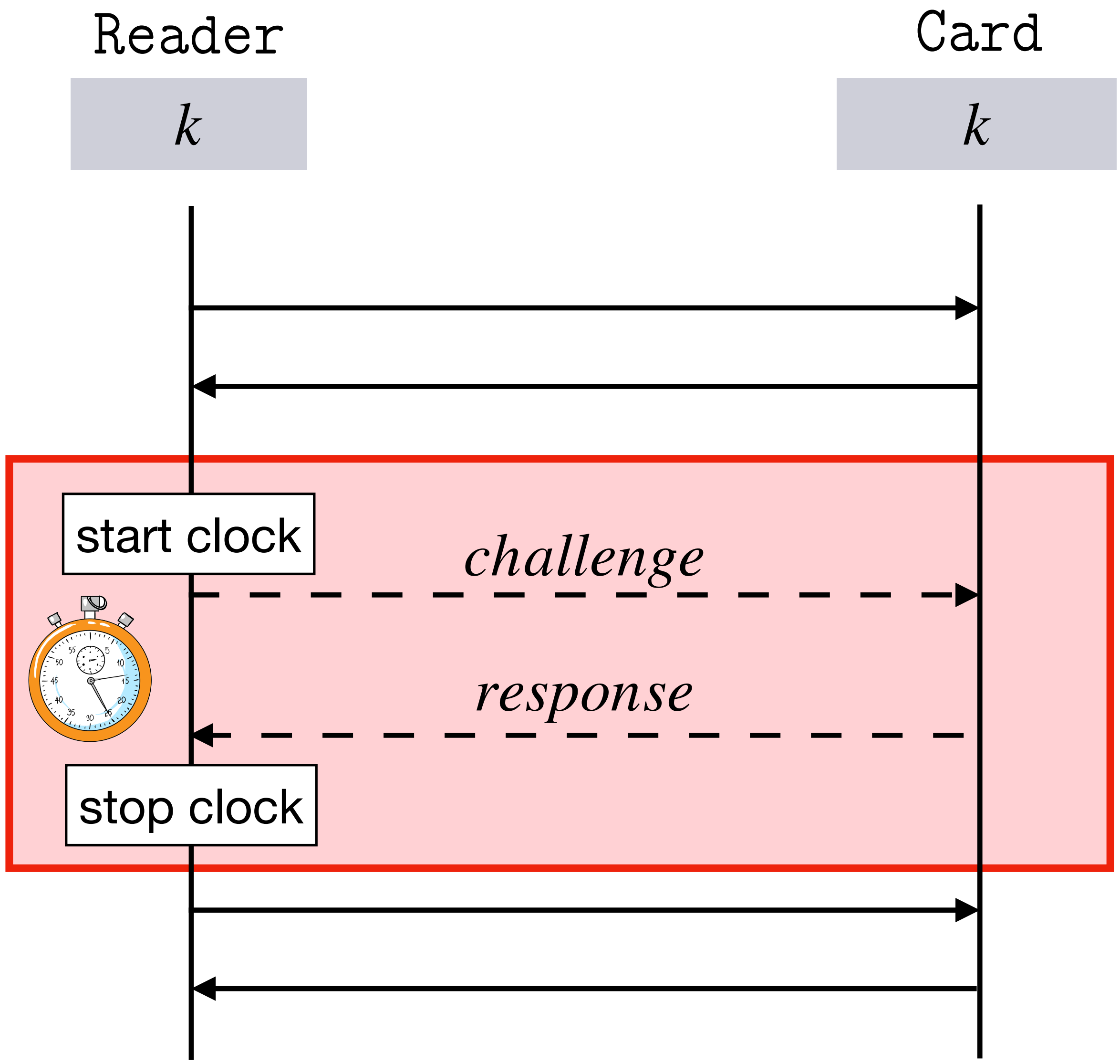
Designing a good protocol is difficult!



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

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 for experts only

Symbolic models

– Some simplifications/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: $\texttt{enc}(x, k)$, $\texttt{sign}(x, k)$, $\texttt{h}(x)$,…
- Equations: $\texttt{dec}(\texttt{enc}(x, k), k) = x$

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

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

ProVerif

TAMARIN
Tamarin prover interactive mode

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5G-AKA

Belenios e-voting

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- Standard models and tools: do not model time and locations!
- Main specific models:
  - Meadows *et al.* (2007),
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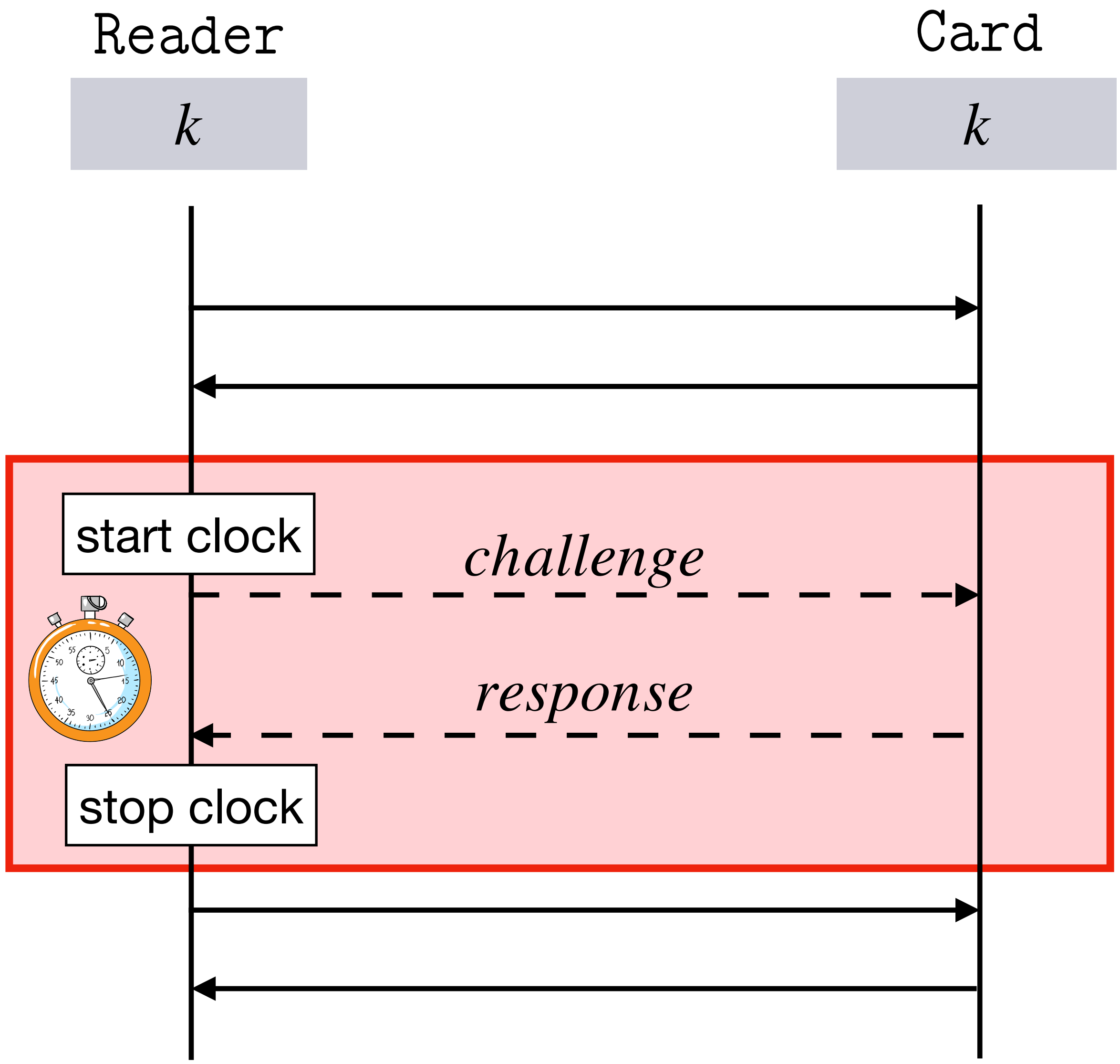
➡ no automated verification procedure…



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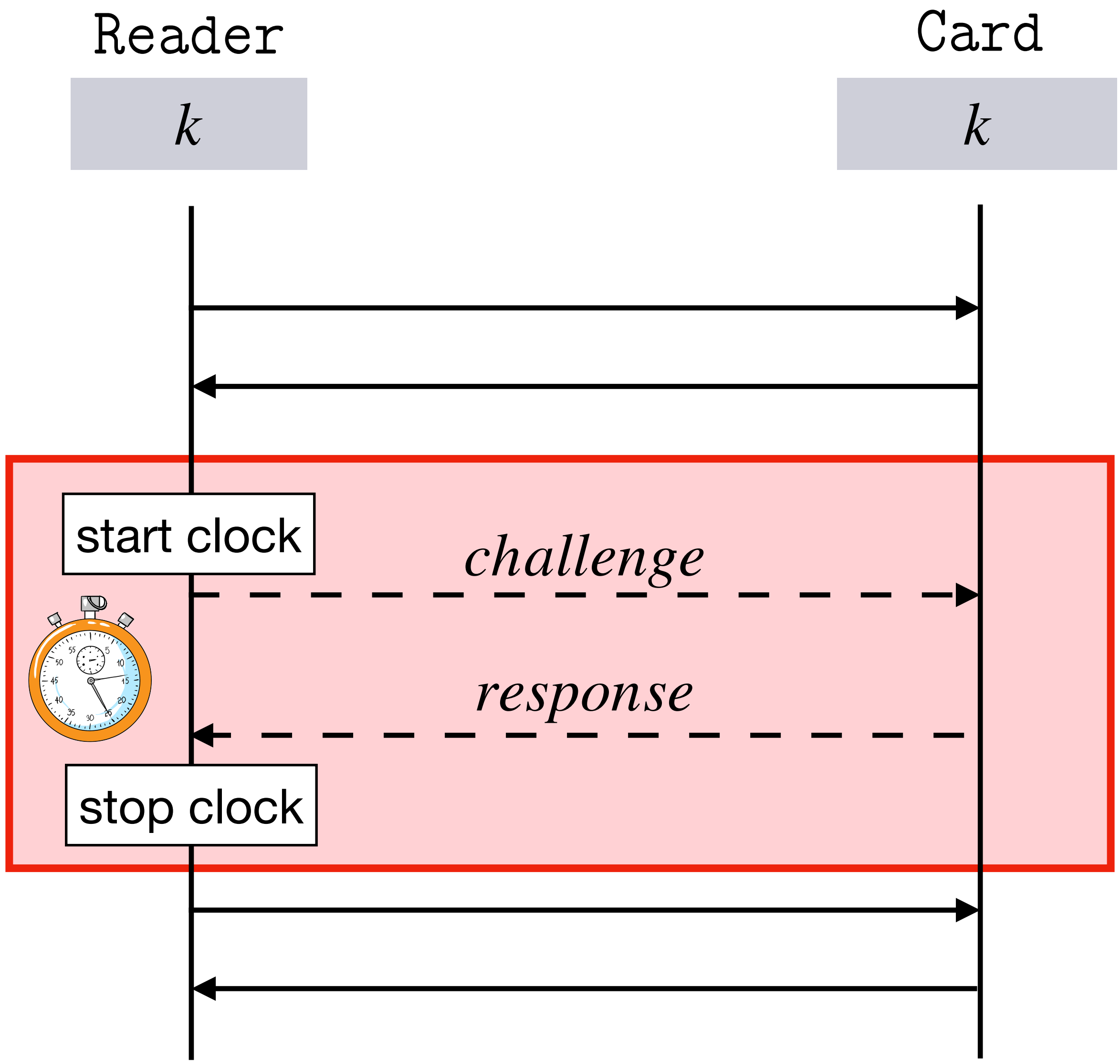

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Can we design a framework that allows for a **fully automated** verification?

