WHAT YOU LOSE IS WHAT YOU LEAK

INFORMATION LEAKAGE IN DECLASSIFICATION POLICIES

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Overview

- By exploiting the strong relation between completeness and non-interference we can obtain the following results:
  - Model declassification as a forward completeness problem for the weakest precondition semantics;
  - Derive counterexamples to a given declassification policy;
  - Refine a given declassification policy;

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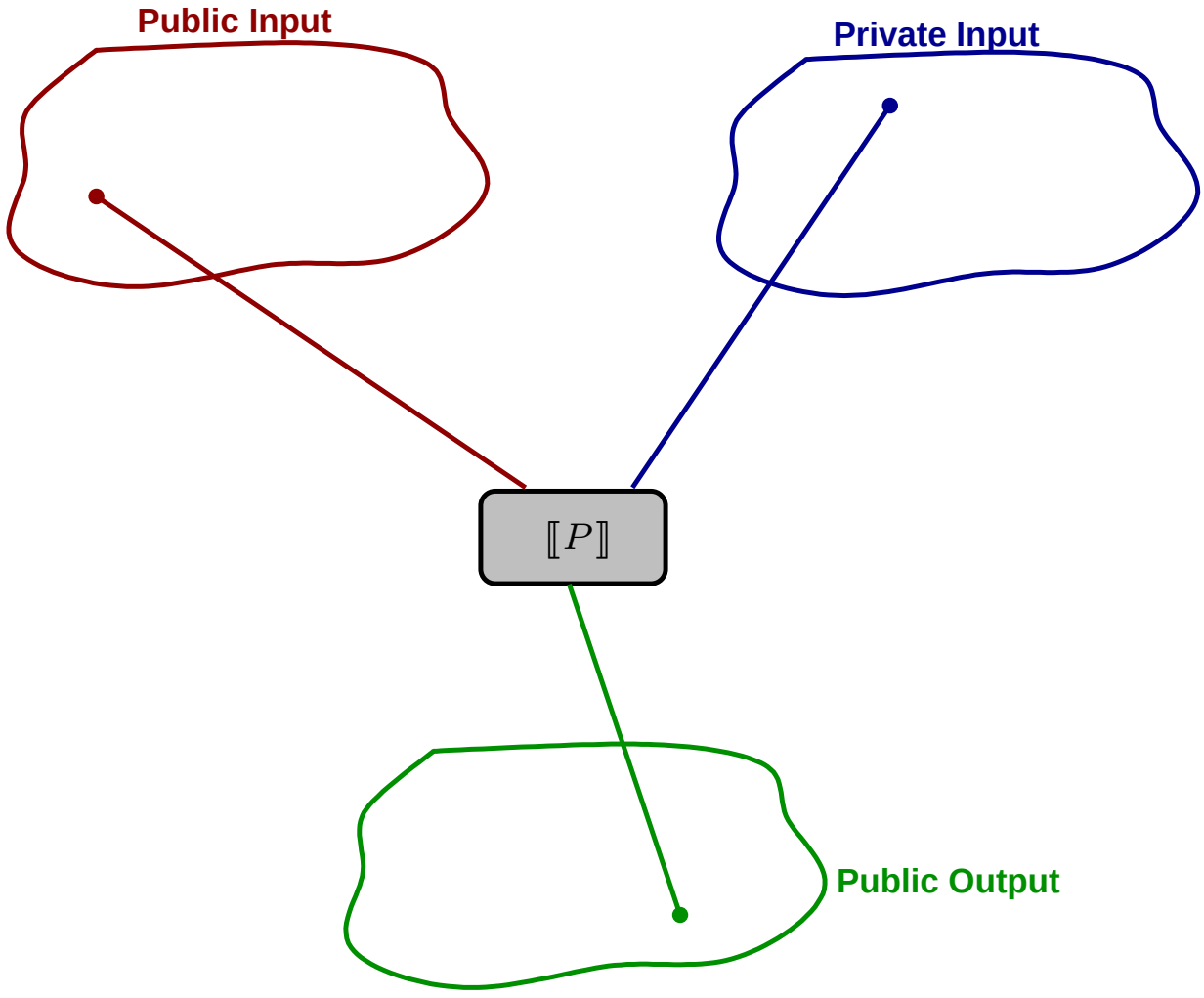
  - Model declassification as a forward completeness problem for the weakest precondition semantics;
  - Derive counterexamples to a given declassification policy;
  - Refine a given declassification policy;
- We can model declassification as a model checking problem (see the relation with robust declassification)

Standard Non-Interference



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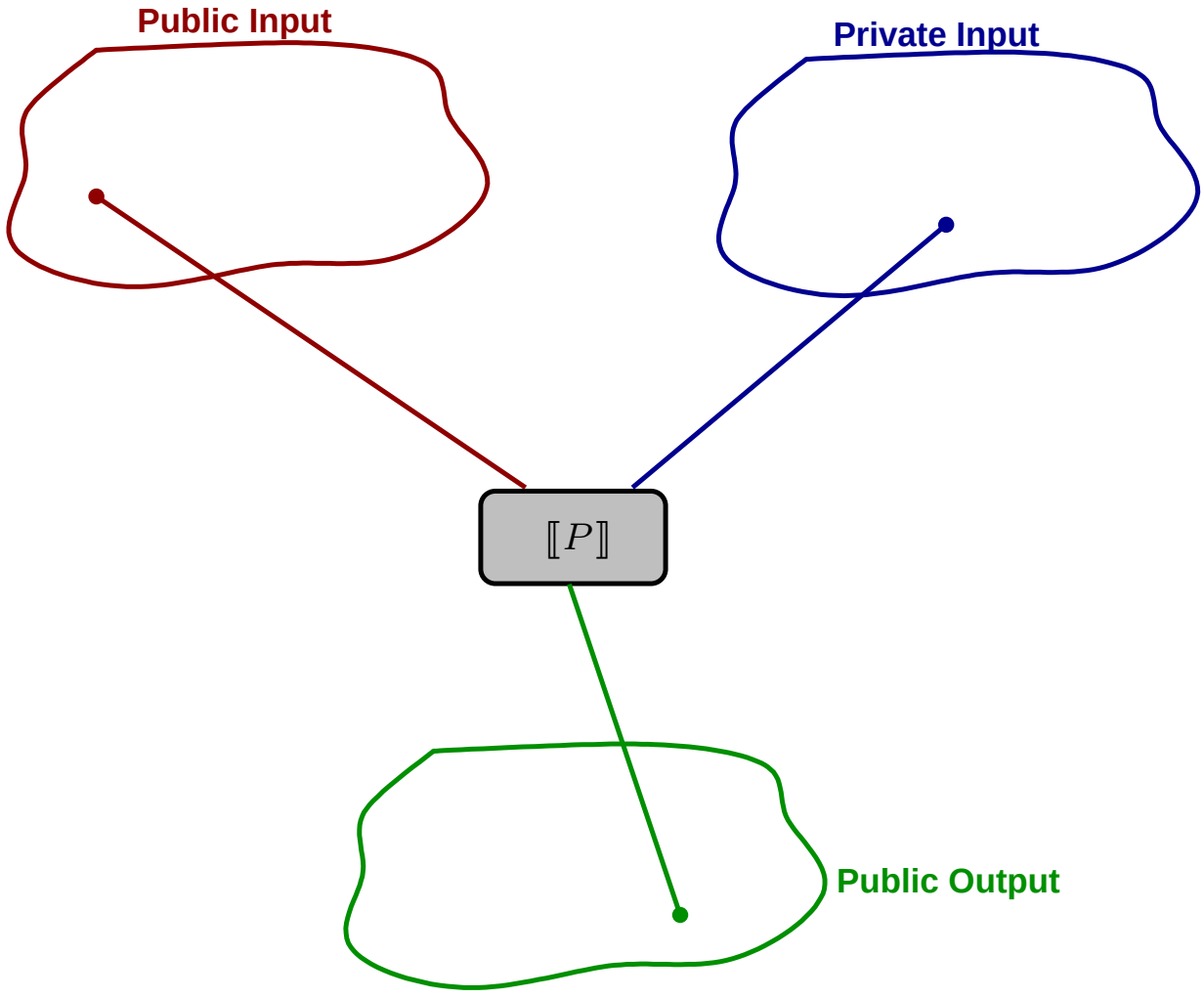

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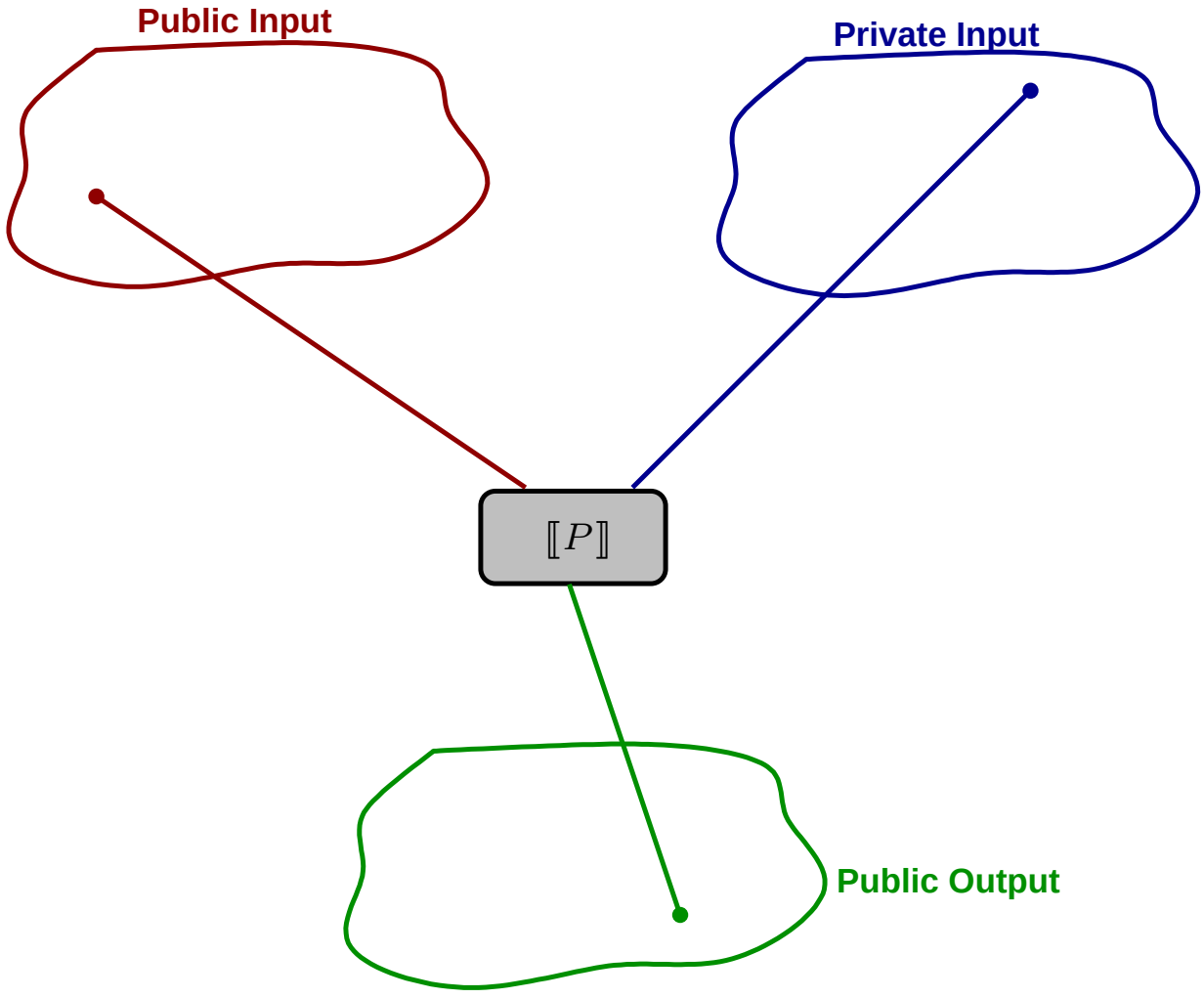

