Symbolic verification of terrorist fraud

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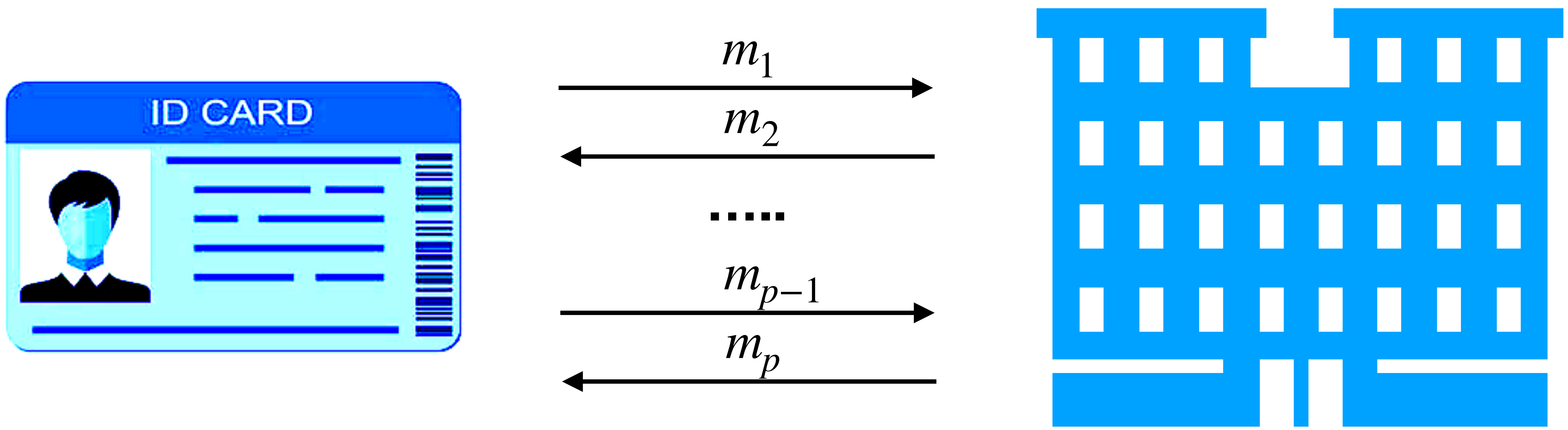
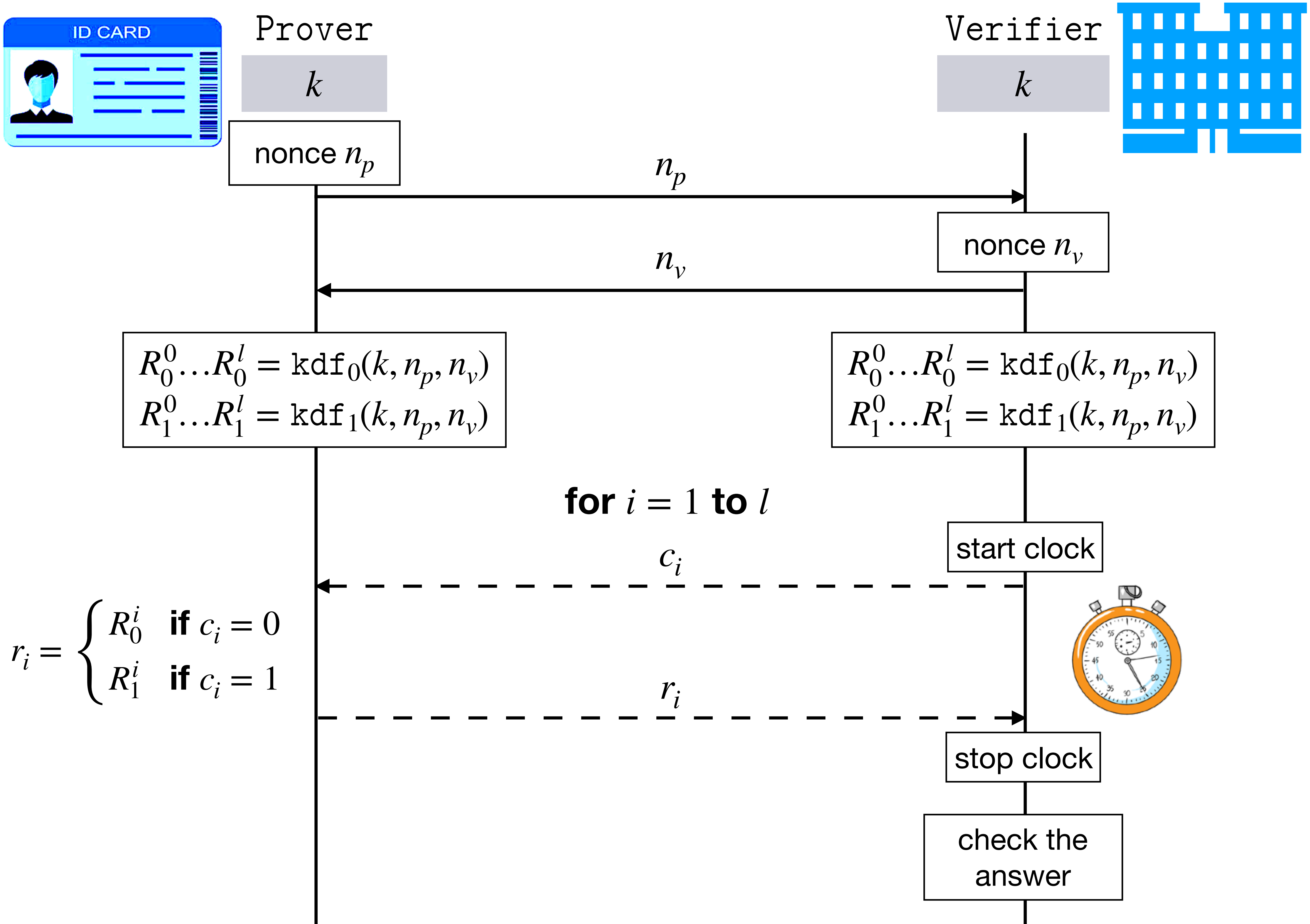
Distance bounding protocols



