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Concurrently Composable Security With Shielded Super-polynomial Simulators

B. Broadnax, N. Döttling, G. Hartung, J. Müller-Quade, and M. Nagel

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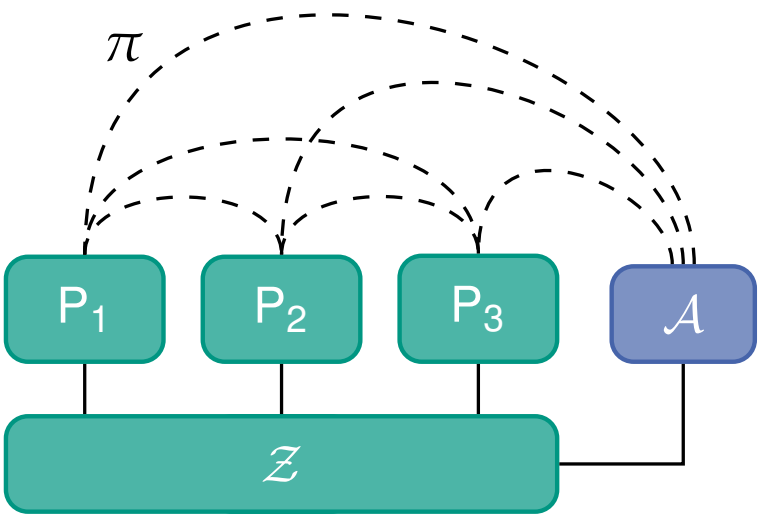
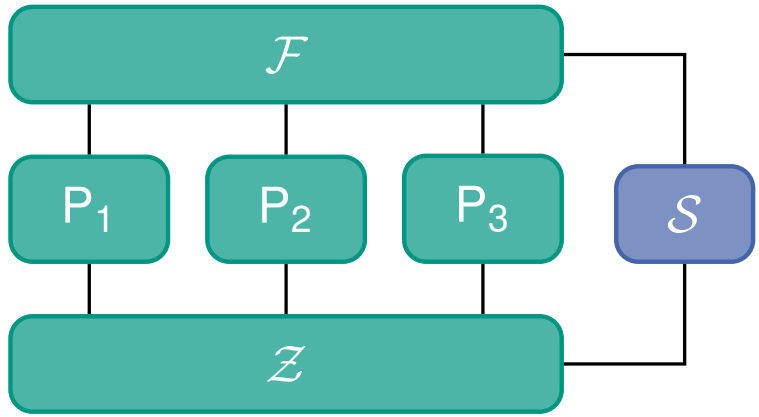
The UC Framework

A Short Introduction

- Security framework for cryptographic protocols (by [Can01])
- Follows the **simulation-based paradigm**
- Interactive distinguisher $\mathcal{Z}$ (“environment”)



Real



Ideal

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The UC Framework

Pros and Cons

Benefits

UC is closed under general protocol **composition**:

- strong concurrent security guarantees
- modular analysis

Limitations

(e. g. [CF01; Can+02; Lin03; Kat07; LPV09; Dac+13])

Very strong: UC **requires setup assumptions** for many cryptographic tasks

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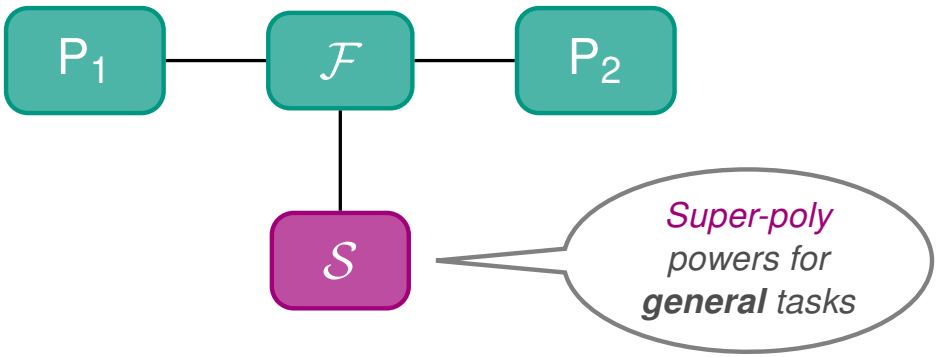
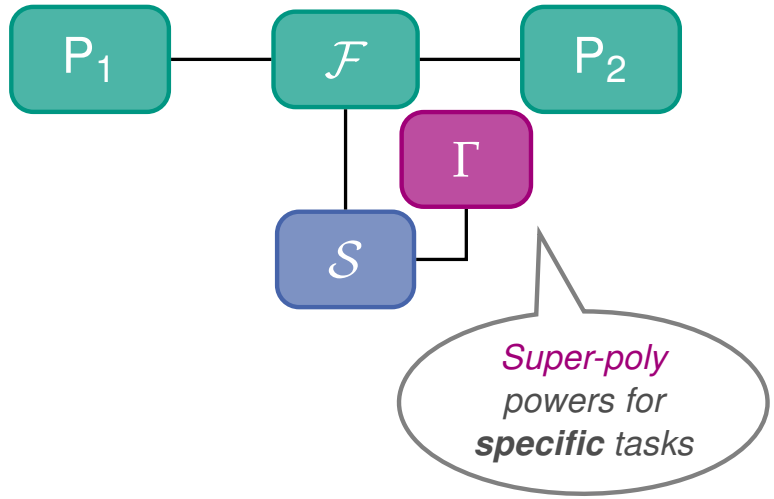
Relaxed Notions of UC Security

A Brief Overview

SPS [Pas03]



Angel-based [PS04; CLP10]



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Relaxed Notions of UC Security

A Brief Overview

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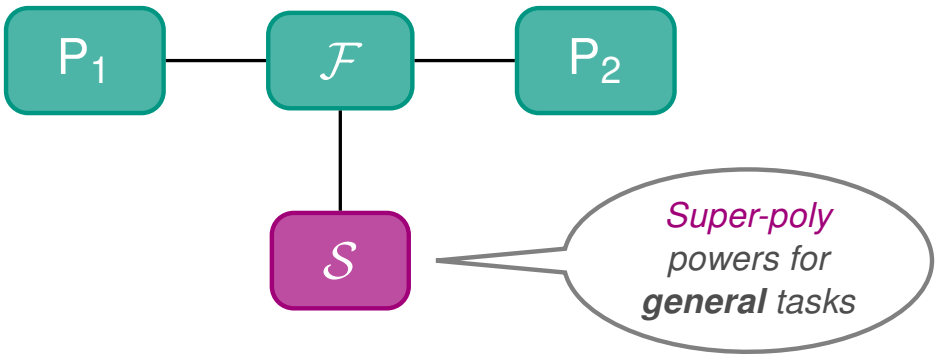
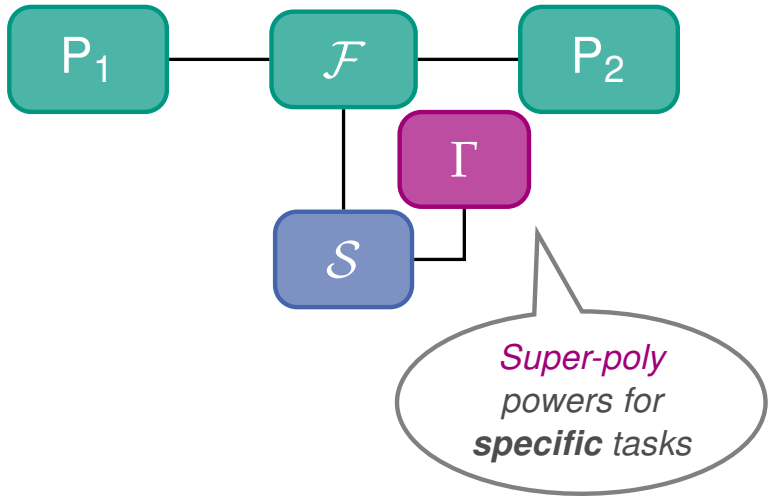


Angel-based [PS04; CLP10]



Multiple-Ideal Query Security and Input Indistinguishability

Not considered here.
See, e. g., [GJO10; Gar+12; GJ13; GGJ13; CGJ15].

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Relaxed Notions of UC Security

Pros and Cons

SPS

[Pas03; BS05; LPV09; LPV12; Gar+12]

+ Meaningful security notion for many cryptographic tasks
+ Constant-round general MPC in the plain model based on standard poly-time assumptions
– Not closed under general composition

Angel-based Security

[PS04; MMY06; CLP10; LP12; KMO14; Kiy14; Goy+15; HV16]

+ Closed under general composition (wrt. pre-chosen Angel)
+ Implies SPS security
+ General MPC in the plain model
– No known construction of general MPC protocol that is **both** constant-round and based on standard poly-time assumptions

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Our Contribution

Relaxed Security Notion

New Security Notion for Concurrently Composable Security

- Lies **strictly** between SPS and Angel-based Security
- Compatible with UC security
- Closed under general protocol composition
  - Implies concurrent security
  - Modular composition via protocols with “strong composition features”

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Our Contribution

Commitment Scheme with Strong Composition Features

Construction of a **commitment scheme** that is

- secure in our framework in the plain model
- provides strong composition features:
  1. Can be plugged into large class of UC-secure protocols
  2. Composite protocol is secure in our framework

Two **constant-round** instantiations:

- based on OWPs
- **black-box** based on homomorphic commitment schemes

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Our Contribution

Constant-round (Black-Box) General MPC in the Plain Model

Feasibility result: **General MPC** in the **plain model**

- in a **constant** number of rounds
- based on standard **poly-time** assumptions

Two constructions:

- non-black-box based on ETDPs

  → Conceptually very different alternative to [Gar+12; LPV12]

- **black-box** based on PKE with oblivious public-key generation and homomorphic commitment schemes

  → **First one**

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Our Contribution

Constant-round (Black-Box) General MPC in the Plain Model

Feasibility result

- in a **cor**
- based

Two constructi

- non-black-box base
  → Conceptually v erent alternative to [Gar+12; LPV12]
- **black-box** base PKE with oblivious public-key generation and homomorphic ommitment schemes
  → **First one**

First one that is

- concurrently secure in the plain model
- black-box
- constant-round
- based on standard poly-time assumptions

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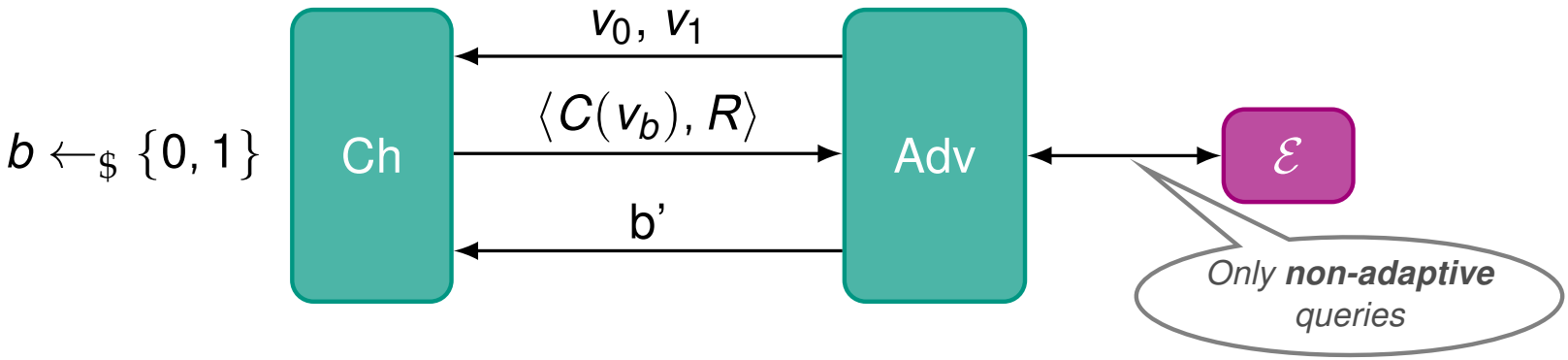
Our Contribution