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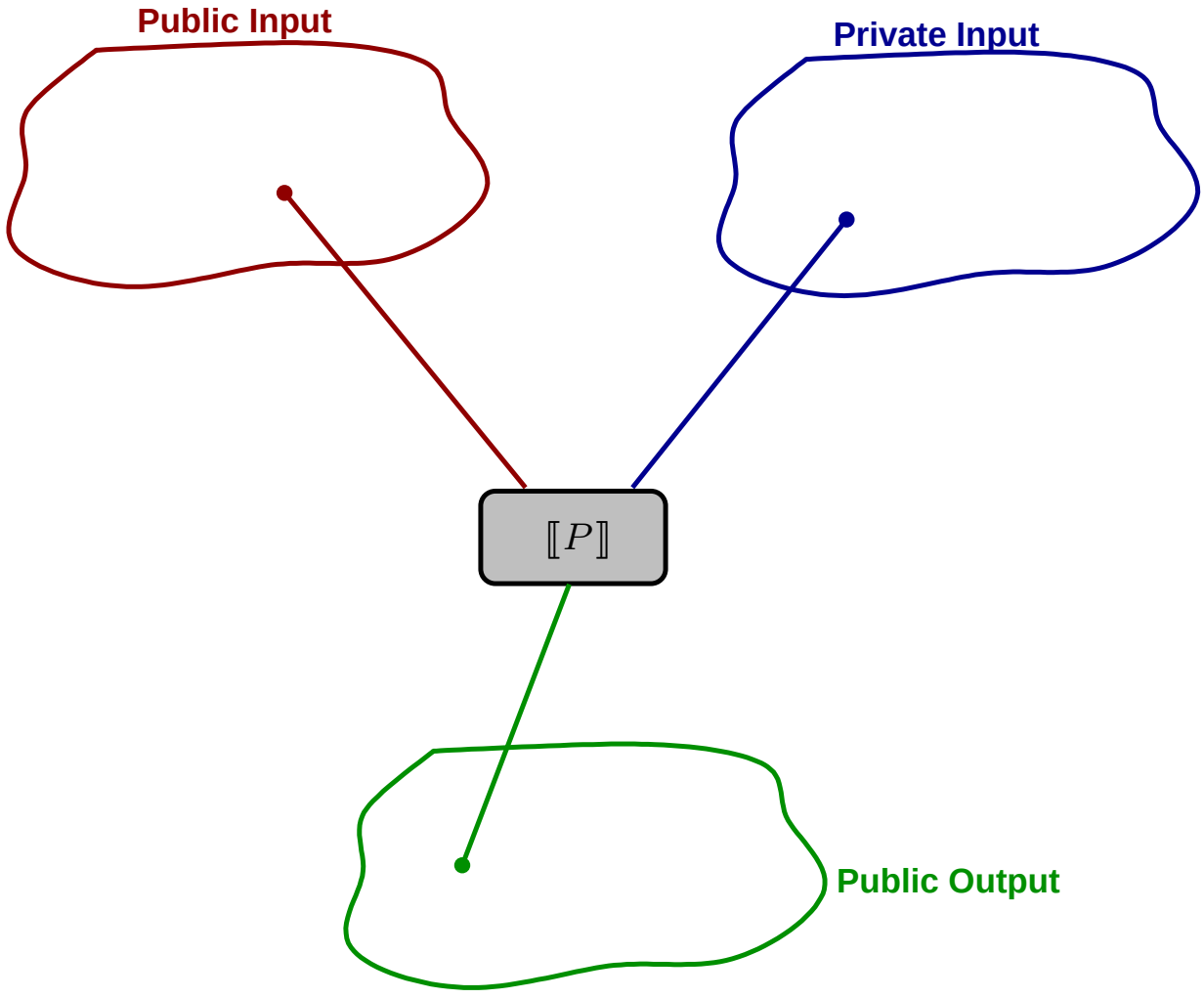

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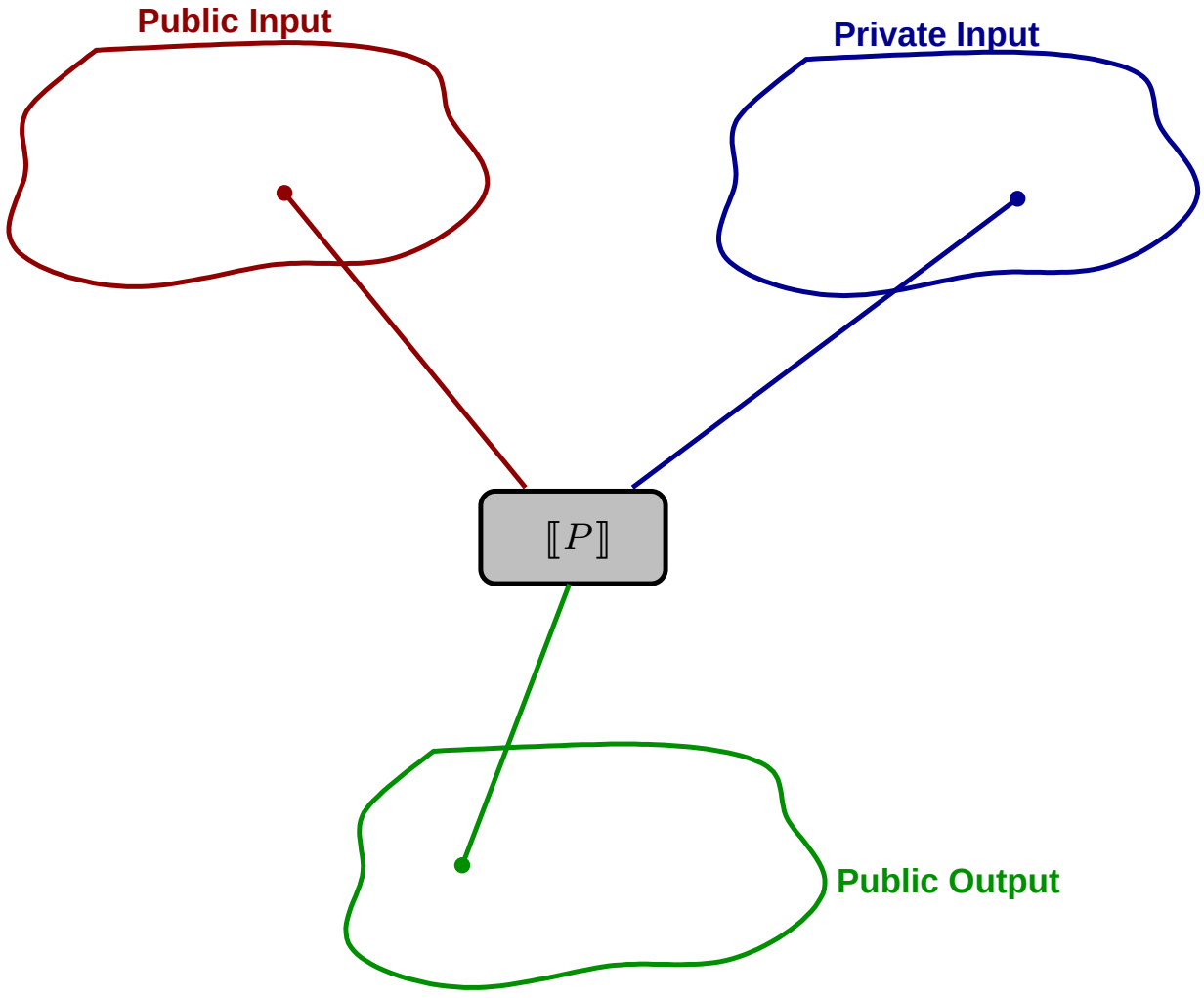

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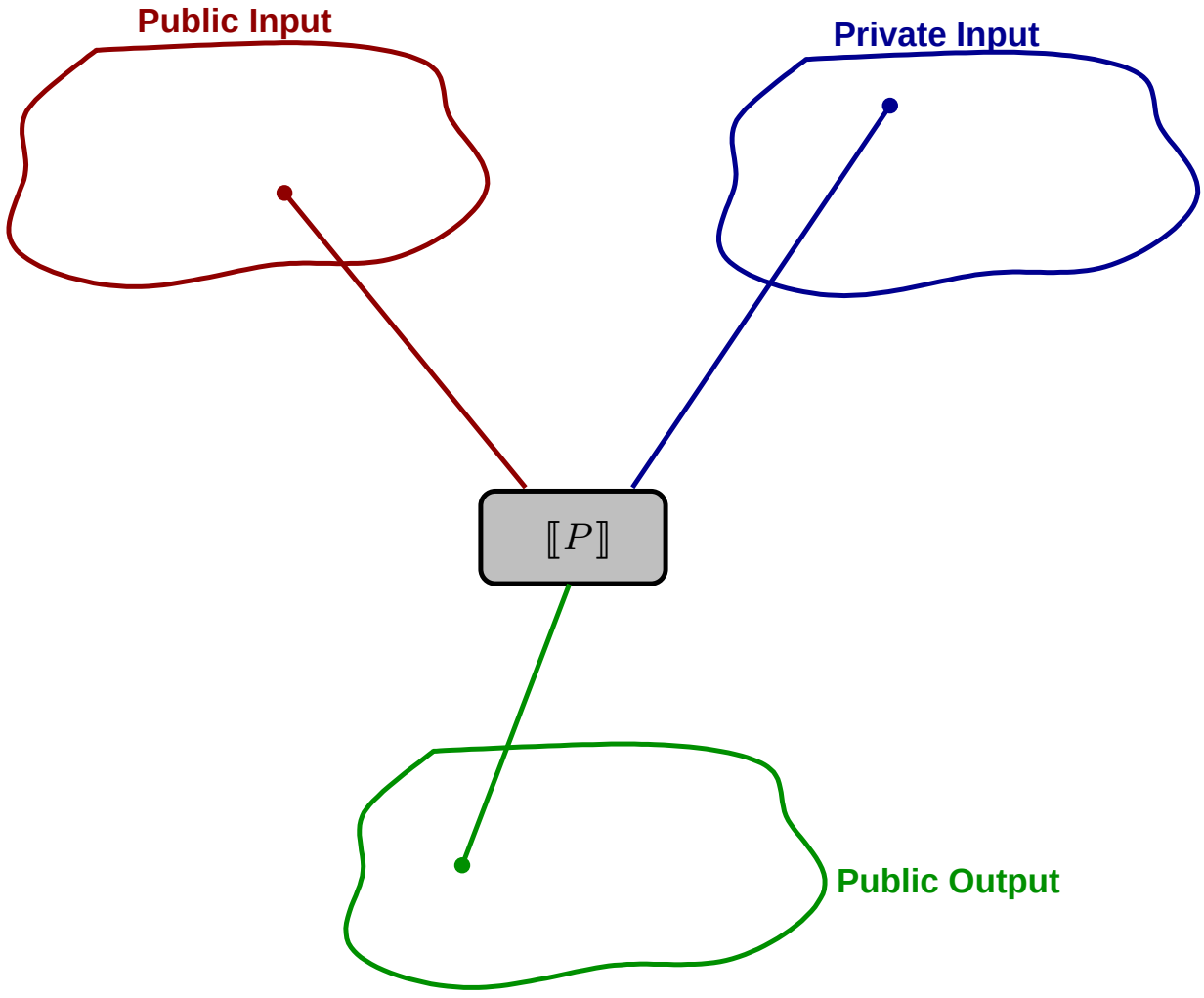