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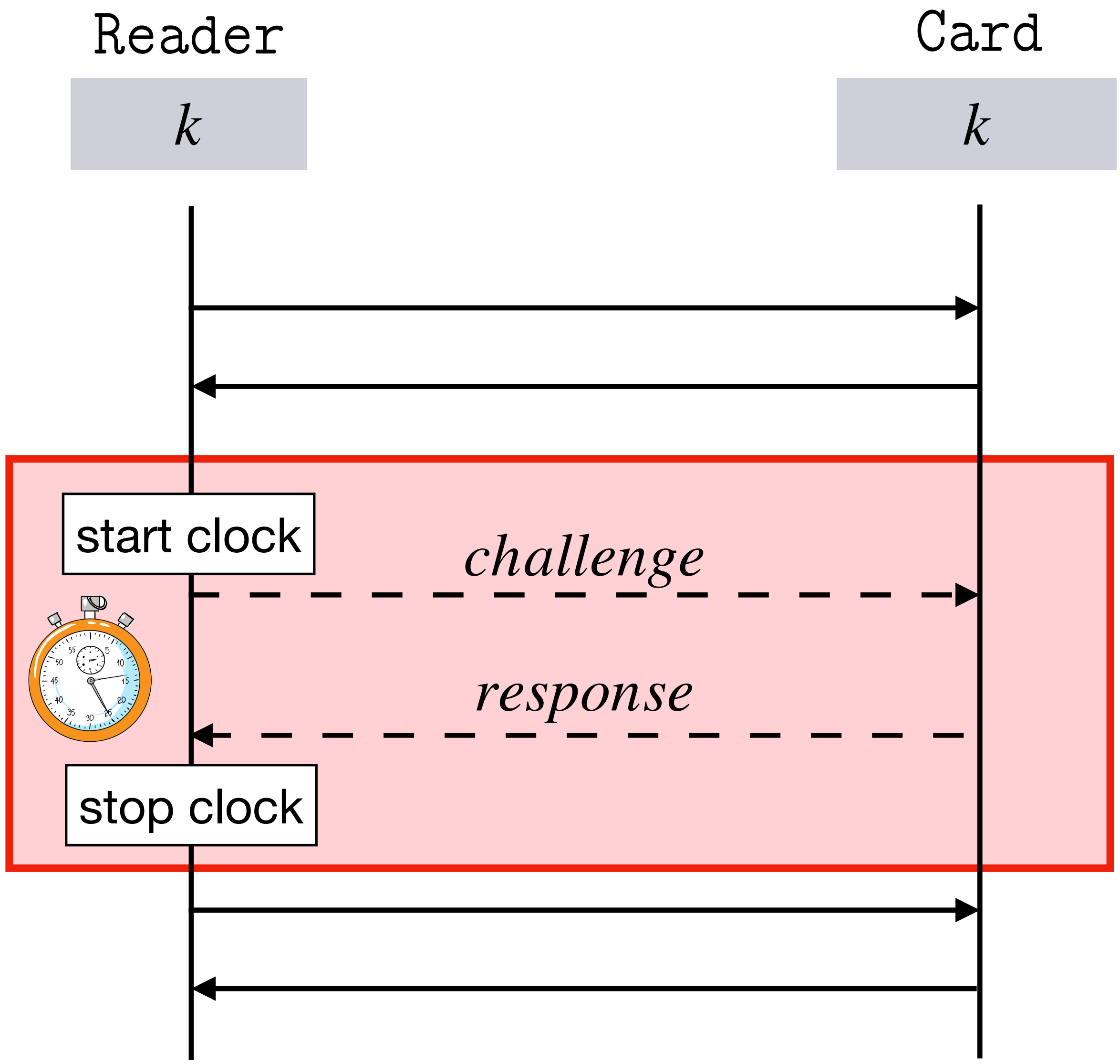
- Recently: Mauw et. al. (2018, 2019)



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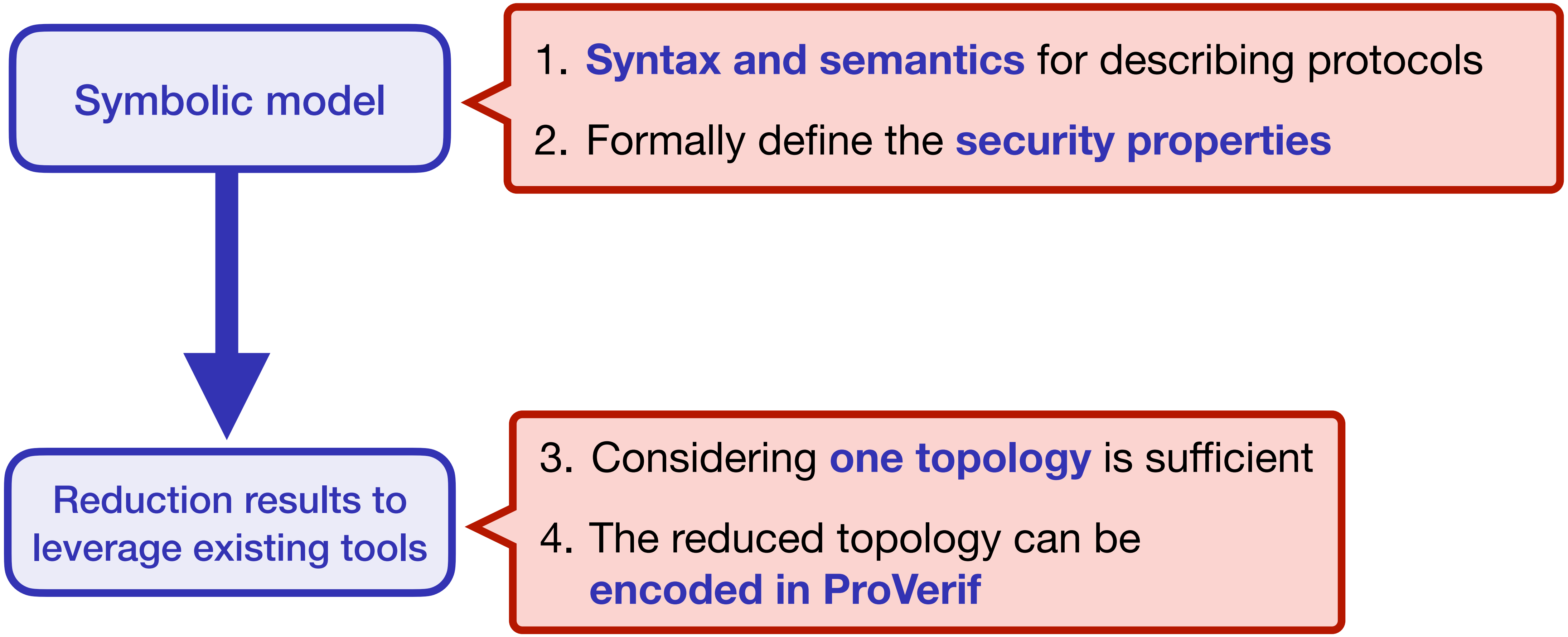
The story of verification

Symbolic model

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

The story of verification



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Reduction results to leverage existing tools

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

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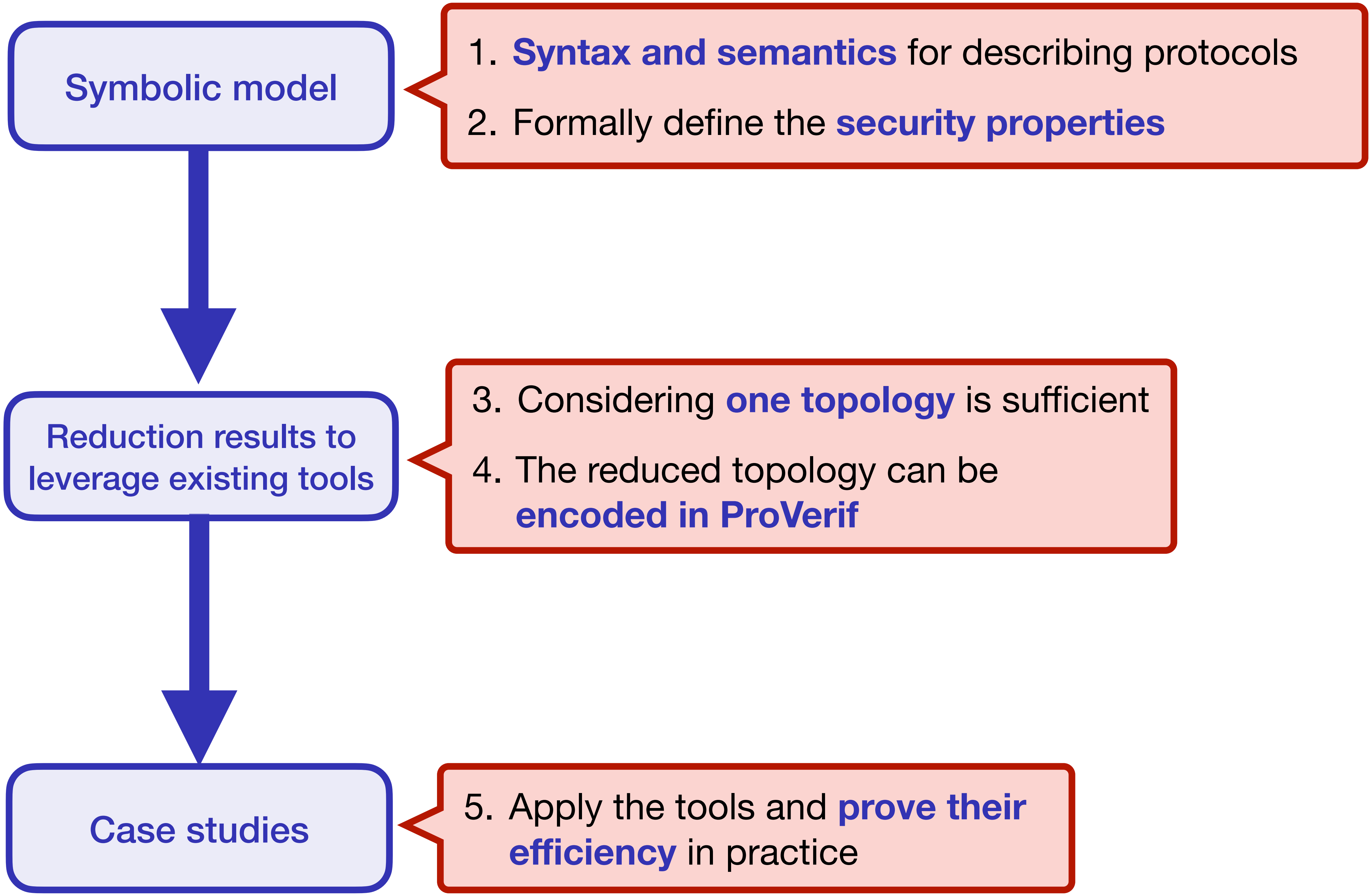

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Case studies

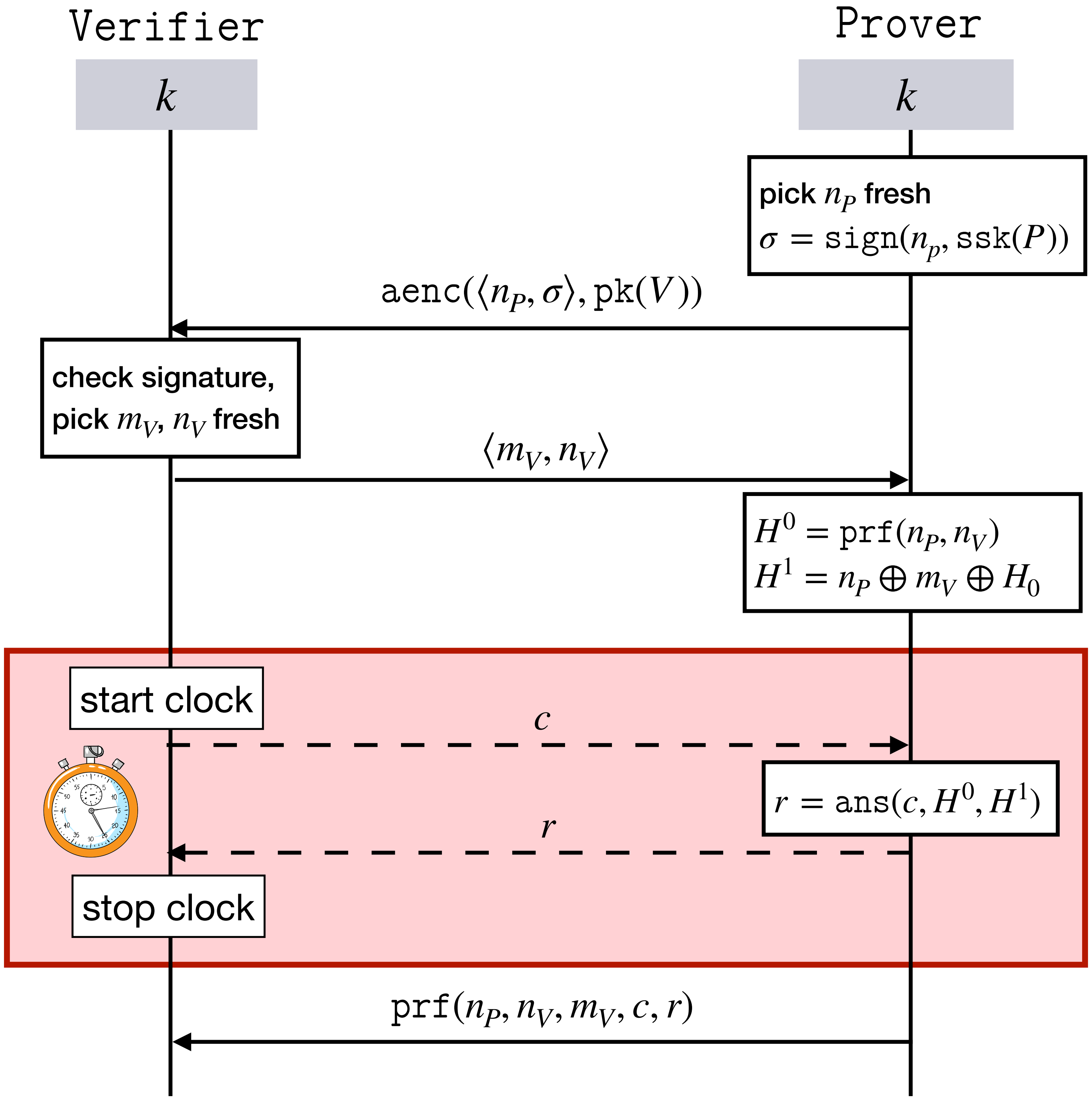
5. Apply the tools and **prove their efficiency** in practice