New Blueprint: Building on Weaker Primitives

Constructions based only on **parallel CCA**-secure commitment schemes (instead of CCA-secure commitment schemes)



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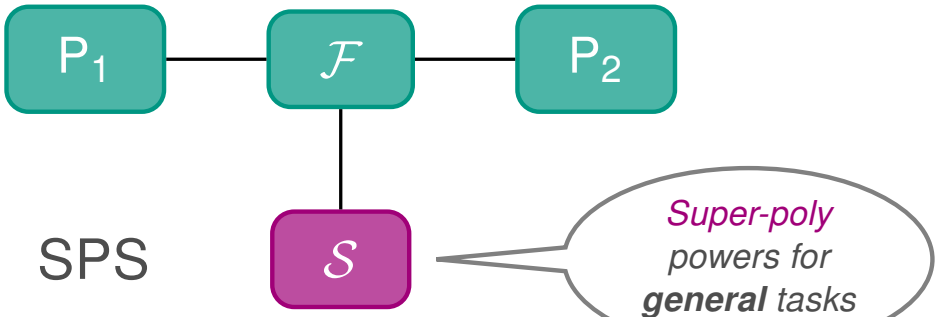
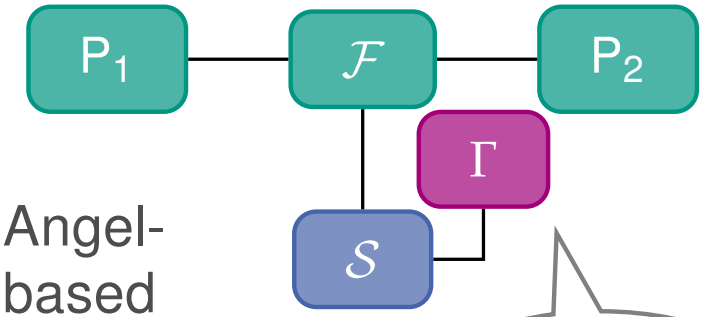
Our Approach

Shielding Away Super-Poly Resources



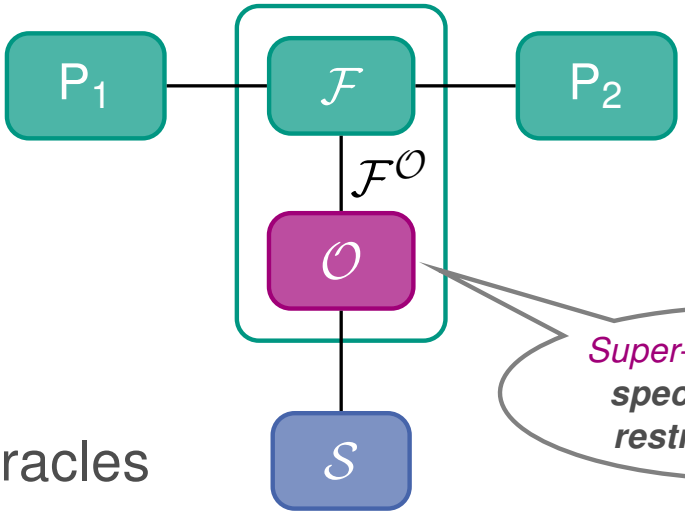
SPS

*Super-poly powers for **general** tasks*



Angel-based

*Super-poly powers for **specific** tasks*



Shielded Oracles

*Super-poly powers for **specific** tasks with **restricted access***

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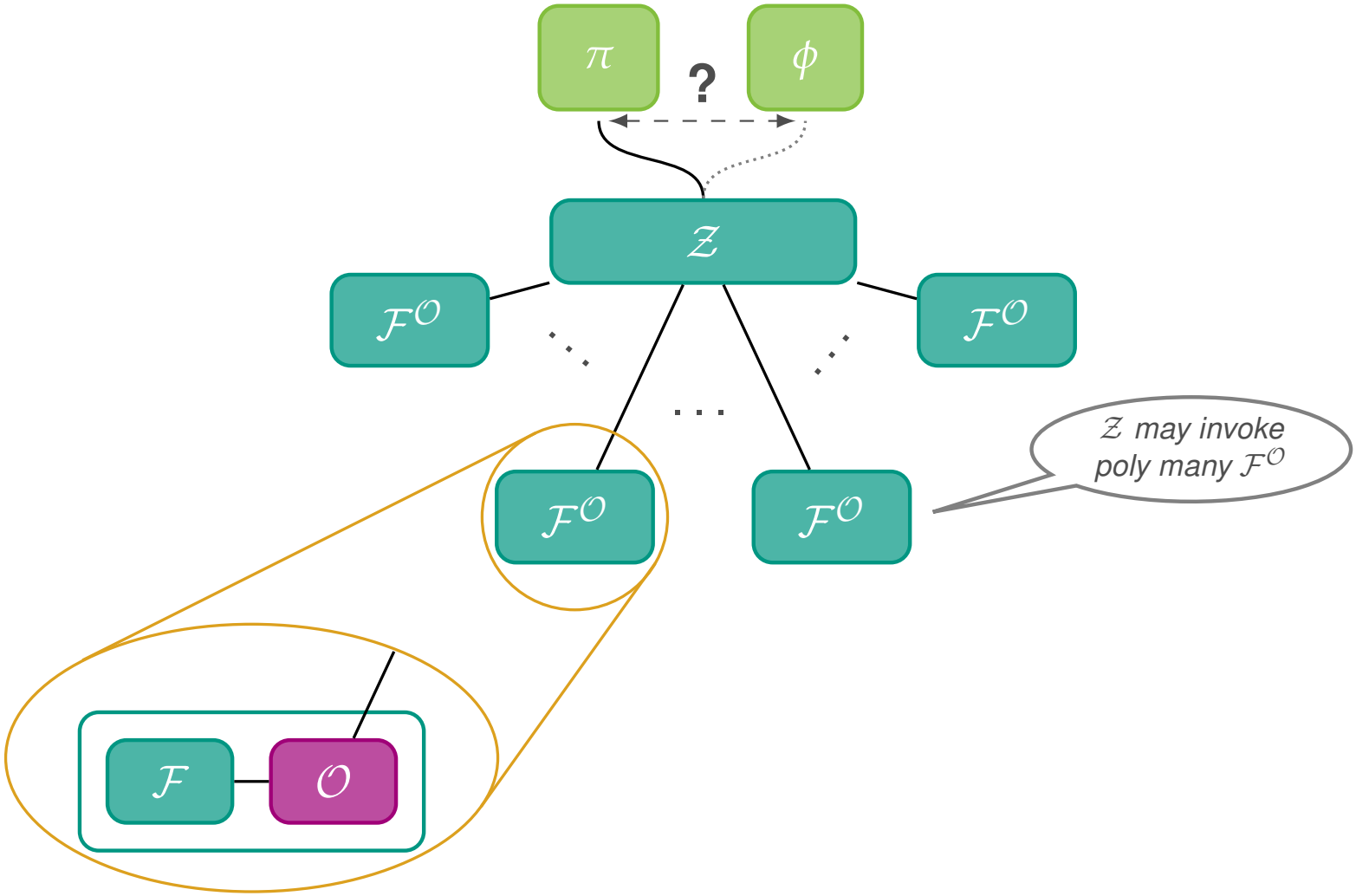
Augmented Environments



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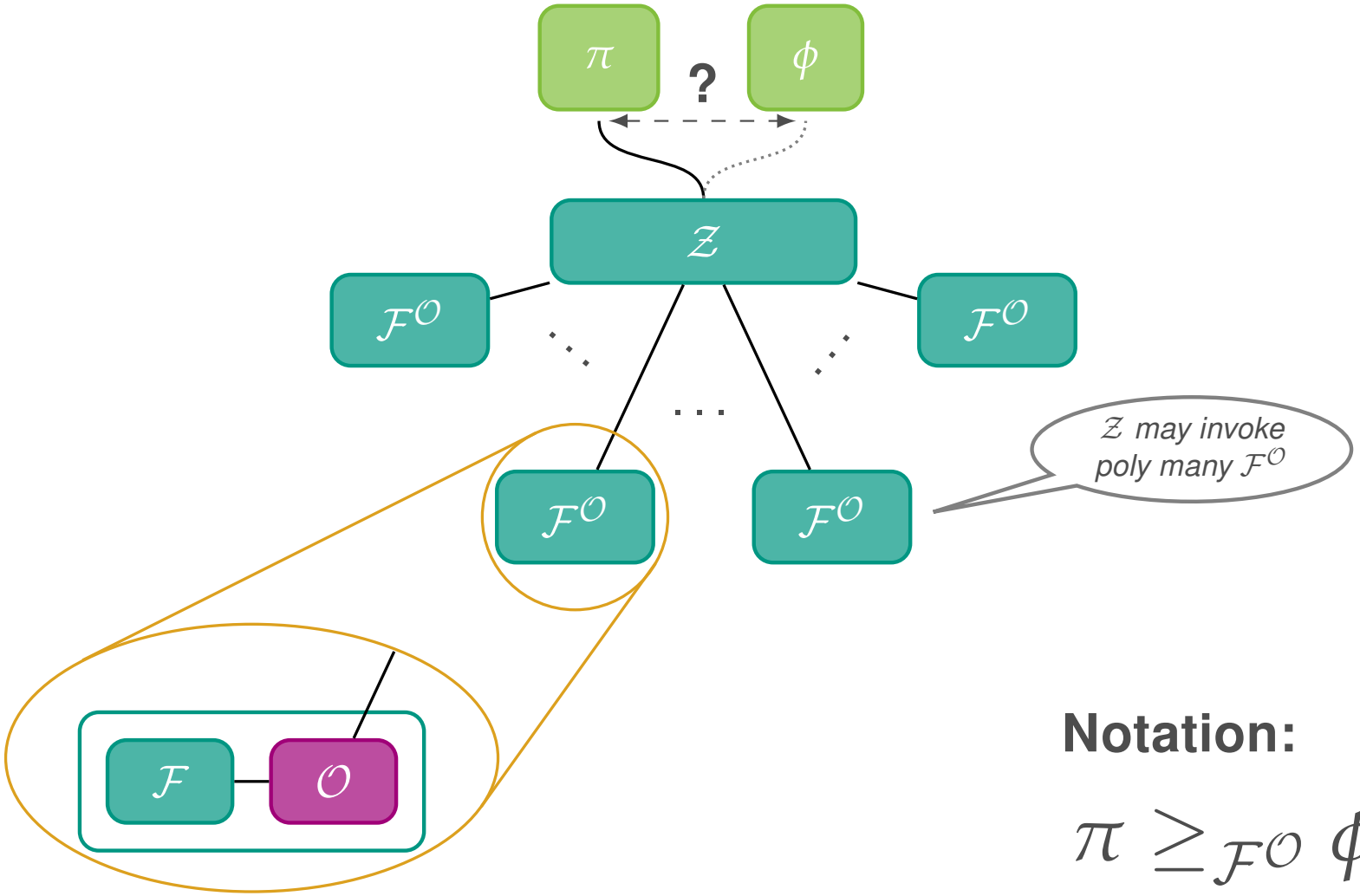
Augmented Environments



Notation:

$$\pi \geq_{\mathcal{F}^{\mathcal{O}}} \phi$$

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Composition Theorem

Augmented environments imply **composition** with protocols that may be in the $\mathcal{F}^{\mathcal{O}}$**-hybrid model**.

$$\pi \underset{\mathcal{F}^{\mathcal{O}}}{\geq} \mathcal{F}^{\mathcal{O}} \quad \Rightarrow \quad \rho^{\pi} \underset{\mathcal{F}^{\mathcal{O}}}{\geq} \rho^{\mathcal{F}^{\mathcal{O}}}$$

