Proving physical proximity using symbolic models

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Symbolic verification

Advantages:

- automated proofs
- efficient tools exist: ProVerif, Tamarin, Avispa...
- can express many security properties (authentication, secrecy, untraceability...)

But: cannot express physical proximity !
omniscient and ubiquitous attacker

How can we handle it?

Table of contents

Term algebra

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

Example

- Names: $\mathcal{N} = \{a, n, k\}$
- Signature: $\Sigma = \{senc, sdec, pair, proj_1, proj_2, \oplus\}$

$$x \oplus 0 = x \qquad (x \oplus y) \oplus z = x \oplus (y \oplus z)$$
$$x \oplus x = 0 \qquad x \oplus y = y \oplus x$$

$$sdec(senc(x, y), y) \to x \qquad proj_1(pair(x, y)) \to x$$
$$proj_2(pair(x, y)) \to y$$

We have that: $sdec(senc(n \oplus 0), k), k)\downarrow =_E n$

Process algebra

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

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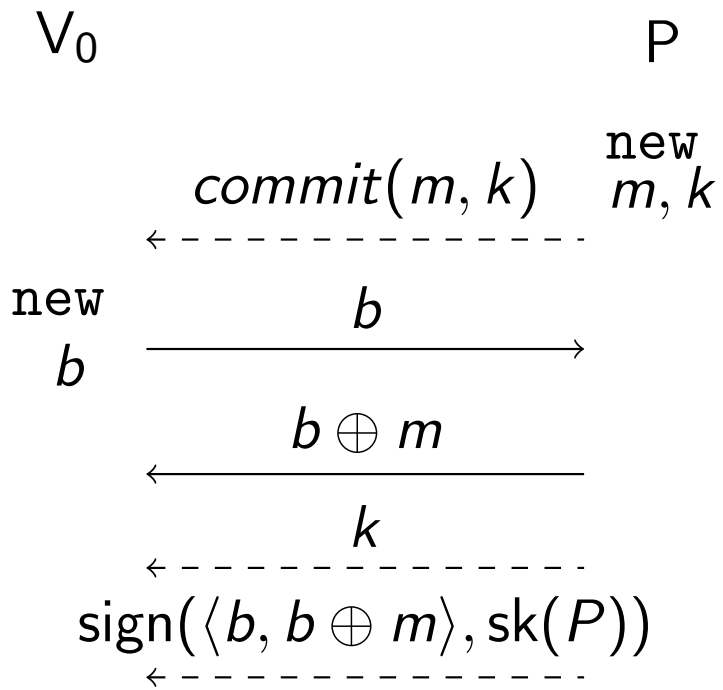
Protocol

A protocol is a set of roles $(\Pi_1, \cdots, \Pi_k)$ describing the behaviour of each honest agents.

Example: Brands and Chaum - 1993



Brands and Chaum

Example: Brands and Chaum - 1993

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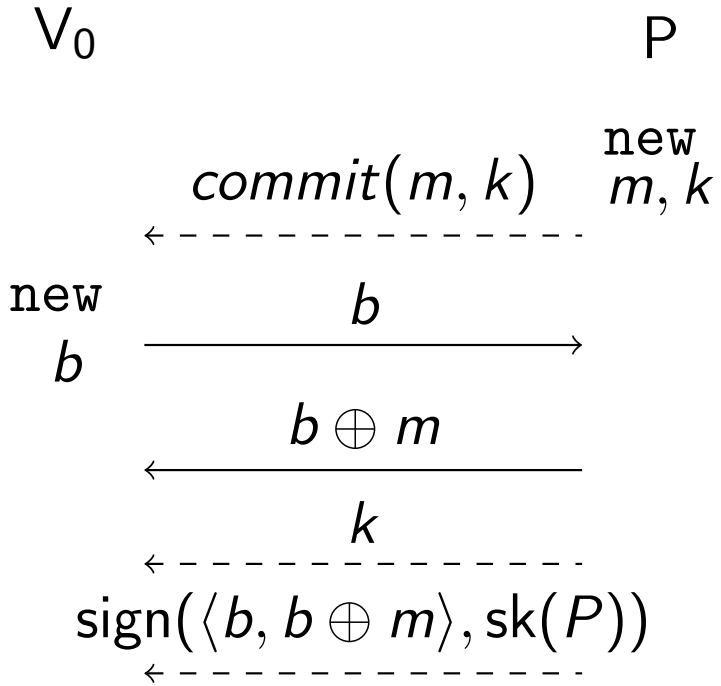
&V(z_V, z_P) := \\
&\quad \mathtt{in}(y_c).\mathtt{new}\ b. \\
&\quad \mathtt{reset}.\mathtt{out}(b).\mathtt{in}^{<2\times t_0}(y_0). \\
&\quad \mathtt{in}(y_k).\mathtt{in}(y_{\mathsf{sign}}). \\
&\quad \mathtt{let}\ y_m = \mathsf{open}(y_c, y_k)\ \mathtt{in} \\
&\quad \mathtt{let}\ y_{msg} = \mathsf{getmsg}(y_{\mathsf{sign}})\ \mathtt{in} \\
&\quad \mathtt{let}\ y_{\mathsf{check}} = \mathsf{check}(y_{\mathsf{sign}}, \mathsf{vk}(z_P))\ \mathtt{in} \\
&\quad \mathtt{let}\ y_{\mathsf{eq}} = \mathsf{eq}(\langle b, b \oplus y_m \rangle, y_{msg})\ \mathtt{in} \\
&\quad 0
\end{aligned}
$$



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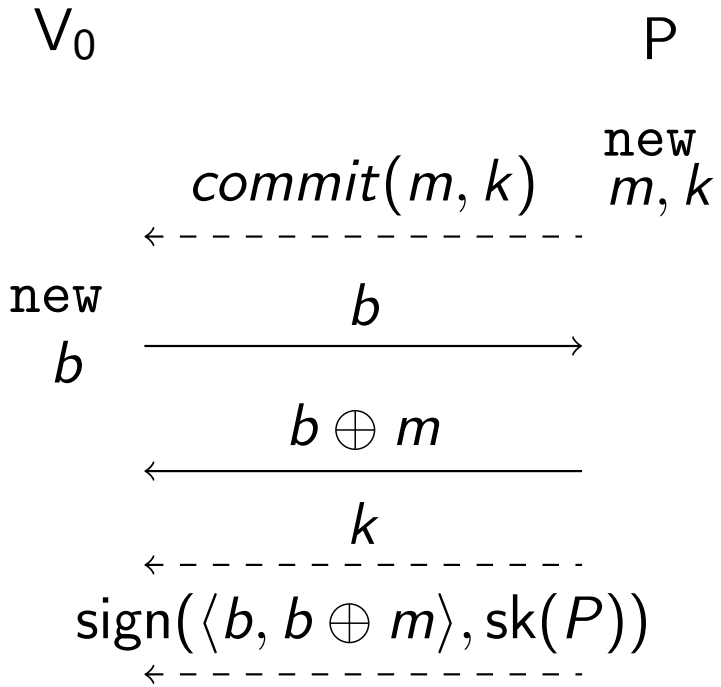