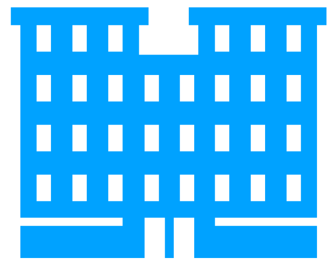
The access reader must **authenticate**
AND
verify the proximity of the card.

Hancke and Kuhn protocol (2005)



Attack scenarios

Mafia fraud (i.e., Man In the Middle)



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Terrorist fraud

An attacker accepts to collude with an accomplice to be authenticated once by a remote verifier but without giving him any avantage for future attacks.

Symbolic verification in a nutshell

Symbolic models:

– few abstractions (messages, attacker…)

\+ automatic procedures and existing tools

Existing tools exist:

TAMARIN
Tamarin prover interactive mode

ProVerif

AVANTSSAR

Some success stories:

Symbolic models for distance-bounding

Existing tools are not suitable to analyse DB protocols…

⟶ no model of time

+ the attacker relay messages without introducing any delay!

First models for DB protocols

Basin *et al*. **[CSF'09]** and Cremers *et al.* **[S&P'12]**

⟶ lack of automation…

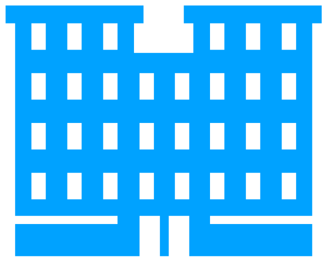
A lot of progress since last year:

➡ ProVerif encoding

- Chothia *et al.* - **[USENIX'18]**
- Our works - **[FSTTCS'18] [ESORICS'19]**

➡ Tamarin encoding: Mauw *et al.* - **[S&P'18] [CCS'19]**

About terrorist fraud



An attacker accepts to collude with an accomplice to be authenticated once by a remote verifier but without giving him any avantage for future attacks.

Chothia *et al*. - [USENIX'18]

- Non realistic definition of terrorist fraud
+ Fully automated verification using ProVerif

Mauw *et al*. - [CCS'19]

+ Satisfying definition of terrorist fraud (which corresponds to ours)
- Not fully automated verification (unbounded number of behaviors for collusion)