A symbolic model with time and locations

syntax and semantics

SPADE

[Bultel *et al.* - 2016]



Verifier
Prover
k
k
pick n_P fresh
$\sigma = \mathtt{sign}(n_p, \mathtt{ssk}(P))$
$\mathtt{aenc}(\langle n_P, \sigma \rangle, \mathtt{pk}(V))$
check signature,
pick m_V, n_V fresh
$\langle m_V, n_V \rangle$
$H^0 = \mathtt{prf}(n_P, n_V)$
$H^1 = n_P \oplus m_V \oplus H_0$
start clock
c
$r = \mathtt{ans}(c, H^0, H^1)$
r
stop clock
$\mathtt{prf}(n_P, n_V, m_V, c, r)$

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:

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

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

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

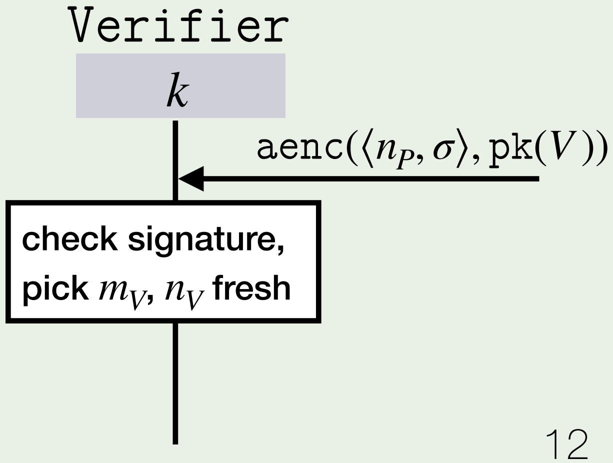
Running example

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

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

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

$\quad \ldots$


Verifier
k
$\mathtt{aenc}(\langle n_P, \sigma \rangle, \mathtt{pk}(V))$
check signature, pick m_V, n_V fresh

Process algebra

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

$$
\begin{array}{lcll}
P & := & 0 & \text{null process} \\
  & | & \mathtt{new}\ n\,.\,P & \text{name restriction} \\
  & | & \mathtt{let}\ x = u\ \mathtt{in}\ P & \text{conditional declaration} \\
  & | & \mathtt{out}(u)\,.\,P & \text{output} \\
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\begin{aligned}
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& \mathtt{out}(\langle m_V, n_V\rangle)\,.\\
& \mathtt{reset}\,.\,\mathtt{new}\ c\,.\,\mathtt{out}(c)\,.\,\mathtt{in}^{<t}(y)\,.\\
& \mathtt{in}(z)\,.\ldots
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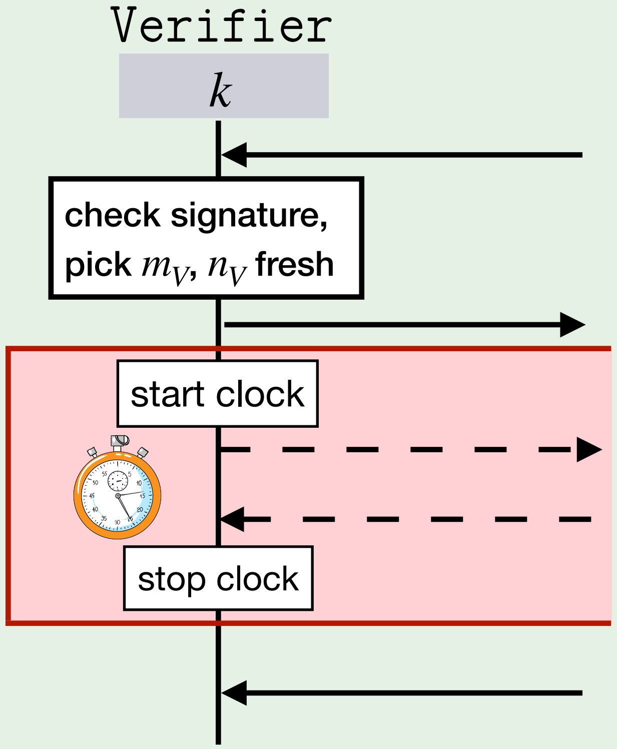
$$



Verifier

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check signature, pick m_V, n_V fresh

start clock

stop clock

Semantics

Physical restrictions

- locations: elements in $\mathbb{R}^3$, i.e. $\texttt{Loc} : \mathscr{A} \to \mathbb{R}^3$
- distance: Euclidean norm between locations, i.e. $\texttt{Dist}(a, b) = \dfrac{\|\texttt{Loc}(a) - \texttt{Loc}(b)\|}{c}$
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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. $w \xrightarrow{a, t_a} u$
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Execution rules

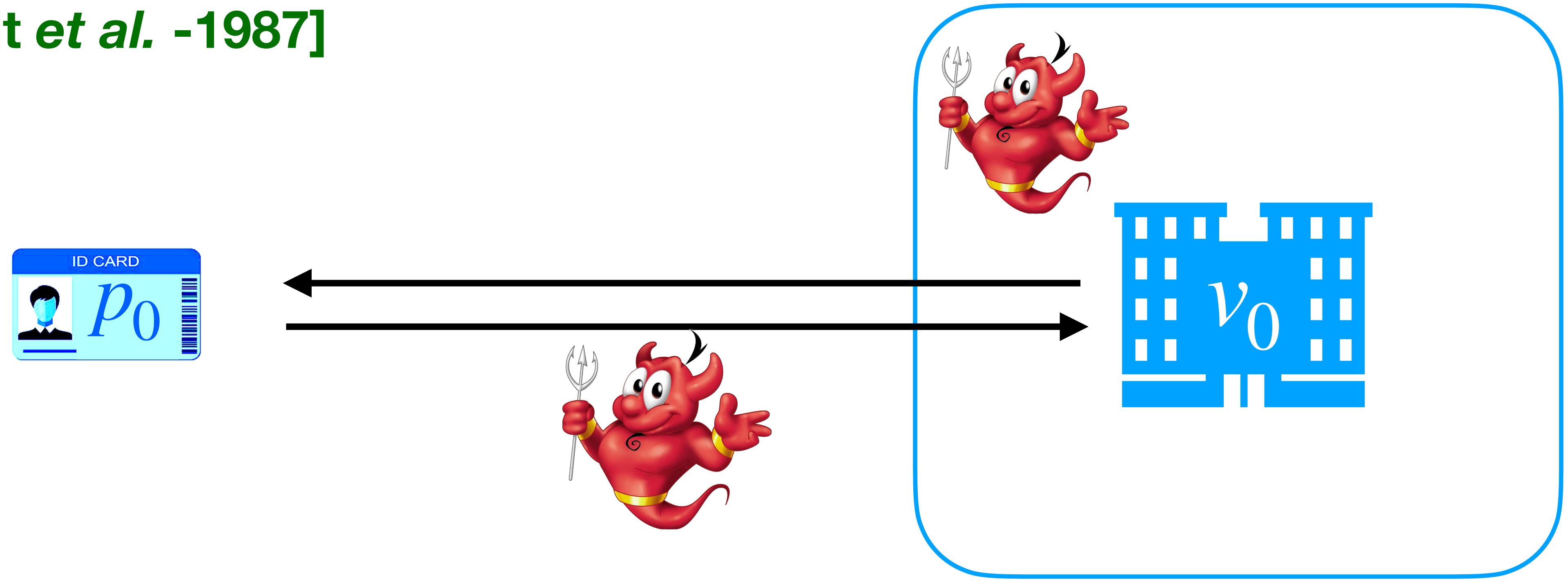
- *TIM*: $(\mathscr{P}, \Phi, t) \longrightarrow (\mathtt{Shift}(\mathscr{P}, \delta), \Phi, t + \delta)$ with $\delta > 0$
- *OUT*: $(\lfloor \mathtt{out}(u) \,.\, P \rfloor_a^{t_a} \uplus \mathscr{P}, \Phi, t) \xrightarrow{a,\mathtt{out}(u)} (\lfloor P \rfloor_a^{t_a} \uplus \mathscr{P}, \Phi \cup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

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]



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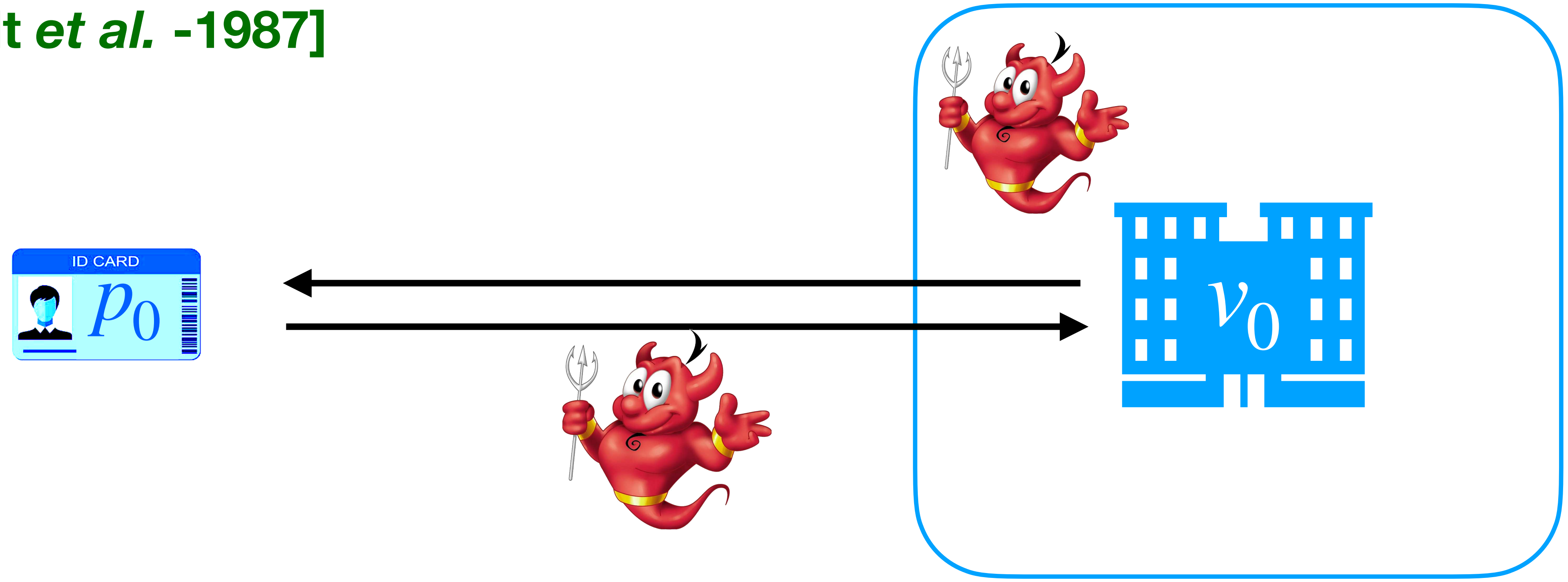