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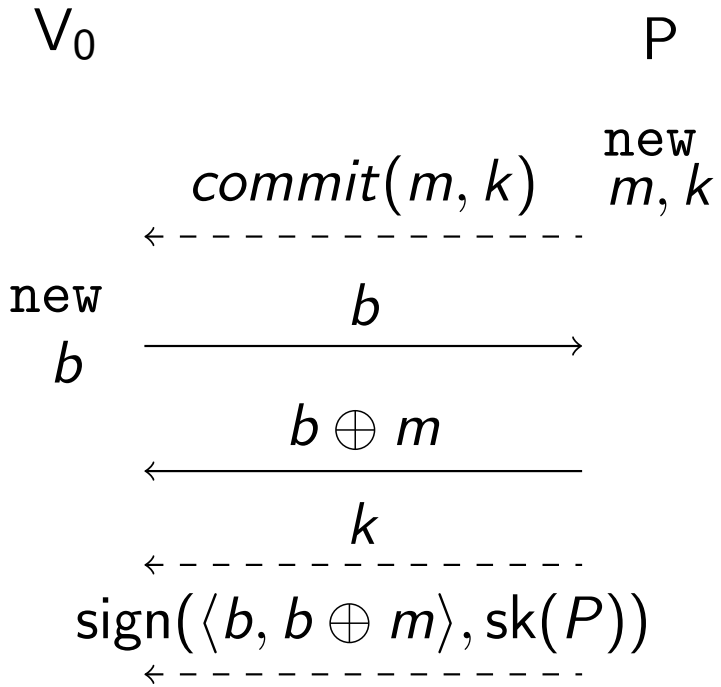

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Topology

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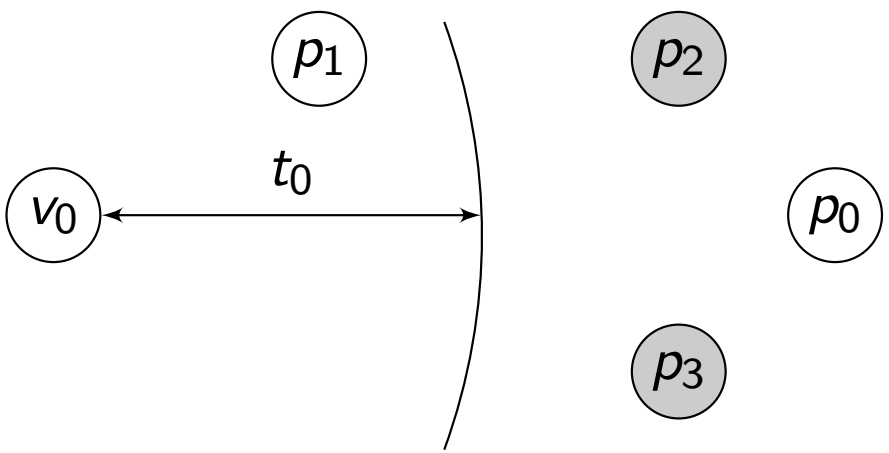

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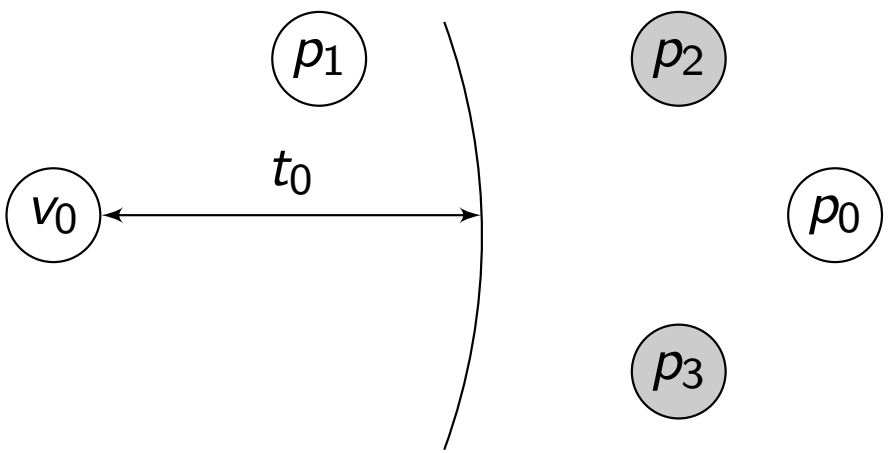

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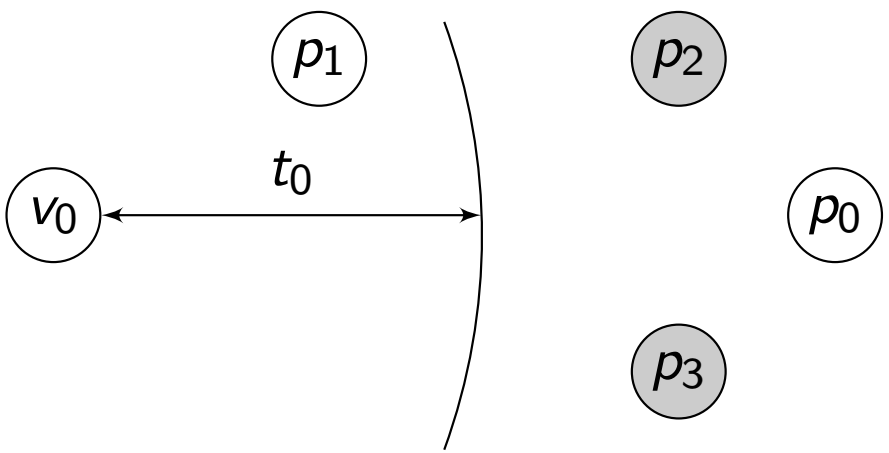

We define $\mathrm{Dist}_{\mathcal{T}}(a, b) = \frac{\|\mathrm{Loc}(a) - \mathrm{Loc}(b)\|}{c}$

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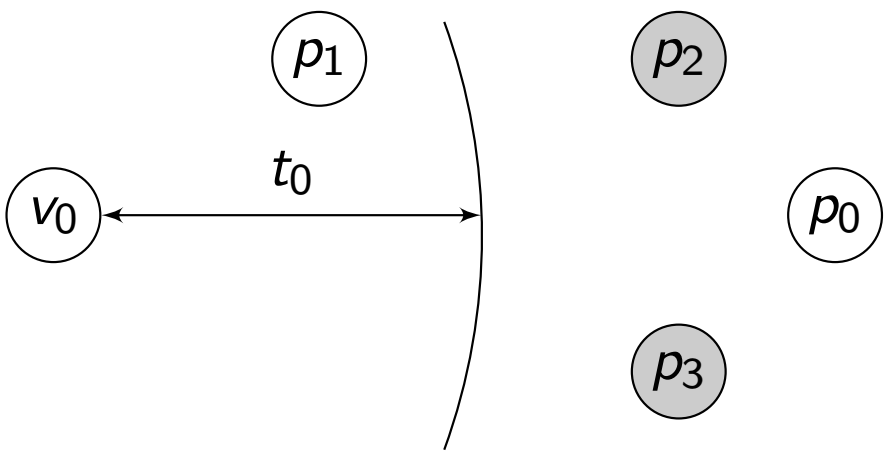
agents locations dishonest agents



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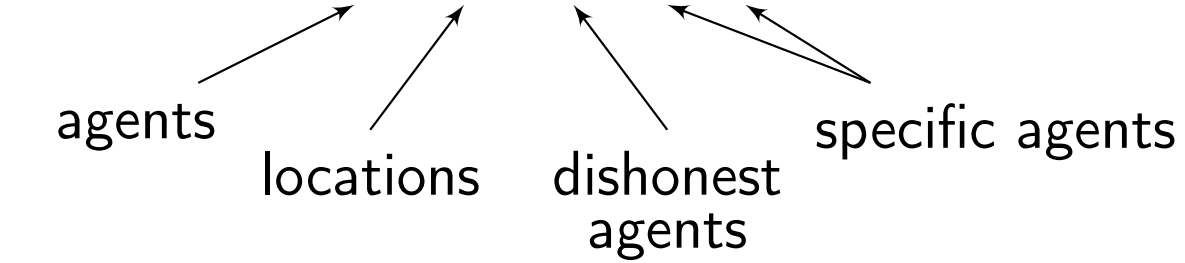