Contributions

1. A formal definition of terrorist fraud

2. Towards automation
   ➡ The attacker has a best strategy to collude
   ➡ There exists a most general topology

3. Case studies

Term algebra

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

Example

- Names: $\mathcal{N} = \{a, n, k\}$
- Signature: $\Sigma = \{\mathtt{senc}, \mathtt{sdec}, \mathtt{pair}, \mathtt{proj}_1, \mathtt{proj}_2, \mathtt{kdf}\}$

$$\mathtt{sdec}(\mathtt{senc}(x, y), y) \to x \qquad \mathtt{proj}_1(\mathtt{pair}(x, y)) \to x$$

$$\mathtt{proj}_2(\mathtt{pair}(x, y)) \to y$$

For example: $\mathtt{sdec}(\mathtt{senc}(\mathtt{proj}_1(\mathtt{pair}(n, m)), k), k) \downarrow =_E n$

Process algebra

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

$$
\begin{array}{rcll}
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} \\
 & | & \mathtt{in}(x)\,.\,P & \text{input}
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 & | & \mathtt{reset}\,.\,P & \text{personal clock reset} \\
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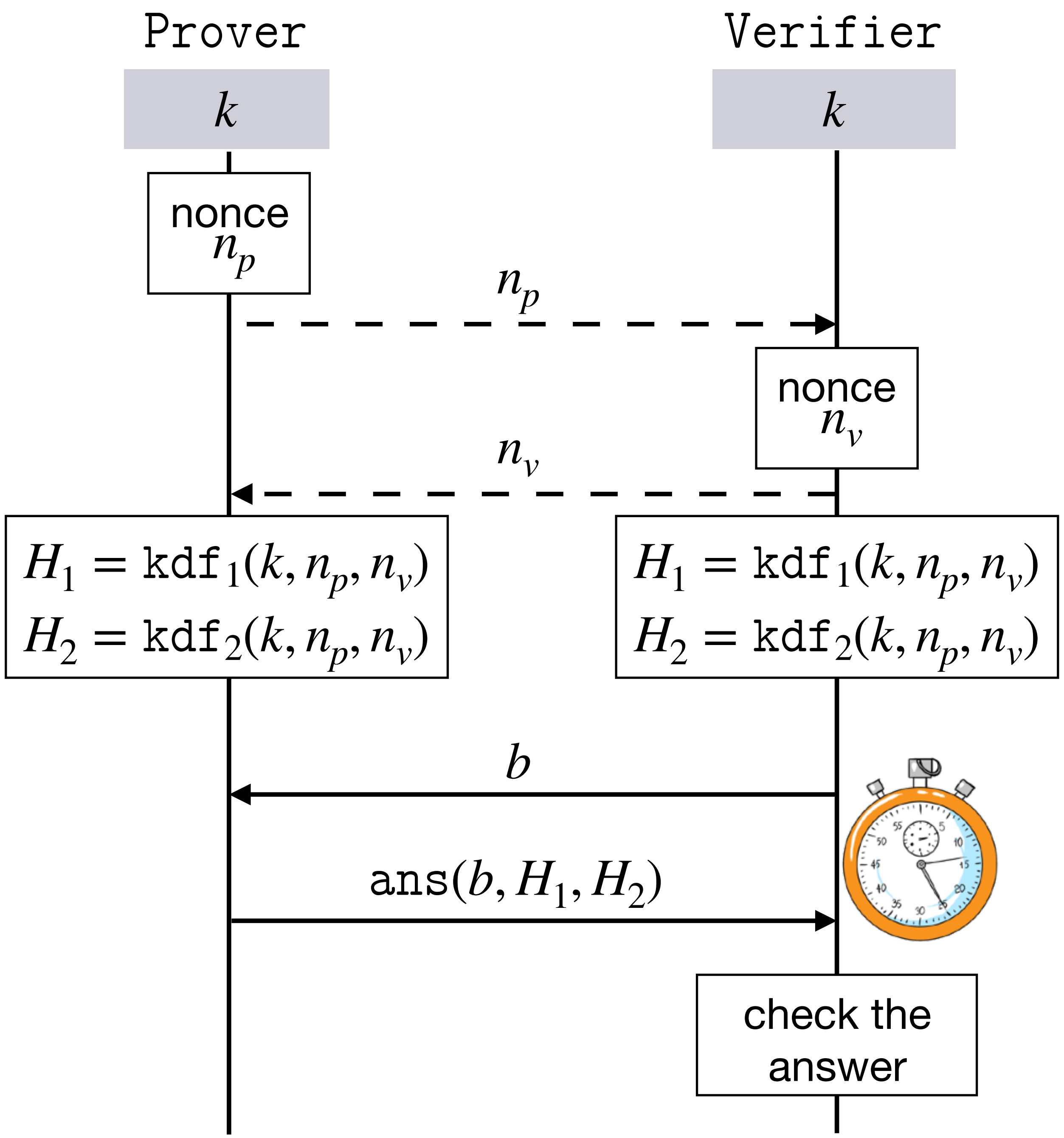
Distance-bounding protocol

A distance-bounding protocol is a pair (V, P) representing the verifier and the prover role.