Definition

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:

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

Distance hijacking attack

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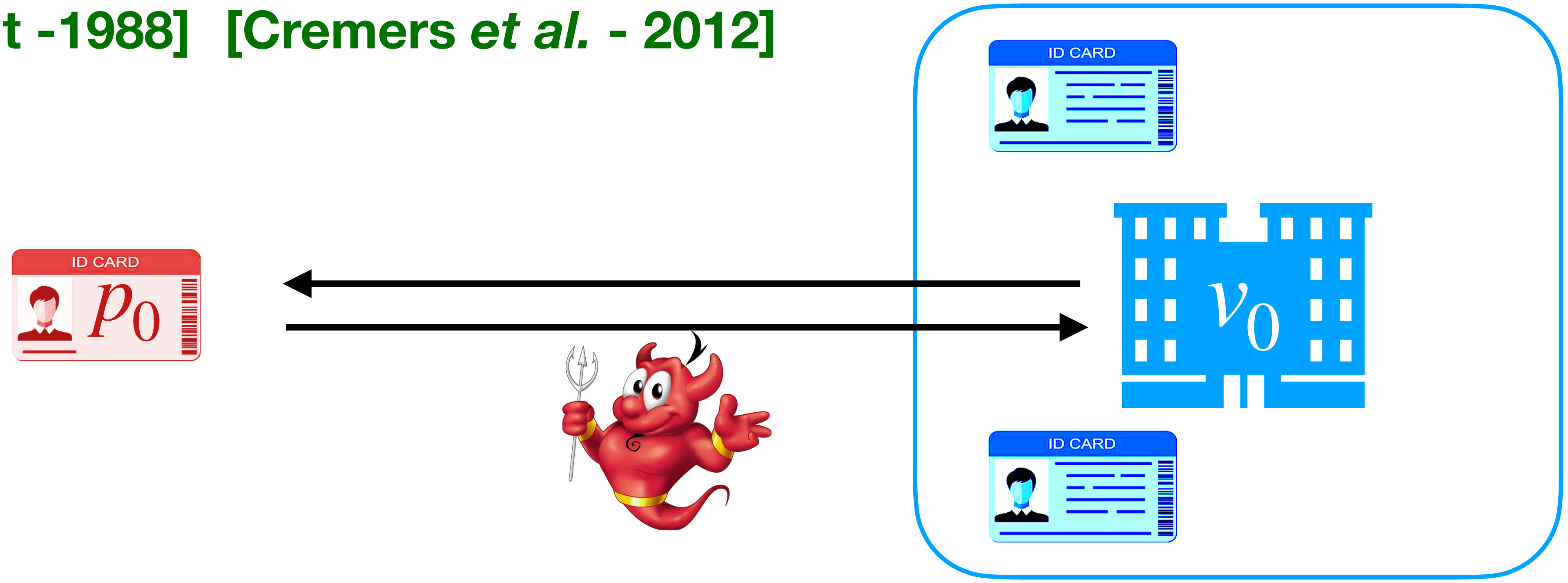

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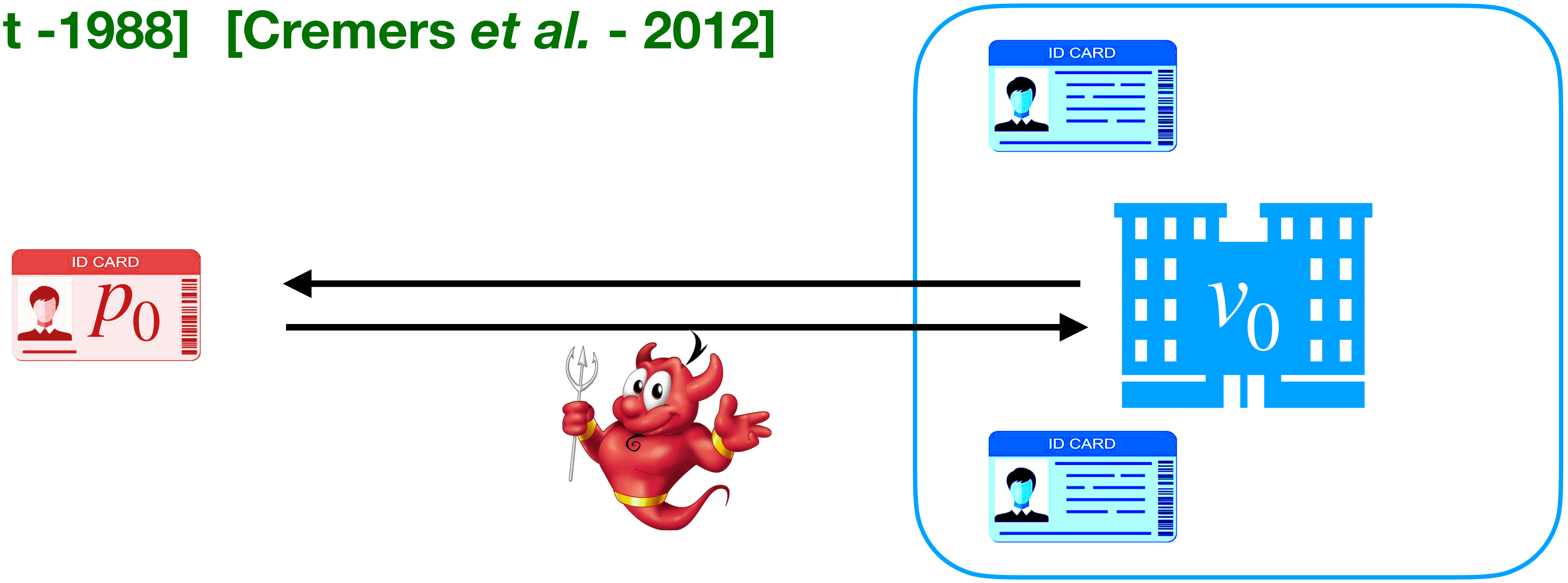

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A protocol admits a distance hijacking attack if there exists a topology $\mathcal{T} \in \mathcal{C}_{\mathtt{DH}}$ and an initial configuration K such that:

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Some reduction results

Topologies and time

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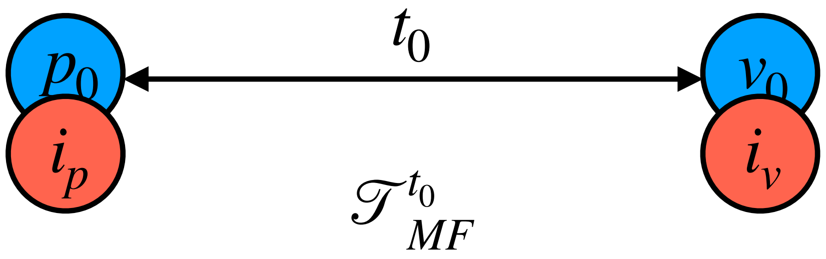

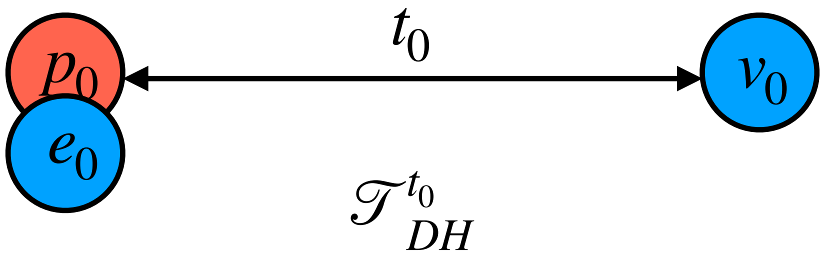

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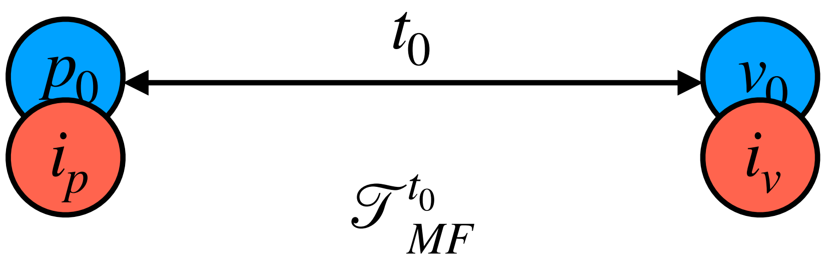

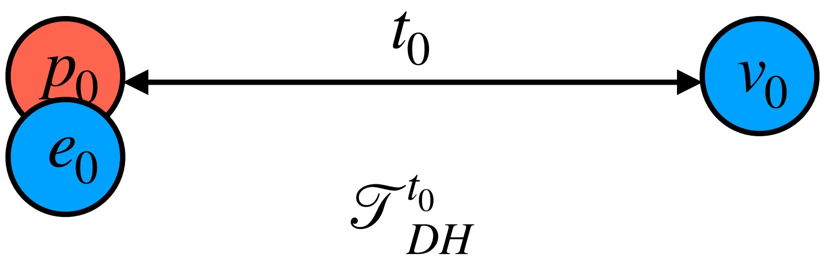

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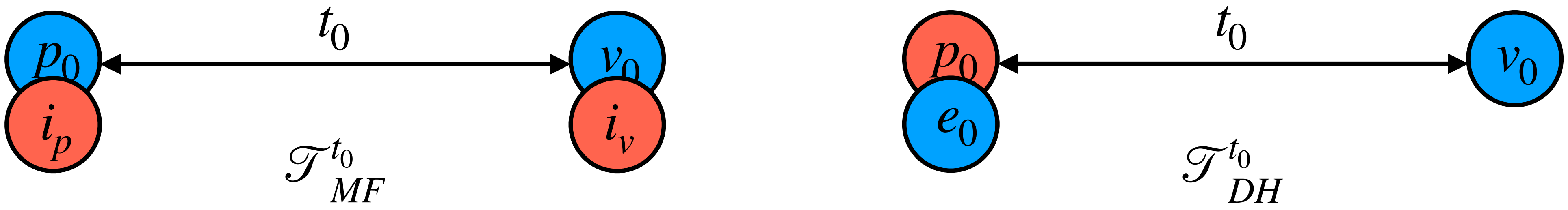

2. We must deal with time when conducting our analyses
   —> we can use ProVerif’s phases to encode the topologies!

Mafia frauds

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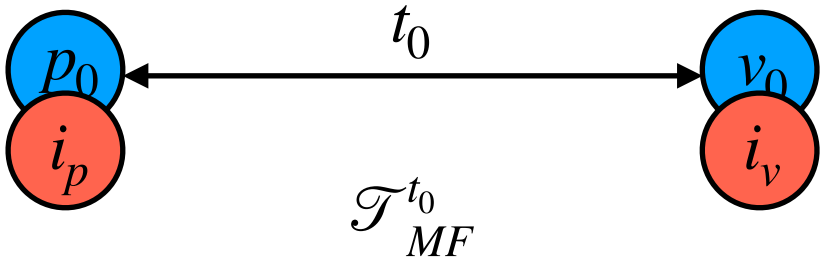
A protocol admits a mafia fraud, if and only if, there is an attack in $\mathscr{T}^{t_0}_{MF}$.