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NI: A completeness problem

Recall that [Joshi & Leino'00]

P is *secure* iff $\texttt{HH} \,;\, P;\, \texttt{HH} \doteq P \,;\, \texttt{HH}$

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$$\begin{array}{ccc} \mathtt{HH}\,;\, P;\, \mathtt{HH} & \doteq & P\,;\, \mathtt{HH} \\ & \Downarrow & \\ \mathcal{H} \circ [\![P]\!] \circ \mathcal{H} & = & \mathcal{H} \circ [\![P]\!] \end{array}$$

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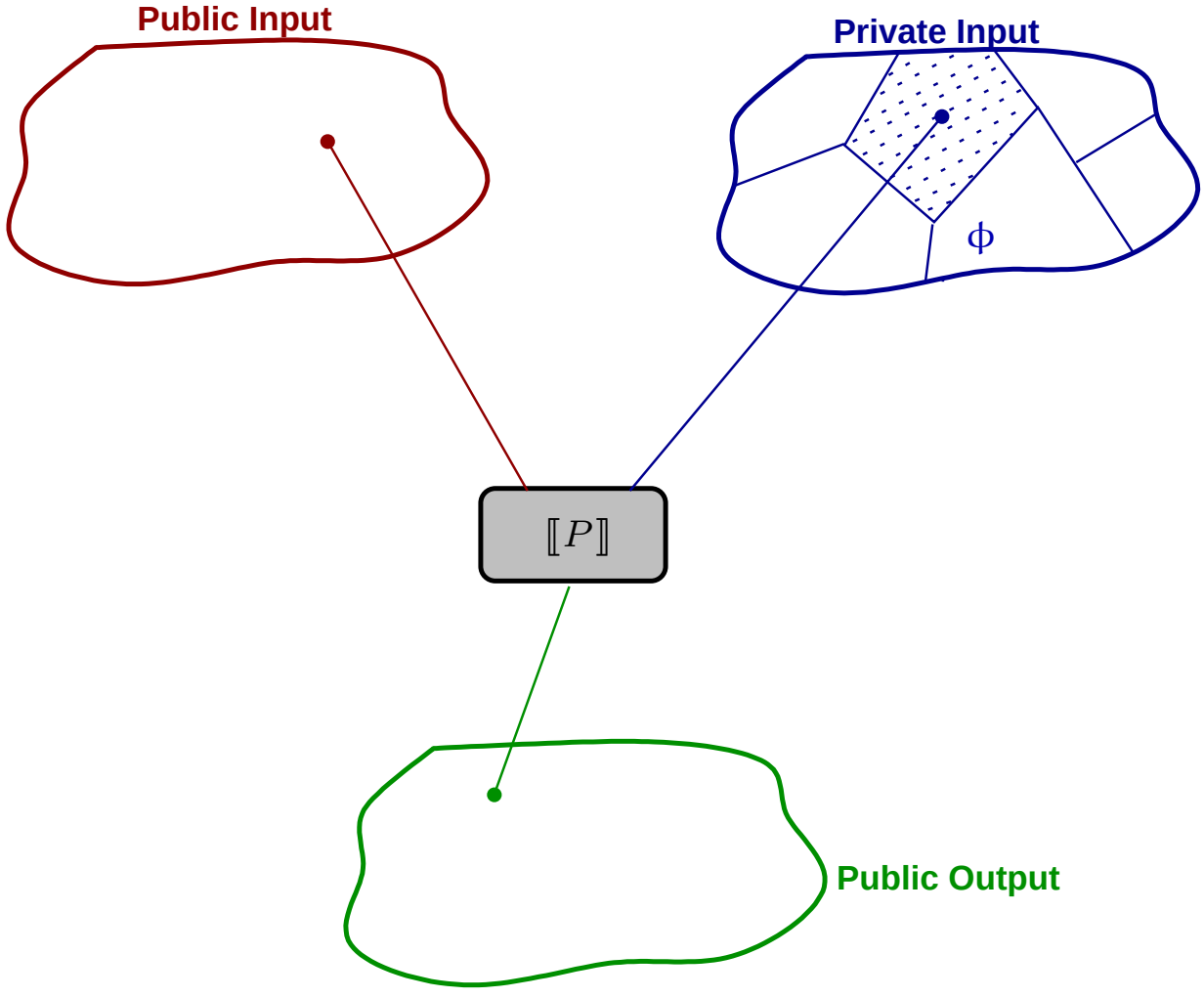
$\Rightarrow$ A COMPLETENESS PROBLEM

[Giacobazzi& Mastroeni '05]

Declassified NI



[Mastroeni '05]

$\phi \in \mathit{Abs}(\wp(\mathbb{V}^{\mathsf{H}}))$: $\phi(h_1) = \phi(h_2) \Rightarrow [\![P]\!](h_1, l)^{\mathsf{L}} = [\![P]\!](h_2, l)^{\mathsf{L}}$

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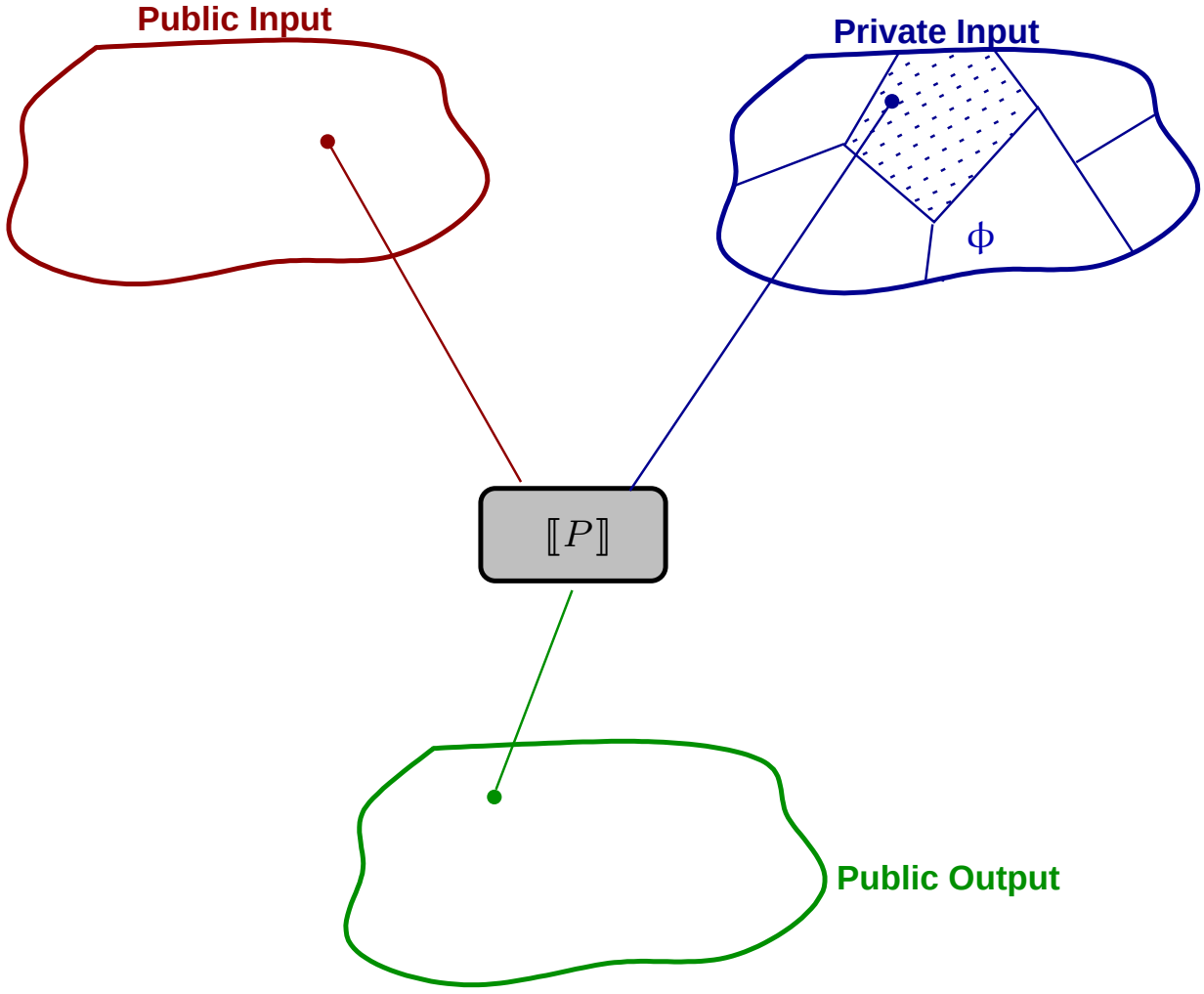

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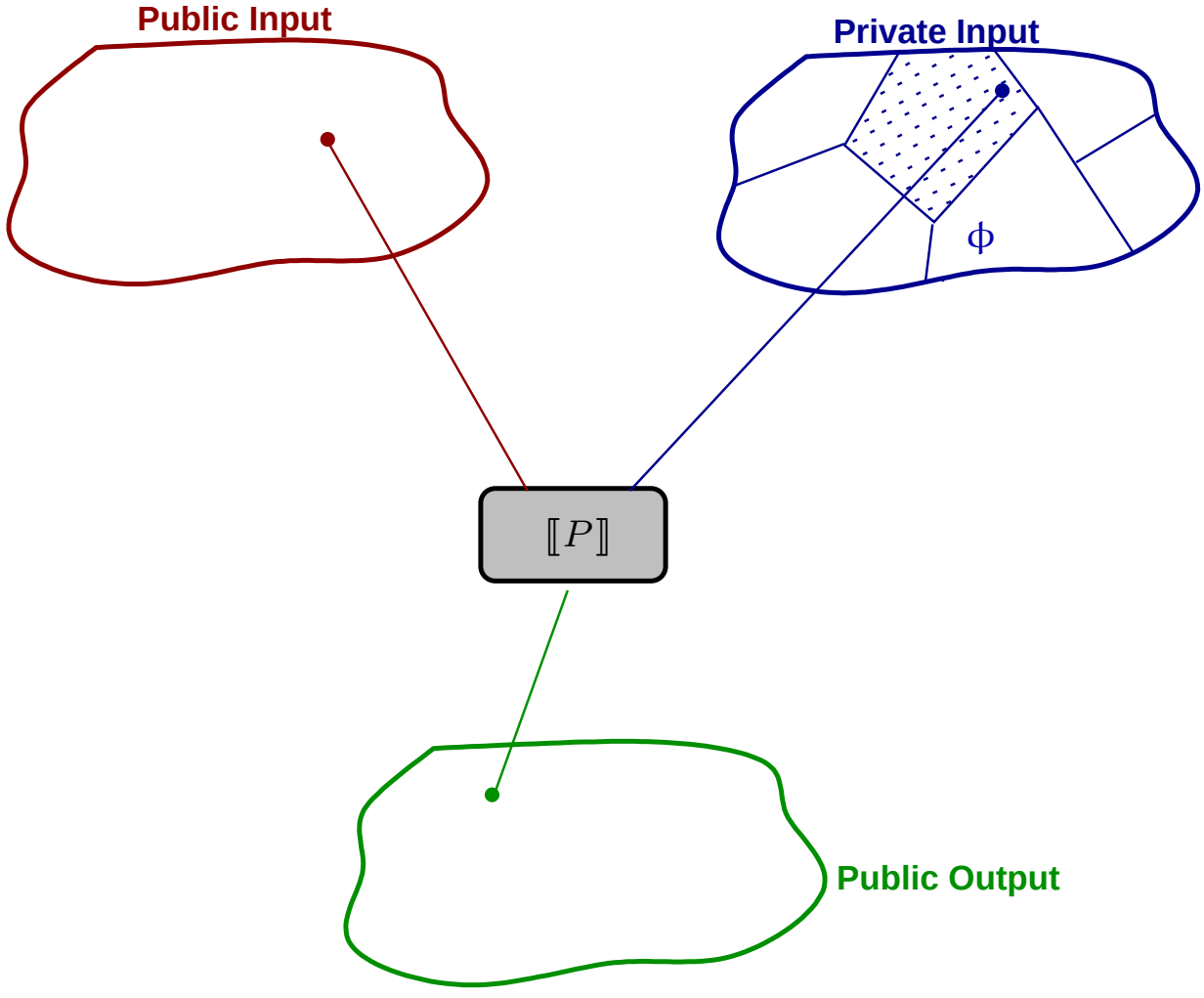