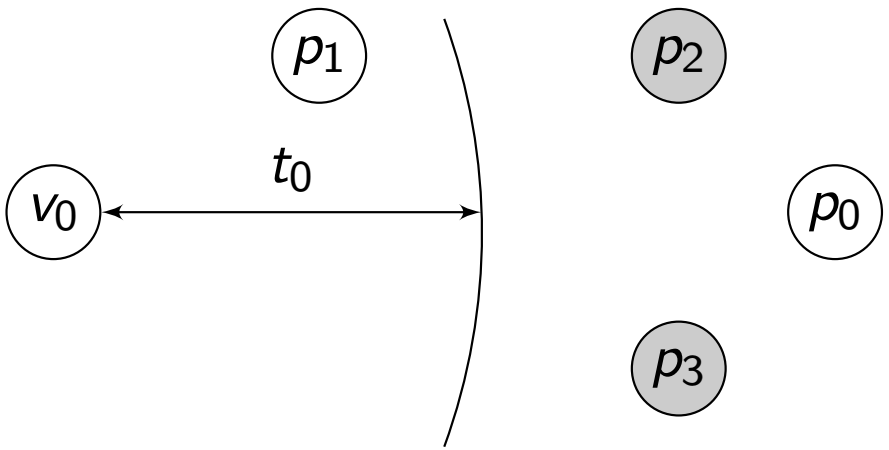

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Configuration and semantics

A **configuration** is a tuple $(\mathcal{P}; \Phi; t)$ where:

- $\mathcal{P}$ is a multiset of $\lfloor P \rfloor_a^{t_a}$ with $a \in \mathcal{A}$ and $t_a \in \mathcal{R}_+$
- $\Phi = \{\mathsf{w}_1 \xrightarrow{a_1, t_1} m_1, \cdots, \mathsf{w}_n \xrightarrow{a_n, t_n} m_n\}$ is a frame
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OUT $\quad (\lfloor \mathtt{out}(u).P \rfloor_a^{t_a}) \uplus \mathcal{P}; \Phi; t) \xrightarrow{a,\mathtt{out}(u)}_{\mathcal{T}_0} (\lfloor P \rfloor_a^{t_a} \uplus \mathcal{P}; \Phi'; t)$
with $\Phi' = \Phi \cup \{w \xrightarrow{a,t} u\}$

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if u is deducible from Φ

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if $\exists b \in \mathcal{A}, t_b \in \mathcal{R}_+$ such that $t_b \leq t - \mathrm{Dist}_{\mathcal{T}}(b, a)$ and:

- if $b \notin \mathcal{M}$ then $u \in img(\lfloor \Phi \rfloor_b^{t_b})$
- if $b \in \mathcal{M}$ then u is deducible from $\bigcup_{c \in \mathcal{A}} \lfloor \Phi \rfloor_c^{t_b - \mathrm{Dist}_{\mathcal{T}}(c,b)}$

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Moreover if $\star =< t_g$ then $t_a < t_g$.

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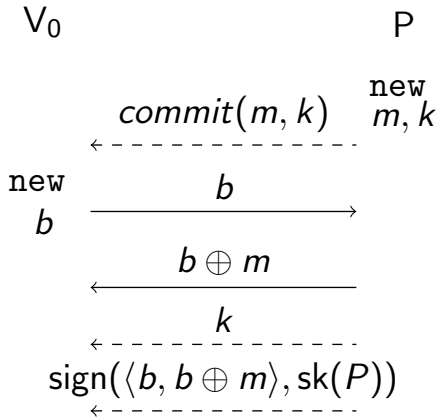
TIME $(\mathcal{P}; \Phi; t) \longrightarrow_{\mathcal{T}} (\mathcal{P}'; \Phi; t')$ with:

- $t' > t$
- $\mathcal{P}' = \{ \lfloor P \rfloor_a^{t_a + (t' - t)} \mid \lfloor P \rfloor_a^{t_a} \in \mathcal{P} \}$

Example: Brands and Chaum - 1993

$K_0 = (\lfloor V(v_0, p_0) \rfloor^0_{v_0} \uplus \lfloor P(p) \rfloor^0_p ; \Phi_0; 0)$ with

$\Phi_0 = \{w_1 \xrightarrow{p_0,0} sk(p_0)\}$



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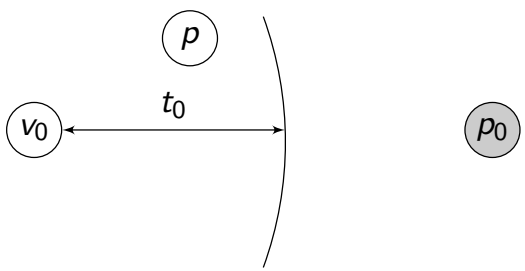

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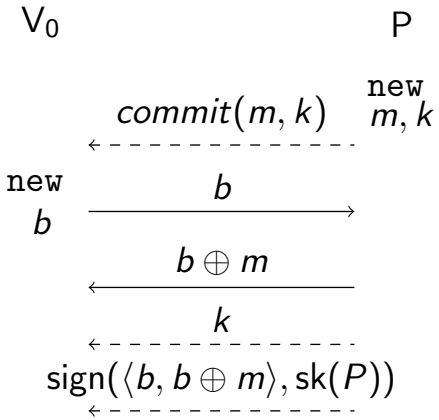
Execution of the protocol:

K_0



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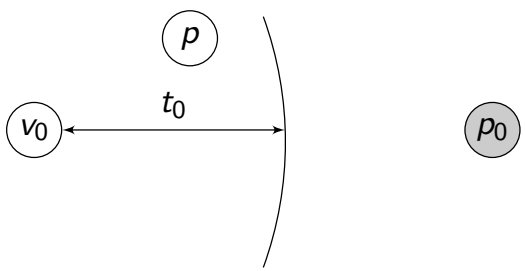

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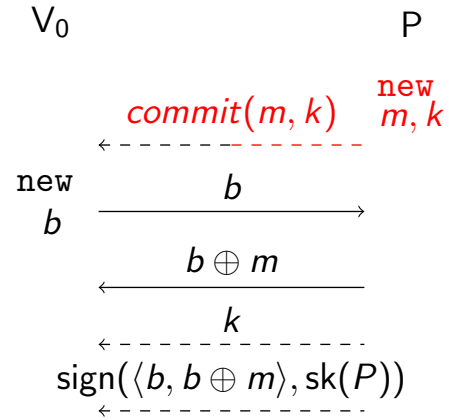
Execution of the protocol:

$$K_0 \xrightarrow{p,\tau} \mathcal{T}_0 \xrightarrow{p,\tau} \mathcal{T}_0 \xrightarrow{p,\mathtt{out}(\mathtt{commit}(m,k))} \mathcal{T}_0$$



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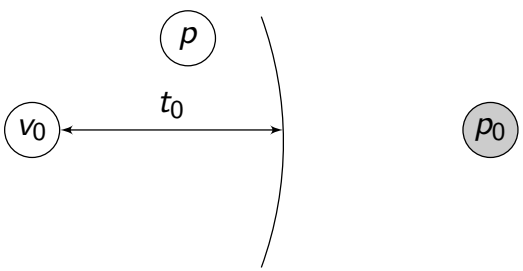