Moreover, we assume that:

- ➡ $V = \mathtt{block}_V \,.\, \mathtt{reset} \,.\, \mathtt{new}\ b \,.\, \mathtt{out}(b) \,.\, \mathtt{in}^{<2\times t_0}(x) \,.\, \mathtt{block}'_V$
- ➡ $P = \mathtt{block}_P \,.\, \mathtt{in}(y_c) \,.\, \mathtt{out}(u) \,.\, \mathtt{block}'_P$

Process algebra: Hancke and Kuhn protocol



Process algebra: Hancke and Kuhn protocol

$V(z_k) :=$

$\quad \mathtt{in}(x)\,.$

$\quad \mathtt{new}\ n_v\,.\,\mathtt{out}(n_v)\,.$

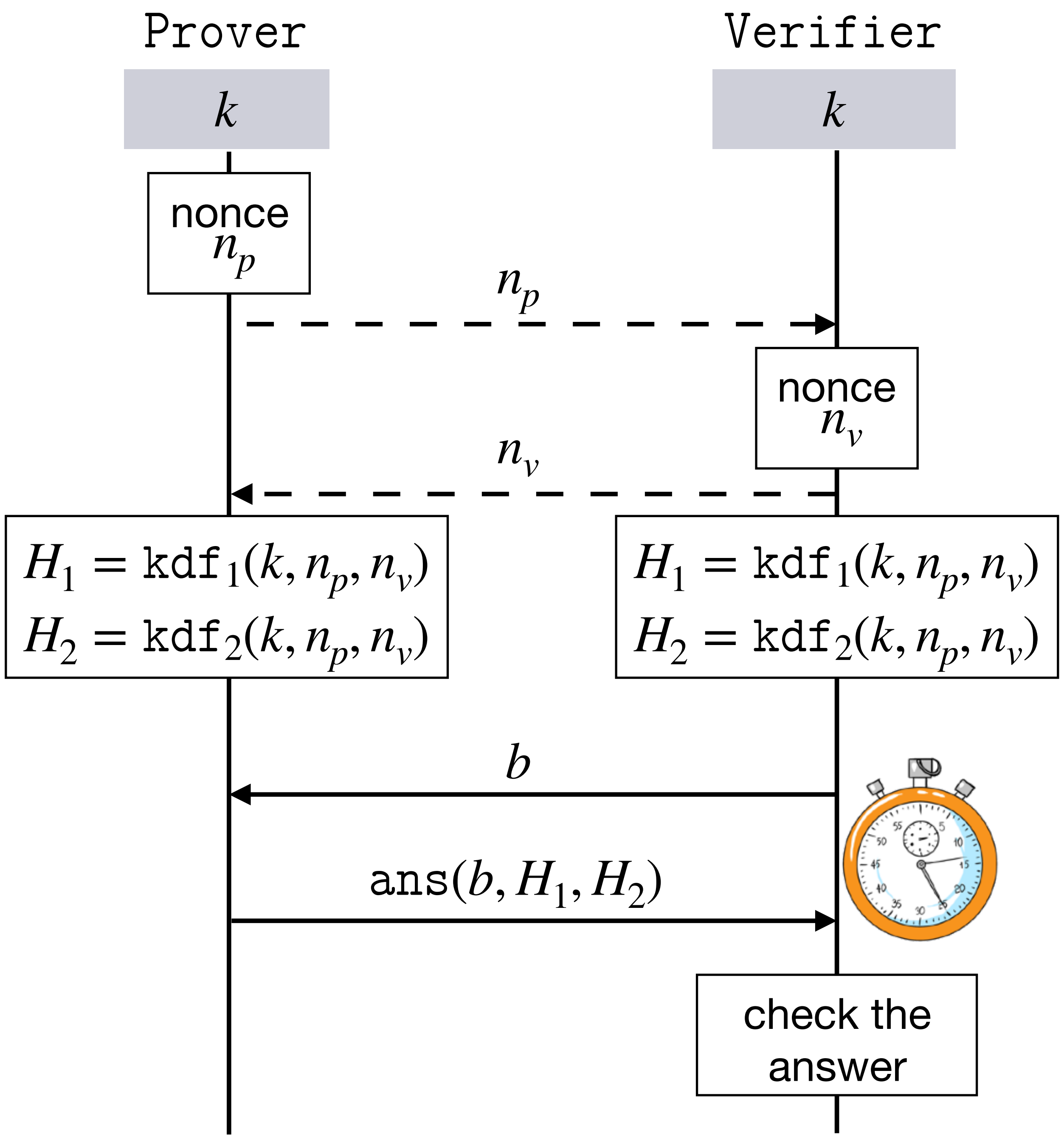
$\quad \mathtt{let}\ H_1 = \mathtt{kdf}_1(z_k, x, n_v)\ \mathtt{in}$

