Composition in the BC model

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Introduction

Practical Context

Who am I ?
A third year PhD Student, working in Paris and Nancy, supervised by:

- Hubert Comon-Lundh - LSV
- Steve Kremer - LORIA

The goal

We want security !
We want formal proofs of security, in the computational model.

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We want formal proofs of security, in the computational model.

But:

- There is few automation;
- proofs are long and error-prone;
- there is no modularity;
- and proofs size grows w.r.t to the size of the protocol.

Our contributions

The composition framework

- Allows to split the security of an unbounded number of sessions of a compound protocol into smaller finite goals;

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Our contributions

The composition framework

- Allows to split the security of an unbounded number of sessions of a compound protocol into smaller finite goals;
- allows to consider protocols with state passing and long term shared secrets;
- naturally translates to the BC model, and allows for the first time to perform proofs for an unbounded number of sessions in this model.

The BC model ?

A quick introduction to the BC model

A protocol

$$A \xrightarrow{\texttt{sign}(r, skA)} B$$

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In BC

Protocols are modelled with sequences of terms:

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Attacker inputs represented with non instantiated function symbol

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How to reason on terms ?
A first order logic built over a predicate:

$$t_1 \sim t_2$$

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A first order logic built over a predicate:

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For all η, for all interpretations of free function symbols by PPT, any attacker can only distinguish between t_1 and t_2 with negligible probability.

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$$t_1, \ldots, t_n \sim t'_1, \ldots, t'_n \Rightarrow f(t_1, \ldots, t_n) \sim f(t'_1, \ldots, t'_n)$$

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- transitivity, branching over conditionals, ...

A quick introduction to the BC model

EUF-CMA
For all terms t such that sk only appears in key position:

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A reminder of our protocol

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A security property

EUF-CMA $\models \phi_1 \sim$

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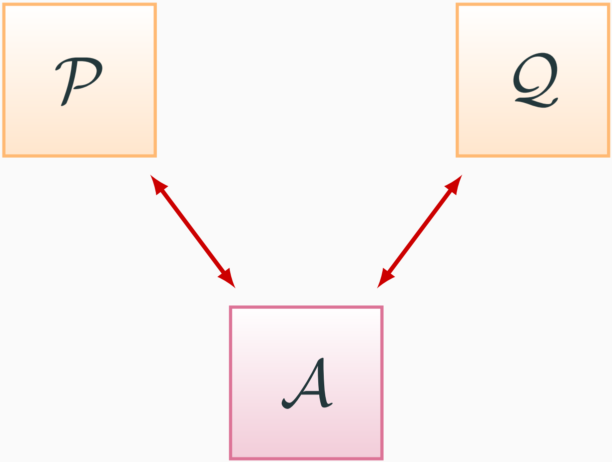
A compositional framework inside the computational model

A classical proof technique

$\mathcal{A}$ is trying to break protocol $\mathcal{P}$, while also having access to $\mathcal{Q}$.



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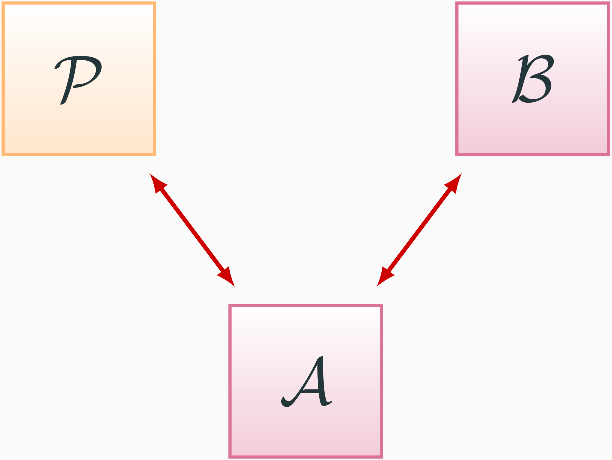