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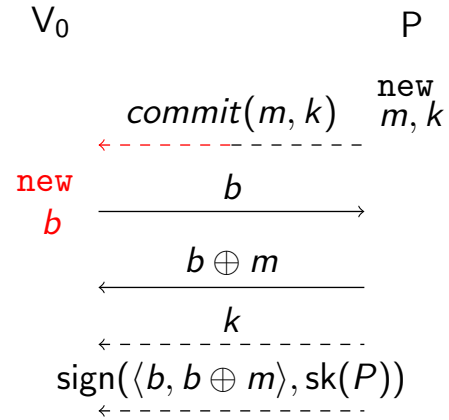
$$K_0 \xrightarrow{p,\tau} \mathcal{T}_0 \xrightarrow{p,\tau} \mathcal{T}_0 \xrightarrow{p,\mathtt{out}(\mathsf{commit}(m,k))} \mathcal{T}_0 \rightarrow \mathcal{T}_0 \xrightarrow{v_0,\mathtt{in}(\mathsf{commit}(m,k))} \mathcal{T}_0 \xrightarrow{v_0,\tau} \mathcal{T}_0$$



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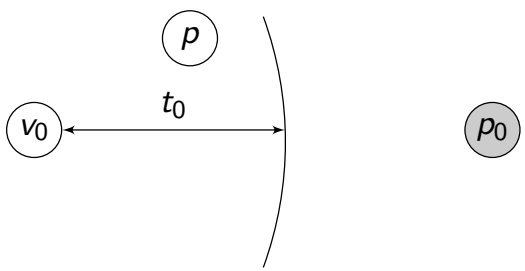

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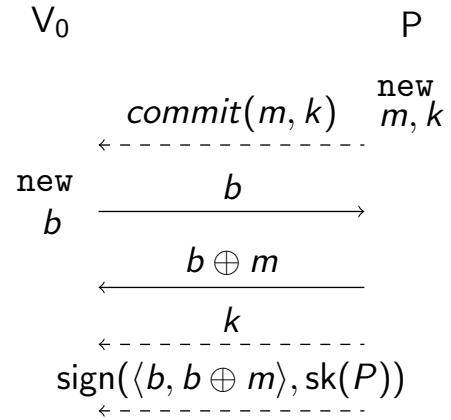
with:

- $\mathcal{P}_1 = \lfloor V_1 \rfloor_{v_0}^{0} \uplus \lfloor P_1 \rfloor_{p}^{\delta_0}$
- $\Phi_1 = \{w_1 \xrightarrow{p_0,0} sk(p_0),\ w_2 \xrightarrow{p,0} \mathsf{commit}(m,k)\}$



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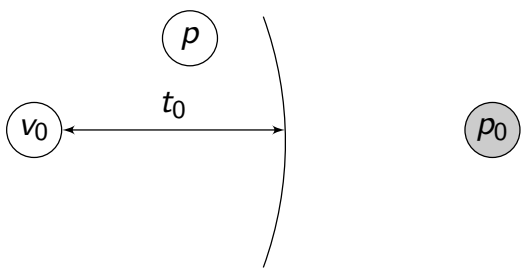


Security property: physical proximity

t_0-proximity

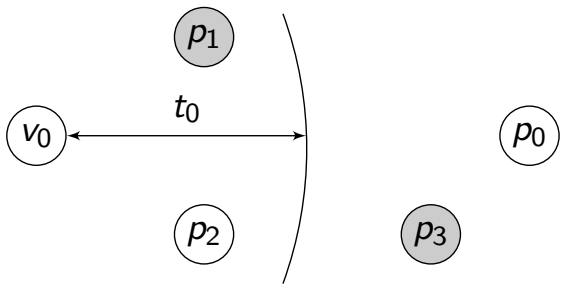
A protocol $\mathcal{P}_{prox}$ ensures t_0-proximity w.r.t. a topology $\mathcal{T} = (\mathcal{A}, \mathsf{Loc}, \mathcal{M}, v_0, p_0)$ and a configuration K if:

$$K \xrightarrow{tr}_{\mathcal{T}} (\lfloor \mathsf{end}(v_0, p_0) \rfloor_{v_0}^{t_{v_0}}; \Phi; t) \Rightarrow \mathsf{Dist}_{\mathcal{T}}(v_0, p_0) < t_0.$$

Classes of attacks

Mafia frauds - $\mathcal{C}_{\mathbf{MF}}$

(v_0 and p_0 are honest)



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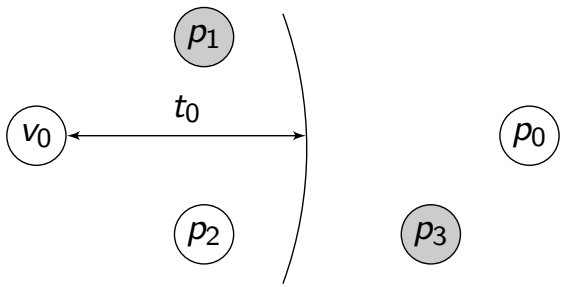
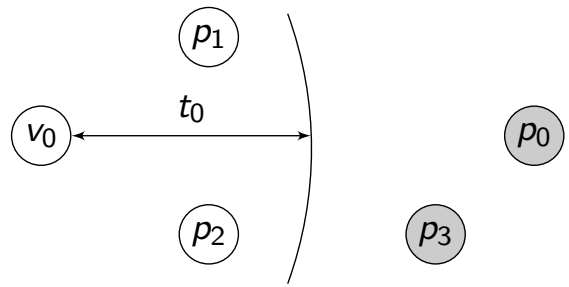


Distance hijacking - $\mathcal{C}_{\mathbf{DH}}$
(no dishonest agents close to v_0)



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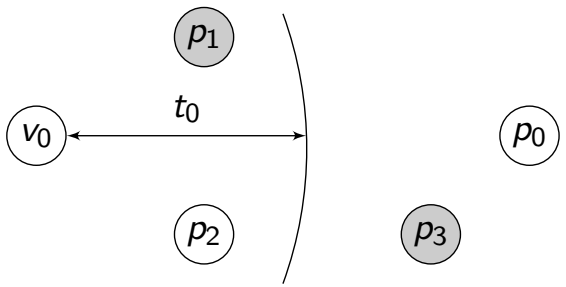

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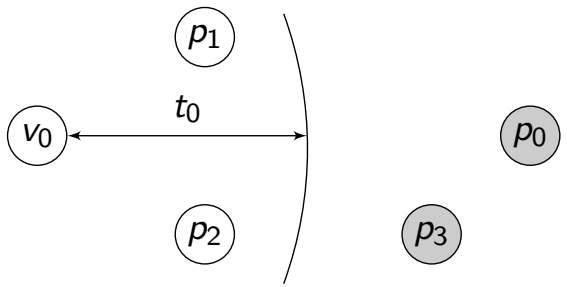
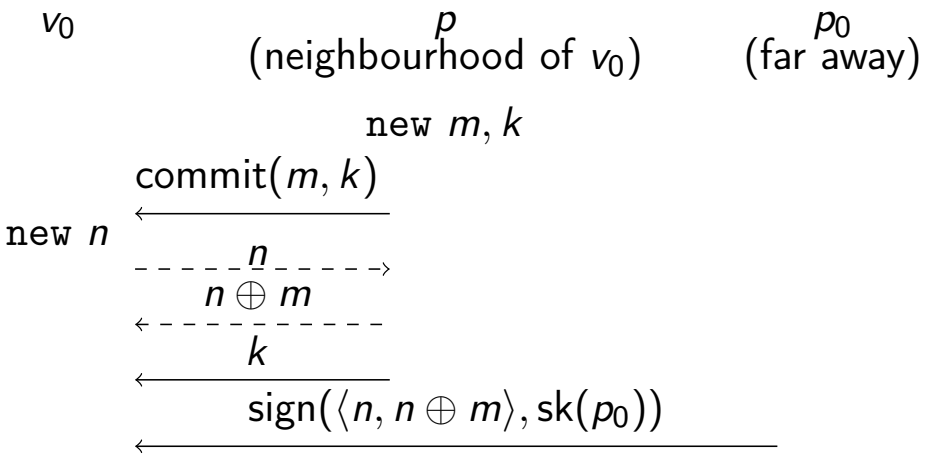


