Sequential Process Calculus and Machine Models for Simulation-based Security

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Joint work with Anupam Datta, John Mitchell, and Ajith Ramanathan

Simulation-based Security

Basic idea:

1. Describe security requirement in terms of an ideal protocol/functionality $\mathcal{F}$.
2. A real protocol $\mathcal{P}$ is secure w.r.t. $\mathcal{F}$ (realizes $\mathcal{F}$) if everything that can happen to $\mathcal{P}$ can also happen to $\mathcal{F}$.
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But... Many different computational settings and security notions.

Canetti 2001 (PITM)

Computational model:

1. Computational entities:

   Probabilistic polynomial-time interacting turing machines (PITMs)

2. Communication model:

   In a real, ideal, and hybrid model specific ways of communication via tapes between an environment, a (real/ideal) adversary, and the (real/ideal) protocol are defined.

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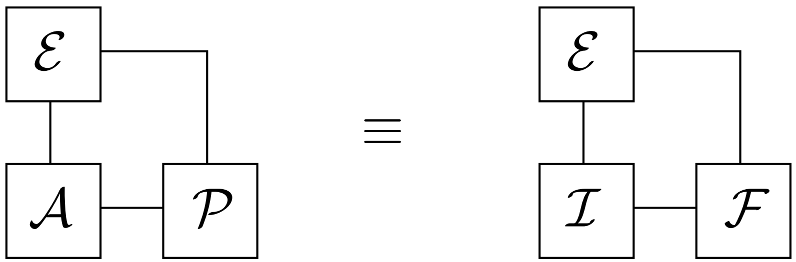
Security notion: Universal composability (UC).

$\mathcal{P}$ and $\mathcal{F}$ are UC if $\forall\, \mathcal{A}\ \exists\, \mathcal{I}\ \forall\, \mathcal{E}$:



Pfitzmann and Waidner 2001 (PIOA)

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1. Computational entities:
   Probabilistic IO automata (PIOAs)
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   General communication model where PIOAs communicate through buffers that need to be triggered to deliver a message. (No need to distinguish between real, ideal, and hybrid communication.)

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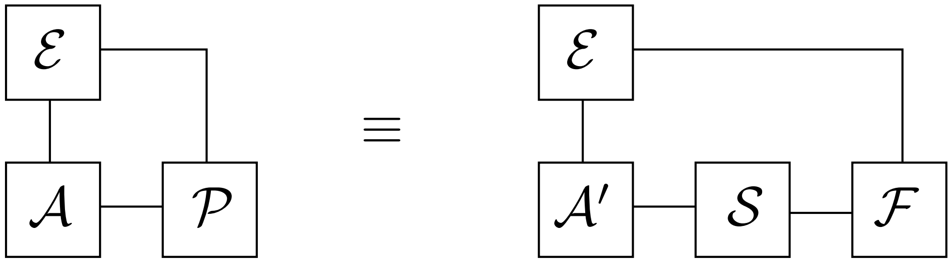
Security notions: UC + (strong) Black-box Simulatability (SBB).

$\mathcal{P}$ and $\mathcal{F}$ are SBB if $\exists\, \mathcal{S}\ \forall\, \mathcal{A}\ \forall\, \mathcal{E}$:



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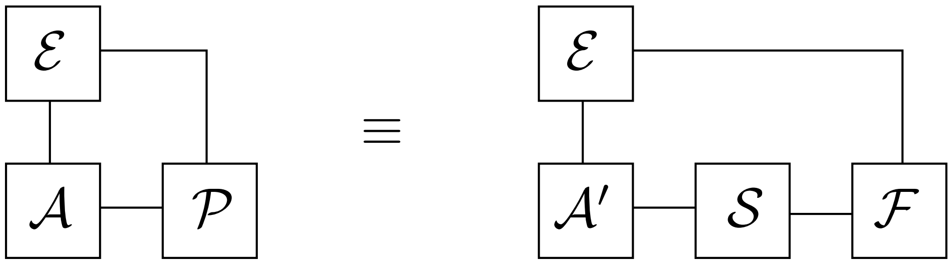

Used in the literature to show UC (obviously: WBB implies UC).