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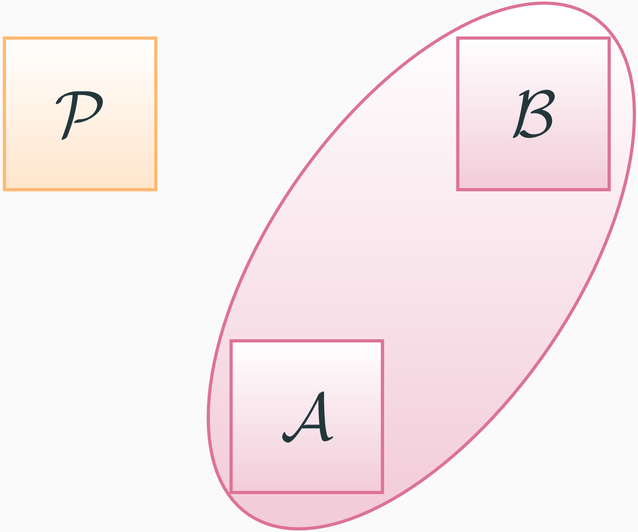

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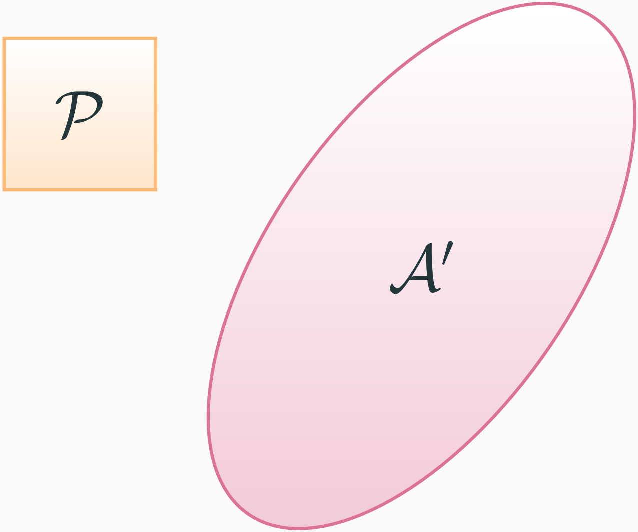

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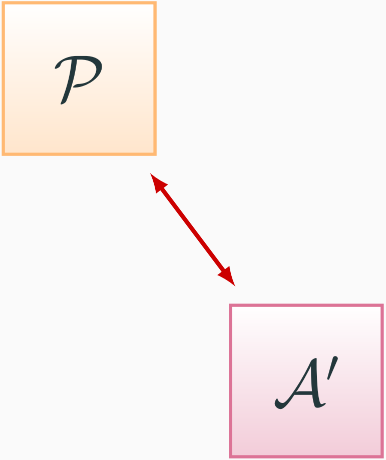

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The main idea

If $\mathcal{A}$ can simulate it, i.e produce exactly all the same messages:

we remove Q from the picture!

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The difficulty
If P and Q share some secret key sk, $\mathcal{A}$ cannot simulate messages which require sk.

The main idea

Exemple for signatures

- $\mathcal{P}_{sk}$ may produce $\texttt{sign}(< m, \text{``tag}_1\text{''} >, sk)$
- $\mathcal{Q}_{sk}$ may produce $\texttt{sign}(< m', \text{``tag}_2\text{''} >, sk)$

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$\hookrightarrow$ We may give an oracle to the attacker, allowing to obtain $\texttt{sign}(< m', \text{"tag}_2\text{"} >, sk)$ but not $\texttt{sign}(< m, \text{"tag}_1\text{"} >, sk)$

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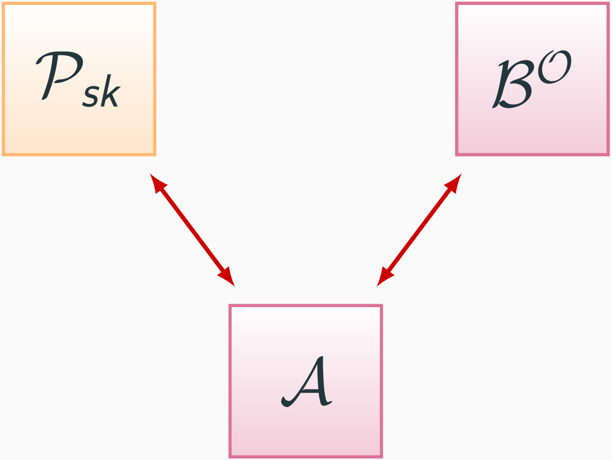
$\mathcal{A}$ is trying to break protocol $\mathcal{P}$, while simulating $\mathcal{Q}$ thanks to oracle $\mathcal{O}$.