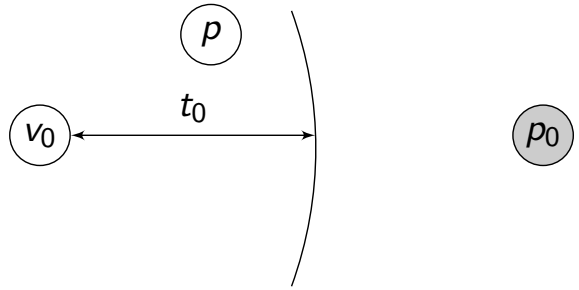
Mafia frauds (resp. Distance hijacking attacks)

A protocol $\mathcal{P}_{prox}$ is resistant against Mafia frauds (resp. Distance hijacking attacks) if for all topologies $\mathcal{T} \in \mathcal{C}_{\mathsf{MF}}$ (resp. $\mathcal{C}_{\mathsf{DH}}$) and initial configurations K:

$$K \xrightarrow{tr}_{\mathcal{T}} (\lfloor \mathsf{end}(v_0, p_0) \rfloor_{v_0}^{t_{v_0}}; \Phi; t) \Rightarrow \mathsf{Dist}_{\mathcal{T}}(v_0, p_0) < t_0.$$

Example: Brands and Chaum - 1993





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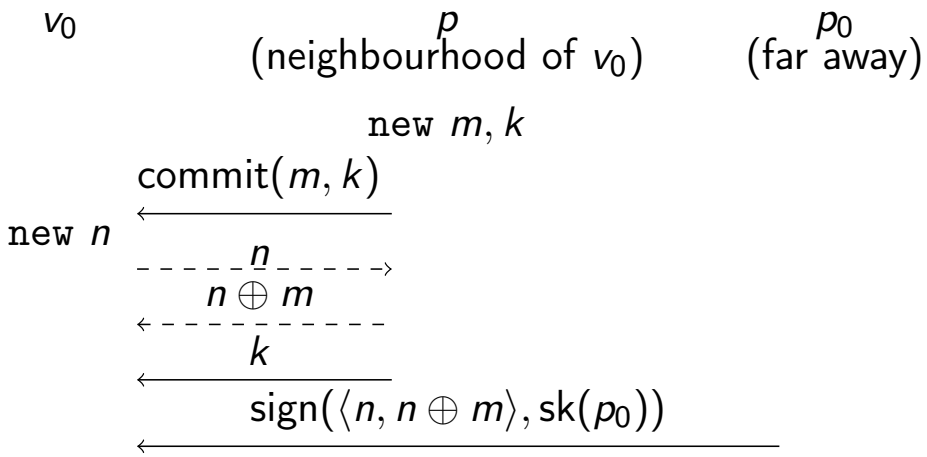

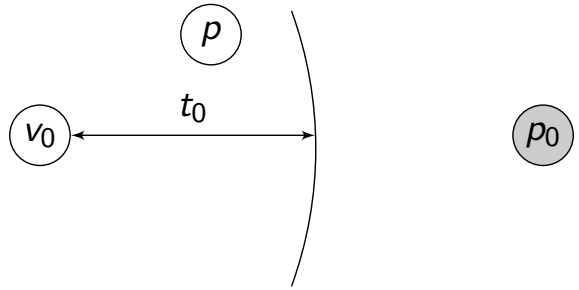

Trace of execution:

$$K_0 \xrightarrow{tr}{}^{*}_{\mathcal{T}} \left(\lfloor V_1 \rfloor^{0}_{v_0} \uplus \lfloor P_1 \rfloor^{\delta_0}_{p} ; \Phi_1; \delta_0 \right)$$

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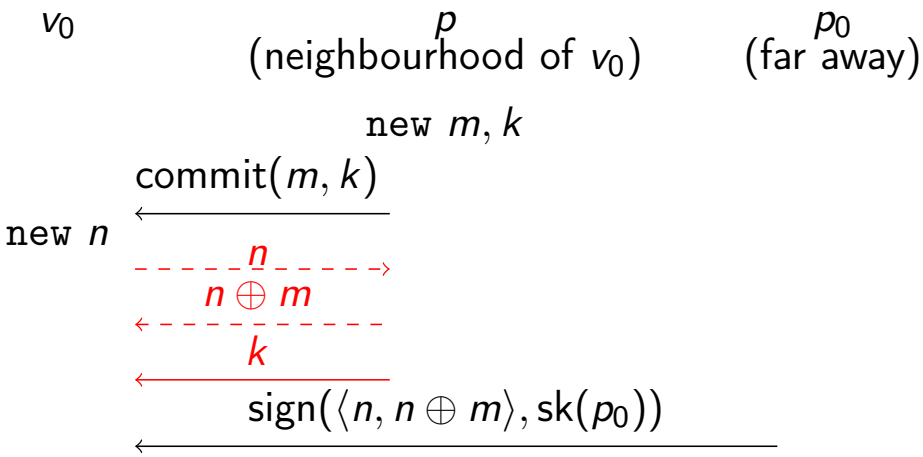

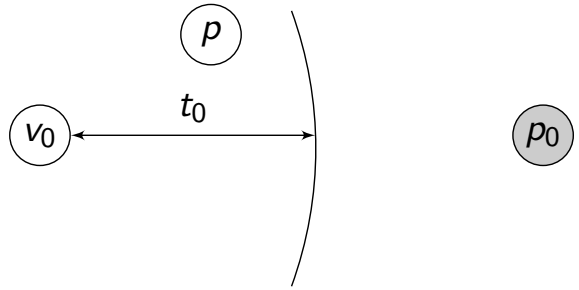

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$$\xrightarrow{v_0,\mathtt{out}(n)} \mathcal{T}_0 \rightarrow \mathcal{T}_0 \xrightarrow{p,\mathtt{in}(n')} \mathcal{T}_0$$

$$\xrightarrow{p,\mathtt{out}(n\oplus m)} \mathcal{T}_0 \xrightarrow{p,\mathtt{out}(k)} \mathcal{T}_0 \rightarrow \mathcal{T}_0 \xrightarrow{v_0,\mathtt{in}^{<2\times t_0}(n\oplus m)} \mathcal{T}_0 \xrightarrow{v_0,\mathtt{in}(k)} \mathcal{T}_0$$