$\quad \mathtt{let}\ H_2 = \mathtt{kdf}_2(z_k, x, n_v)\ \mathtt{in}$

$\quad \mathtt{reset}\,.\,\mathtt{new}\ b\,.\,\mathtt{out}(b)\,.\,\mathtt{in}^{<2\times t_0}(y)\,.$

$\quad \mathtt{let}\ y_{test} = \mathtt{eq}(y, \mathtt{ans}(b, H_1, H_2))\ \mathtt{in}$

$\quad 0$



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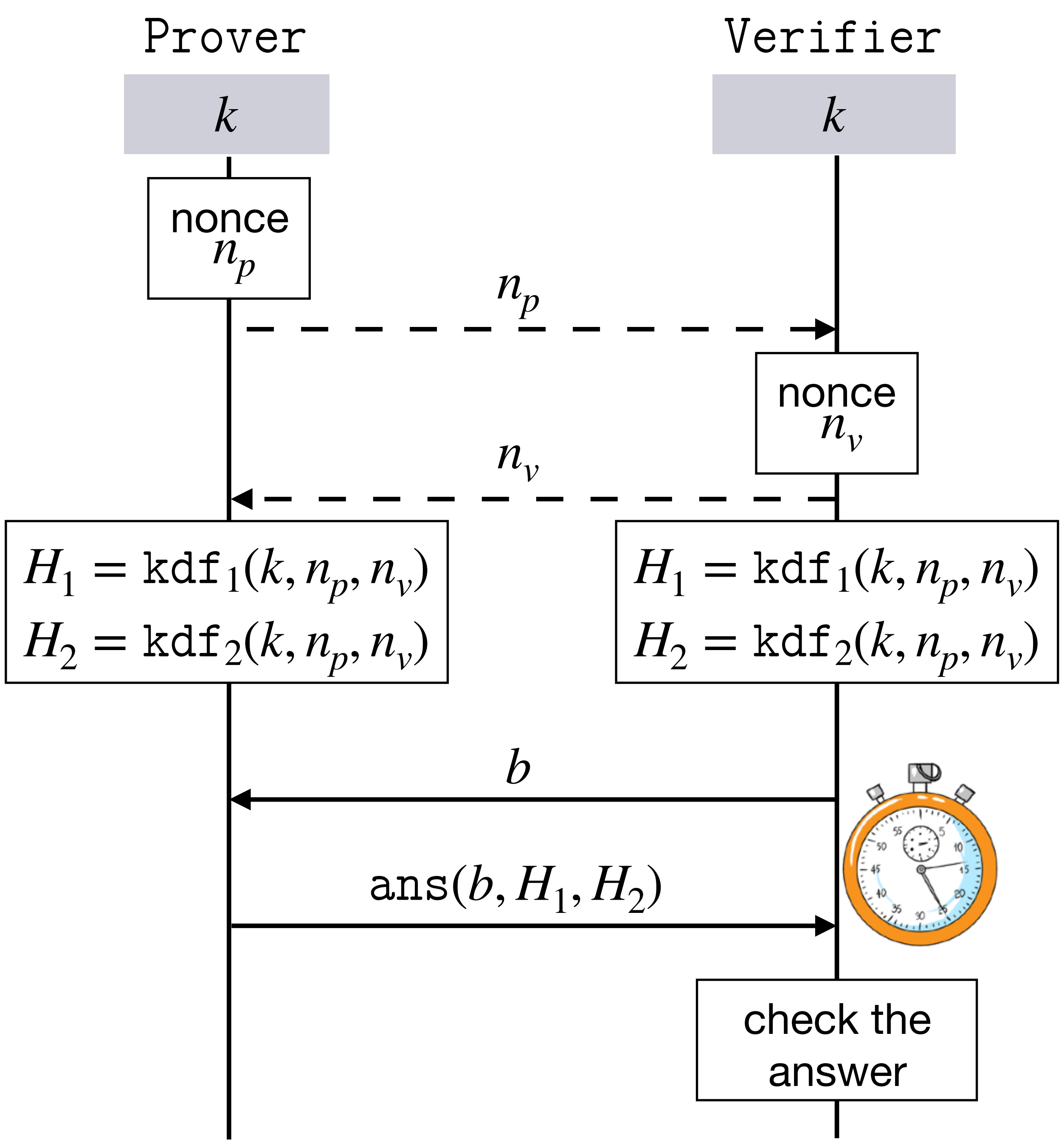
0