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Modelling declassification: A running example

Let $\phi = \text{Parity} \stackrel{\text{def}}{=} \{\top, \mathit{Even}, \mathit{Odd}, \varnothing\}$,

$$P = \left[\begin{array}{l} h := |h|; \\ \textbf{while } (h > 0) \textbf{ do } (h := h - 1; l := h) \textbf{ endw} \end{array} \right.$$

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$$
\begin{array}{l}
\quad \{h \in \mathbb{Z}\} \\
h := |h|; \\
\quad \{(h = 0 \wedge l = 0) \ \vee h > 0\} \\
\textbf{while } (h > 0) \textbf{ do } (h := h - 1; l := h) \textbf{ endw} \\
\quad \{l = 0\}
\end{array}
$$

$\mathbb{Z} \in \phi \Rightarrow \phi$ is ok!

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\qquad \{l = a \neq 0\}
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$\{0\} \notin \phi \Rightarrow \phi$ is not ok!

Modelling declassification: A running example

Let ϕ = Parity $\stackrel{\text{def}}{=} \{\top, \mathit{Even}, \mathit{Odd}, \varnothing\}$,

$H_a = \left\{ \langle h, l \rangle \;\middle|\; h \in \mathbb{Z}, l = a \right\}$ (a value observed in output).

$$P = \left[\begin{array}{l} h := |h|; \\ \textbf{while } (h > 0) \textbf{ do } (h := h - 1; l := h) \textbf{ endw} \end{array} \right.$$

$$\mathit{Wlp} : \left\{ \begin{array}{lcll} H_0 & \mapsto & \{\langle h, l \rangle \mid h \neq 0, l \in \mathbb{Z}\} \cup \{\langle 0, 0 \rangle\} & \\ H_a & \mapsto & \{\langle 0, a \rangle\} & (a \neq 0) \end{array} \right.$$

P secure with ϕ declassified $\Leftrightarrow$ $\mathcal{H}^{\Phi} \circ \mathit{Wlp}_P \circ \mathcal{H} = \mathit{Wlp}_P \circ \mathcal{H}$

DNI: A completeness problem (1)

Let $\mathcal{H}^{\Phi}$ the abstract domain declassifying the property ϕ of the private *input*:

$$\mathcal{H} \circ [\![P]\!] \circ \mathcal{H}^{\Phi} = \mathcal{H} \circ [\![P]\!] \Leftrightarrow \mathcal{H}^{\Phi} \circ \mathit{Wlp}_P \circ \mathcal{H} = \mathit{Wlp}_P \circ \mathcal{H}$$

$\Downarrow$

To release ϕ *means* to distinguish between elements in ϕ!

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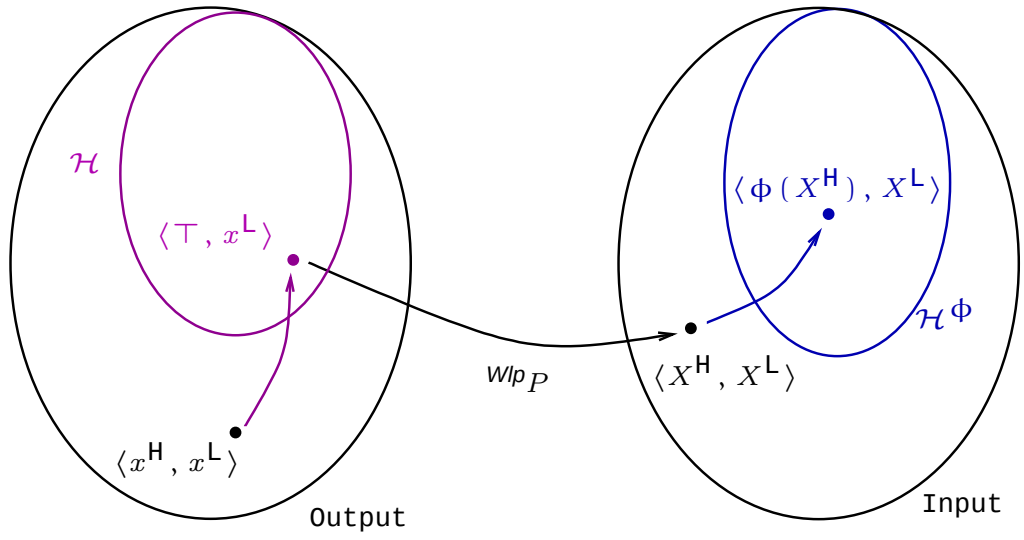

Deriving counterexamples: A running example

Consider again $\phi = \text{Parity} \stackrel{\text{def}}{=} \{\top, \mathit{Even}, \mathit{Odd}, \varnothing\}$,

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Deriving counterexamples: A running example

Consider again $\phi = \text{Parity} \stackrel{\text{def}}{=} \{\top, \mathit{Even}, \mathit{Odd}, \varnothing\}$,

$$\{h = 0\} \qquad \Rightarrow \mathit{Even} \text{ split in } \{0\} \text{ and } \mathit{Even} \setminus \{0\}$$
$$h := |h|;$$
$$\{h = 0 \wedge l = a\}$$
$$\textbf{while } (h > 0) \textbf{ do } (h := h - 1; l := h) \textbf{ endw}$$
$$\{l = a \neq 0\}$$

Let $l = 5$, $h_1 = 0 \in \mathit{Even}$ and $h_2 = 2 \in \mathit{Even}$:
$$[\![P]\!](\langle 0, 5\rangle) = \langle 0, 5\rangle \neq \langle 0, 0\rangle = [\![P]\!](\langle 2, 5\rangle)$$

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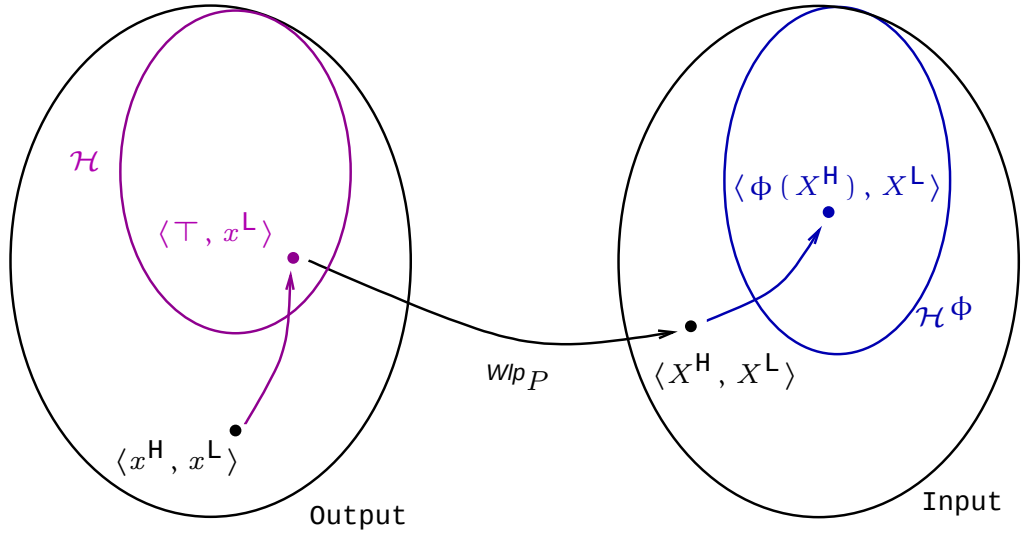

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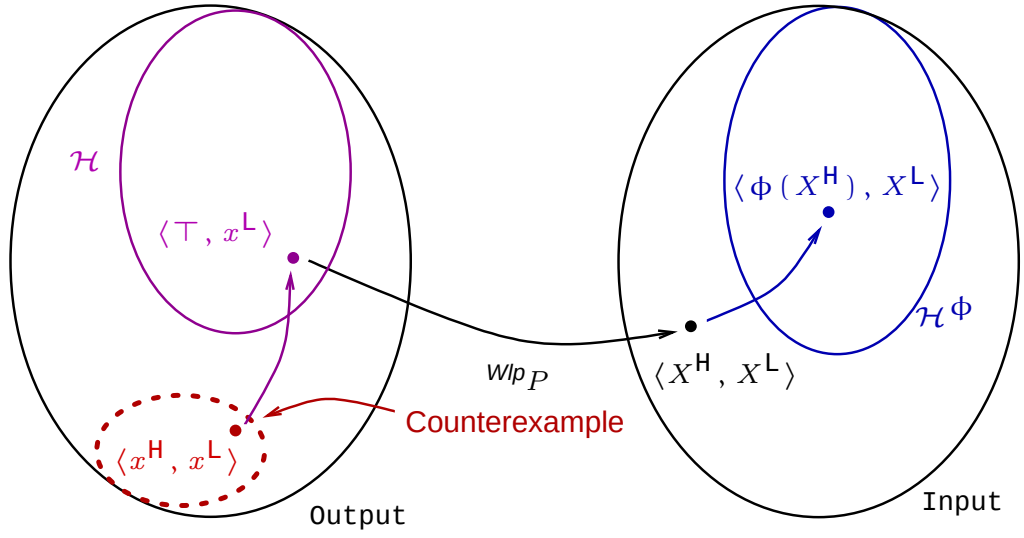