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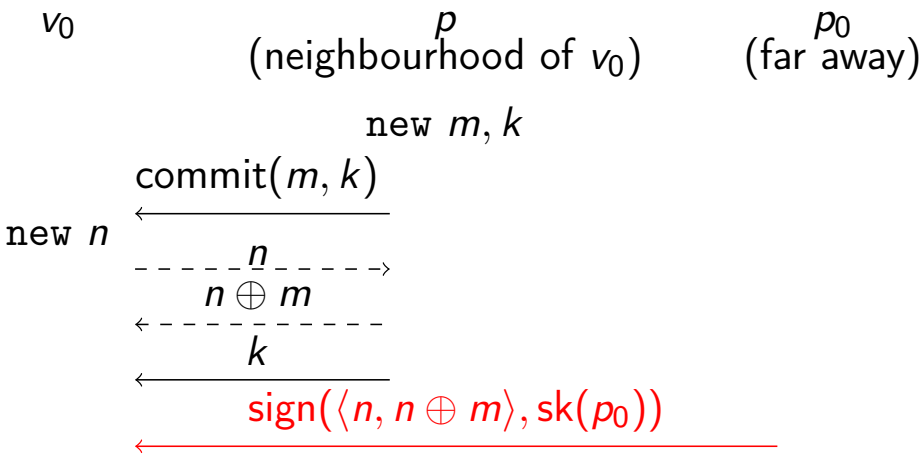

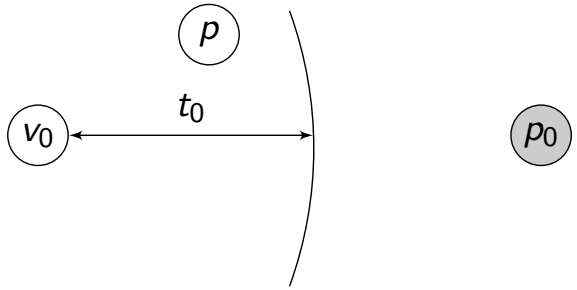

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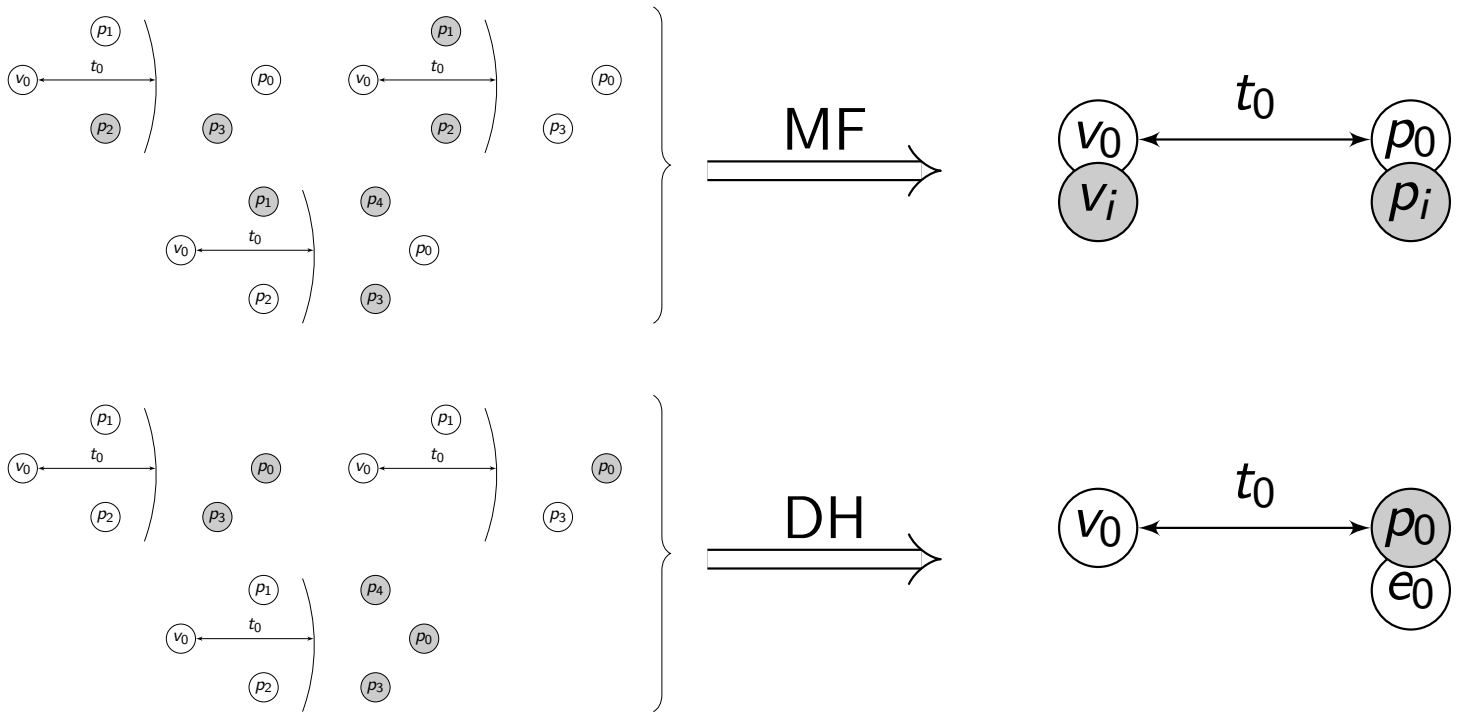
$$\rightarrow \mathcal{T}_0 \xrightarrow{v_0,\mathtt{in}(\mathsf{sign}(\langle n, n\oplus m\rangle, \mathsf{sk}(p_0)))} \mathcal{T}_0$$

$$\left(\lfloor P_2 \rfloor^{3\delta_0+2\delta'_0}_{p} \uplus \lfloor \mathsf{end}(v_0, p_0) \rfloor^{2\delta_0+2\delta'_0}_{v_0} ; \Phi; 3\delta_0 + 2\delta'_0 \right)$$

Table of contents

Reduction results

Only one topology is sufficient !

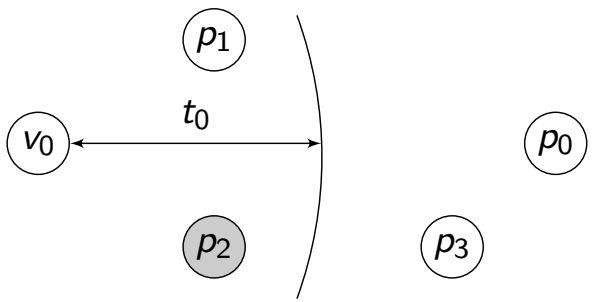


Mafia fraud attacks

Theorem

Let $\mathcal{P}_{prox}$ be an **executable** protocol.
$\mathcal{P}_{\text{prox}}$ admits a Mafia fraud attack w.r.t. t_0-proximity, if and only if, there is an attack against t_0-proximity in the topology $\mathcal{T}_{\text{MF}}$.

Sketch of proof:



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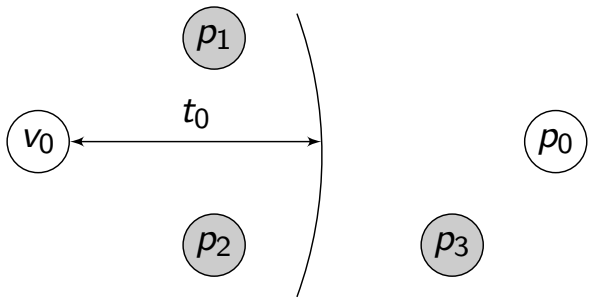

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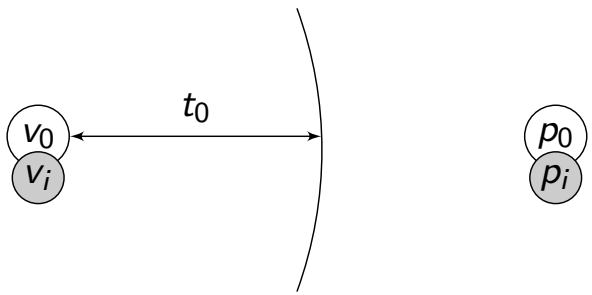

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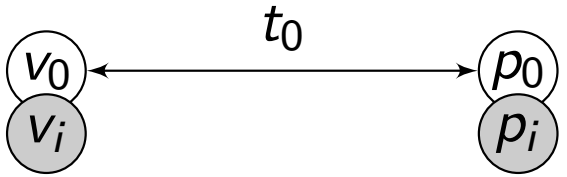

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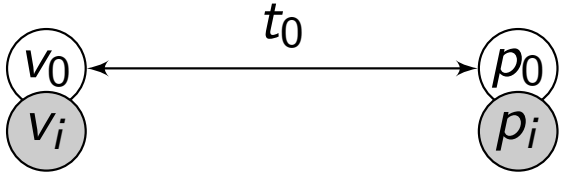


Remark. This proof cannot be adapted for distance hijacking attacks !