Lincoln, Mitchell^2, Scedrov 1998 (PPC)

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1. Computational entities:
   Probabilistic Polynomial-time Processes
2. Communication model:
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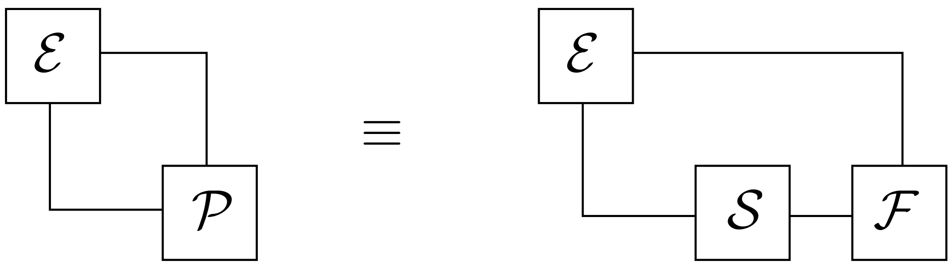
Security notions: Process Congruence/Strong Simulatability (SS)

$\mathcal{P}$ and $\mathcal{F}$ are SS if $\exists\, \mathcal{S}\ \forall\, \mathcal{E}$:



Even More Variety

Different variants of UC, BB, and SS have been considered!

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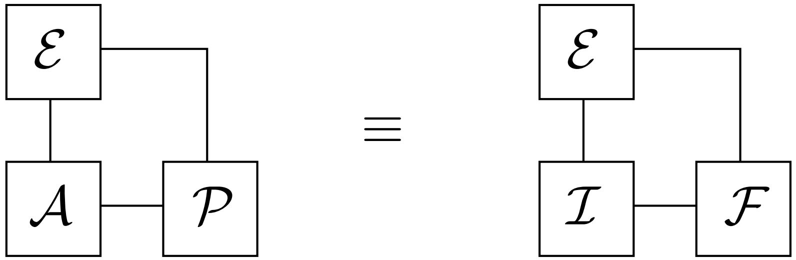

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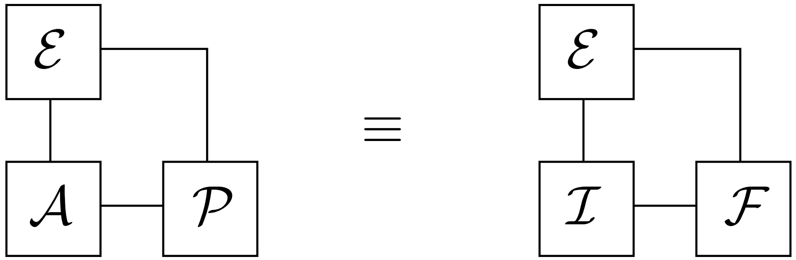

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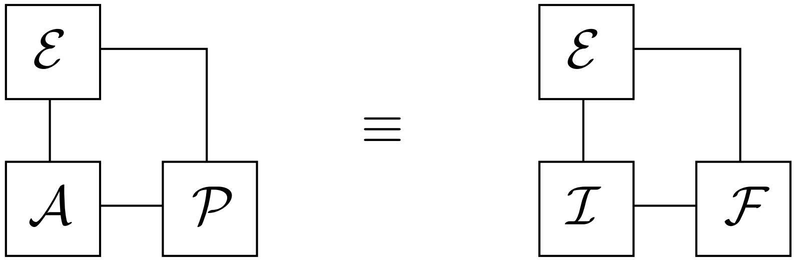

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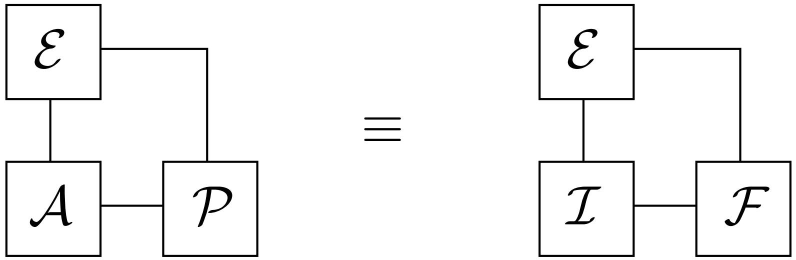