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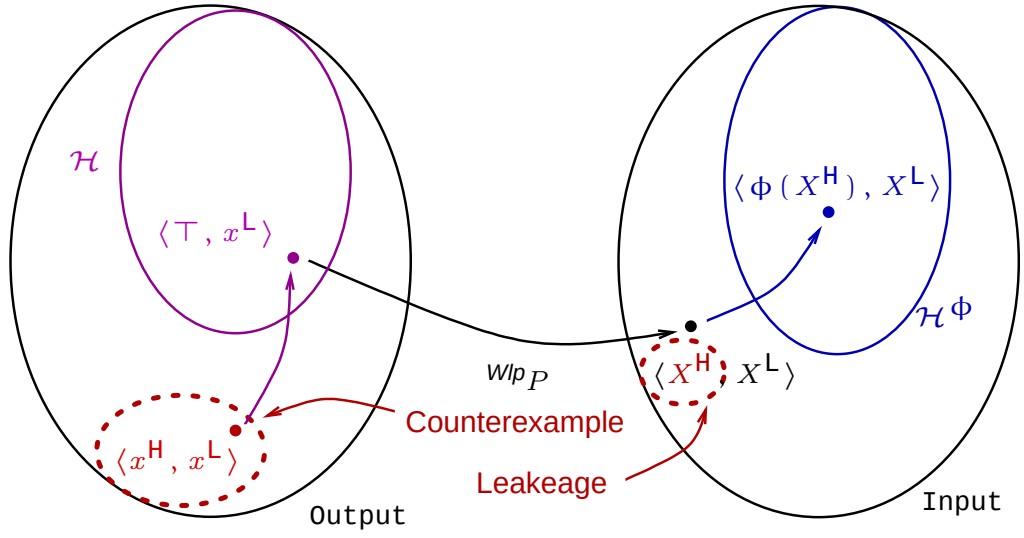

Refining policies: An example

Consider $\phi = \left\{ \left\{ \langle h_1, h_2, \ldots, h_n \rangle \;\middle|\; (h_1 + h_2 + \ldots + h_n)/n = a \right\} \;\middle|\; a \in \mathbb{Z} \right\}$

$$P = \left[\begin{array}{l} h_1 := h_1;\ h_2 := h_2; \ldots;\ h_n = h_n \\ avg := \mathsf{declassify}((h_1 + h_2 + \ldots + h_n)/n); \end{array} \right.$$

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$$
\begin{array}{l}
\quad \{h_1 = a\} \\
h_1 := h_1;\ h_2 := h_2; \ldots;\ h_n = h_n \\
\quad \{(h_1 + h_2 + \ldots + h_n)/n = a\} \\
avg := \mathsf{declassify}((h_1 + h_2 + \ldots + h_n)/n); \\
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\end{array}
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$\left\{ \langle h_1, h_2, \ldots, h_n \rangle \,\middle|\, (h_1 + h_2 + \ldots + h_n)/n = a, h_1 = a \right\} \notin \phi \Rightarrow \phi$ is not ok!

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$$\mathit{Wlp}: \quad H_a \quad \mapsto \quad \left\{ \langle a, h_2, \ldots, h_n, a \rangle \;\middle|\; avg = a \right\}$$

P secure with ϕ' declassified $\Leftrightarrow \quad \phi' = \phi \sqcap \left\{ \mathit{Wlp}(H_a) \;\middle|\; a \in \mathbb{Z} \right\}$

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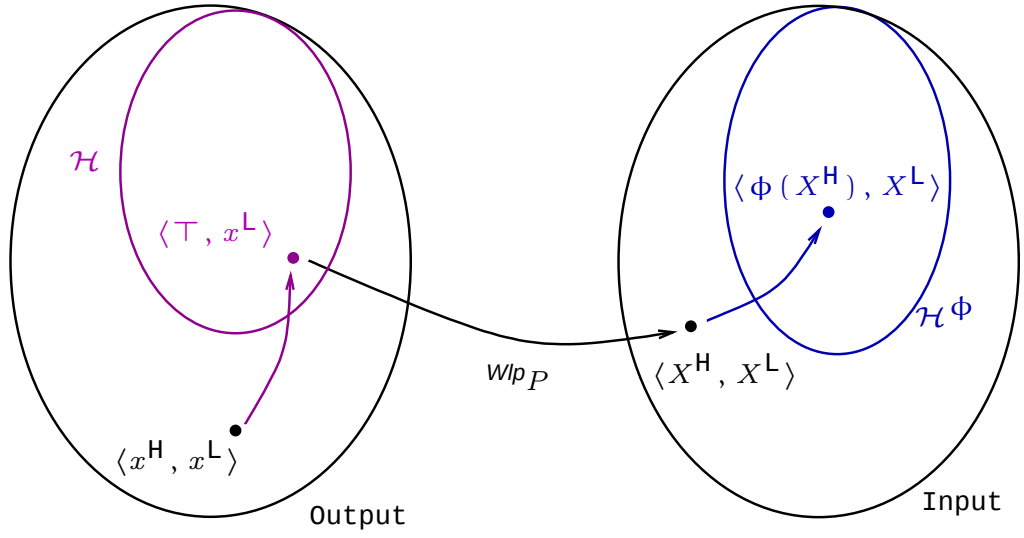

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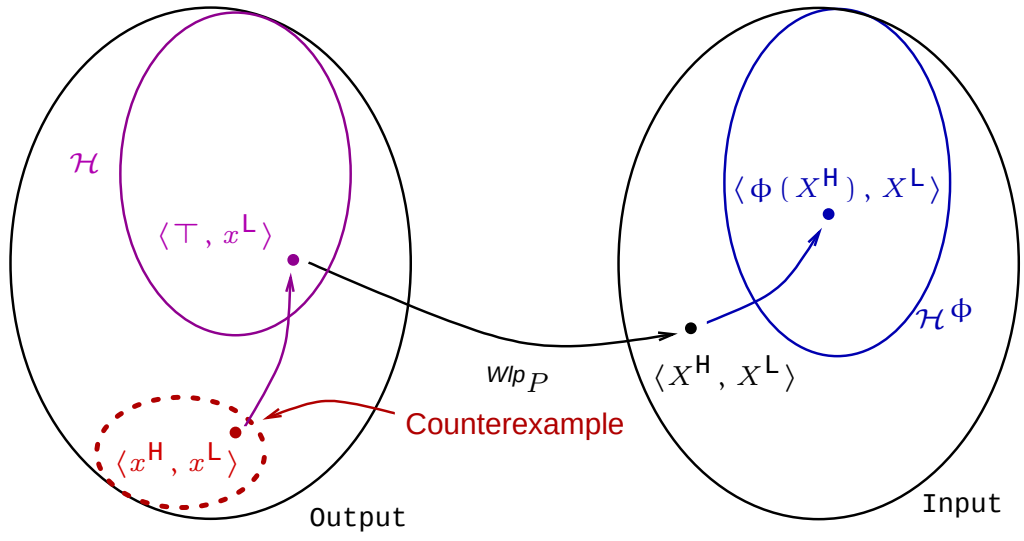

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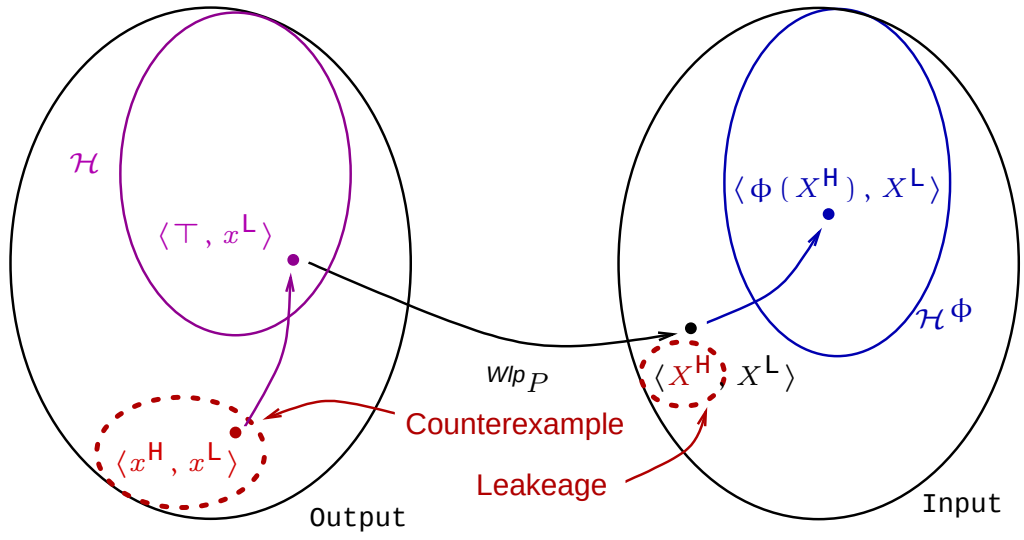

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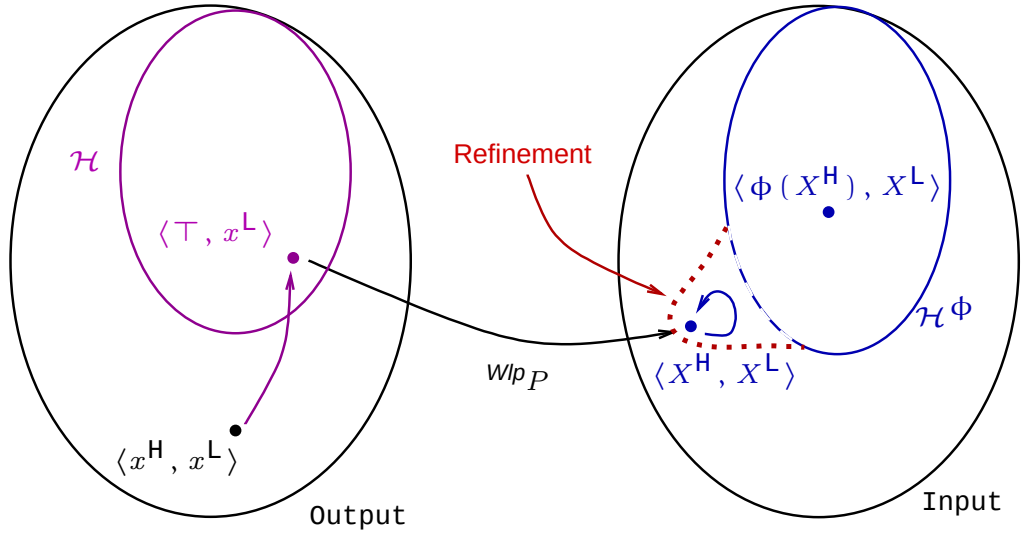


Example: Oblivious Transfer Protocol

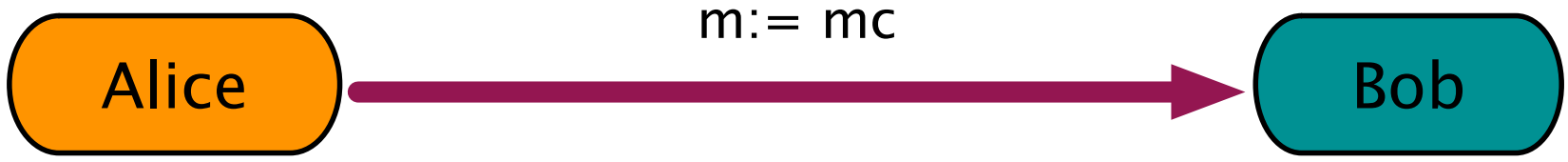
[C. Morgan]

Alice has two messages;
Bob knows their "names",
but not their contents.

Bob asks for one,
by name.

m0, m1: M

c: {0,1}



Alice sends the message...