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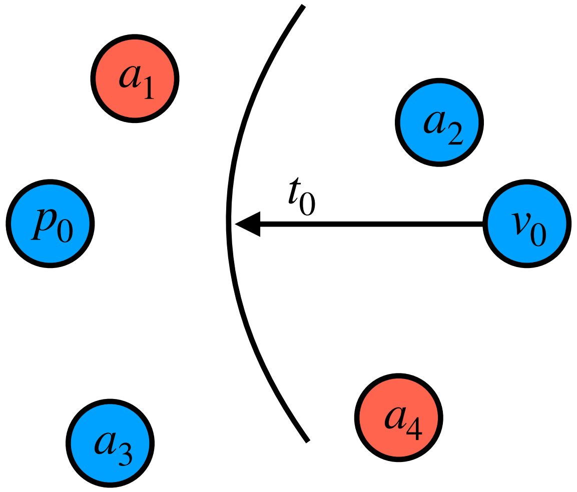
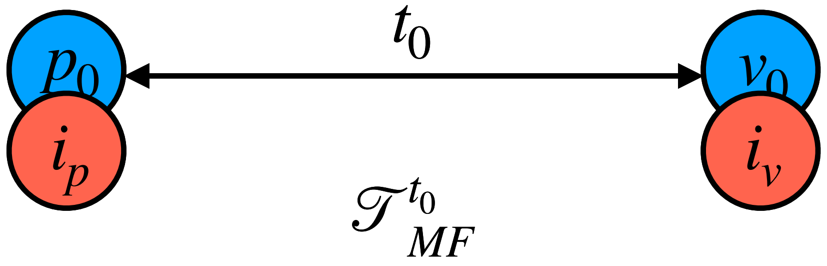


An attack trace in an **arbitrary** topology



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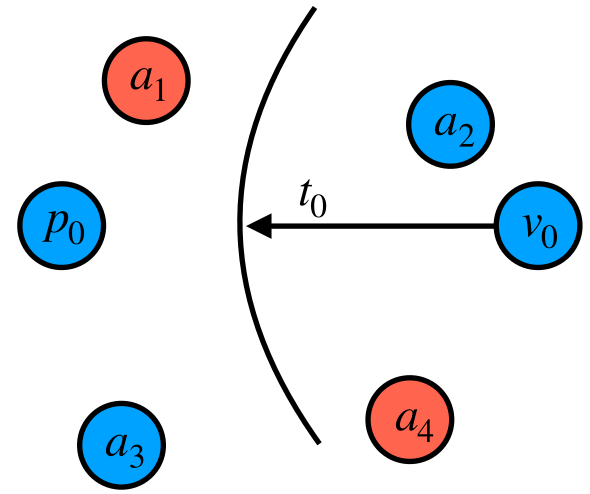
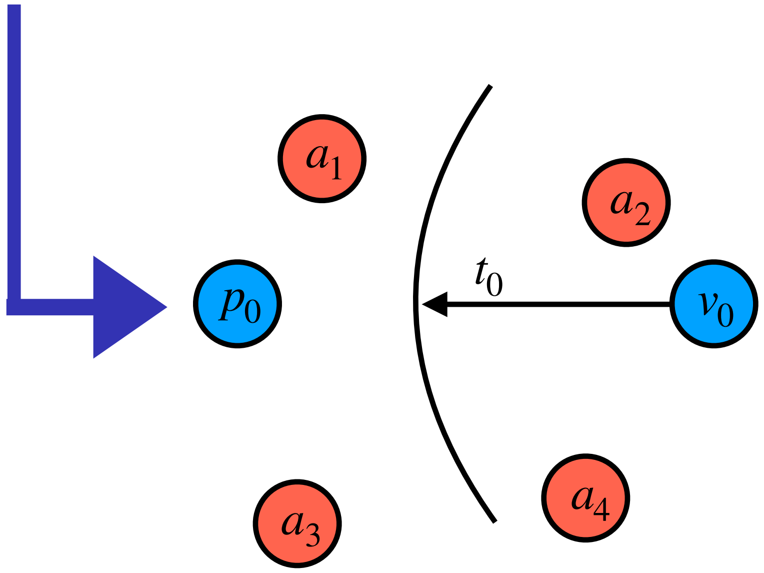
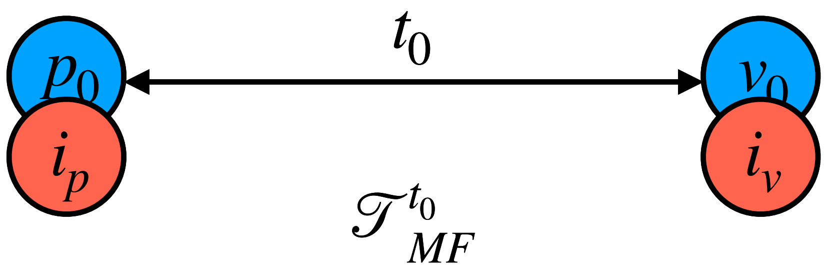


An attack trace in an **arbitrary** topology

Assume everyone **malicious**





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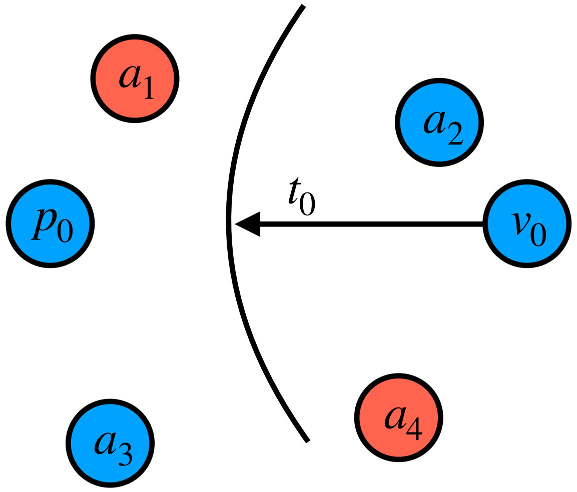

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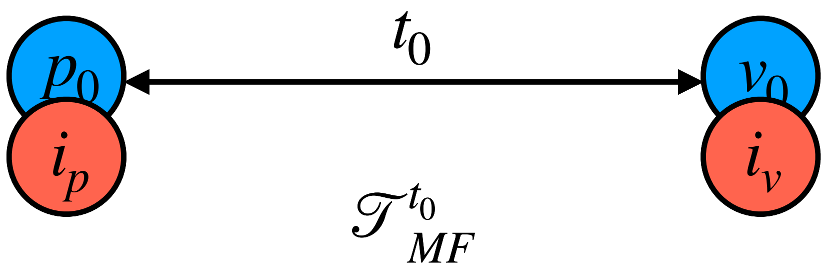

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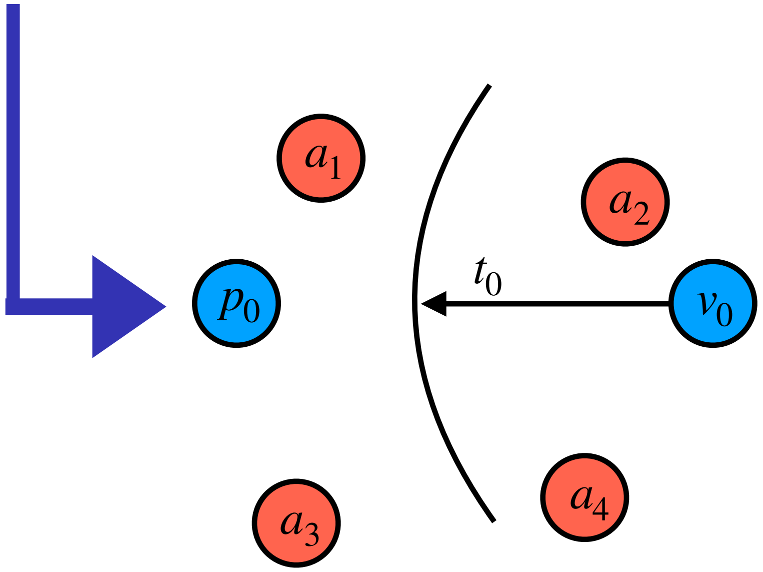
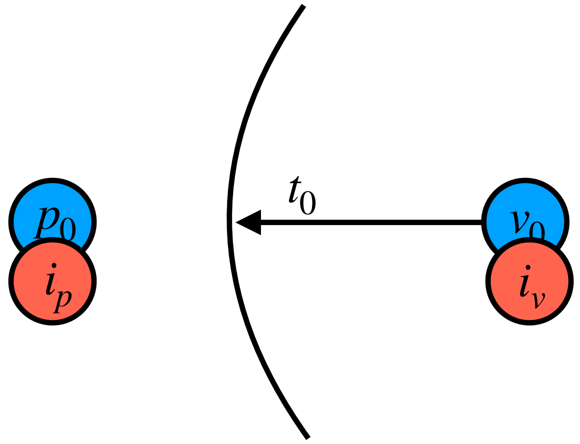


[Nigam *et al.* - 2016]

Place malicious agents **ideally**



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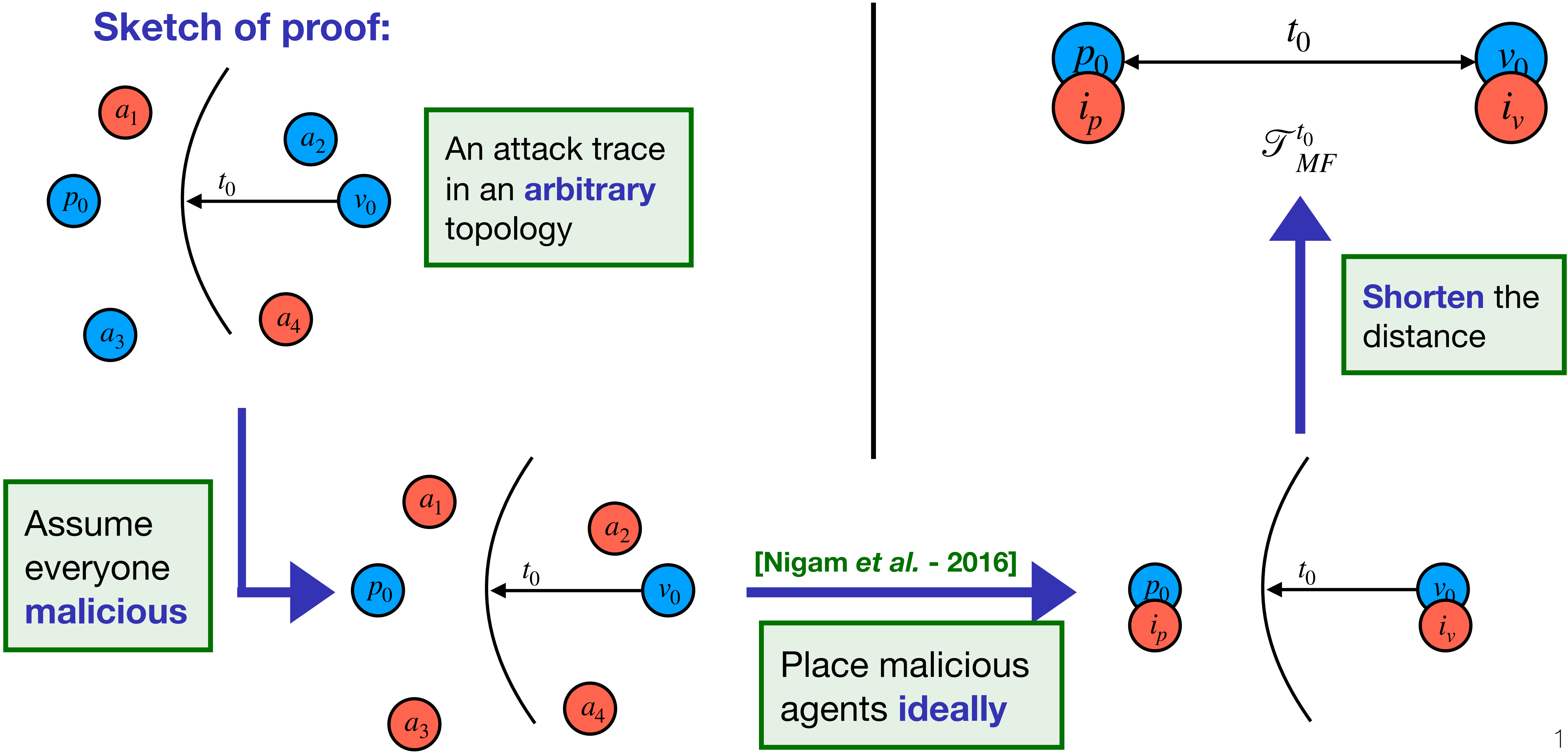

An attack trace in an **arbitrary** topology

Assume everyone **malicious**

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Place malicious agents **ideally**

Shorten the distance

Distance hijacking attacks

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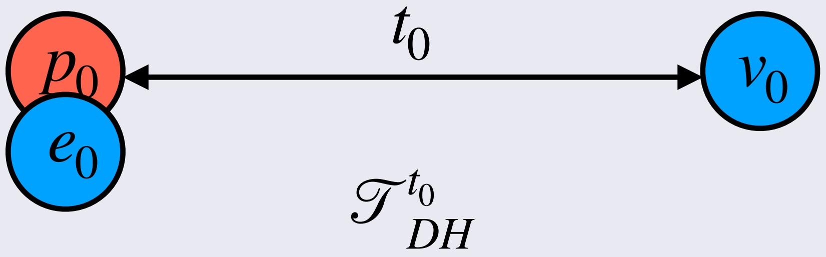
If $\mathscr{P}_{\mathtt{db}}$ admits a distance hijacking attack, then $\overline{\mathscr{P}_{\mathtt{db}}}$ admits an attack in $\mathscr{T}^{t_0}_{DH}$.