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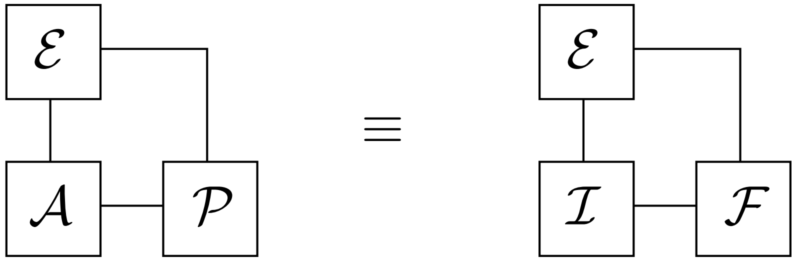

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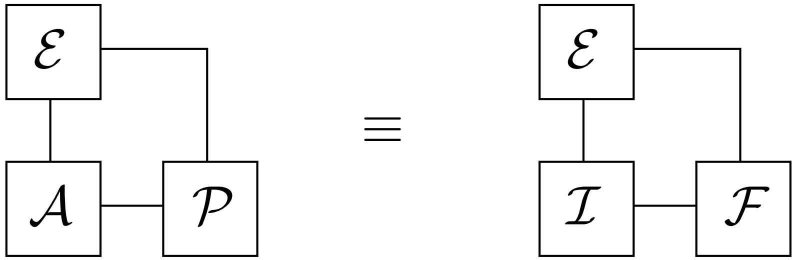

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Who should be the master process?

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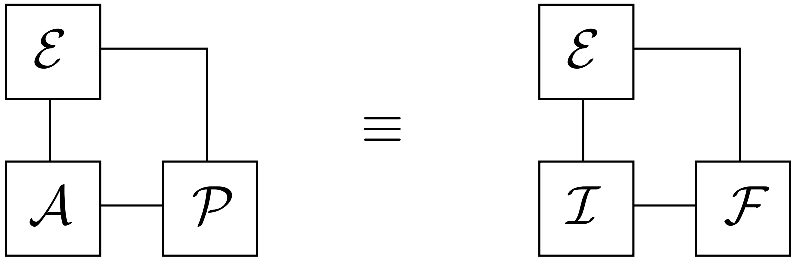

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UC($\mathcal{A}$: **R**, $\mathcal{I}$: **R**, $\mathcal{E}$: **MD**) Canetti 2001

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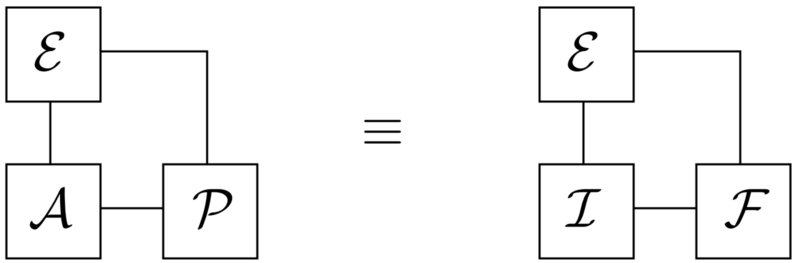

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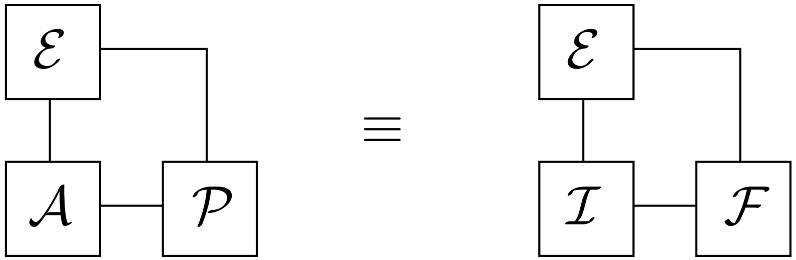

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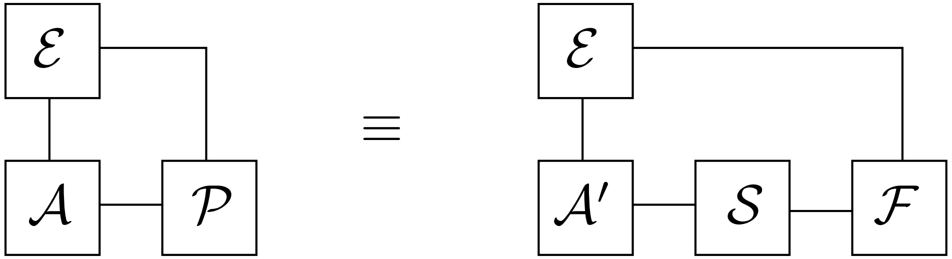