...Bob receives it

PROBLEM: Alice is not to know which message Bob asked for
Bob is not to know the other message

Example: Oblivious Transfer Protocol

[C. Morgan]
Ted: Trusted party

	Alice	Bob
Hid:	$r; d; c \in \{0,1\}; m$	$m_0; m_1; r_0; r_1$
Vis:	$m_0; m_1; r_0; r_1; f_0; f_1; e$	$c; m; d; r; f_0; f_1; e$

$$P \stackrel{\text{def}}{=} \left[\begin{array}{l} r_0, r_1 :\in M;\ d :\in \{0,1\}; \\ r := r_d; \\ e := c \oplus d; \\ f_0, f_1 := m_0 \oplus r_e,\ m_1 \oplus r_{1\oplus e}; \\ m := f_c \oplus r; \end{array}\right.$$

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Vis:	$m_0; m_1; r_0; r_1; f_0; f_1; e$	$c; m; d; r; f_0; f_1; e$

Bob's point of view: He has not to see $m_{1 \oplus c}$

$r_0, r_1 :\in M;\ d :\in \{0,1\};$
$r := r_d;$
$\quad \{(c = d, f_0 = m_0 \oplus r_0, f_1 = m_1 \oplus r_1) \vee (c \neq d, f_0 = m_0 \oplus r_1, f_1 = m_1 \oplus r_0)\}$
$e := c \oplus d;$
$\quad \{f_0 = m_0 \oplus r_e, f_1 = m_1 \oplus r_{1 \oplus e}\}$
$f_0, f_1 := m_0 \oplus r_e,\ m_1 \oplus r_{1 \oplus e};$
$m := f_c \oplus r;$
$\quad \{f_0; f_1; m\}$

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Hid:	$r; d; c \in \{0,1\}; m$	$m_0; m_1; r_0; r_1$
Vis:	$m_0; m_1; r_0; r_1; f_0; f_1; e$	$c; m; d; r; f_0; f_1; e$

Bob's point of view: He has not to see $m_{1 \oplus c}$

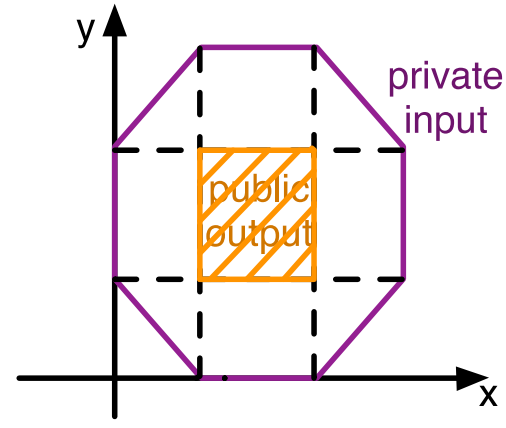
Soundness guarantees that Bob knows $m = m_c, f_c, r_d$
Wlp guarantees that Bob knows only $f_c = m_c \oplus r_d$ and $f_{1 \oplus c} = m_{1 \oplus c} \oplus r_{1 \oplus d}$

$\Downarrow$

$f_{1 \oplus c}$ tells *almost nothing* of the secret $m_{1 \oplus c}$

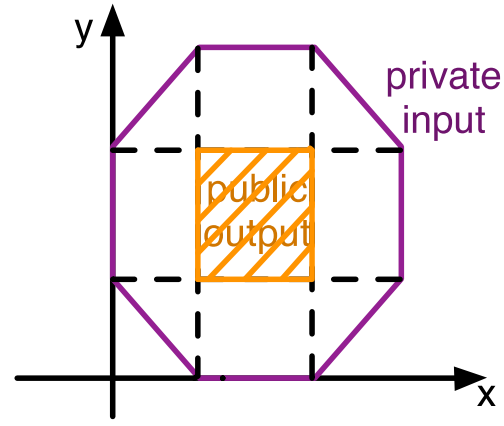
Declassified *Abstract* non-interference

$$P \stackrel{\text{def}}{=} \left[\begin{array}{l}
\textbf{if}(d \leq x+y \leq d+d_x+d_y \ \wedge\ -d_y \leq x-y \leq d_x)\ \textbf{then} \\
\quad \textbf{if}(x \geq 0 \ \wedge x \leq d)\ \textbf{then}\ x_L := d; \\
\quad \textbf{if}(x > d \ \wedge\ x \leq d_x)\ \textbf{then}\ \ x_L := x; \\
\quad \textbf{if}(x > d_x \ \wedge\ x \leq d_x + d)\ \textbf{then}\ x_L := d_x; \\
\quad \textbf{if}(y \geq 0 \ \wedge y \leq d)\ \textbf{then}\ y_L := d; \\
\quad \textbf{if}(y > d \ \wedge\ y \leq d_y)\ \textbf{then}\ \ y_L := y; \\
\quad \textbf{if}(y > d_y \ \wedge\ y \leq d_y + d)\ \textbf{then}\ y_L := d_y;
\end{array}\right.$$



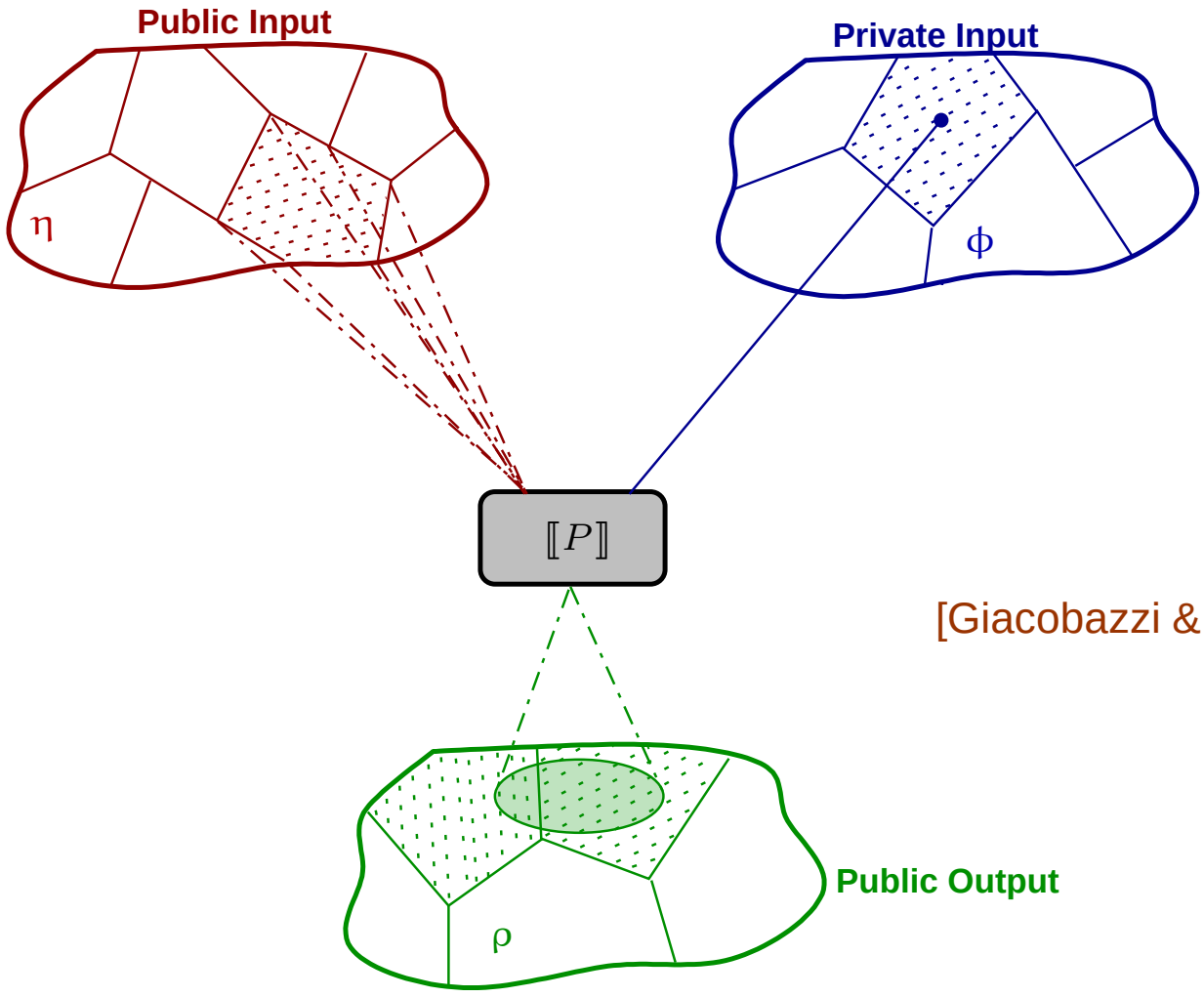
Declassified *Abstract* non-interference

$$P \stackrel{\text{def}}{=} \left[\begin{array}{l}
\textbf{if}(d \le x+y \le d+d_x+d_y \ \wedge\ -d_y \le x-y \le d_x)\ \textbf{then} \\
\quad \textbf{if}(x \ge 0 \ \wedge x \le d)\ \textbf{then}\ x_L := d; \\
\quad \textbf{if}(x > d \ \wedge\ x \le d_x)\ \textbf{then}\ \ x_L := x; \\
\quad \textbf{if}(x > d_x \ \wedge\ x \le d_x + d)\ \textbf{then}\ x_L := d_x; \\
\quad \textbf{if}(y \ge 0 \ \wedge y \le d)\ \textbf{then}\ y_L := d; \\
\quad \textbf{if}(y > d \ \wedge\ y \le d_y)\ \textbf{then}\ \ y_L := y; \\
\quad \textbf{if}(y > d_y \ \wedge\ y \le d_y + d)\ \textbf{then}\ y_L := d_y;
\end{array}\right.$$



$$\mathcal{H}^{\Phi}{}_{\eta} \circ \mathit{Wlp}_P \circ \mathcal{H}_{\rho} = \mathit{Wlp}_P \circ \mathcal{H}_{\rho}$$

Declassified *Abstract* non-interference



[Giacobazzi & Mastroeni '04]

$\rho, \eta \in \mathit{Abs}(\wp(\mathbb{V}^{\mathsf{L}})), \phi \in \mathit{Abs}(\wp(\mathbb{V}^{\mathsf{H}}))$: $(\eta)P(\phi \Rightarrow \rho)$:

$\eta(l_1) = \eta(l_2)$ and $\phi(h_1) = \phi(h_2) \Rightarrow \rho(\llbracket P \rrbracket(h_1, \eta(l_1))^{\mathsf{L}}) = \rho(\llbracket P \rrbracket(h_2, \eta(l_2))^{\mathsf{L}})$

