Categories for Cryptographic Composability

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Advised by Angélica and Adam

Cryptography

The Simulation Paradigm

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2. A real protocol to analyze
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We will treat the more limited setting of N-party computation.

Ideal Functionalities

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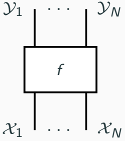

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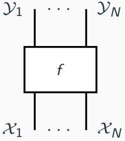

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Running example: $f(x, y) = (*, xy)$.

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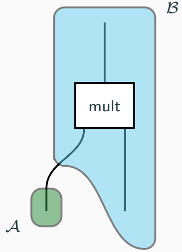

Adversarial Behavior

We will treat *honest* adversaries. Usually you want to quantify over adversarial machines $\mathcal{A}'$.

Computational Indistinguishability

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Definition
Two probability ensembles $\{X_n\}$ and $\{Y_n\}$ (over the set A) are *computationally indistinguishable* if for any distinguisher $\mathcal{D}$,

$$\Big| \Pr[\mathcal{D}(X_n) = 1] - \Pr[\mathcal{D}(Y_n) = 1] \Big| = \mathsf{negl}(n).$$

We write $\{X_n\} \stackrel{c}{\equiv} \{Y_n\}$.

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Definition
A protocol $\langle \mathcal{A}_1, \ldots, \mathcal{A}_N \rangle$ is *secure* if for each choice of inputs $x_1, \ldots, x_N$ and each party i, there exists a simulator $\mathcal{S}$ such that

$$\mathcal{S}(x_i, f_i(x_1, \ldots, x_N)) \stackrel{c}{\equiv} \mathsf{view}_i^{\langle \mathcal{A}_1, \ldots, \mathcal{A}_N \rangle}(x_1, \ldots, x_N).$$

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Our running example is secure: the simulator can compute xy/y.

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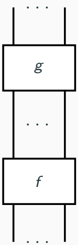
At least two ways to compose ideal functionalities:



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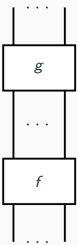

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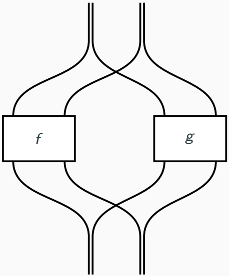

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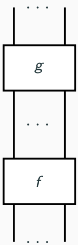

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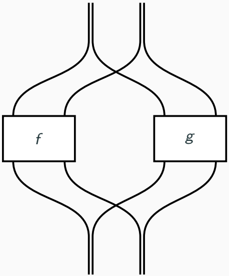

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Many more things to consider.

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- High proof burdens

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- Arbitrary adversarial behavior
- Asymptotic and polynomial bounds
- Very general composition operations

Category Theory

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A category has:

- objects $x, y, z, \ldots$;
- morphisms $x \xrightarrow{f} y, \ldots$;
- identities $x \xrightarrow{1_x} x$;
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- $\textsc{Chem}$: multisets of chemicals and reactions (Baez-Pollard 2017);
- functional programming languages & logics.

Functors

A *functor* $F : \mathcal{C} \to \mathcal{D}$ assigns:

- to each $x \in \mathcal{C}$, an $Fx \in \mathcal{D}$;
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- the free group, vector space, etc.

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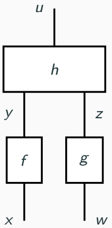
- $\textsc{Chem}$ with the union of multisets of molecules;
- Concurrent languages with concurrent joining and the do-nothing program.

String Diagrams

Given $f : x \to y$, $g : w \to z$, and $h : y \otimes z \to u$, interpret



as $h(f \otimes g)$.

Categorical Cryptography

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- A functorial construction of a SMC of protocols;
- A security definition which works over any SMC.

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Final try (Pavlovic 2014): Comp (binary-encoded sets and lifts of computable functions).