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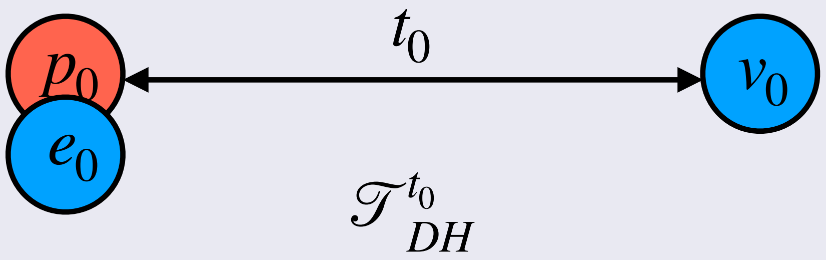

Remark: the previous proof does not apply!

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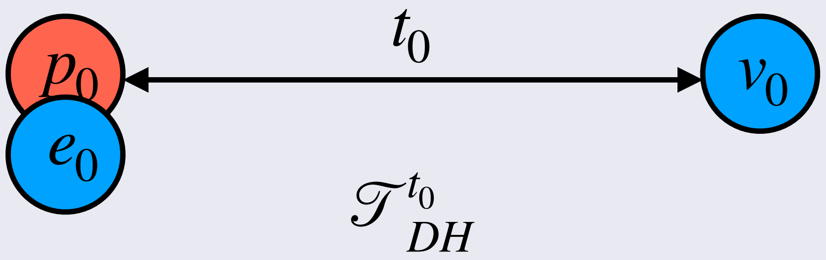
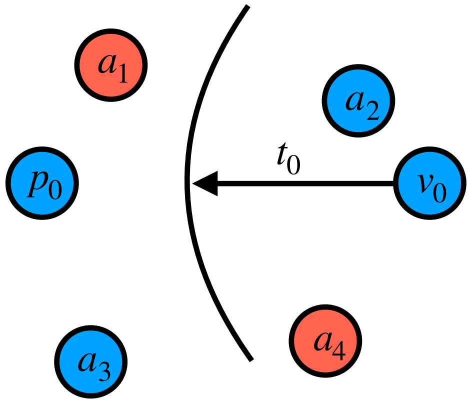


Remark: the previous proof does not apply!

Sketch of proof:



An attack trace in an **arbitrary** topology

Distance hijacking attacks

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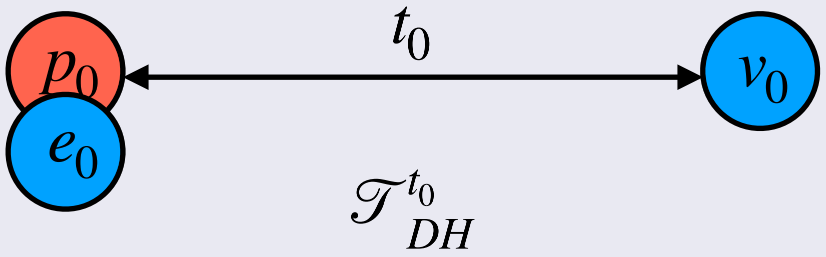

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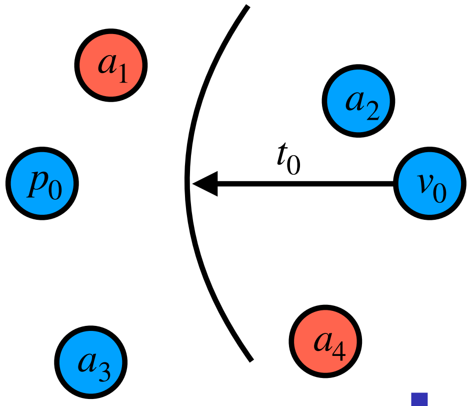

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Untimed witness of attack

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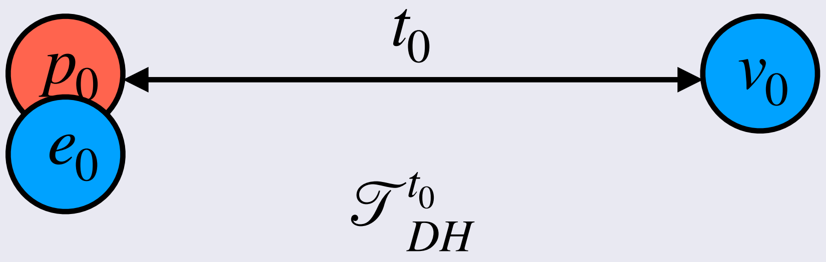

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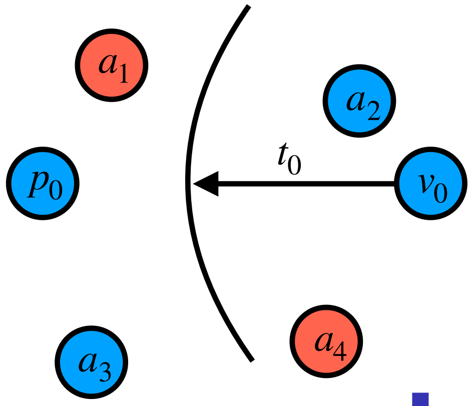

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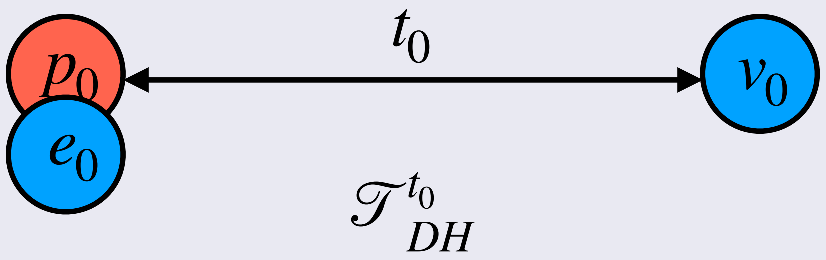

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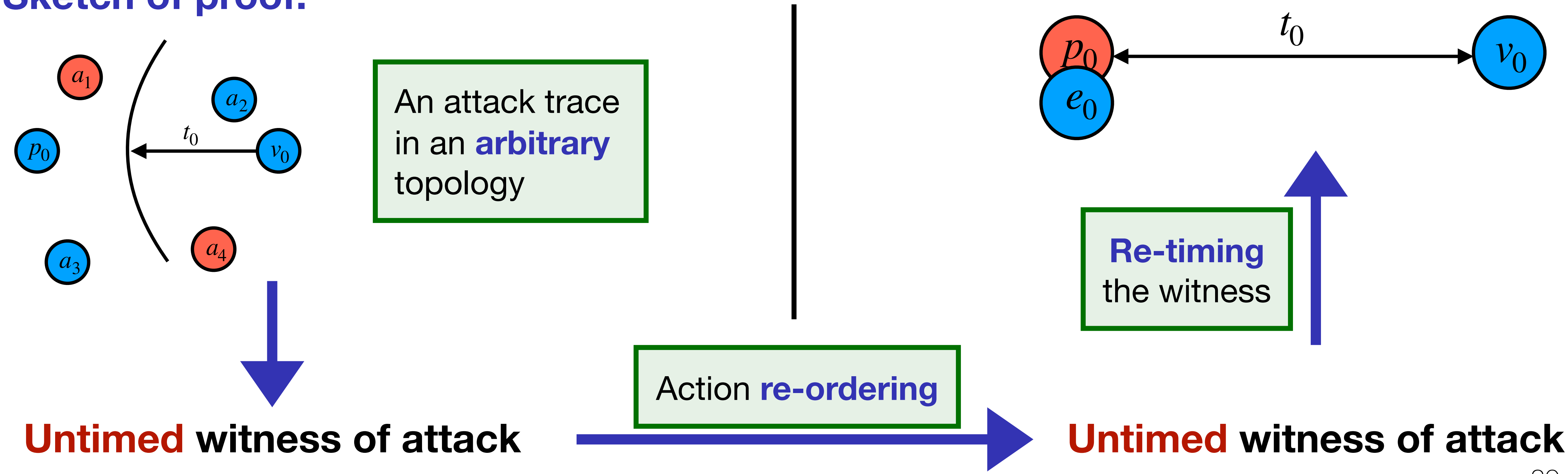


An attack trace in an **arbitrary** topology

Untimed **witness of attack**

Action **re-ordering**

Untimed **witness of attack**

Re-timing the witness

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

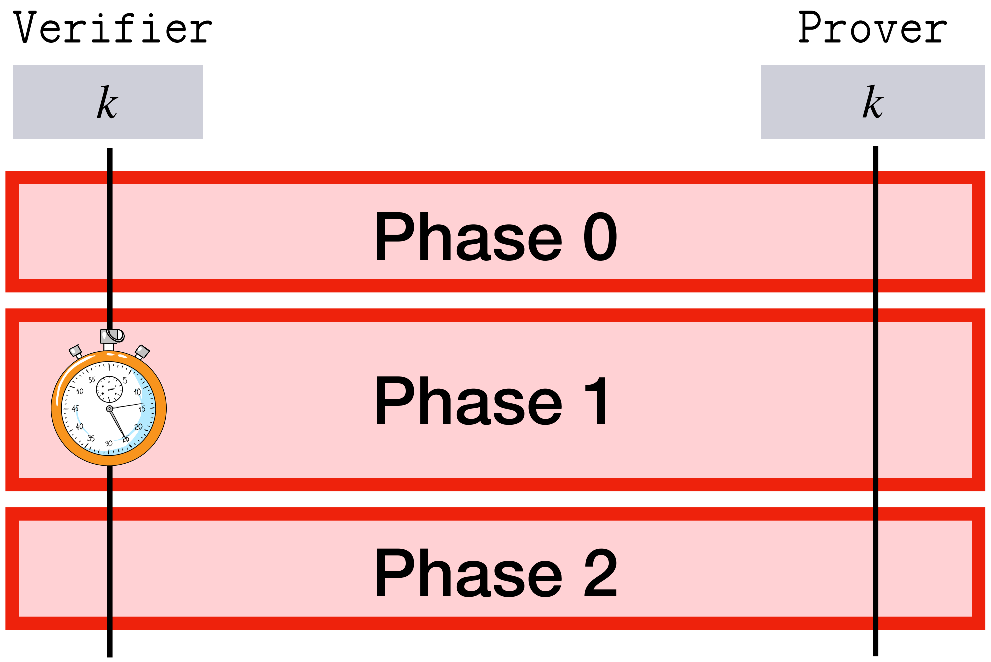
Encoding the two topologies with phases

[Chothia *et al.* - 2015]