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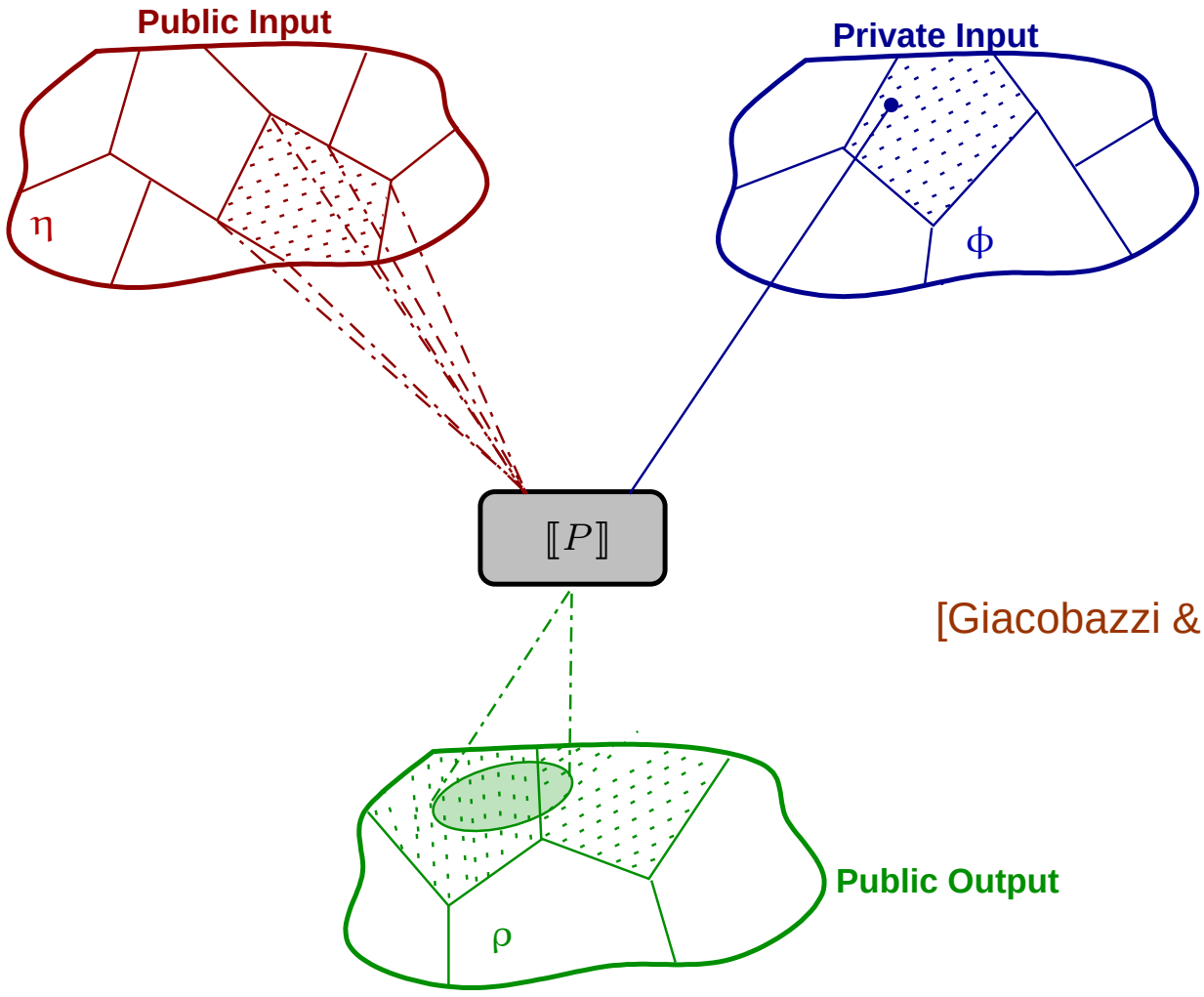

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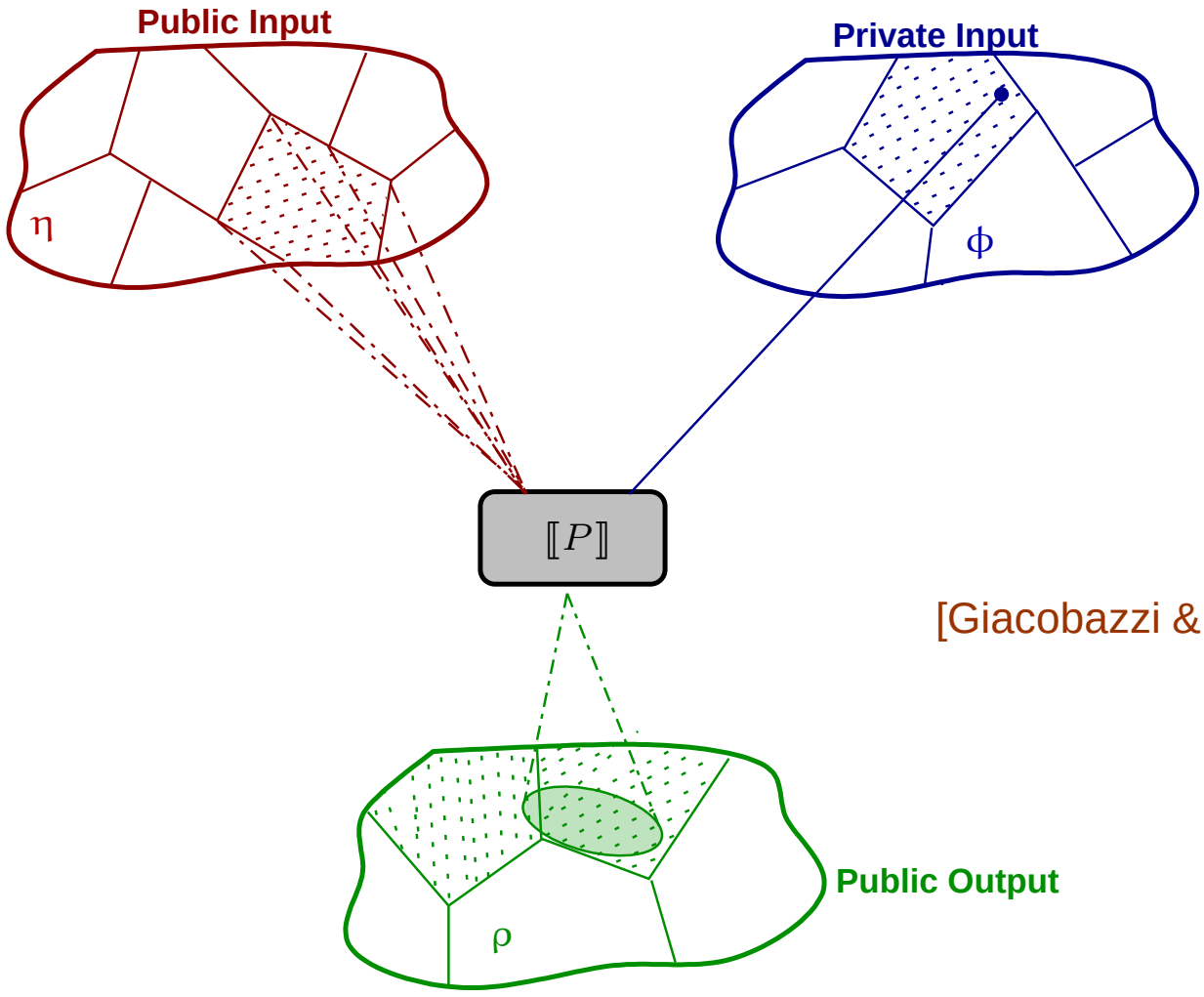

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Abstract Model checking DNI

- Robust declassification transforms the attacker observational capability [Zdancewic & Myers '01]:

$$\forall \sigma, \sigma' \in \Sigma \,.\, \langle \sigma, \sigma' \rangle \in S[\approx] \;\Leftrightarrow\; Obs_{\sigma}(S, \approx) \equiv Obs_{\sigma'}(S, \approx)$$

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- $S[\approx] = \approx$ iff $\approx$ backward complete for *post*

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- Example:

$$\begin{array}{lcll}
\langle t, h, p, q, r \rangle & \mapsto & \langle t, h, p, q, r \rangle & \\
\langle 0, h, q, q, 0 \rangle & \mapsto & \langle 1, h, q, q, 1 \rangle & \\
\langle 0, h, q, q, 1 \rangle & \mapsto & \langle 1, h, q, q, 0 \rangle & \\
\langle 0, h, p, q, 0 \rangle & \mapsto & \langle 1, h, p, q, 0 \rangle & p \neq q \\
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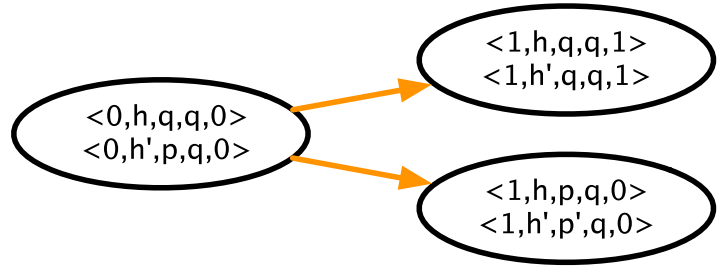
\end{array}$$



The public variables are t, q, r, hence the partition induced by $\mathcal{H}$ is:

$$\langle t, h, p, q, r \rangle \;\equiv\; \langle t', h', p', q', r' \rangle \text{ iff } t = t' \;\wedge\; q = q' \;\wedge\; r = r'$$

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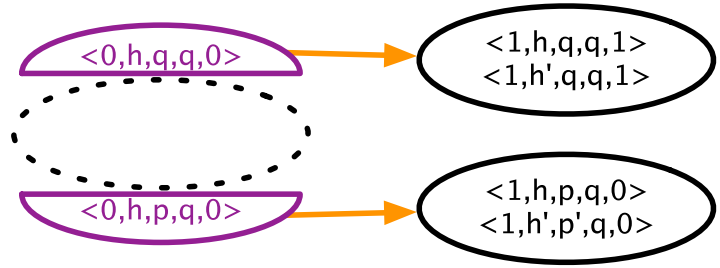

$$\langle 0, h, p, q, 0 \rangle \mapsto \left\{ \begin{array}{l} \langle 1, h, q, q, 1 \rangle \\ \langle 1, h, p, q, 0 \rangle \end{array} \right. \quad \widetilde{pre}_P : \left\{ \begin{array}{l} \langle 1, h, q, q, 1 \rangle \mapsto \langle 0, h, q, q, 0 \rangle \\ \langle 1, h, p, q, 0 \rangle \mapsto \langle 0, h, p, q, 0 \rangle \end{array} \right. \quad p \neq q$$

Discussion

- What already exists: *Several studies about declassification, derivation of counterexamples and refinements... nothing that combines all together*
  - Several approaches for modelling and checking declassification policies: PER model [Sabelfeld and Sands], dynamic logic [Darvas et al.], robust declassification [Zdancewic and Myers], Delimited release [Sabelfeld and Myers], Relaxed non-interference [Li and Zdancewic],...;
  - Derivation of counterexamples of secure information flows (without declassification) [Unno et al.];
  - Preservation of secrecy under refinement [Alur et al.];

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- What we have done: Modelling declassification as a completeness problem;
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  - We create a connection with abstract model checking;
- What we have to do: We are interested in...
  - ...extending our approach to more complex systems;
  - ...exploiting this connection for implementing our approach;

Abstract Interpretation

Consider the complete lattice $< C, \leq, \wedge, \vee, \bot, \top >$, $A_i \in \mathit{uco}(C)$

Lattice of Abstract Domains $\equiv$ Lattice *uco*

$\mathsf{A} \equiv \wp(C)$

$< \mathit{uco}(C), \sqsubseteq, \sqcap, \sqcup, \lambda x.\ \top, \lambda x.\ x >$

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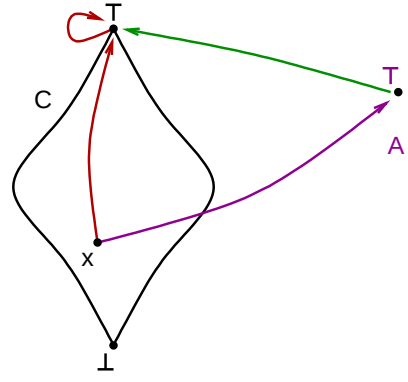