Composition with protocol ρ

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Polynomial Simulatability

Making $\mathcal{F}^{\mathcal{O}}$-augmented environments efficient

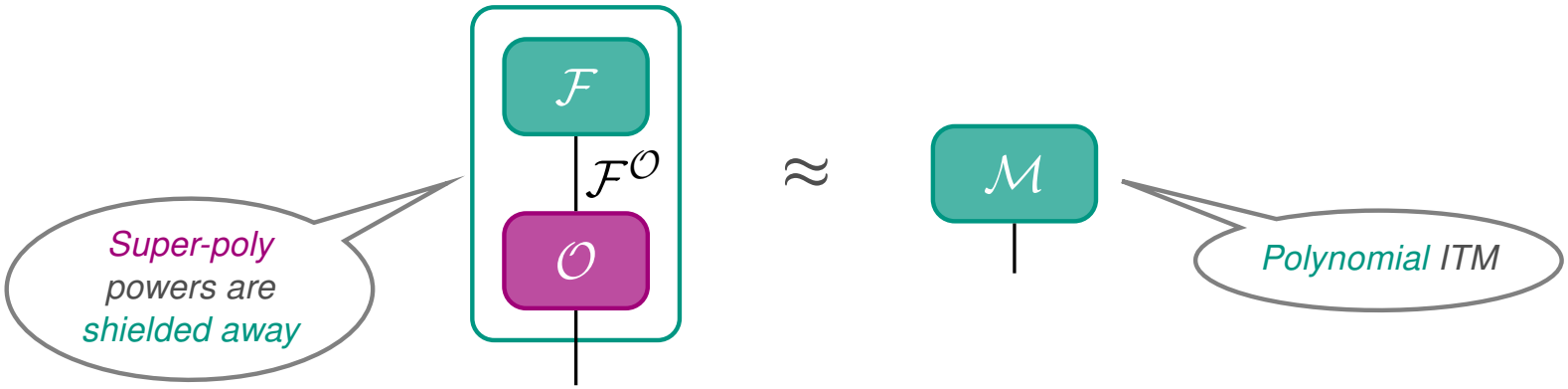
Main Technique

Replacing super-polynomial entities by polynomial ones

→ Making $\mathcal{F}^{\mathcal{O}}$-augmented environments efficient

Intuition

Shielded Oracles “look like poly” from the outside.



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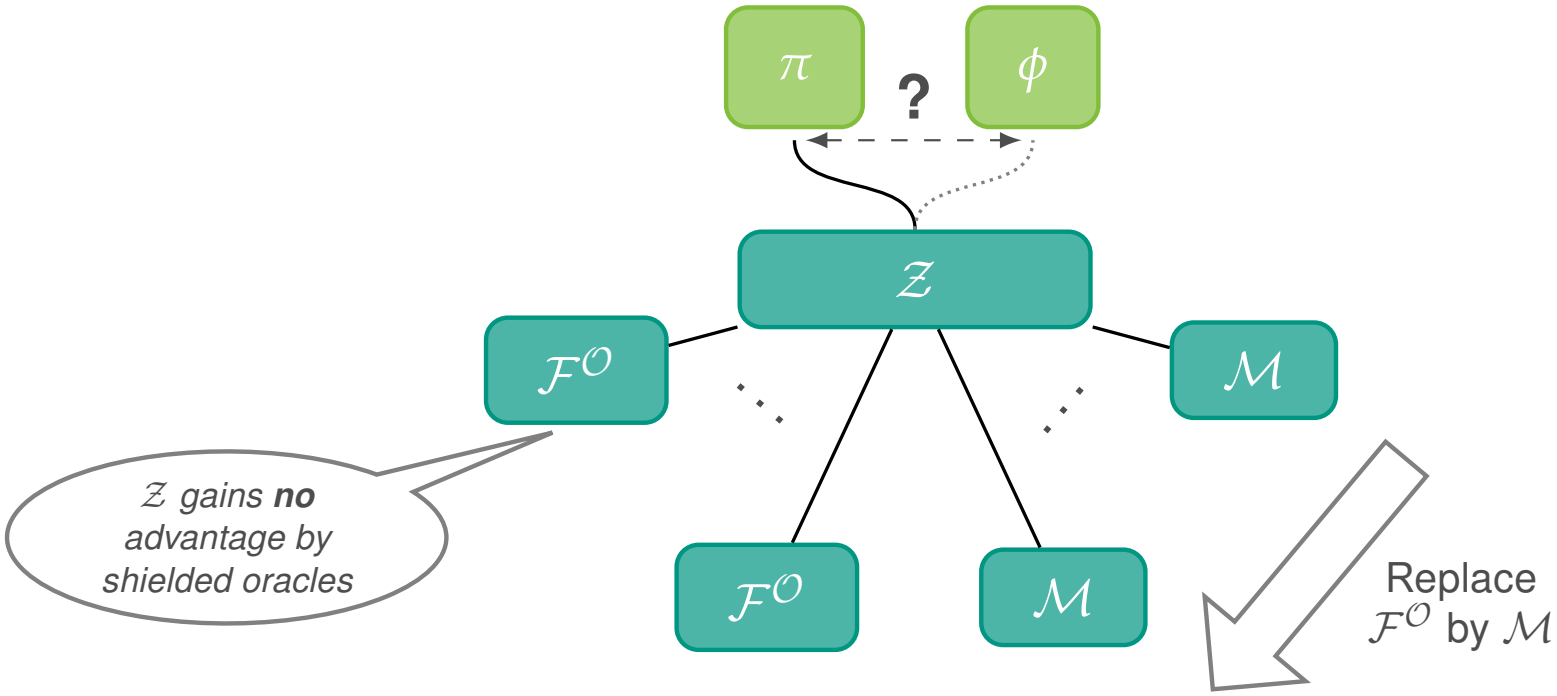
Polynomial Simulatability

Making $\mathcal{F}^{\mathcal{O}}$-augmented environments efficient



Augmented environment

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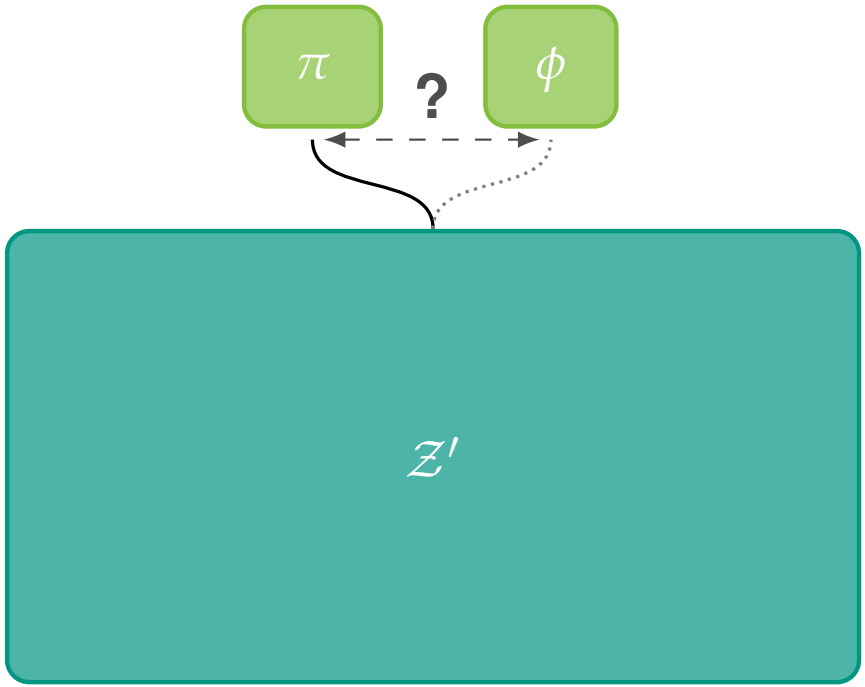
Polynomial Simulatability

Making $\mathcal{F}^{\mathcal{O}}$-augmented environments efficient



Standard poly-time UC environment

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Secure Commitment Scheme

Goal

Construct a protocol Π such that

$$\Pi \underset{\mathcal{F}_{\text{com}}^{\mathcal{O}}}{\geq} \mathcal{F}_{\text{com}}^{\mathcal{O}}$$

for a suitable $\mathcal{O}$.

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Secure Commitment Scheme

Necessary Prerequisites for Π

- Hiding can be broken with super-poly powers (extractability)
- Binding can be broken with super-poly powers (equivocality)

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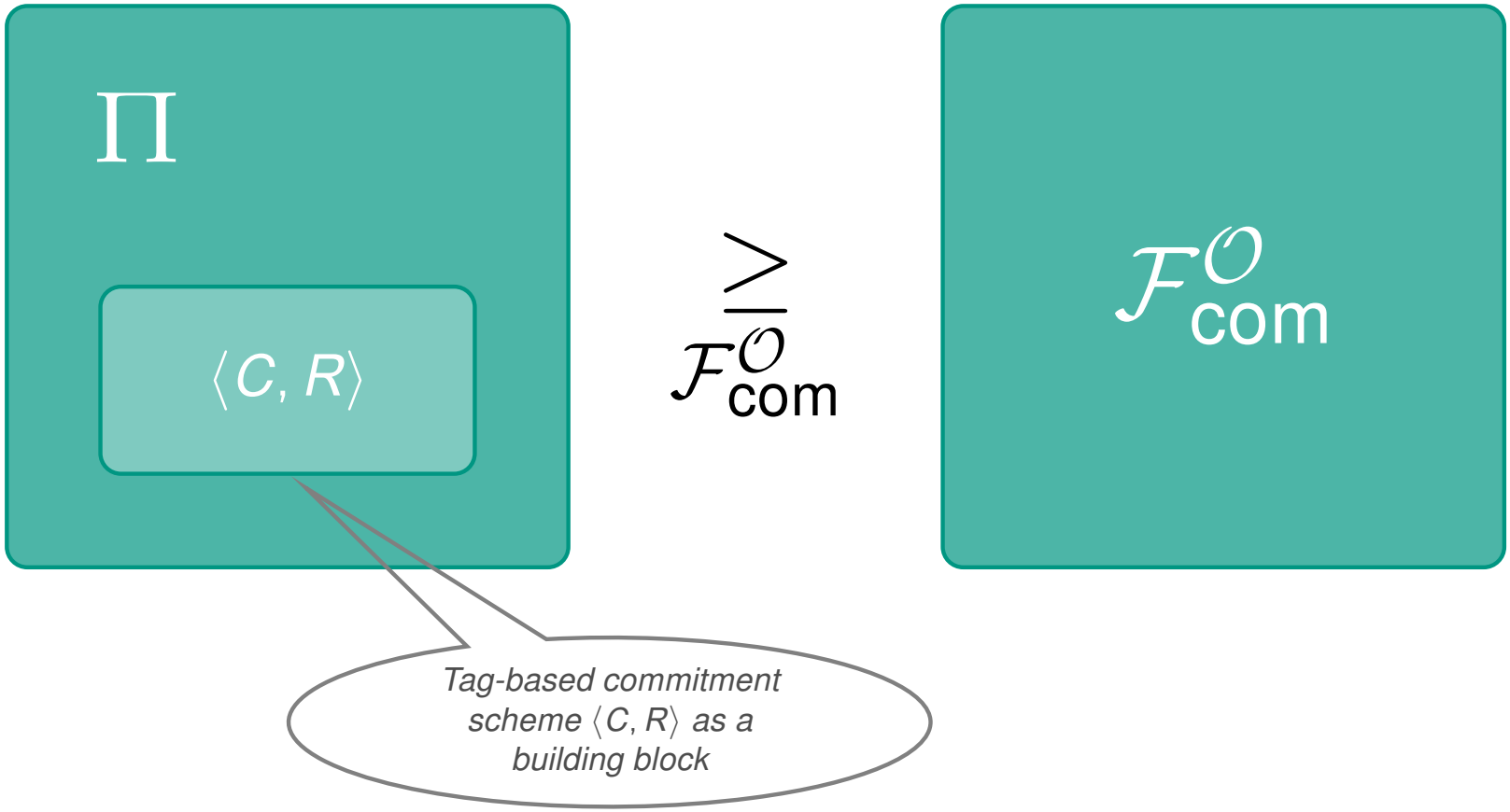
Secure Commitment Scheme