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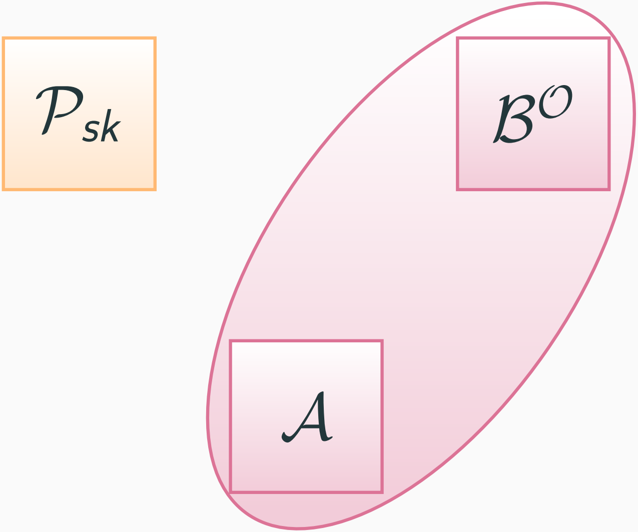

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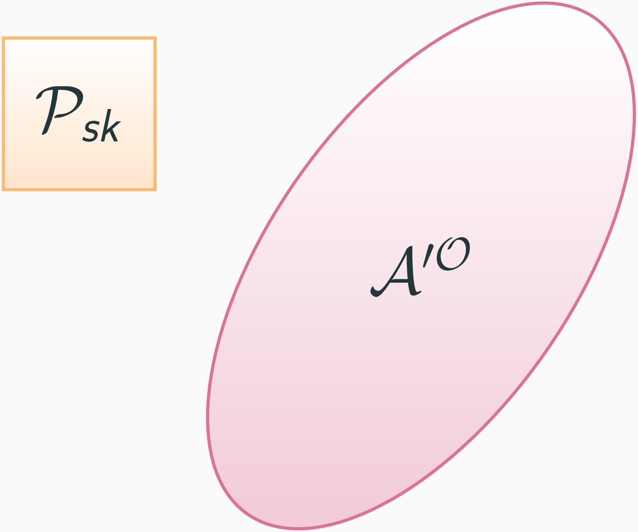

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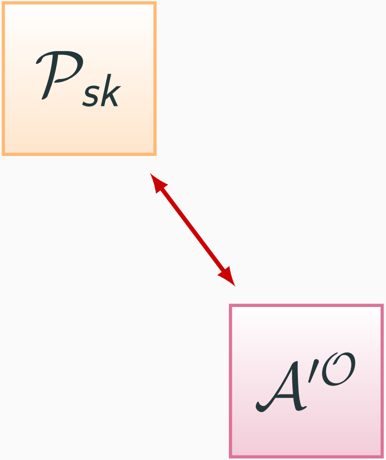

In the BC model

Classical Setting

To prove the security of $\mathcal{P}$ against $\mathcal{A}$, we define axioms Ax that are sound for any PPT, and prove that $Ax \models \phi_P$.

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New Axioms
To prove $\mathcal{P}$ against $\mathcal{A}^{\mathcal{O}}$, we just have find axioms $Ax_{\mathcal{O}}$ that are sounds for all PPTOM.

On an example

A small DDH example

Signed DDH

$$
\begin{array}{ccc}
A(a, skA) & & B(b, skB) \\
& \xrightarrow{\text{sign}(g^a, skA)} & \\
& & x_B = g^a \\
& \xleftarrow{\text{sign}(<g^a, g^b>, skB)} & \\
x_A = g^b & & \\
& \xrightarrow{\text{sign}(<g^a, g^b>, skA)} & \\
k_A = x_A^a & & k_B = x_B^b
\end{array}
$$

A small DDH example

The security property:

$$\|^{i\leq N}(A(a_i, skA); \mathbf{out}(k_A) \| B(b_i, skB); \mathbf{out}(k_B))$$

$$\sim$$

$$\begin{aligned}
&\|^{i\leq N-1}(A(a_i, skA); \mathbf{out}(k_A) \| B(b_i, skB); \mathbf{out}(k_B)) \\
&\| \ A(a_N, skA); \textbf{ if } x_A = g^{b_N} \textbf{ then } \mathbf{out}(k_{N,N}) \\
&\qquad\qquad\qquad \textbf{else if } x_A \notin \{g^{b_i}\}_{1\leq i\leq N} \textbf{ then } \perp \\
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Let's assume the attacker can simulate