$P(z_k) :=$

$\mathtt{new}\ n_p\,.\,\mathtt{out}(n_p)\,.$
$\mathtt{in}(x)\,.$
$\mathtt{let}\ H_1 = \mathtt{kdf}_1(z_k, n_p, x)\ \mathtt{in}$
$\mathtt{let}\ H_2 = \mathtt{kdf}_2(z_k, n_p, x)\ \mathtt{in}$
$\mathtt{in}(y)\,.$
$\mathtt{out}(\mathtt{ans}(y, H_1, H_2))$
0



Topology

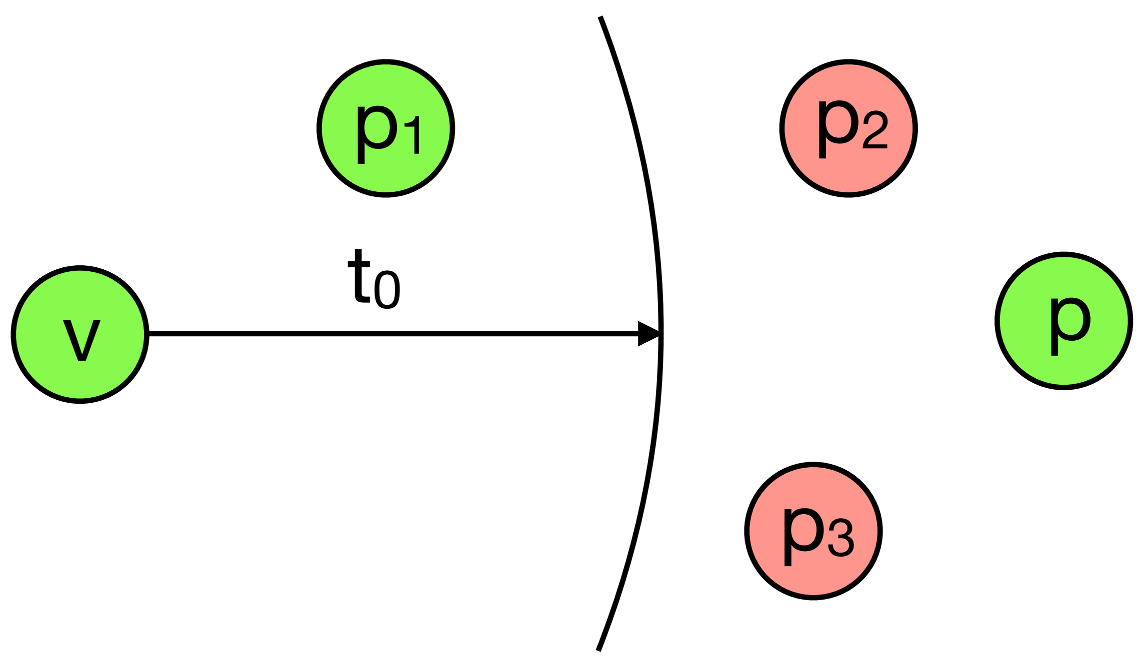
A **topology** is a tuple $\mathscr{T} = (\mathscr{A}, \texttt{Loc}, \mathscr{M}, v, p)$.

agents

locations

dishonest agents

specific agents



We define $\texttt{Dist}_{\mathscr{T}}(a,b) = \dfrac{\|\texttt{Loc}(a) - \texttt{Loc}(b)\|}{c}$

Configuration and semantics

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

- $\mathscr{P}$ is a multiset of $\lfloor P \rfloor_a^{t_a}$ with $a \in \mathscr{A}$ and $t_a \in \mathscr{R}_+$
- $\Phi = \{\mathtt{w}_1 \xrightarrow{a_1, t_1} m_1, \ldots, \mathtt{w}_n \xrightarrow{a_n, t_n} m_n\}$ is a frame
- $t \in \mathscr{R}_+$ is the global time