➡ it relies on the phases of ProVerif

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

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



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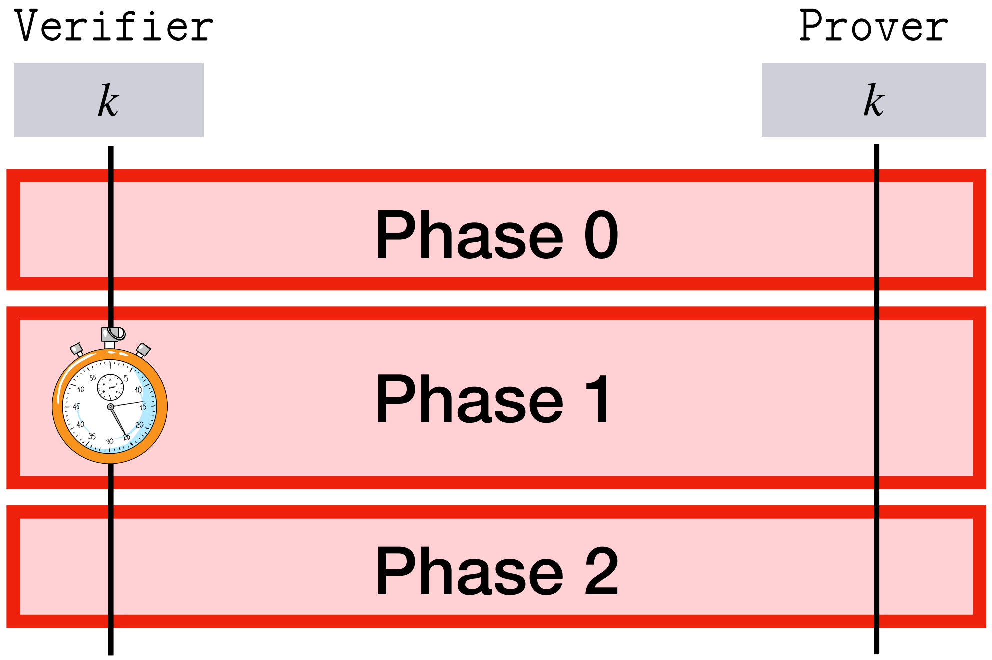


Verifier

Prover

k

k

Phase 0

Phase 1

Phase 2

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

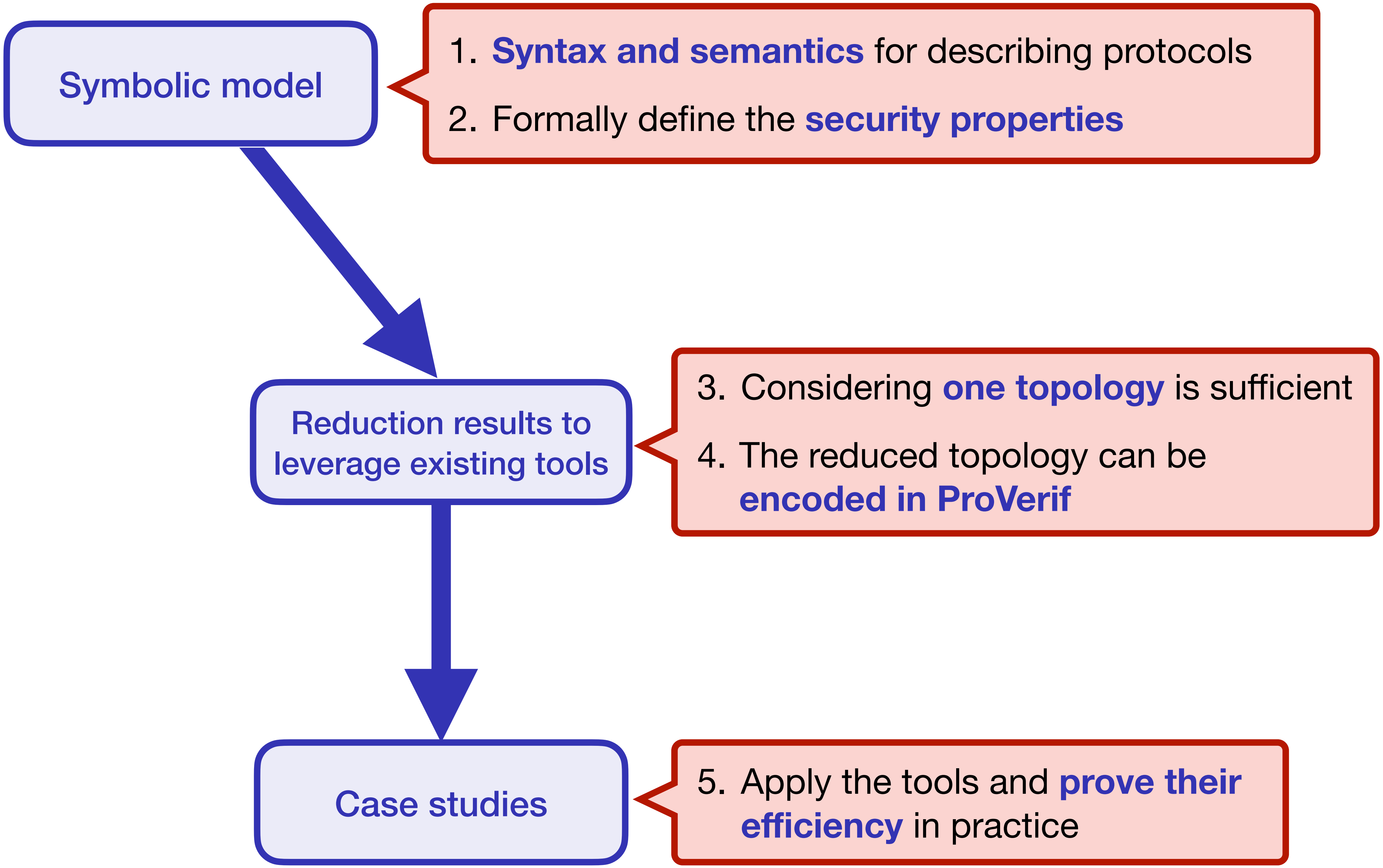
tool limitation

Application to real-world protocols

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

Conclusion

Finally we have…



Symbolic model

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

Reduction results to leverage existing tools

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

Case studies

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

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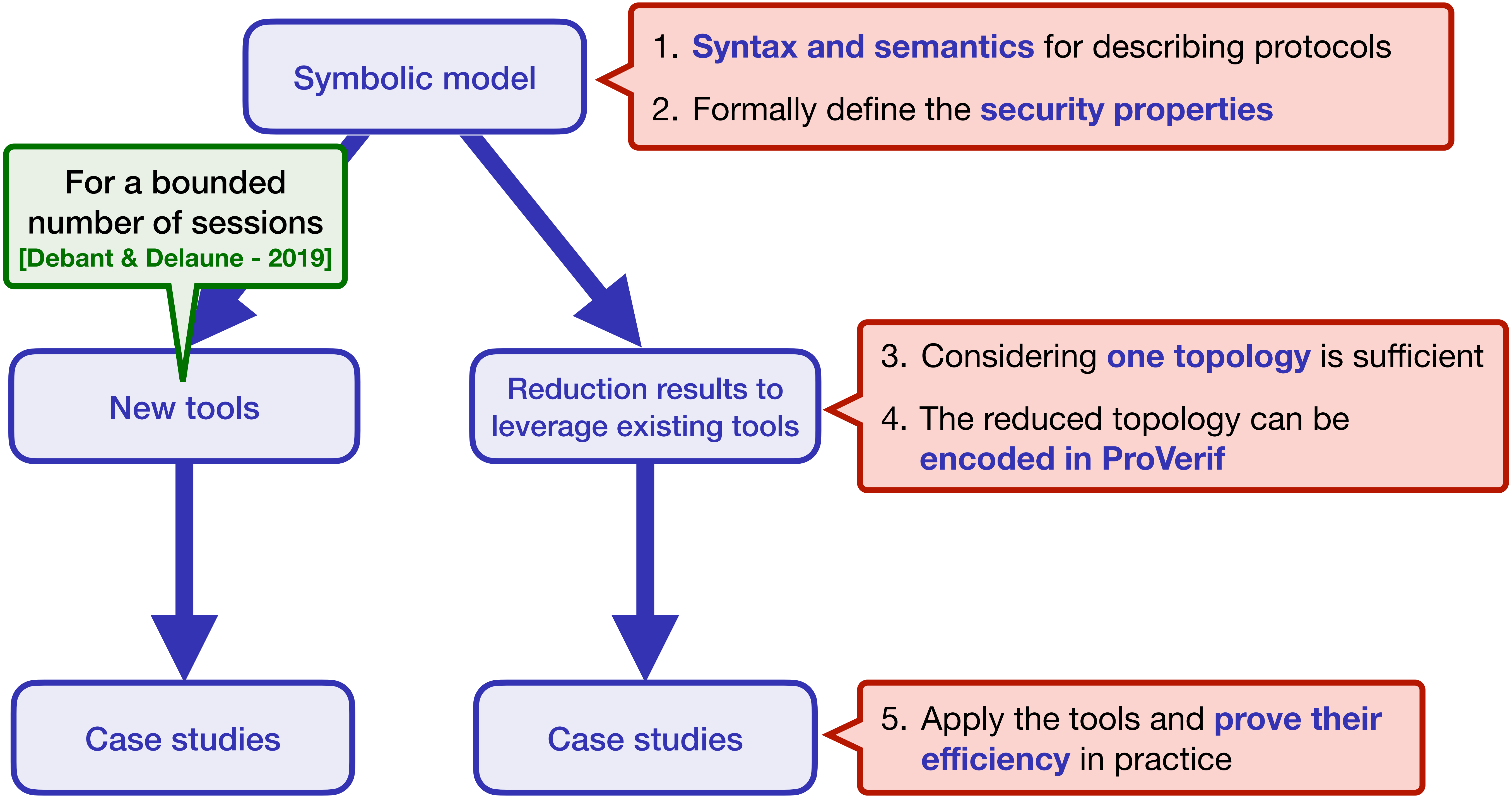

Symbolic model

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

For a bounded number of sessions **[Debant & Delaune - 2019]**

New tools

Reduction results to leverage existing tools

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Case studies

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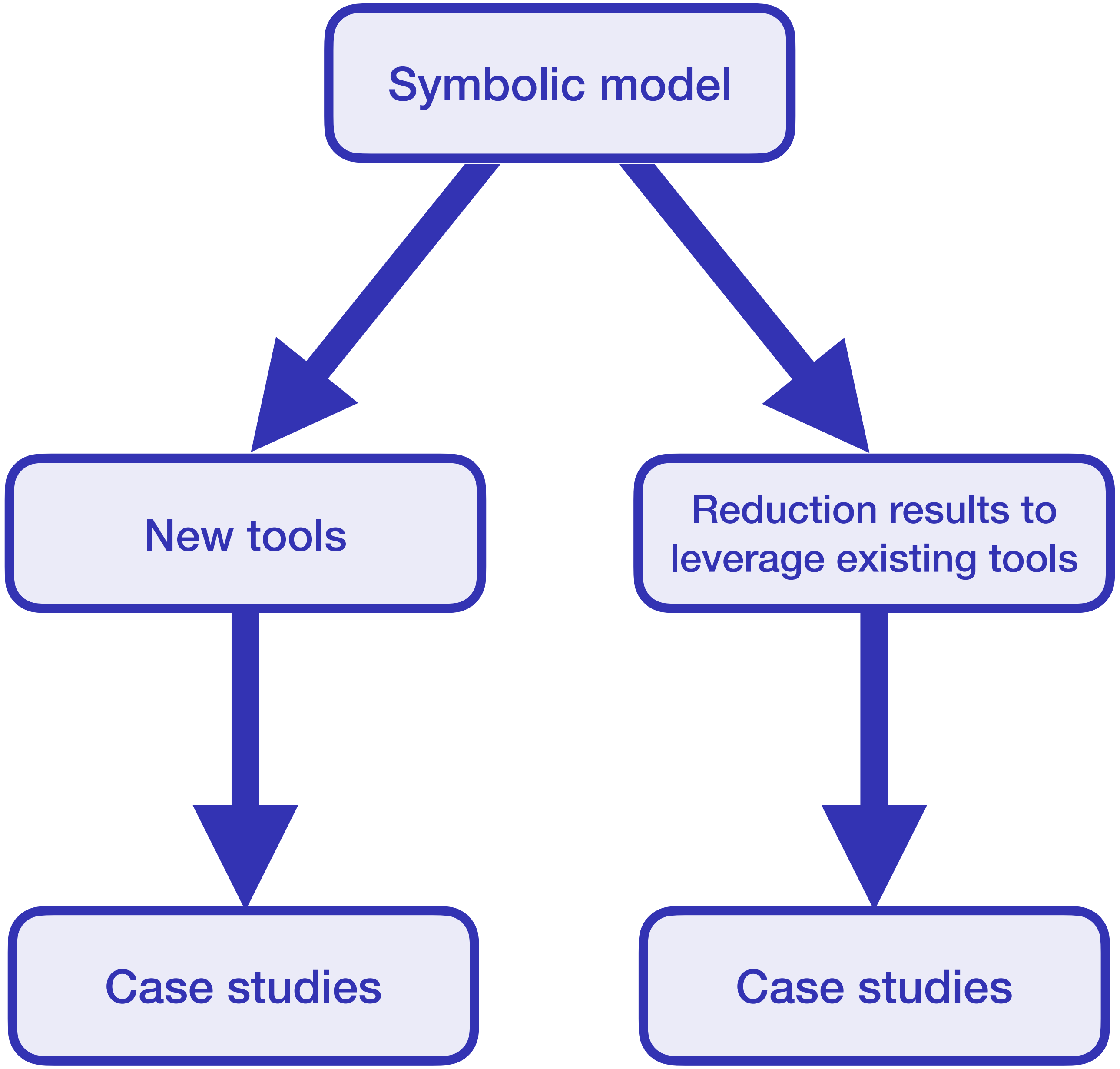
5. Apply the tools and **prove their efficiency** in practice