The Big Picture



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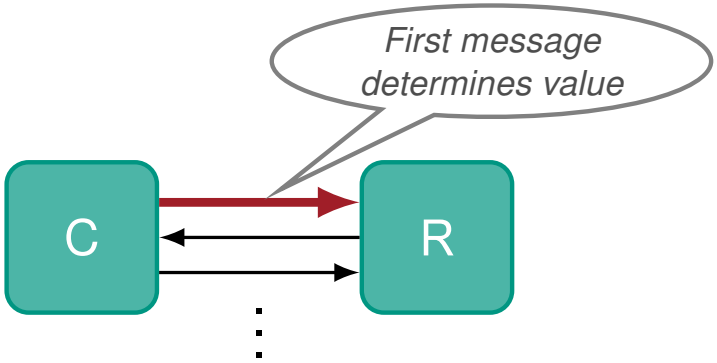
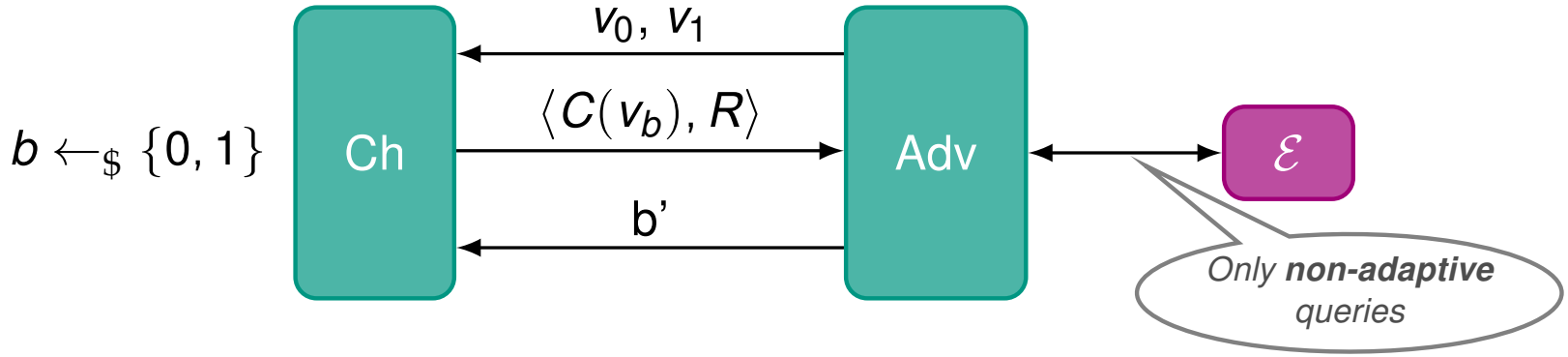
Secure Commitment Scheme

Building Block – Tag-based Commitment Scheme $\langle C, R \rangle$

- **Immediately Committing**
  → super-poly extractable



- **Parallel-CCA secure**



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Secure Commitment Scheme

The Scheme Π

Extractability (in super-poly time)

. . . follows from the extractability of $\langle C, R \rangle$.

Equivocality (in super-poly time)

. . . using the transformation of [DS13]:

Receiver of Π commits to equivocation trapdoor at the beginning.

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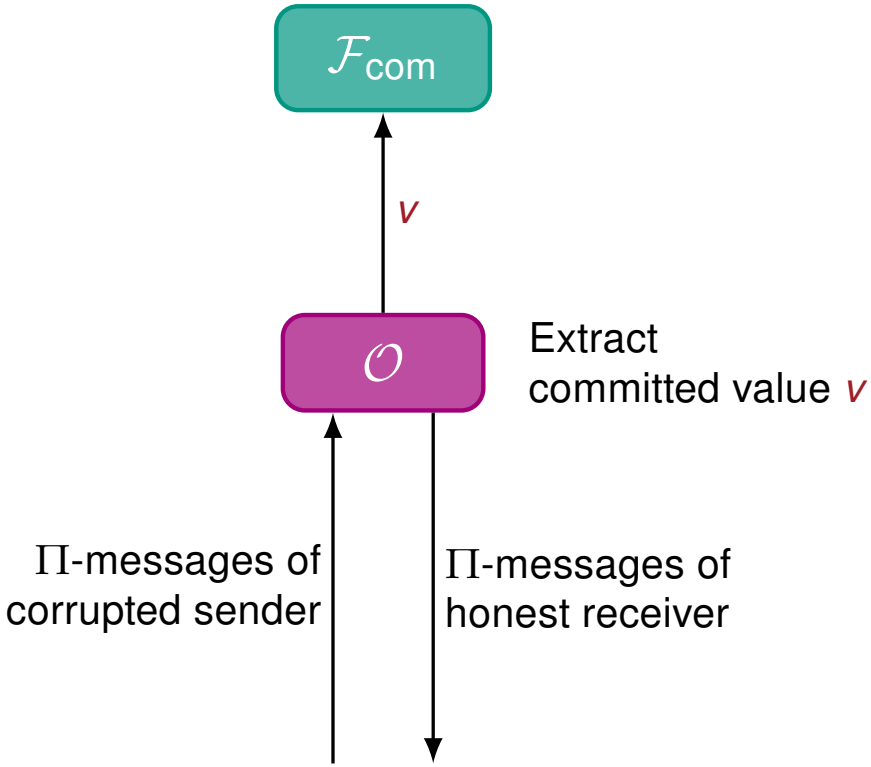
Secure Commitment Scheme

Definition of the Shielded Oracle $\mathcal{O}$

Corrupted Sender

$\mathcal{O}$ plays role of honest receiver



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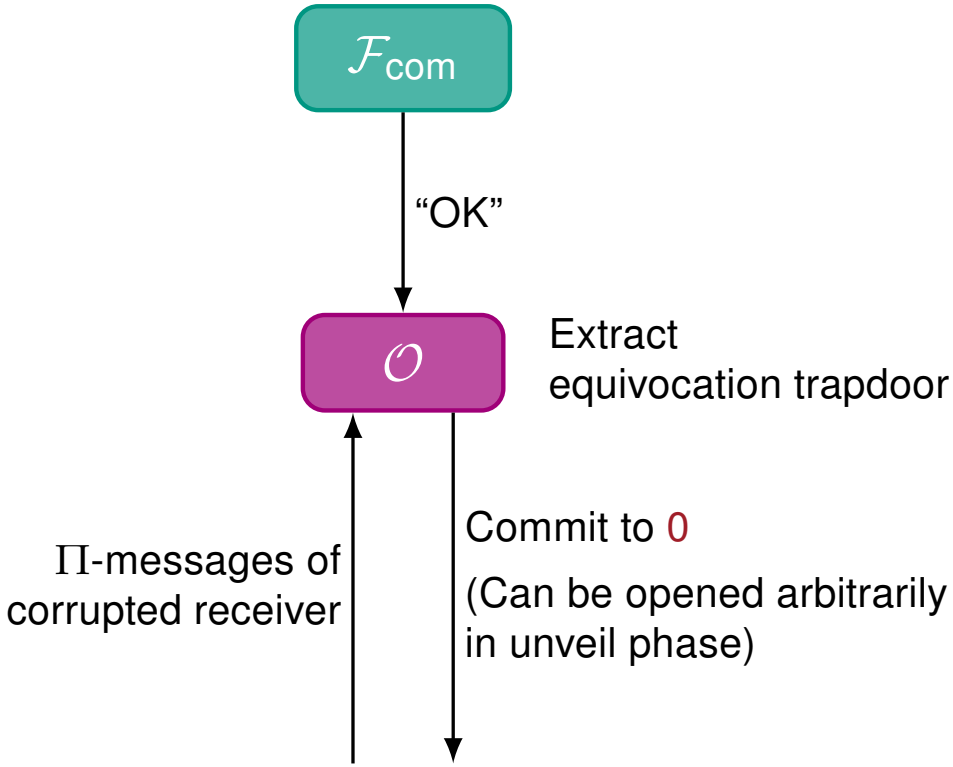
Secure Commitment Scheme

Definition of the Shielded Oracle $\mathcal{O}$

Corrupted Receiver

$\mathcal{O}$ plays role of sender



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Secure Commitment Scheme

Security Statement

Theorem

If $\langle C, R \rangle$ is immediately committing and parallel-CCA-secure, then

$$\Pi \underset{\mathcal{F}_{\mathsf{com}}^{\mathcal{O}}}{\geq} \mathcal{F}_{\mathsf{com}}^{\mathcal{O}}$$

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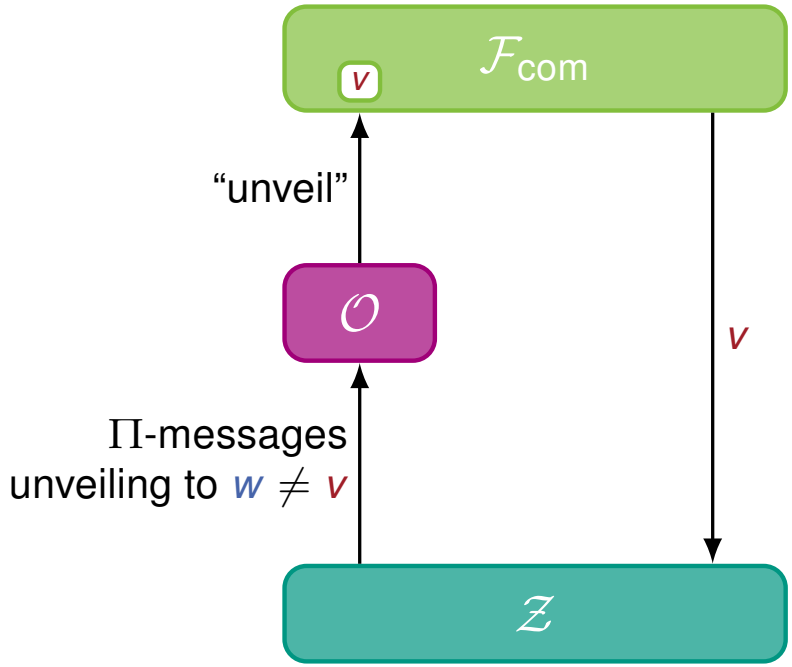
Secure Commitment Scheme

Proof Idea – Discrepancy

Let the **sender** be corrupted.

- Environment commits to value v but unveils different value w
- Output of receiver in real model: w
- Output of receiver in ideal model: v (value extracted by $\mathcal{O}$)

$\rightarrow$ Environment can distinguish



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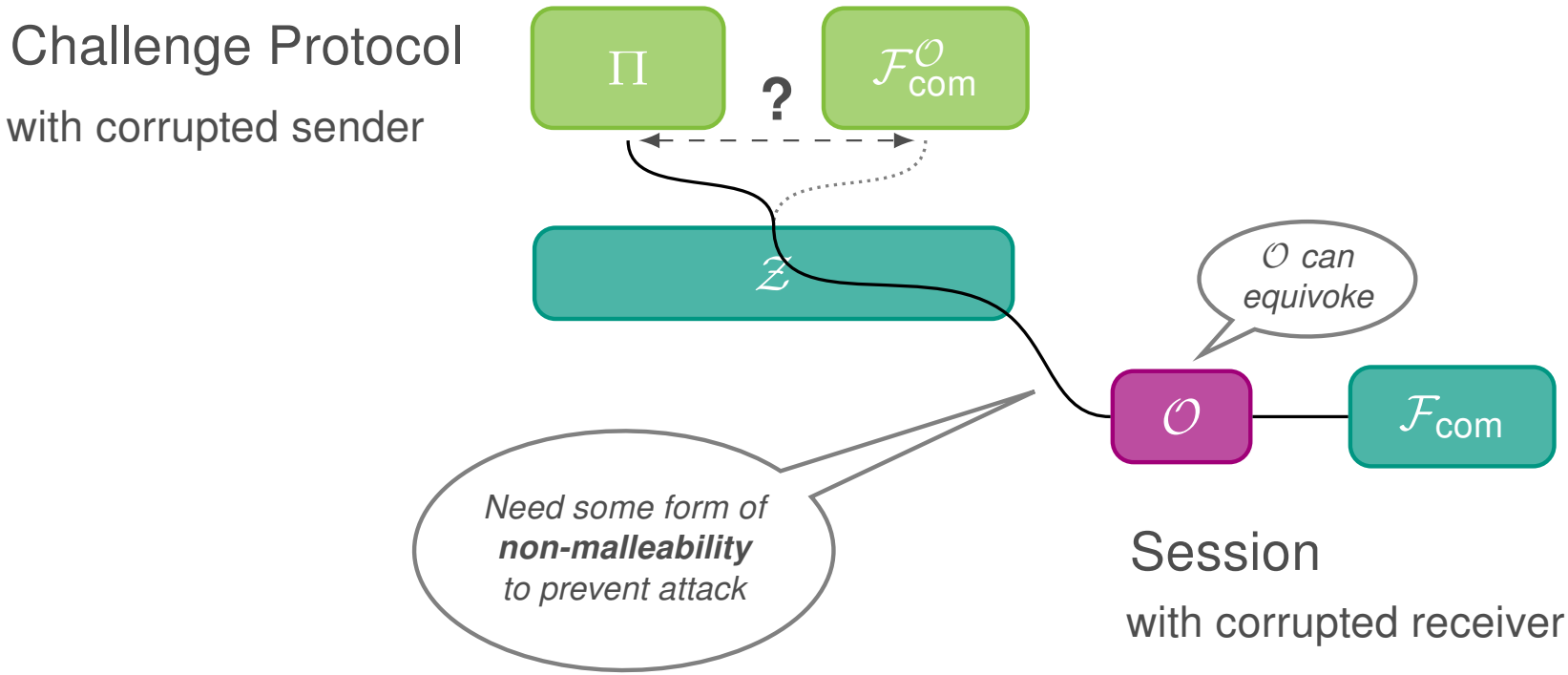
Secure Commitment Scheme