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TIME $\quad (\mathcal{P}; \Phi; t) \longrightarrow_{\mathcal{T}_0} (\mathcal{P}'; \Phi; t')$

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

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OUT $$(\lfloor \mathtt{out}(u).P \rfloor_a^{t_a} \uplus \mathscr{P}; \Phi; t) \xrightarrow{a, \mathtt{out}(u)}_{\mathscr{T}_0} (\lfloor P \rfloor_a^{t_a} \uplus \mathscr{P}; \Phi'; t)$$

with $\Phi' = \Phi \cup \{w \xrightarrow{a, t} u\}$

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IN $\quad (\lfloor \mathtt{in}^*(x) . P \rfloor_a^{t_a} \uplus \mathcal{P}; \Phi; t) \xrightarrow{a, \mathtt{in}^*(u)}_{\mathcal{T}_0} (\lfloor P\{x \mapsto u\} \rfloor_a^{t_a} \uplus \mathcal{P}; \Phi; t)$

if $\exists b \in \mathcal{A}, t_b \in \mathcal{R}_+$ such that $t_b \leq t - \mathtt{Dist}_{\mathcal{T}_0}(b, a)$ 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 $\bigcup_{c \in \mathcal{A}} \lfloor \Phi \rfloor_c^{t_b - \mathtt{Dist}_{\mathcal{T}_0}(c, b)}$

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NEW, LET, RESET…

Terrorist fraud resistance

Terrorist fraud resistance: A protocol is terrorist fraud resistant if for any possible attacker's behavior enabling his accomplice to be authenticated once, the accomplice gets an advantage to be authenticated later on.

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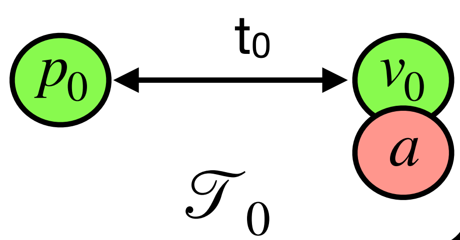
Given a protocol, a semi-dishonest prover is a process P_{sd} such that:

$$(\lfloor V(v_0, p_0)\rfloor_{v_0}^{0} \uplus \lfloor P_{\mathsf{sd}}\rfloor_{p_0}^{0}; \{\,\}; 0) \xrightarrow{tr}_{\mathcal{T}_0} (\lfloor 0\rfloor_{v_0}^{0} \uplus \lfloor 0\rfloor_{p_0}^{0}; \Phi_{\mathsf{sd}}; t)$$



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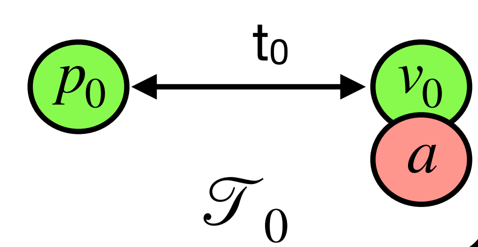

Terrorist fraud resistance

A protocol $\mathcal{P}$ is terrorist fraud resistant if for every semi-dishonest prover P_{sd}, there exists a topology $\mathcal{T} = (\mathcal{A}_0, \mathcal{M}_0, \mathtt{Loc}_0, v_0, p_0)$ such that $v_0, p_0 \notin \mathcal{M}_0$ and $\mathtt{Dist}_{\mathcal{T}}(v_0, p_0) \geq t_0$ and an initial configuration $(\mathcal{P}_0; \Phi_0; t_0)$ such that:

$$(\mathcal{P}_0; \Phi_0 \cup \Phi_{\mathsf{sd}}; t) \xrightarrow{tr}_{\mathcal{T}} (\lfloor \mathtt{end}(v_0, p_0)\rfloor_{v_0}^{t_v} \uplus \mathcal{P}; \Phi; t')$$

Contributions

1. A formal definition of terrorist fraud

2. **Towards automation**
   ➡ **The attacker has a best strategy to collude**
   ➡ **There exists a most general topology**

3. Case studies

Best strategy

Given a distance-bounding protocol, with a prover role

$$P = \texttt{block}_P \,.\, \texttt{in}(y_c) \,.\, \texttt{out}(u) \,.\, \texttt{block}'_P$$

the most general semi-dishonest prover P^* is defined as follows:

$$P^* = \texttt{block}_P \,.\, \texttt{out}(u_1, \ldots, u_n) \,.\, \texttt{in}(y_c) \,.\, \texttt{out}(u) \,.\, \texttt{block}'_P$$

where $u_1, \ldots, u_n$ are terms such that $u = \mathscr{C}[y_c, u_1, \ldots, u_n]$