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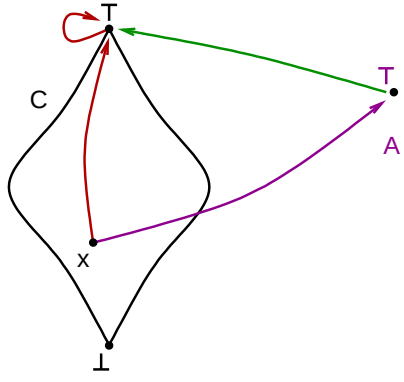
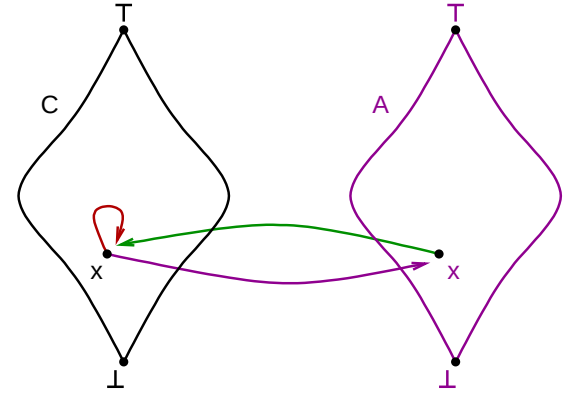


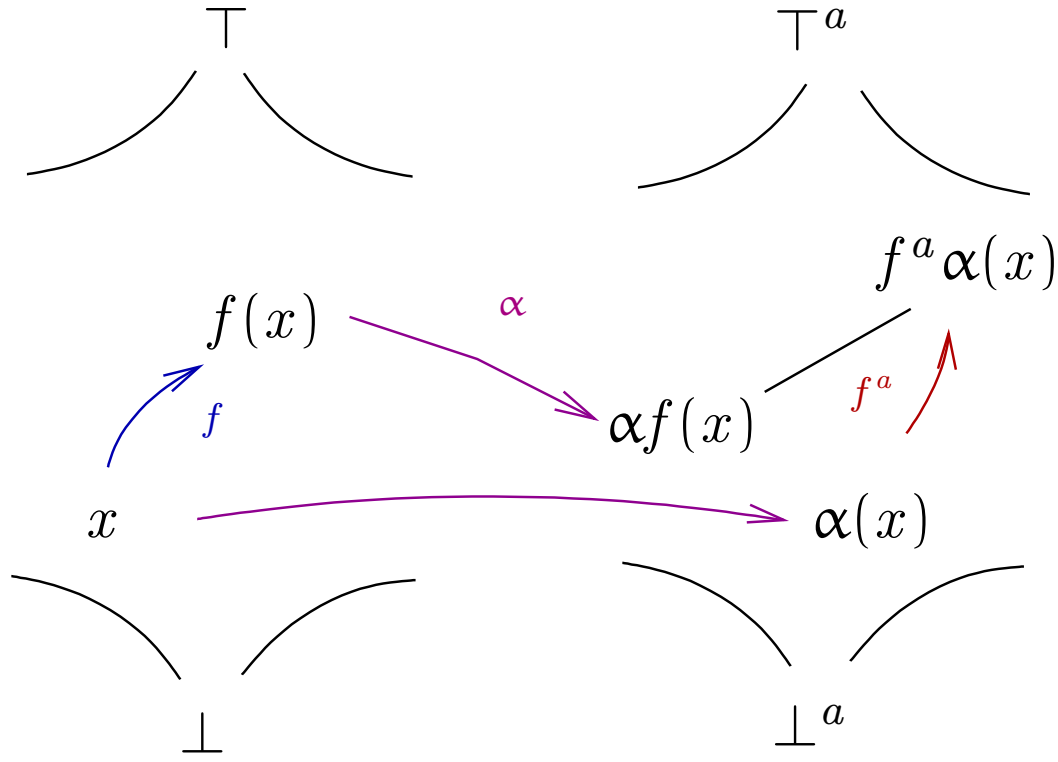
Bottom:



Abstract domain *backward* completeness

Let $< A, \alpha, \gamma, C >$ a Galois insertion. [Cousot & Cousot '77,'79]
$f : C \longrightarrow C$, $f^a = \alpha \circ f \circ \gamma : A \longrightarrow A$ (b.c.a. of f) and $\rho = \gamma \circ \alpha$

ρ correct for f



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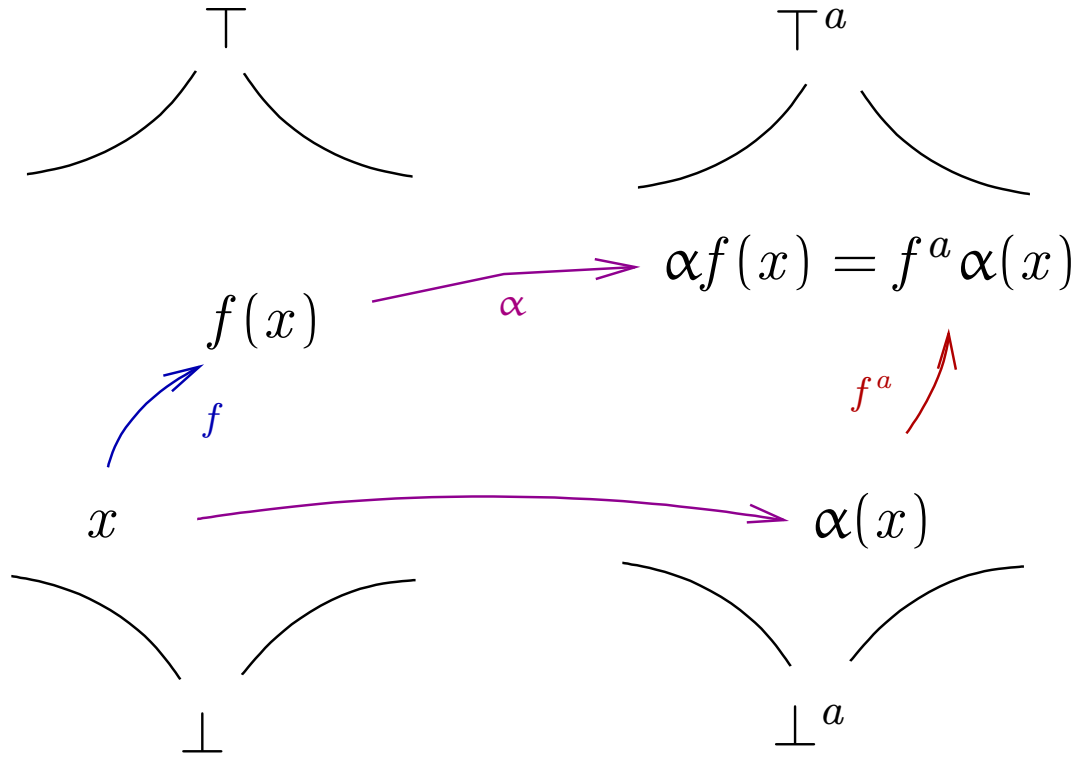
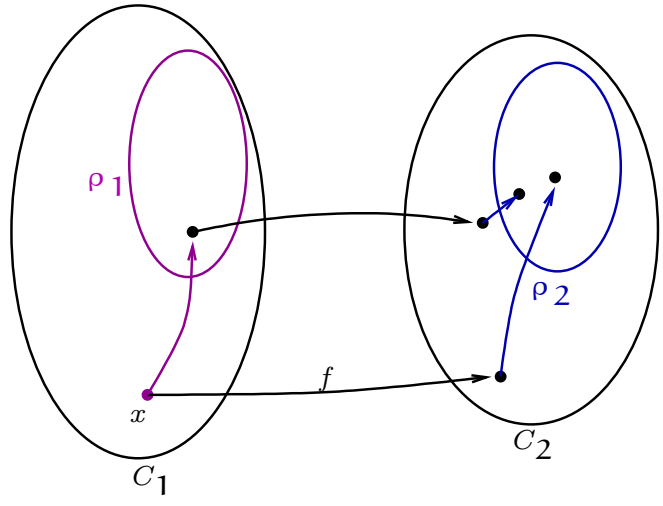
$\Updownarrow$

$\rho f \rho = \rho f$



Making *backward* complete

Giacobazzi et al. ‘00



$$\rho_2 f \rho_1 = \rho_2 f$$

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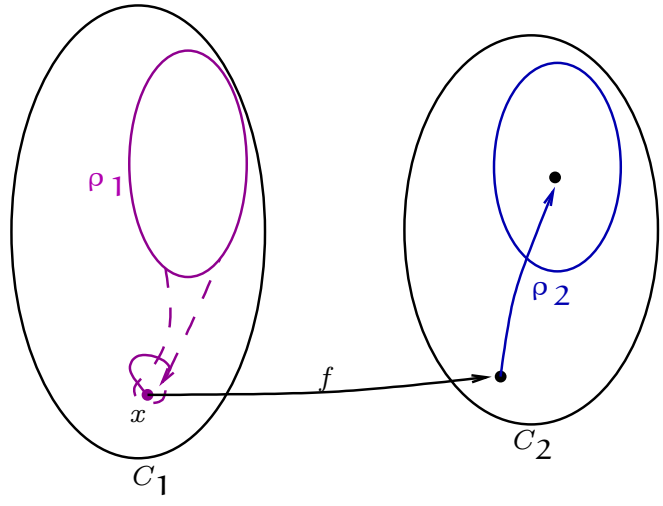

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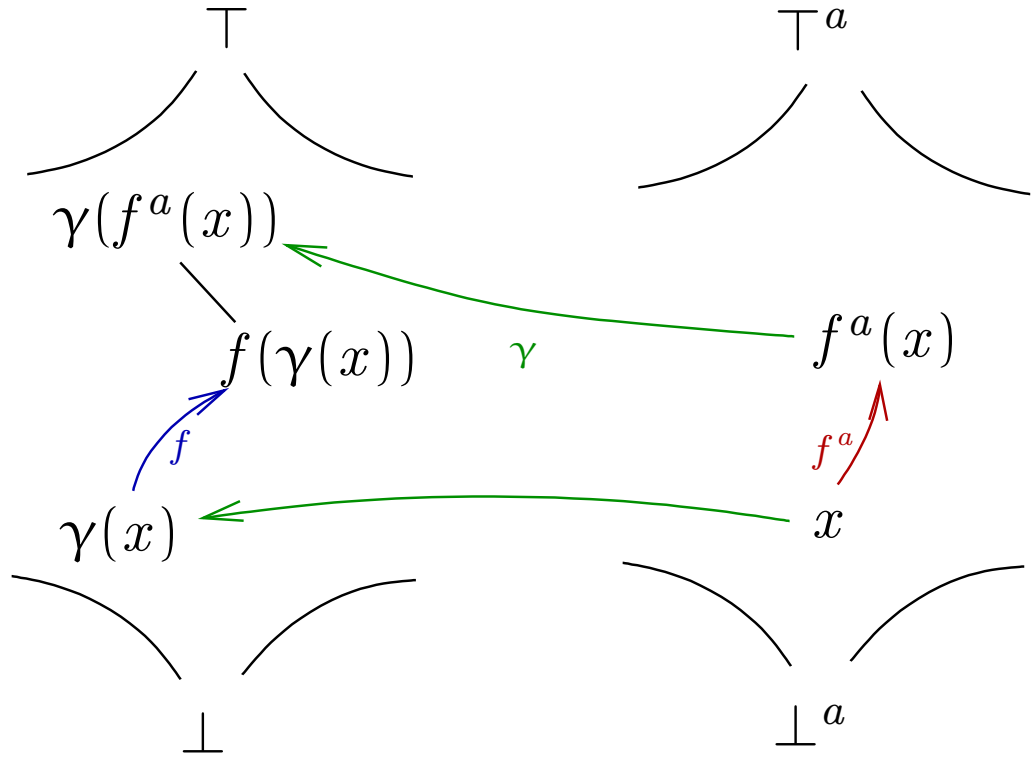

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