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. We can simply prove:

$$\begin{array}{c} A(a_N, skA); \mathbf{out}(k_A) \| B(b_N, skB); \mathbf{out}(k_B) \\ \sim \\ A(a_N, skA);\ \mathbf{if}\ x_A = g^{b_N}\ \mathbf{then}\ \mathbf{out}(k_{N,N}) \\ \qquad\qquad \mathbf{else\ if}\ x_A \notin \{g^{b_i}\}_{1 \leq i \leq N}\ \mathbf{then}\ \bot \\ \|\ B(b_N, skB);\ \mathbf{if}\ x_B = g^{a_N}\ \mathbf{then}\ \mathbf{out}(k_{N,N}) \\ \qquad\qquad \mathbf{else\ if}\ x_B \notin \{g^{a_i}\}_{1 \leq i \leq N}\ \mathbf{then}\ \bot \end{array}$$

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$\hookrightarrow$ How to simulate the $N-1$ sessions ?

Simulating the sessions

What must the attacker be able to produce ?
He must be able to start some A:

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And for any DDH share r he receives, he should be able to produce:

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- $\forall 1 \leq i \leq N-1.\ \mathrm{sign}(< g^{a_i}, r >, skA)$
- $\forall 1 \leq i \leq N-1.\ \mathrm{sign}(< r, g^{b_i} >, skB)$

Generic signing oracles

T signing oracle

$$\begin{aligned}\mathcal{O}^{\mathsf{sign}}_{T,sk} : \ & \mathsf{input}(m) \\ & \textbf{if } T(m) \textbf{ then} \\ & \quad \mathsf{output}(\mathsf{sign}(m, sk)))\end{aligned}$$

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Give the attacher access to $\mathcal{O}^{sign}_{T,skA}$ and $\mathcal{O}^{sign}_{T,skB}$ with:

$$
T(m) = \mathrm{true} \Leftrightarrow \exists 1 \leq i \leq N-1, r. \begin{cases} m = g^{a_i} \\ m = < g^{a_i}, r > \\ m = < r, g^{b_i} > \end{cases}
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$\hookrightarrow$ How to make the proof for such attackers ?

T-EUFCMA

For any computable function T, for all terms t such that sk only appears in key position:

$$
\begin{aligned}
&\mathtt{checksign}(t, pk(sk))) \Rightarrow \\
&\quad T(\ \mathtt{getmess}(t)) \\
&\quad \bigvee_{\mathsf{sign}(x,sk) \in\ \mathtt{St}(t)} (t \doteq \mathsf{sign}(x, sk))) \\
&\sim \mathit{true}
\end{aligned}
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The final proof

Assumption

$$\begin{array}{l} \texttt{checksign}(t, pk(sk))) \Rightarrow \\ \quad \exists 1 \leq i \leq N-1, r.\ \ \texttt{getmess}(t) \in \{g^{a_i}, < g^{a_i}, r >, < r, g^{b_i} >\} \\ \quad \bigvee_{\mathsf{sign}(x,sk) \in \texttt{St}(t)} (t \doteq \mathsf{sign}(x, sk))) \\ \sim \mathit{true} \end{array}$$

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\qquad \bigvee_{\mathsf{sign}(x,sk) \in \mathtt{St}(t)} (t \doteq \mathsf{sign}(x, sk))) \\
\quad \sim \mathit{true} \\
\wedge \quad DDH : g^{a_N}, g^{b_N}, g^{a_N b_N} \sim g^{a_N}, g^{b_N}, k_{N,N}
\end{array}
$$

The final proof

Goal

$$A(a_N, skA); \mathbf{out}(k_A) \| B(b_N, skB); \mathbf{out}(k_B)$$

$$\sim$$

$$\begin{aligned} & A(a_N, skA);\ \mathbf{if}\ x_A = g^{b_N}\ \mathbf{then}\ \mathbf{out}(k_{N,N}) \\ & \qquad \mathbf{else\ if}\ x_A \notin \{g^{b_i}\}_{1 \leq i \leq N}\ \mathbf{then}\ \perp \\ \| \ & B(b_N, skB);\ \mathbf{if}\ x_B = g^{a_N}\ \mathbf{then}\ \mathbf{out}(k_{N,N}) \\ & \qquad \mathbf{else\ if}\ x_B \notin \{g^{a_i}\}_{1 \leq i \leq N}\ \mathbf{then}\ \perp \end{aligned}$$

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Synchronization

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3. similar to (2);
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Conclusion

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The composition framework

- Composition results for parallel and sequential composition (in the BC model),
- allows for long-term shared secrets and state-passing,
- allows for reduction from unbounded number of sessions to a single one,
- applied to key exchange (with key confirmations).