Variants:

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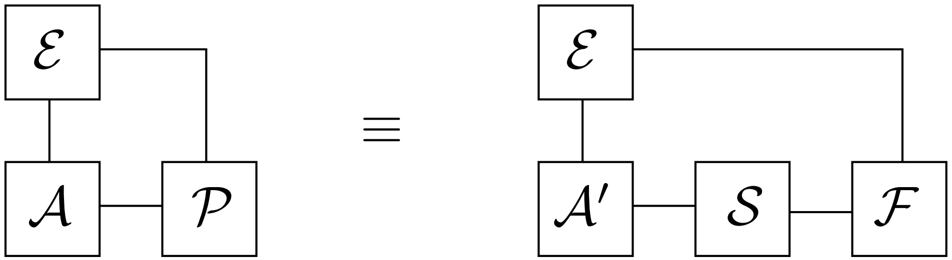

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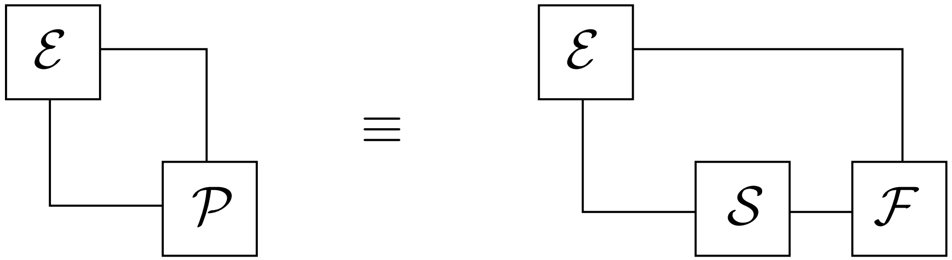

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We introduce Sequential Probabilistic Process Calculus (SPPC).

Sequential Probabilistic Process Calculus (SPPC)

Syntactic and semantic restriction and extension of PPC.

Example process (simplified) corresponding to an IO automaton/ITM:

$$\mathcal{Q} = \quad !_{q(\mathbf{n})}\ \mathtt{in}(c_{\mathtt{s}}, x_s). \quad \sum_{c \in \mathcal{C}_{\mathtt{in}}} \mathtt{in}(c, x). \Bigg(\mathtt{out}(c_{\mathtt{ns}}, T_{ns}(c, x, x_s)) \mid\mid \sum_{c' \in \mathcal{C}_{\mathtt{out}}} \mathtt{in}(c_{\mathtt{ns}}, \langle x'_s, c', y \rangle). \Big(\mathtt{out}(c_{\mathtt{s}}, x'_s) \mid\mid \mathtt{out}(c', y) \Big) \Bigg)$$

Parallel composition of processes:

$$\mathcal{E} \mid\mid \mathcal{A} \mid\mid \mathcal{P}$$

Polynomial composition of processes (used in composition theorem):

$$\mathcal{E} \mid\mid \mathcal{A} \mid\mid !_{q(\mathbf{n})}\ \mathcal{P}$$

Important Feature of SPPC

Sequentiality (unlike PPC): Consider for instance $\mathcal{E} \mid\mid \mathcal{A} \mid\mid \mathcal{P}$.

1. At most one of the three processes is active.
2. The active process may send *at most one* message on an external channel *directly* to another process, and by reading the message, this other process is activated.

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In comparison: PITM and PIOA are also sequential, but

PITM: Activation scheme is "hard-wired" into real, ideal, hybrid model.

PIOA: IO automaton may send *many* messages into different buffers (asynchronous network) and by triggering one buffer one message is delivered.

Advantage of SPPC

Simplicity: Details of network communication (buffers, specific triggering mechanisms, tapes) are not made explicit in SPPC, but

Flexibility: Are part of the protocol specification. For instance, all of the following can be modeled:

1. Insecure, authenticated, secure channels (with your favorite buffers, tapes,...)
2. Synchronous communication.
3. Broadcasting, etc.