Future work

Remove hypotheses in the theorems



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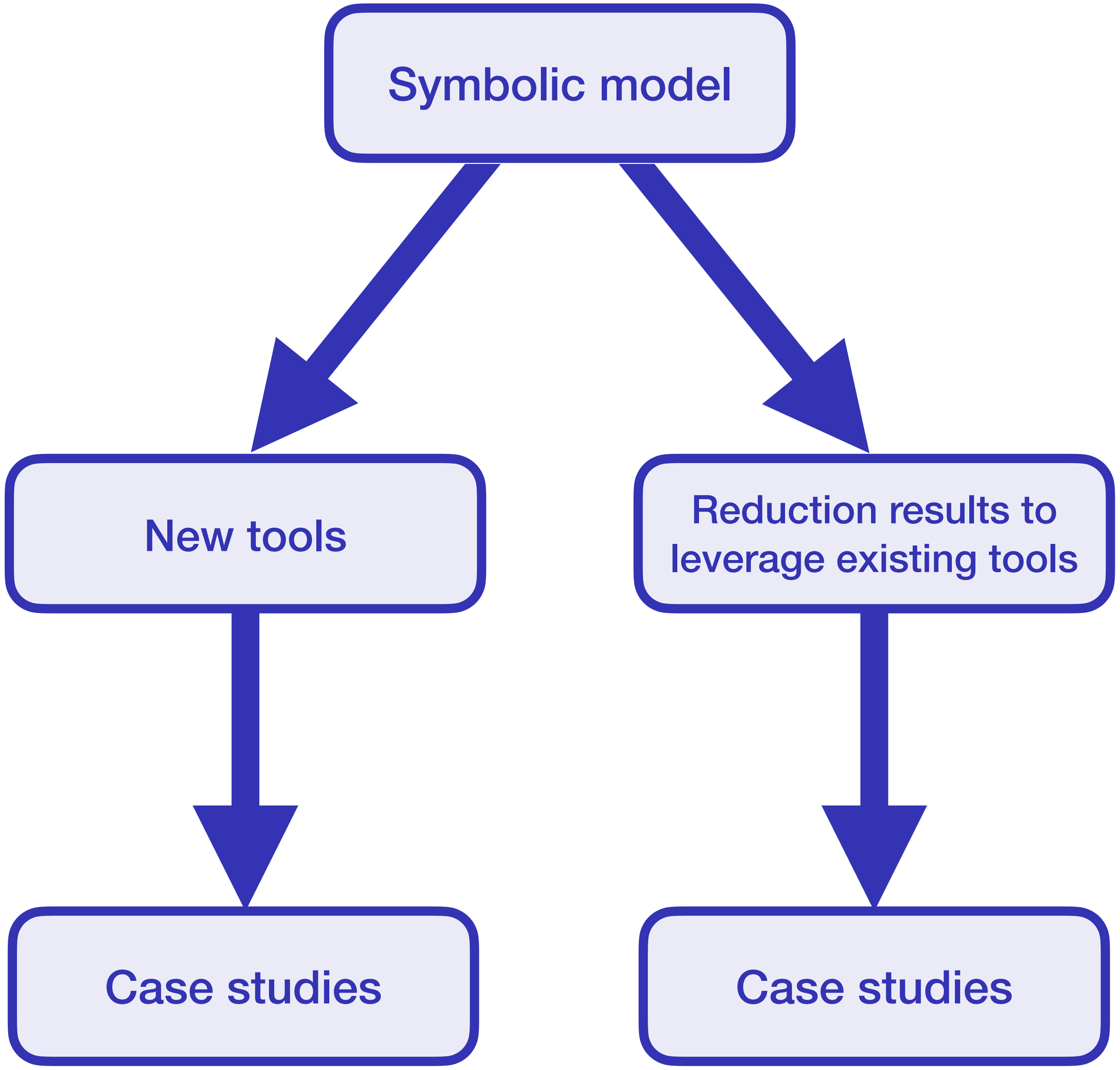
- improve automation for Tamarin



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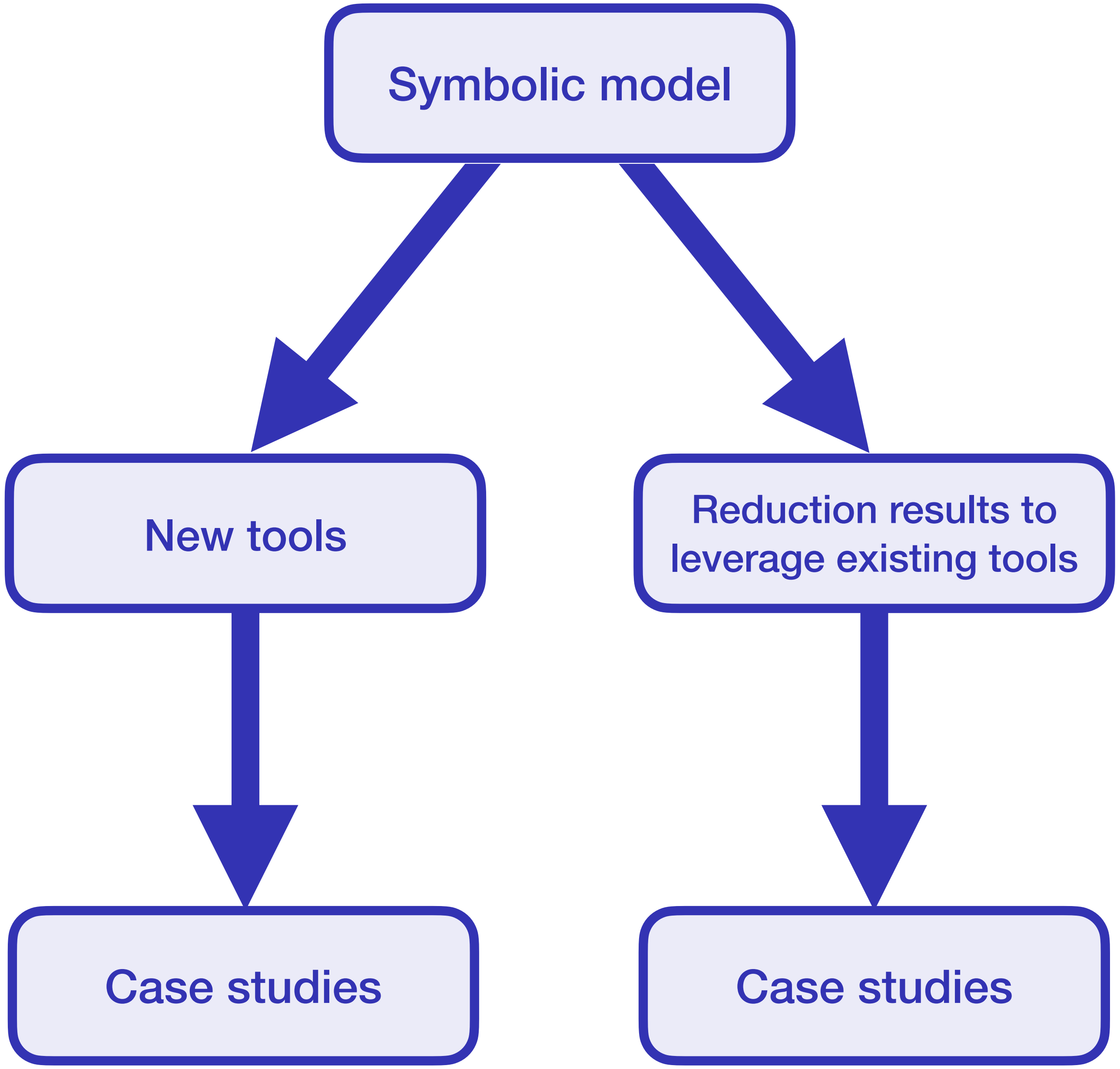

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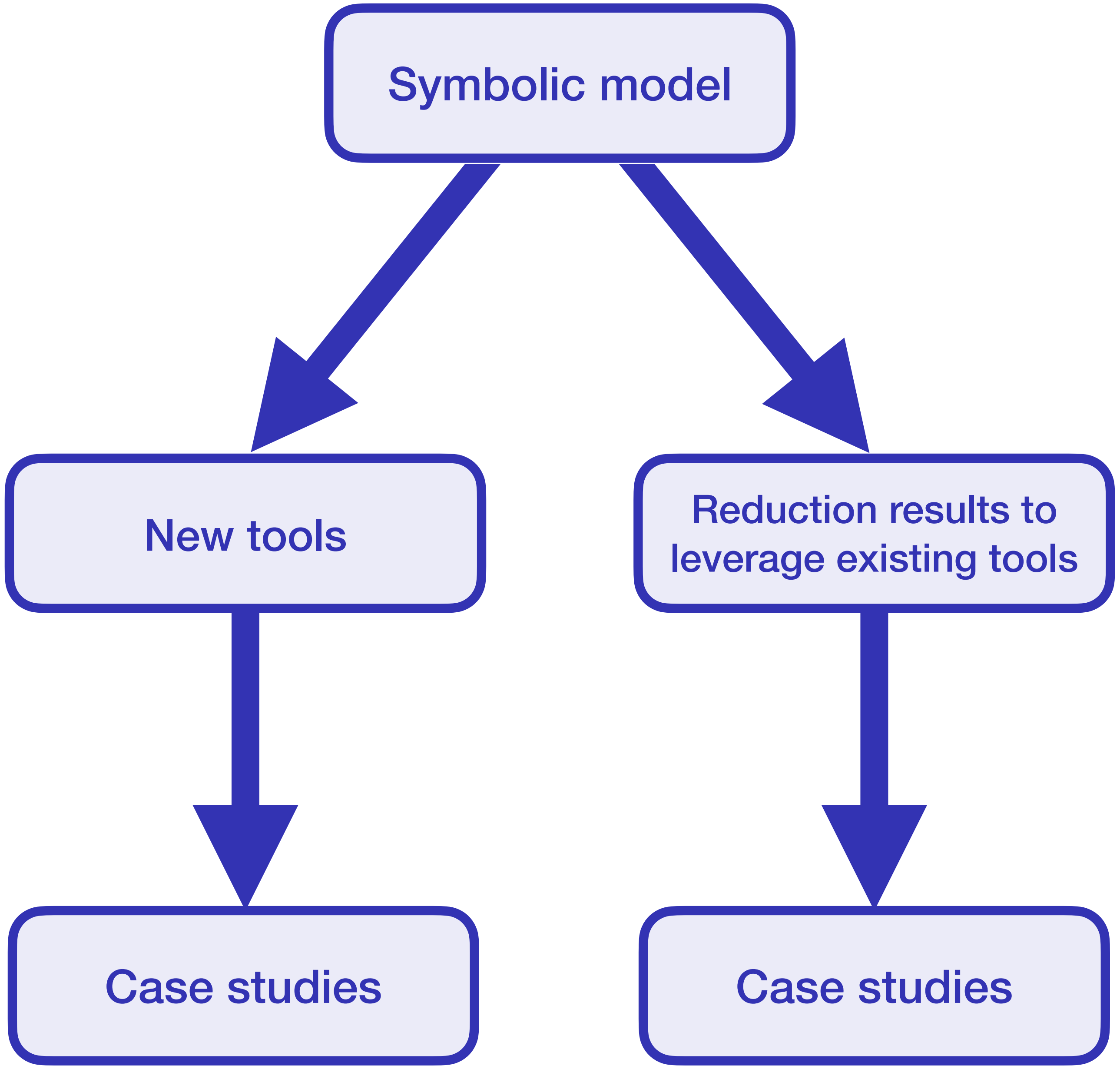
Model bit-level operations

- consider probabilistic processes and properties
- model messages with bitstrings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