Done and to do?

A tool
We are working on an interactive prover:

1. First allow to performe (un)-reachability proofs, (WIP)

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A tool

We are working on an interactive prover:

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2. then integrate with indistinguishability proofs,

Done and to do?

A tool

We are working on an interactive prover:

1. First allow to performe (un)-reachability proofs, (WIP)
2. then integrate with indistinguishability proofs,
3. and use the composition framework along with the tool to perform case studies.

Extra slides with too many details

A core theorem

Composition without replication

Let $C[\_1, \dots, \_n]$ be a context such that the variable k_i is bound in each hole $\_i$ and $P_1(x), \dots, P_n(x)$ be parametrized protocols, such that all channels are disjoint. Given an oracle $\mathcal{O}$, with $\overline{n} \supset \mathcal{N}(C) \cap \mathcal{N}(P_1, \dots, P_n)$, if, with $k'_1, \dots, k'_n$ fresh names,

1. $C[\mathbf{out}(1, k_1), \dots, \mathbf{out}(n, k_n)] \cong_{\mathcal{O}} C[\mathbf{out}(1, k'_1), \dots, \mathbf{out}(n, k'_n)]$
2. $\nu \overline{n}.\mathbf{in}(x).P_1(x) \| \dots \| \mathbf{in}(x).P_n(x)$ is $\mathcal{O}$-simulatable

Then $C[P_1(k_1), \dots, P_n(k_n)] \cong_{\mathcal{O}} C[P_1(k'_1), \dots, P_n(k'_n)]$

A core theorem

Unbounded parallel Composition
Let $\mathcal{O}_r$ be an oracle and Ax a set of axioms both parametrized by a sequence of names $\overline{s}$. Let $\overline{p}$ be a sequence of shared secrets, $P(\overline{x})$, $R(\overline{x}, \overline{y}, \overline{z})$ and $Q(\overline{x}, \overline{y})$ be parametrized protocols. If we have, for a sequence of names $\overline{lsid}$ and any integers n, if with $\overline{s} = \overline{lsid}_1, \dots, \overline{lsid}_n$ n copies of $\overline{lsid}$:

1. $\forall\ 1 \leq i \leq n, \nu \overline{p}.t_{R(\overline{p}, \overline{lsid}_i, \overline{s})}$ is $\mathcal{O}_r$ simulatable.
2. Ax is $\mathcal{O}_r$ sound.
3. $Ax \models t_{P(\overline{p})} \sim t_{Q(\overline{p}, \overline{s})}$

Then, for any integer n:

$$P(\overline{p}) \| \, !_n R(\overline{p}, \overline{lsid}, \overline{s}) \\ \cong Q(\overline{p}, \overline{s}) \| \, !_n R(\overline{p}, \overline{lsid}, \overline{s})$$

A core theorem

Unbounded parallel Composition
Let $\mathcal{O}_r$ be an oracle and Ax a set of axioms both parametrized by a sequence of names $\overline{s}$. Let $\overline{p}$ be a sequence of shared secrets, $P(\overline{x}, \overline{y})$ and $Q(\overline{x}, \overline{y}, \overline{z})$ be parametrized protocols. If we have, for sequences of names $\overline{lsid}_p, \overline{lsid}_q$ and any integers n, if with $\overline{s} = \overline{lsid}_{p,1}, \dots, \overline{lsid}_{p,n}, \dots, \overline{lsid}_{q,n}$ sequences of copies of $\overline{lsid}_p, \overline{lsid}_q$

1. $\forall\ 1 \leq i \leq n, \nu\overline{p}.t_{P(\overline{p}, \overline{lsid}_{p,i})}$ is $\mathcal{O}_r$ simulatable.
2. $\forall\ 1 \leq i \leq n, \nu\overline{p}.t_{Q(\overline{p}, \overline{lsid}_{q,i}, \overline{s})}$ is $\mathcal{O}_r$ simulatable.
3. Ax is $\mathcal{O}_r$ sound.
4. $Ax \models t_{P(\overline{p}, \overline{lsid}_p)} \sim t_{Q(\overline{p}, \overline{lsid}_q, \overline{s})}$

Then, for any integers n:

$$!_n P(\overline{p}, \overline{lsid}_p) \cong_{\mathcal{O}} !_n Q(\overline{p}, \overline{s}, \overline{lsid}_q)$$