Proof Idea – A Possible Attack Strategy



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Secure Commitment Scheme

Proof Idea

To show

$\mathcal{Z}$ cannot cause a discrepancy (except with negligible probability)

Proof by contradiction

Assume $\mathcal{F}_{\text{com}}^{\mathcal{O}}$-augmented environment can cause a discrepancy:

- Make environment efficient

  (interacting with only one $\mathcal{F}_{\text{com}}^{\mathcal{O}}$-session with a corrupted sender)
- Proof that no efficient environment can cause a discrepancy

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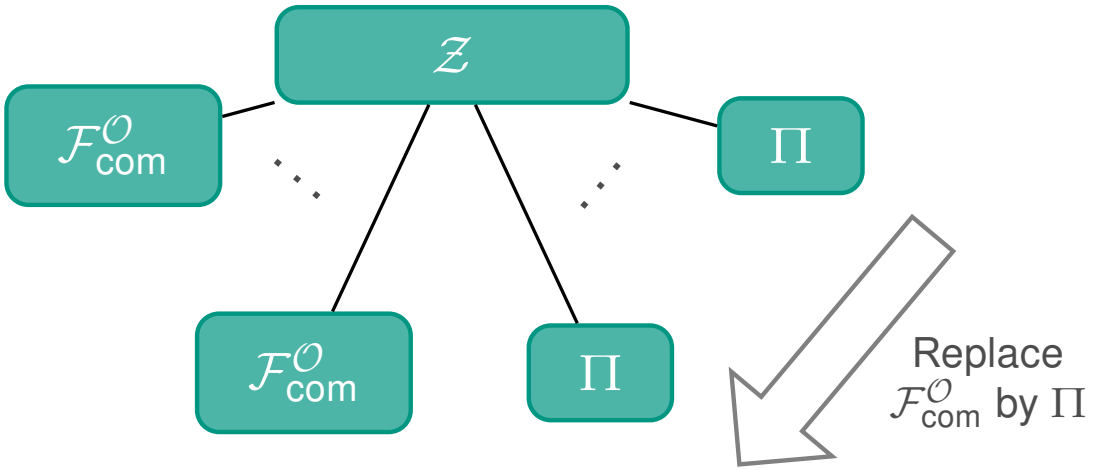
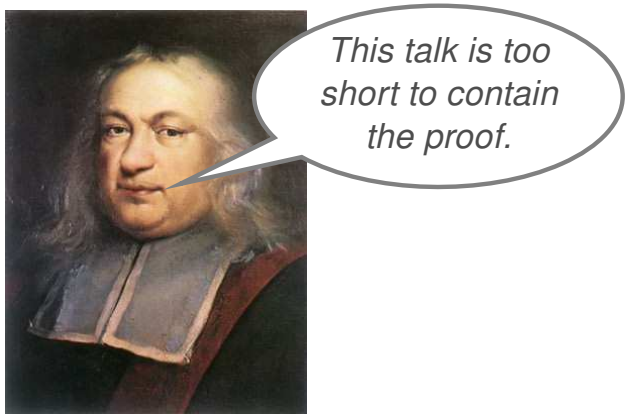
Secure Commitment Scheme

Making the Environment Efficient

"Carefully" replace $\mathcal{F}_{\text{com}}^{\mathcal{O}}$-sessions with the real protocol Π in a specific order

→ Non-uniform reduction to parallel-CCA-security of $\langle C, R \rangle$





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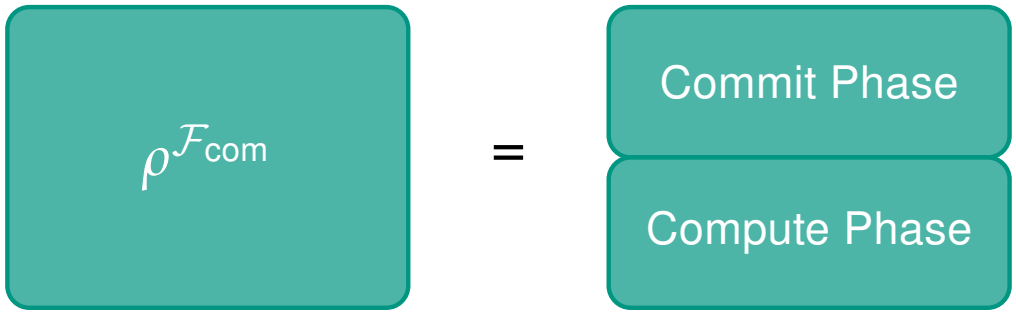
Modular Composition Theorem for Π

Composing with constant-round UC-secure protocols

If $\langle C, R \rangle$ has additional property ("*r*-non-adaptively robust")

as well as

$\rho^{\mathcal{F}_{\text{com}}}$ constant-round and



then

$$\rho^{\mathcal{F}_{\text{com}}} \underset{\text{UC}}{\geq} \mathcal{G} \quad \Rightarrow \quad \exists \text{ shielded oracle } \mathcal{O}' : \rho^{\Pi} \underset{\mathcal{G}^{\mathcal{O}'}}{\geq} \mathcal{G}^{\mathcal{O}'}$$

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Modular Composition Theorem for Π

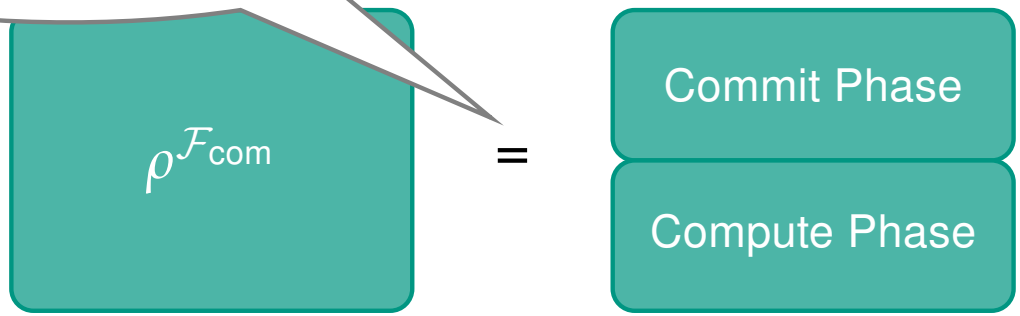
Composing with constant-round UC-secure protocols

If $\langle C, R \rangle$ has additi st")

as well as

$\rho^{\mathcal{F}_{\text{com}}}$ constant-round and

Any (poly-round) protocol can be **compiled** into one obeying this structure



then

$$\rho^{\mathcal{F}_{\text{com}}} \underset{\text{UC}}{\geq} \mathcal{G} \quad \Rightarrow \quad \exists \text{ shielded oracle } \mathcal{O}' : \rho^{\Pi} \underset{\mathcal{G}^{\mathcal{O}'}}{\geq} \mathcal{G}^{\mathcal{O}'}$$

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Secure Commitment Scheme

Constant-round Instantiations of Π

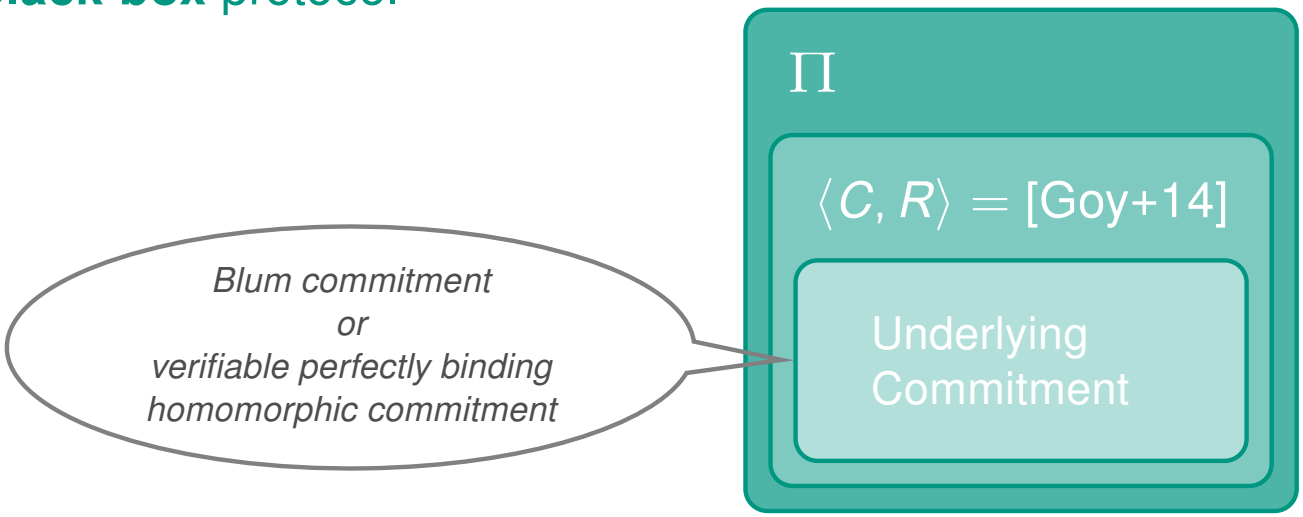
$\langle C, R \rangle$ can be instantiated with a modified version of the 8-round protocol in [Goy+14] . . .

- . . . using OWPs

  → Constant-round protocol based on OWPs.