Continuing our example:

$$\begin{aligned} P :=\ & \texttt{new}\ n_p.\texttt{out}(n_p) \,.\, \texttt{in}(x) \,.\, \texttt{let}\ H_1 = \texttt{kdf}_1(k, n_p, x)\ \texttt{in}\ \texttt{let}\ H_2 = \texttt{kdf}_2(k, n_p, x)\ \texttt{in} \\ & \quad \texttt{out}(\texttt{pair}(H_1, H_2)) \,. \\ & \quad \texttt{in}(y) \,.\, \texttt{out}(\texttt{ans}(y, H_1, H_2)) \,.\, 0 \end{aligned}$$

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Theorem: one semi-dishonest prover is enough

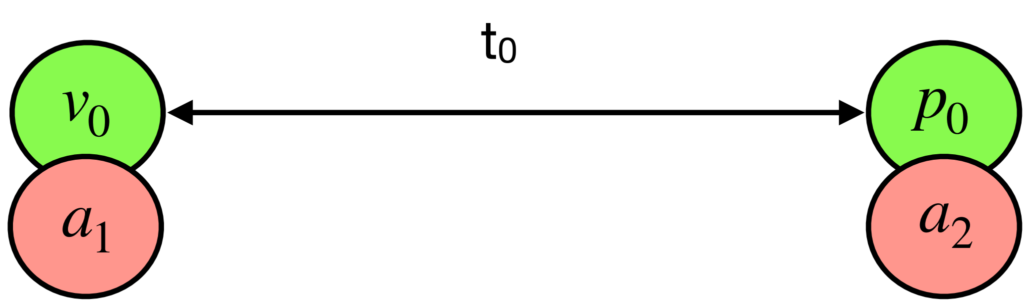
A distance-bounding protocol $\mathscr{P}_{\mathtt{prox}}$ is terrorist fraud resistant if and only if $\mathscr{P}_{\mathtt{prox}}$ is terrorist fraud resistant w.r.t. P^*.

One topology is enough

Theorem: one topology is enough

An executable distance-bounding protocol $\mathscr{P}_{\mathtt{prox}}$ is terrorist fraud resistant w.r.t. P^* if and only if there exists a valid initial configuration $(\mathscr{P}_0; \Phi_0; t_0)$ such that:

$$(\mathscr{P}_0; \Phi_0 \cup \Phi^*; t_0) \xrightarrow{tr}_{\mathscr{T}_{\text{MF}}} (\lfloor \mathtt{end}(v_0, p_0) \rfloor_{v_0}^{t_v} \uplus \mathscr{P}; \Phi; t)$$



$\mathscr{T}_{\mathtt{MF}}$

(similar to the reduction result proposed for mafia fraud at FSTTCS'18)

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Terrorist fraud resistance

Protocols	Assumptions for reducing: topologies	Assumptions for reducing: semi-dis. prover	Terrorist fraud resistance
Hancke and Kuhn	✓	✓	✗
Hancke and Kuhn *modified*	✓	✓	✓
Brands and Chaum	✓	✗	✗
Swiss-Knife	✓	✓	✓
SKI	✓	✓	✓
TREAD-Asymmetric	✓	✓	✓
TREAD-Asymmetric *fixed*	✓	✓	✓
TREAD-Symmetric	✓	✓	✓
Spade	✓	✓	✓
Spade *fixed*	✓	✓	✓
Munilla *et al.*	✓	✓	✗
MAD	✓	✗	✗
PaySafe	✓	✓	✗
NXP	✓	✓	✗

(✗: doesn't hold/attack found, ✓: holds/proved secure)
(we never obtained false attacks or non-termination)

Conclusion

Contributions

1. We propose a symbolic definition of terrorist fraud
2. We prove two reduction results enabling automation
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3. We verify numbers of protocols with the ProVerif tool

[FSTTCS'18] + [ESORICS'19] provide a framework to automatically analyse DB protocols w.r.t. the three main classes of attacks (i.e., MF, DH, TF).
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Future work:

Extend the model with mobility i.e., **enable agents to move** during a session:
→ redefine each class of attacks
→ adapt existing results to enable automation
→ ….