Efficient and Effectful Computation

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Name	Computational Bound	Effect
Enc	none	none
Comp	computability	none
CompStoch	computability	probability
Poly	poly-time computability	none
PPT	poly-time computability	probability

Non-interactive "Protocols"

The category $\mathcal{C} \times \mathcal{D}$ has:

- for objects, pairs (c, d) from $\mathcal{C}$ and $\mathcal{D}$;
- for morphisms, pairs (f, g) from $\mathcal{C}$ and $\mathcal{D}$;
- composition and identities componentwise.

States

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The category $\mathrm{st}(\mathcal{C} \xrightarrow{F} \mathcal{D})$ has:

- for objects, maps $I \to Fx$ in $\mathcal{D}$;
- for morphisms $(I \xrightarrow{s} Fx) \to (I \xrightarrow{t} Fy)$, maps $x \xrightarrow{f} y$ in $\mathcal{C}$ such that $(Ff)s = t$;
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We think of $\mathcal{C}$ as “free” processes in $\mathcal{D}$.

Combs

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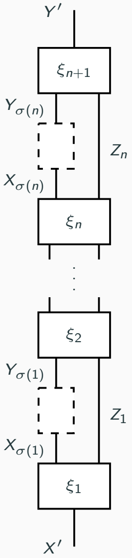

Assigning Resources

In n-comb($\mathcal{C}$), there are two ways we control the assignment of resources:

- a function α assigns each pair in the codomain some resources from the domain;
- a permutation σ orders the resources assigned to each comb.

Let's play with this!

The category of protocols

The category

$$\mathrm{prot}_N(\mathcal{C}) := \mathrm{st}(\text{n-comb}(\mathcal{C}^N) \xrightarrow{\text{n-comb}(\otimes^{N-1})} \text{n-comb}(\mathcal{C}))$$

has:

- for objects, objects maps $(X_1 \otimes \cdots \otimes X_N) \to (Y_1 \otimes \cdots \otimes Y_N)$ in $\mathcal{C}$;
- for morphisms, combs drawn from $\mathcal{C}^N$ which preserve the chosen maps.

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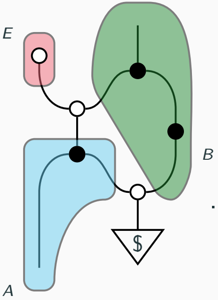

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1-4) $\cdots$

5) If $h \in \mathbb{A}(f \otimes g)$ such that $\operatorname{dom} h = x \otimes y$ for some objects x and y, then there is some $h' \in \mathbb{A}1_{\operatorname{cod} f \otimes \operatorname{cod} g}$, $f' \in \mathbb{A}f$, and $g' \in \mathbb{A}g$ such that $\operatorname{dom} f' = x$, $\operatorname{dom} g' = y$, and $h = h' \circ (f' \otimes g')$.

The Security Definition

Definition

Let $\mathcal{C} \xrightarrow{F} \mathcal{D} \xrightarrow{G} \mathcal{E}$ be a string of symmetric monoidal functors so that F is strong monoidal. Let $\mathbb{A}$ be an attack model on $\mathcal{D}$. Let $f : (x, s) \to (y, t)$ be a map in $\mathrm{st}(GF)$ and let a be a map in $\mathcal{D}$ with $\operatorname{dom} a = Fx$.

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Further, f is $\mathbb{A}$-*secure* if it is secure against all attacks in $\mathbb{A}Ff$ with domain Fx.

The Composition Theorem

Let $\mathcal{C} \xrightarrow{F} \mathcal{D} \xrightarrow{G} \mathcal{E}$ be a string of symmetric monoidal functors so that F is strong monoidal. Let $\mathbb{A}$ be an attack model on $\mathcal{D}$. Then the class of $\mathbb{A}$-secure maps is closed under monoidal product and sequential composition.

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What about *bi*categories?

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- Many-round composition, dynamic linking, etc

Evaluation

Some concerns:

- Limitations of attack models and the security definition
- Limited forms of composition
- Many-round composition, dynamic linking, etc

Thanks for your time!