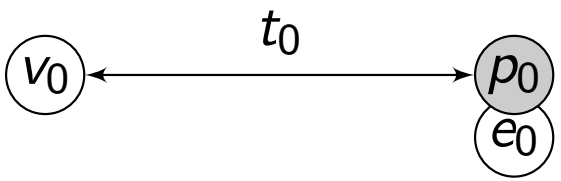
Distance hijacking attacks

Theorem

Let $\mathcal{P}_{prox}$ be a protocol such that the Verifier role respects the following grammar:

$$P, Q := \mathsf{end}(z_0, z_1) \mid \mathtt{in}(x).P \mid \mathtt{let}\ x = v\ \mathtt{in}\ P \mid \mathtt{new}\ n.P \mid \mathtt{out}(u).P \mid \mathtt{reset.out}(u').\mathtt{in}^{<t}(x).P$$

If $\mathcal{P}_{\mathsf{prox}}$ admits a Distance hijacking attack w.r.t. t_0-proximity, then $\overline{\mathcal{P}_{\mathsf{prox}}}$ admits an attack against t_0-proximity in the topology $\mathcal{T}_{\mathsf{DH}}$.



$\mathcal{T}_{\mathsf{DH}}$

In $\overline{\mathcal{P}_{\mathsf{prox}}}$ we only keep guards computed by v_0.

Table of contents

ProVerif [Blanchet, 01]

ProVerif is a verifier tool for cryptographic protocols.

http://proverif.inria.fr/

Advantages:

- fully automated
- can model many cryptographic primitives
- handles an unbounded number of sessions
- can model protocols defined by phases (*e.g.* e-voting)

Issues:

- termination not guaranteed
- can answer *"cannot be proved"*
- no time and locations

Phases in ProVerif

Common use: model protocols defined by steps (*e.g.* e-voting) and security properties (*e.g.* forward secrecy).

Process algebra: $P := 0 \mid \mathtt{new}\ n.P \mid \mathtt{let}\ x = v\ \mathtt{in}\ P \mid \mathtt{out}(u).P \mid \mathtt{in}(x).P \mid !\,P \mid i : P$

The semantics is extended with:

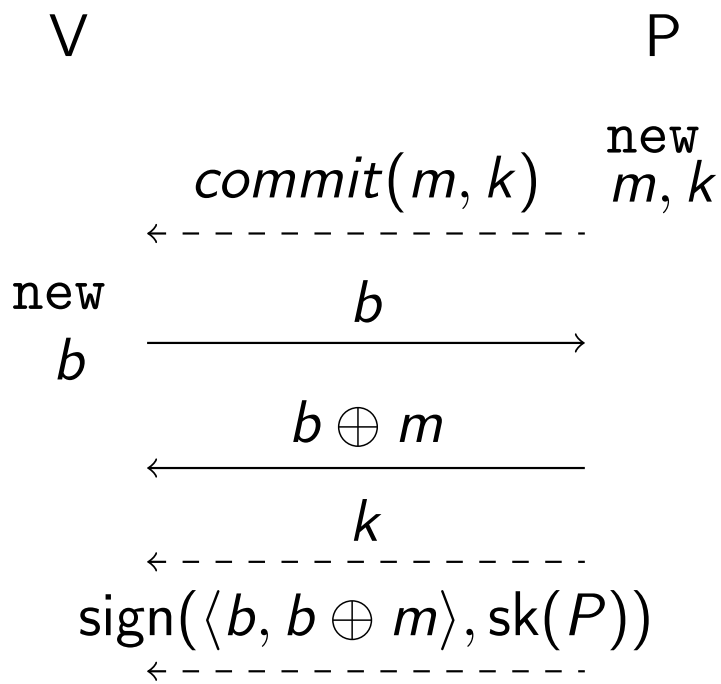
$$(\mathcal{P}; \phi; i) \xrightarrow{\text{phase } i'} (\mathcal{P}; \phi; i') \quad \text{with } i' > i.$$

$$(i : \mathtt{out}(u).P \uplus \mathcal{P}; \phi; i) \xrightarrow{\mathtt{out}(u)} (i : P \uplus \mathcal{P}; \phi \uplus \{\mathsf{w} \to u\}; i)$$

Example: $\mathcal{P} := \{0 : out(n_0).1 : out(n_1);\ 0 : in(x_0).1 : in(x_1)\}$

Translation into ProVerif
$Transf(\mathcal{T}, \mathcal{P}, t_0)$

$V_0(v_0, p_0) :=$
$\quad \mathtt{in}(y_c).\mathtt{new}\ b.$
$\quad \mathtt{reset}.\mathtt{out}(b).\mathtt{in}^{<2\times t_0}(y_0).$
$\quad \mathtt{in}(y_k).\mathtt{in}(y_{\mathsf{sign}}).$
$\quad \mathtt{let}\ y_m = \mathsf{open}(y_c, y_k)\ \mathtt{in}$
$\quad \mathtt{let}\ y_{msg} = \mathsf{getmsg}(y_{\mathsf{sign}})\ \mathtt{in}$
$\quad \mathtt{let}\ y_{\mathsf{check}} = \mathsf{check}(y_{\mathsf{sign}}, \mathsf{vk}(z_P))\ \mathtt{in}$
$\quad \mathtt{let}\ y_{\mathsf{eq}} = \mathsf{eq}(\langle b, b \oplus y_m \rangle, y_{msg})\ \mathtt{in}$
$\quad \mathsf{end}(z_V, z_P).$
$\quad 0$