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$\Longrightarrow$ SPPC allows to embed other models.

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More specifically, the following notions are equivalent:

1. UC($\mathcal{A}$: **R**, $\mathcal{I}$: **R**, $\mathcal{E}$: **MD**).
2. UC($\mathcal{A}$: **M**, $\mathcal{I}$: **M**, $\mathcal{E}$: **MD**).
3. WBB($\mathcal{A}$: **R**/**M**, $\mathcal{S}$: **R**/**M**, $\mathcal{E}$: **MD**).
4. All variants of SS and SBB (independent of whether $\mathcal{E}$ is **D** or **MD**).

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Assuming the real protocol $\mathcal{P}$ is network predictable, i.e., it is possible to predict on what network channels $\mathcal{P}$ accepts messages depending on the traffic on the network channels.

Without this assumption, SS and SBB are stronger than the other two notions.

Our Results

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and all variants of SS and SBB

$\Longrightarrow$ $\not\Longleftarrow$

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$\Searrow$ $\Nwarrow$? $\Nearrow$ $\not\Swarrow$

WBB($\mathcal{A}$: **M**, $\mathcal{S}$: **R**, $\mathcal{E}$: **D**)

Consequences for other models

PITM (Canetti 2001):

$$\text{UC}(\mathcal{A}\text{: }\mathbf{R},\ \mathcal{I}\text{: }\mathbf{R},\ \mathcal{E}\text{: }\mathbf{MD}) \iff \text{WBB}(\mathcal{A}\text{: }\mathbf{R},\ \mathcal{S}\text{: }\mathbf{R},\ \mathcal{E}\text{: }\mathbf{MD})$$

$$\approx \text{UC'}(\mathcal{A}\text{: }\mathbf{R},\ \mathcal{I}\text{: }\mathbf{R},\ \mathcal{E}\text{: }\mathbf{MD})$$

Consequences for other models

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Problem: Buffers and trigger mechanism used in PIOA.

Solution: Drop buffers and let IO automata talk to each other directly (similar to SPPC).

Results provide counterexamples for a theorem proved in Backes et al. 2004.

Correspondence Between PITM and PIOA Results

Embedding PITM into SPPC:

$$\mathrm{UC}_{PITM}(\mathcal{P},\mathcal{F}) \quad \text{iff} \quad \mathrm{UC}_{SPPC}(\mathrm{SPPC}(\mathcal{P}),\mathrm{SPPC}(\mathcal{F}))$$

Embedding PIOA* (PIOA without buffers) into SPPC:

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Equivalence: $\mathcal{P}_{PITM}$ (PITM) is equivalent to $\mathcal{P}_{PIOA^*}$ (PIOA*) iff

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i.e., $\mathcal{E} \mid\mid \text{SPPC}(\mathcal{P}_{PITM}) \equiv \mathcal{E} \mid\mid \text{SPPC}(\mathcal{P}_{PIOA^*}) \ \forall\, \mathcal{E}$.

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Consequence of our results:

Given $\mathcal{P}_{PITM} \cong \mathcal{P}_{PIOA^*}$ and $\mathcal{F}_{PITM} \cong \mathcal{F}_{PIOA^*}$, we have:

$$\text{UC}_{PITM}(\mathcal{P}_{PITM},\mathcal{F}_{PITM}) \quad \text{iff} \quad \text{SBB}_{PIOA^*}(\mathcal{P}_{PIOA^*},\mathcal{F}_{PIOA^*})$$

Conclusion

- Introduced SPPC as a general computational model for simulation-based security notions that allows to embed other models.

  $\Longrightarrow$ Theorems proved in this model are valid for a broad class of other more specific models.

- Clarified the relationships between different security notions (UC, SBB, WBB, SS) and their variants as considered in the literature. Our proofs are based on a few equational principles.

  $\Longrightarrow$ "Making the environment the master process unifies all security notions."

  $\Longrightarrow$ With appropriate modifications (drop buffers in PIOA), results for SBB/UC proved in PIOA carry over to UC in PITM, and vice versa.

- Proved composition theorem for SPPC.

- Future work: Are there realistic attacks in a concurrent (non-sequential) framework (such as concurrent PPC) not captured by a sequential framework (such as SPPC, PIOA, PITM)?