- . . . using a verifiable perfectly binding homomorphic commitment scheme

  → Constant-round **black-box** protocol



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Modular Composition Theorem for Π

Constant-round Instantiations of Π

Constant-round Instantiations of Π

- Π_r = instantiation of Π based on OWPs
- Π_r^{BB} = black-box instantiation of Π based on verifiable perfectly binding homomorphic commitment schemes

(Instantiated with a *r*-non-adaptively robust modified version of [Goy+14])

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Constant-round (Black-box) General MPC

UC-secure Protocol

Secure in Our Framework (in the Plain Model)

$$\rho^{\mathcal{F}_{\text{com}}} + \Pi_r \Longrightarrow \rho^{\Pi_r}$$

[Can+02; IPS08]

Constant-round, based on ETDPs

Constant-round, based on ETDPs

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Constant-round (Black-box) General MPC

UC-secure Protocol				Secure in Our Framework (in the Plain Model)
$\rho^{\mathcal{F}_{\text{com}}}$	$+$	Π_r	$\Rightarrow$	ρ^{Π_r}
[Can+02; IPS08]				
Constant-round, based on ETDPs				Constant-round, based on ETDPs
$\rho^{\mathcal{F}_{\text{com}}}$	$+$	Π_r^{BB}	$\Rightarrow$	$\rho^{\Pi_r^{\text{BB}}}$
[HV15]				
Constant-round, black-box, based on PKE with oblivious public-key generation				Constant-round, black-box, based on cryptographic primitives with polynomial hardness

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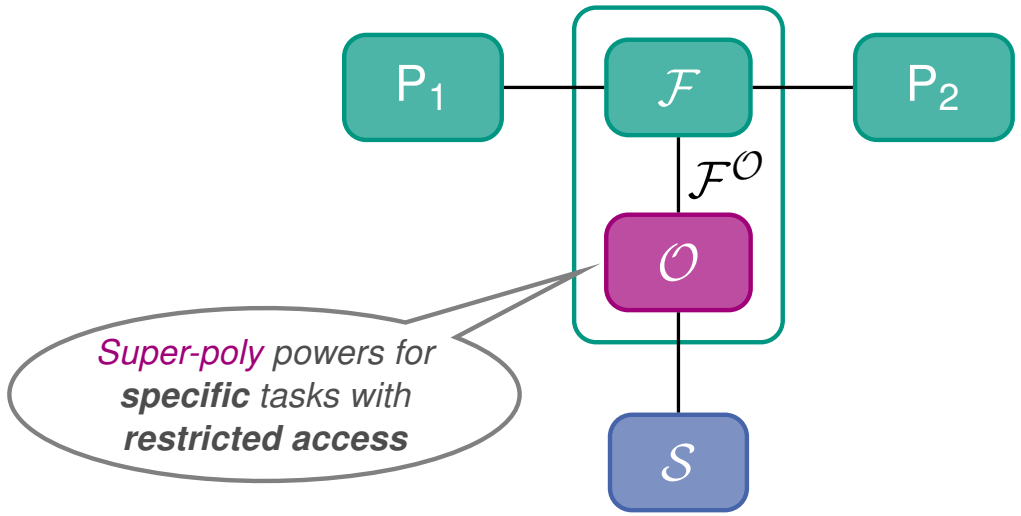
The End

Take Away Messages

- New universally composable security framework
- Secure commitment scheme with modular composition property
- Constant-round black-box general MPC based on standard assumptions
- All results based only on parallel-CCA-secure commitments

Thank You



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Appendix

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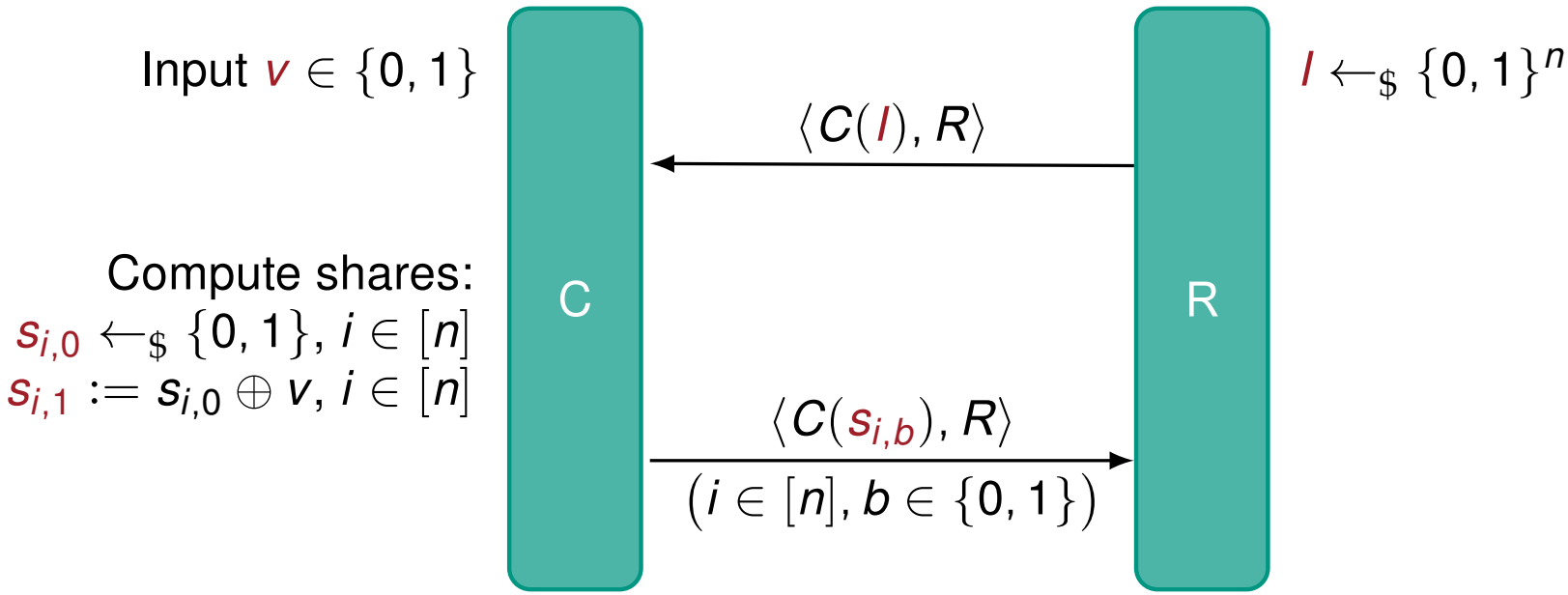
KASTEL

Constant-round Commitment Scheme

The Scheme Π (Reminiscent of [DS13])

Commit Phase



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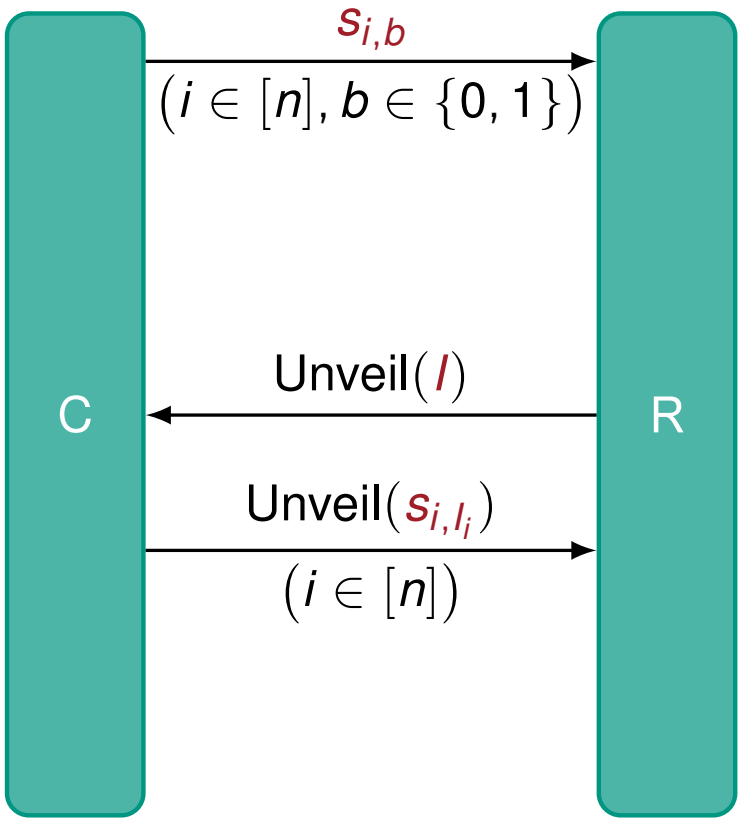
Constant-round Commitment Scheme

The Scheme Π

Unveil Phase



Check
$s_{1,0} \oplus s_{1,1} = \ldots = s_{n,0} \oplus s_{n,1}$,
else abort

If unveil valid, output
$w = s_{1,0} \oplus s_{1,1}$

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Constant-round Commitment Scheme

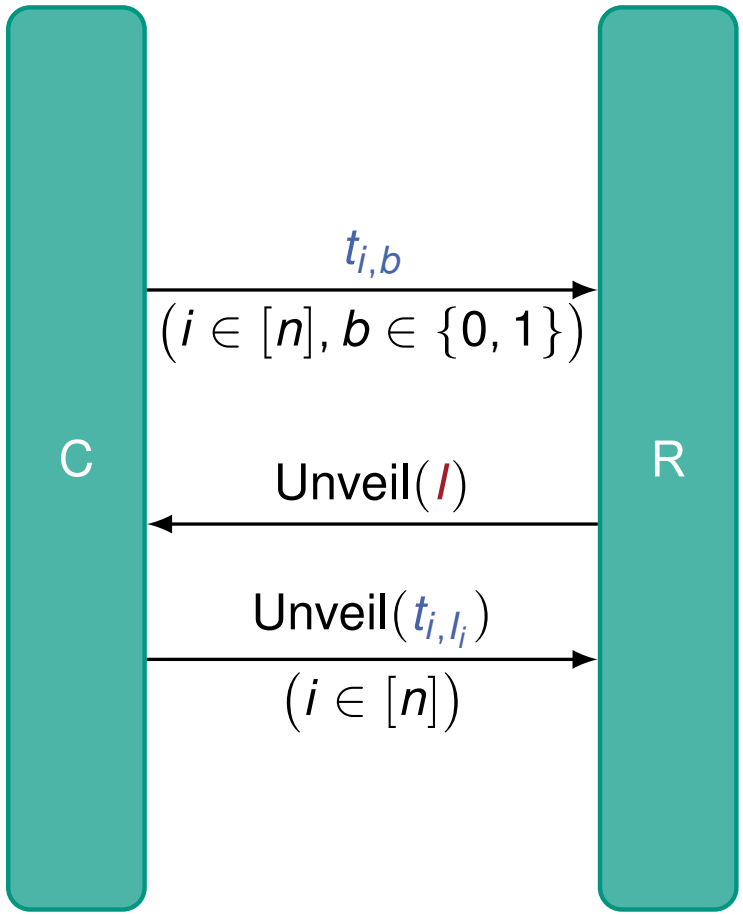
The Scheme Π

Equivocation Trapdoor Index set I serves as trapdoor

Compute "fake shares":

$t_{i,I_i} := s_{i,I_i}, i \in [n]$

$t_{i,\neg I_i} := s_{i,\neg I_i} \oplus 1, i \in [n]$



Check ...

If unveil valid, output

$w = t_{1,0} \oplus t_{1,1} = v \oplus 1$

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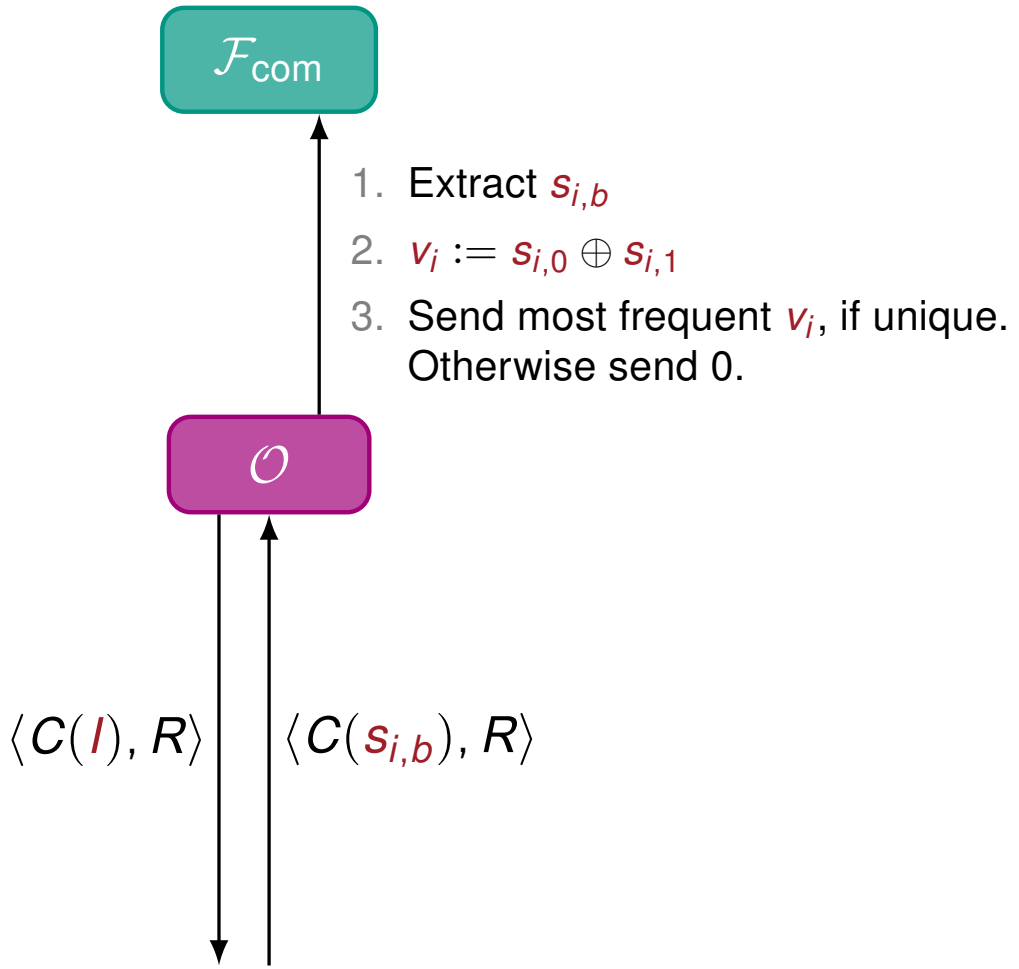
Constant-round Commitment Scheme