Brands and Chaum

Translation into ProVerif
$Transf(\mathcal{T}, \mathcal{P}, t_0)$

$\overline{V_0}(v_0, p_0) :=$
$\mathtt{in}(y_c).\mathtt{new}\ b.$
$1 : \mathtt{out}(b).\mathtt{in}(y_0).$
$2 : \mathtt{in}(y_k).\mathtt{in}(y_{\mathsf{sign}}).$
$\mathtt{let}\ y_m = \mathsf{open}(y_c, y_k)\ \mathtt{in}$
$\mathtt{let}\ y_{msg} = \mathsf{getmsg}(y_{\mathsf{sign}})\ \mathtt{in}$
$\mathtt{let}\ y_{\mathsf{check}} = \mathsf{check}(y_{\mathsf{sign}}, \mathsf{vk}(z_P))\ \mathtt{in}$
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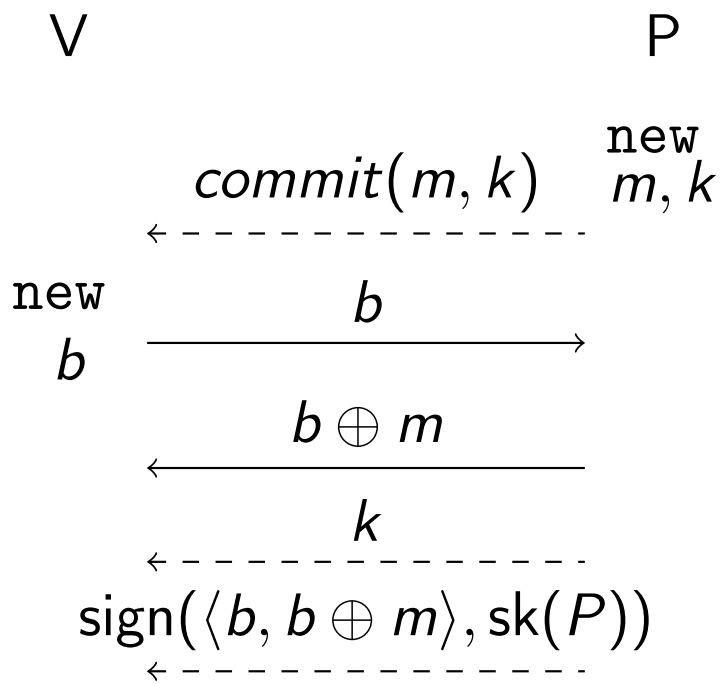


Brands and Chaum

Translation into ProVerif
$Transf(\mathcal{T}, \mathcal{P}_{\text{prox}}, t_0)$

Given a process P we define:

- $P^{<}$: all the possible ways of spitting P in the phases 0, 1 and 2
- $P^{\geq}$: all the possible ways of spitting P in the phases 0 and 2

$Transf(\mathcal{T}, \mathcal{P}, t_{\text{prox}})$ is the multiset of processes derived from $\mathcal{P}$ when applying:

- $\cdot^{<}$ for all instantiated roles of $\mathcal{P}$ executed by agents close to v_0
- $\cdot^{\geq}$ for all instantiated roles of $\mathcal{P}$ executed by agents far from v_0

Proposition

If $(\mathcal{P}_{\text{prox}} \cup V_0)$ admits an attack w.r.t. t_0-proximity in $\mathcal{T}$ then $(Transf(\mathcal{T}, \mathcal{P}, t_0) \uplus \overline{V_0}(v_0, p_0); \Phi_{init}; 0)$ admits an attack in ProVerif.

Case analysis - DB protocols

Protocols	MF	DH
Brands and Chaum	✓	×
Meadows *et al.* $(n_V \oplus n_P, P)$	✓	✓
Meadows *et al.* $(n_V, n_P \oplus P)$	✓	×
TREAD-Asymmetric	×	×
TREAD-Symmetric	✓	×
MAD (One-Way)	✓	×
Swiss-Knife	✓	✓
Munilla *et al.*	✓	✓
CRCS	✓	×
Hancke and Kuhn	✓	✓

(×: attack found, ✓: proved secure)

Coherent with the formal analysis recently done by Mauw *et. al.* using Tamarin

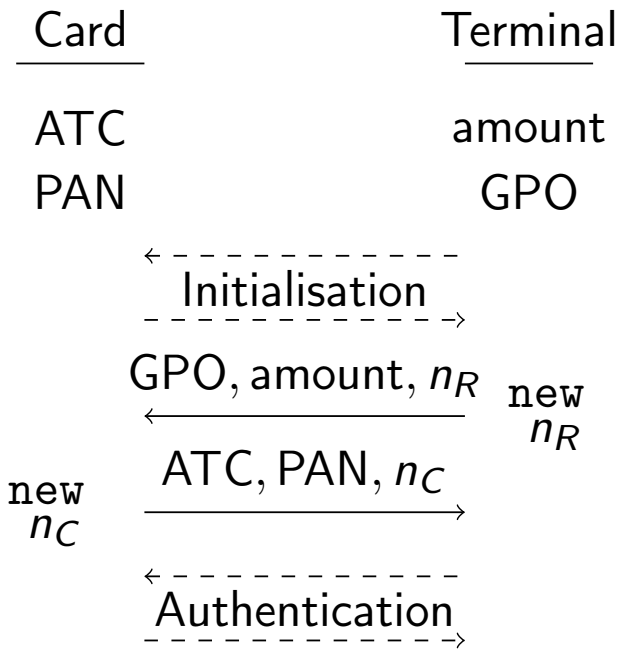
PaySafe

[Chothia *et. al.*, *2015*]

Goal: prevent relay attacks

Existing formal analyses:

- Chothia *et. al.*, 2015: similar approach using ProVerif's phases but without formal development
- Mauw *et. al.*, 2018: cannot analyse specifically mafia fraud attacks
  $\rightarrow$ find a DF attack which is not relevant



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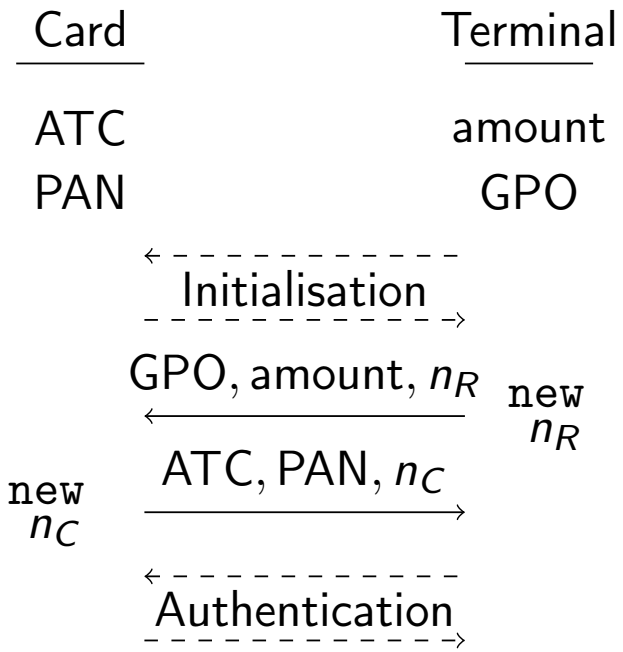
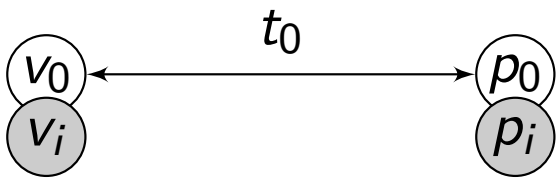


Our analysis: PaySafe is proved MF-resistant

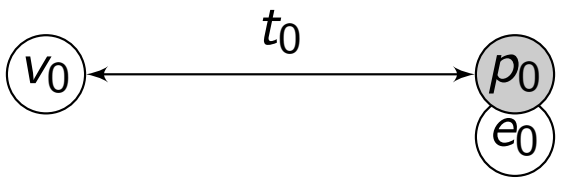
Conclusion

We have adapted the standard applied Pi-Calculus to take into account time and locations.

We obtained **two reduction results** that reduce the number of relevant topologies that need to be studied to only 2.



$\mathcal{T}_{\mathsf{MF}}$



$\mathcal{T}_{\mathsf{DH}}$

We provide a solution to prove t_0-proximity using a **usual verification tool**, ProVerif, and we applied it to analyse well-known protocols.

Future work

$\Rightarrow$ Define a more precise notion of time.

$\Rightarrow$ Take into account **Terrorist frauds**:

Terrorist frauds

A remote dishonest prover cooperates with another dishonest agent, close to the verifier, to authenticates himself to the prover without giving any advantages for future attacks.