Definition of the Shielded Oracle $\mathcal{O}$

Corrupted Sender



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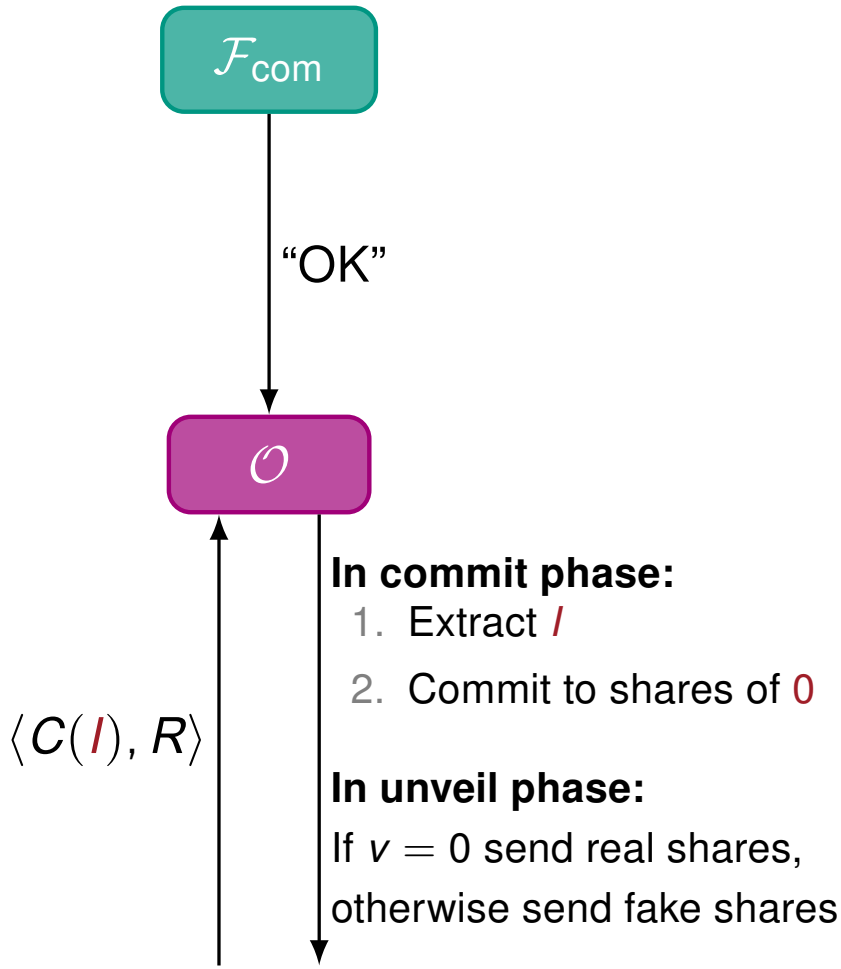
Constant-round Commitment Scheme

Definition of the Shielded Oracle $\mathcal{O}$

Corrupted Receiver



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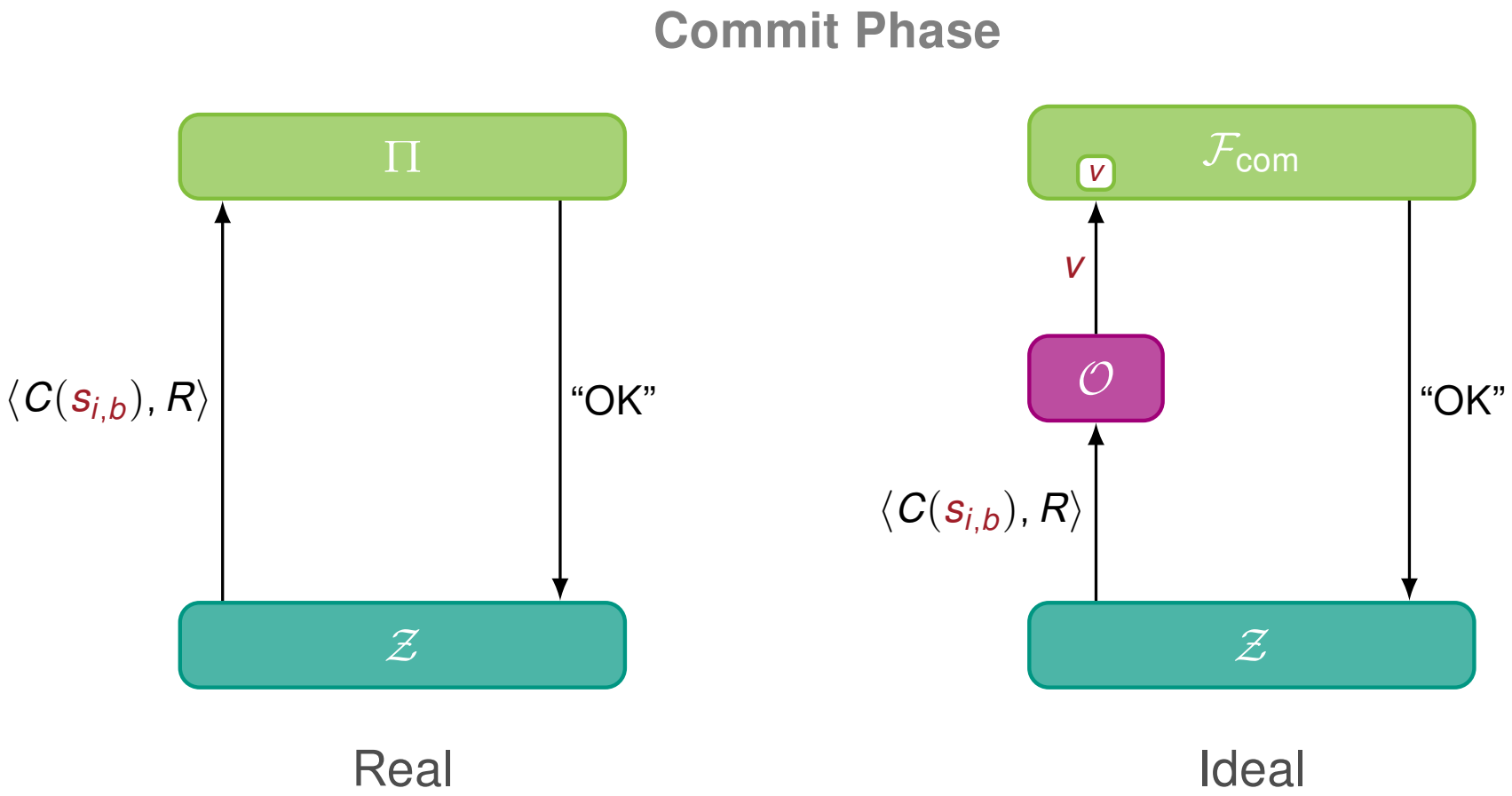
Constant-round Commitment Scheme

Proof Idea – Discrepancy

Let the sender be corrupted.



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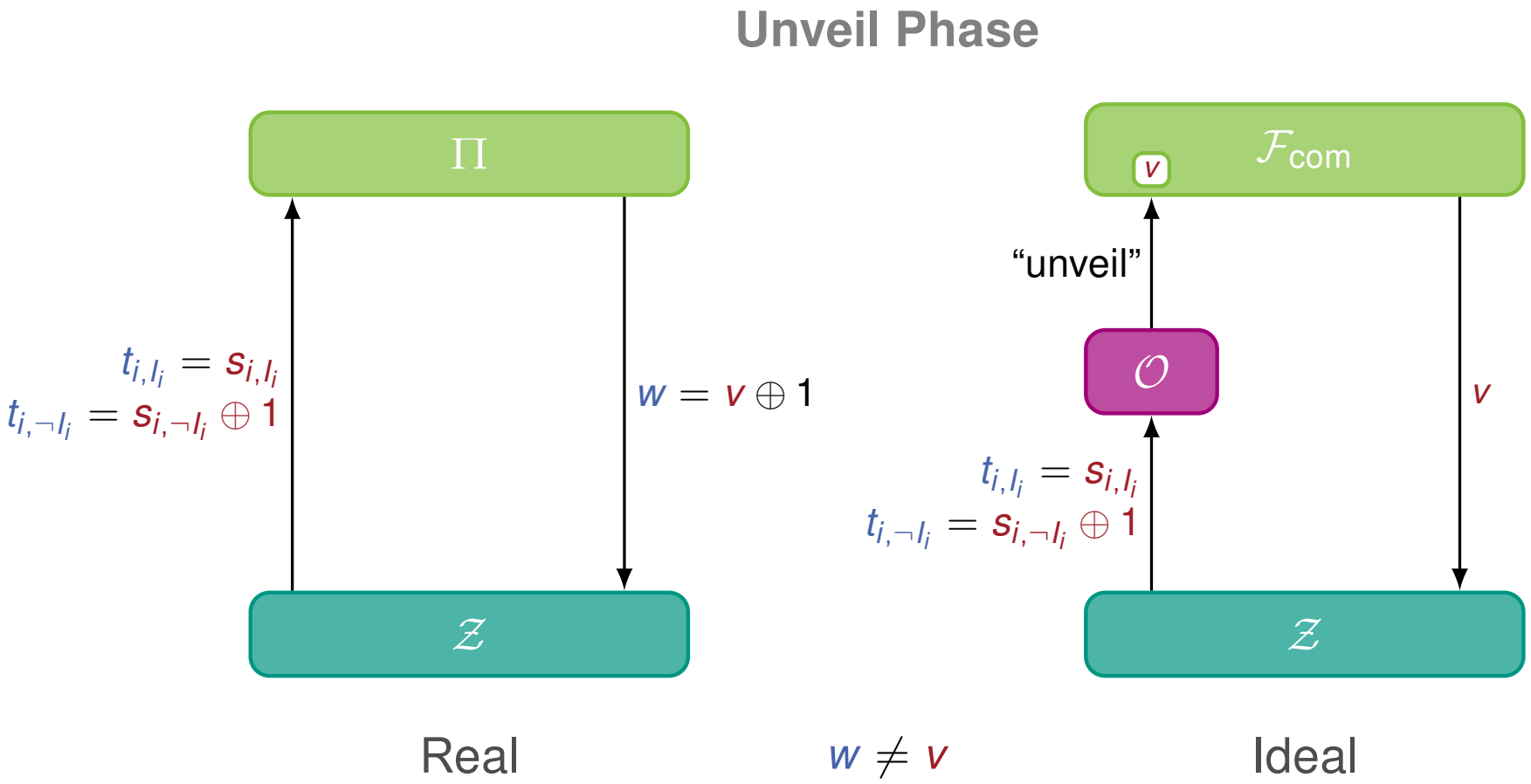
Constant-round Commitment Scheme

Proof Idea – Discrepancy

Let the sender be corrupted.



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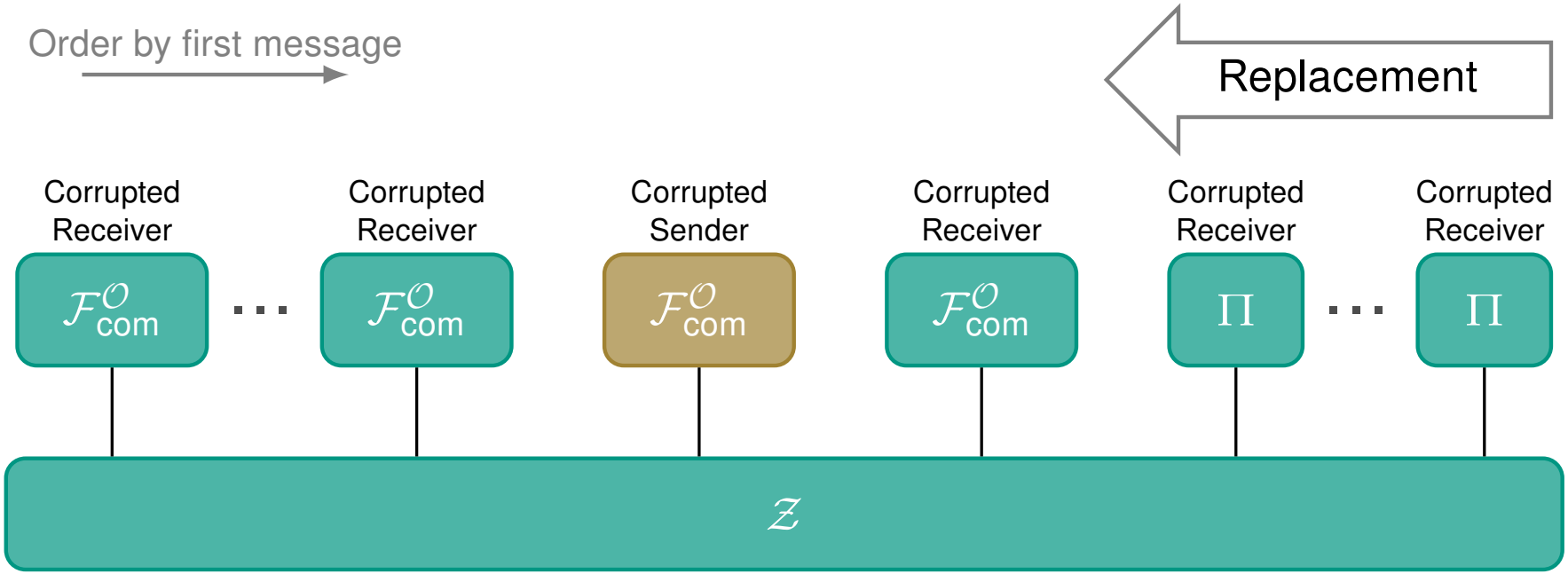
Constant-round Commitment Scheme

Proof Idea

- W. l. o. g.: Consider at most one $\mathcal{F}_{\text{com}}^{\mathcal{O}}$ with a corrupted sender
- Iteratively replace all $\mathcal{F}_{\text{com}}^{\mathcal{O}}$ with a corrupted receiver by Π, starting with the last session



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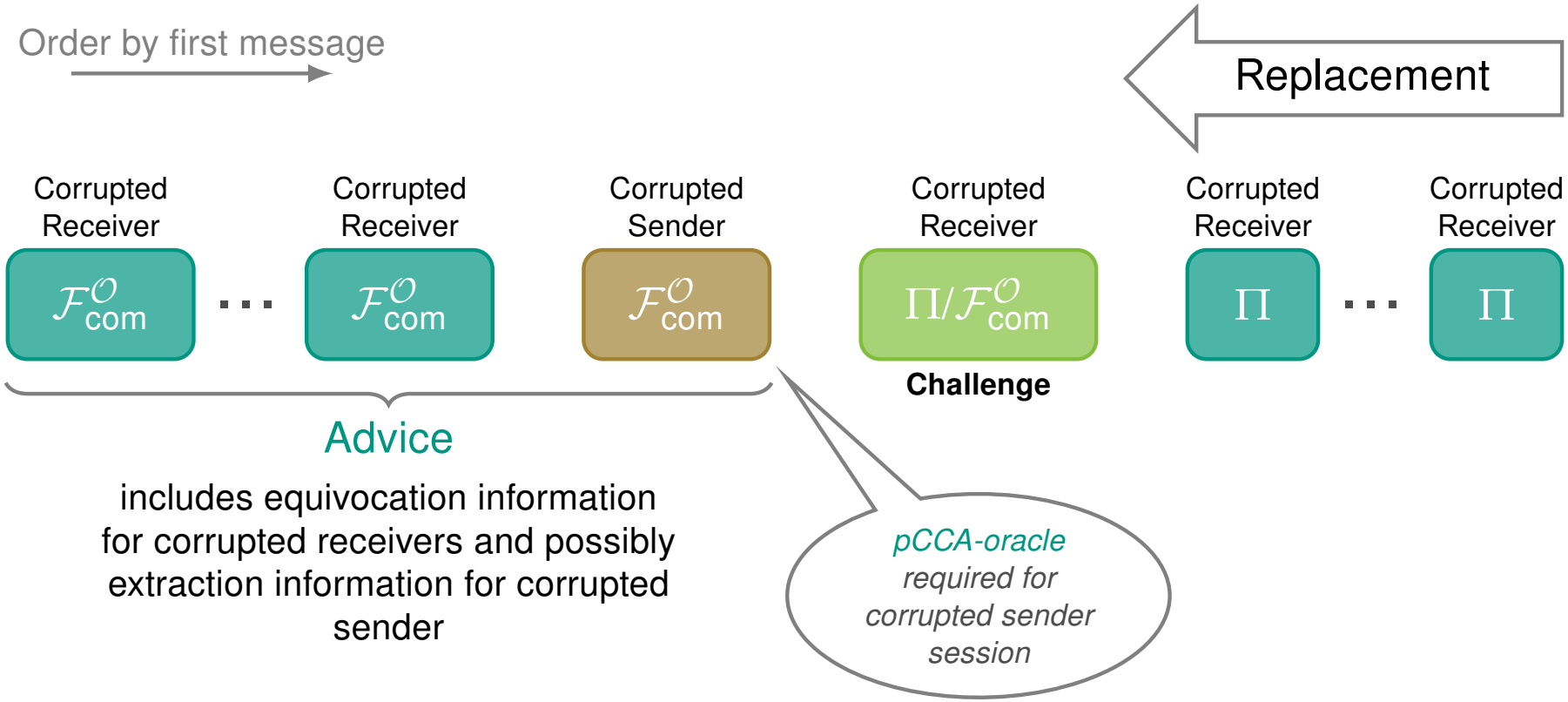
Constant-round Commitment Scheme

Proof Idea

Non-uniform reduction to parallel-CCA security of $\langle C, R \rangle$



Modular Composition Theorem for Π

Next Goal

- Want to plug Π into UC-secure protocols
- Composite protocol secure in our framework

  → Allows to **re-use existing UC results**

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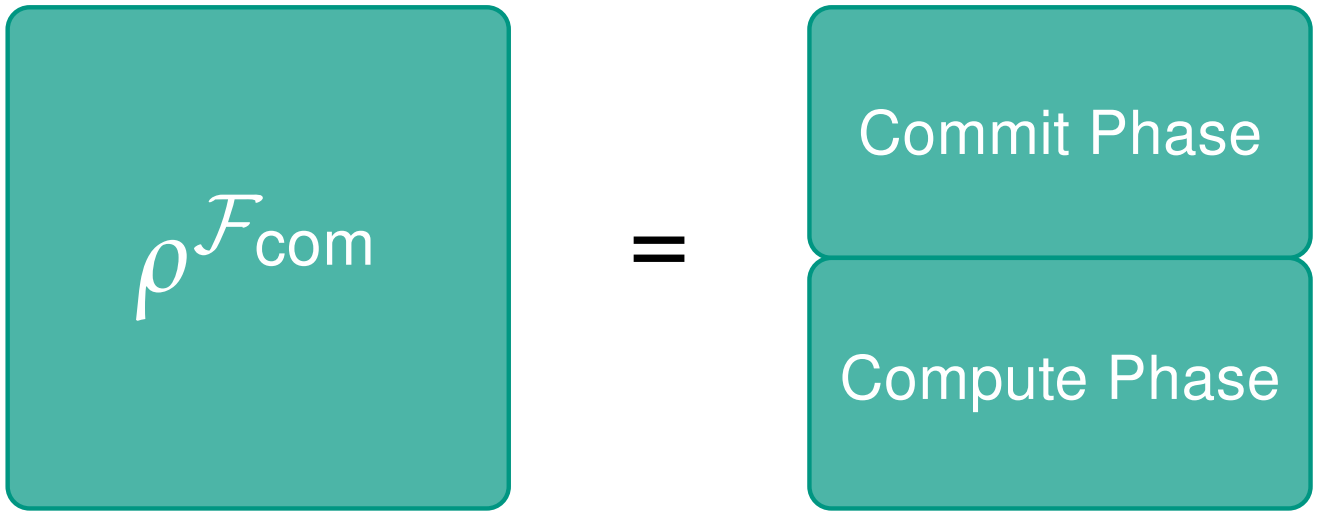
Modular Composition Theorem for Π

Commit-Compute Protocols



Any (poly-round) protocol can be **compiled** into one obeying this structure
(using randomized commitments)

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Modular Composition Theorem for Π

The Theorem

Let $\rho^{\mathcal{F}_{\text{com}}}$ be a commit-compute protocol and Π as before.

$$\rho^{\mathcal{F}_{\text{com}}} \underset{\mathcal{E}\text{-pCCA}}{\geq} \mathcal{G} \quad \Rightarrow \quad \exists \text{ shielded oracle } \mathcal{O}' : \rho^{\Pi} \underset{\mathcal{G}^{\mathcal{O}'}}{\geq} \mathcal{G}^{\mathcal{O}'}$$

UC-environment has non-adaptive access to the decommitment oracle $\mathcal{E}$ of $\langle C, R \rangle$

This talk is too short to contain the proof.

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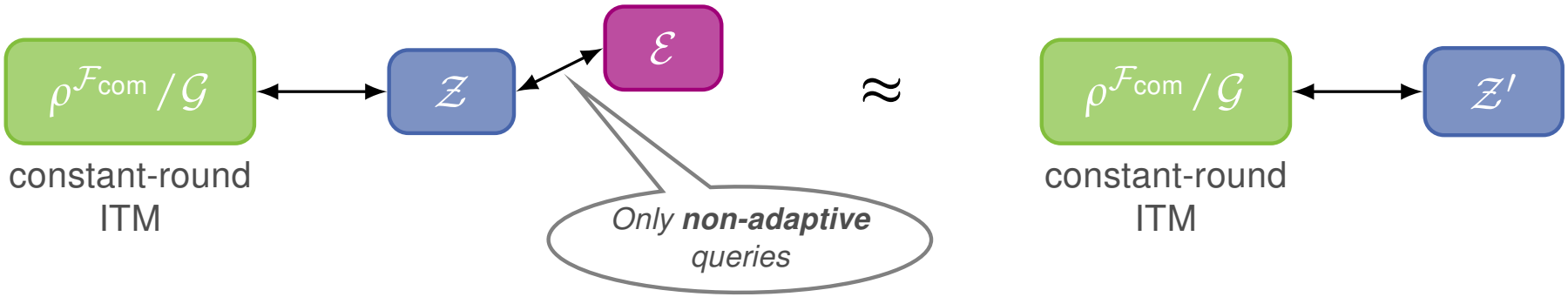
Modular Composition Theorem for Π

Composing with any constant-round UC-secure protocol

Given any constant-round $\rho^{\mathcal{F}_{\text{com}}} \geq_{\text{UC}} \mathcal{G}$.

- Compile $\rho^{\mathcal{F}_{\text{com}}}$
- Additionally require $\langle C, R \rangle$ to be *r*-non-adaptively robust

  (for sufficiently large *r*)



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