Perfectly-Secure Asynchronous MPC for General Adversaries

Ashish Choudhury, **Nikhil Pappu**

INDOCRYPT 2020

ज्ञानमुत्तमम्

Secure Multi-Party Computation (MPC)

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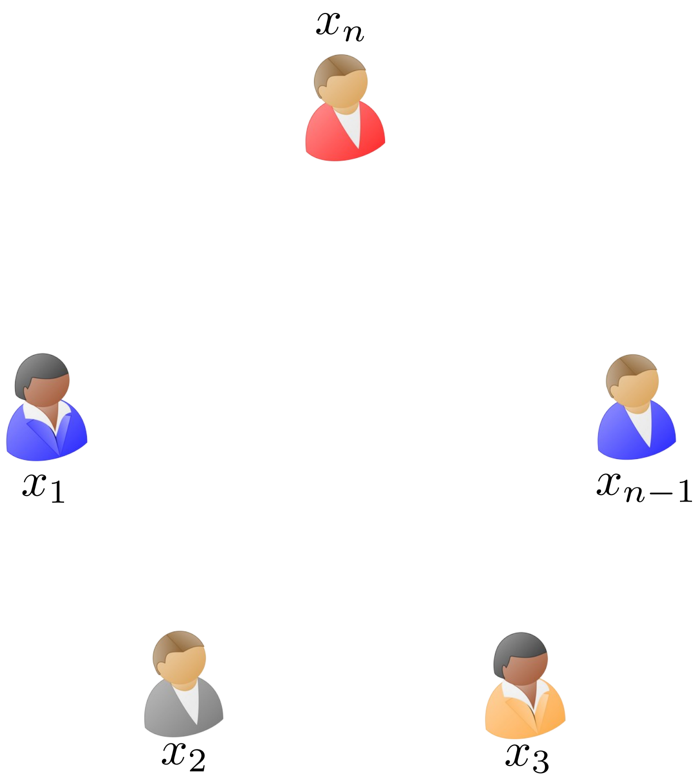

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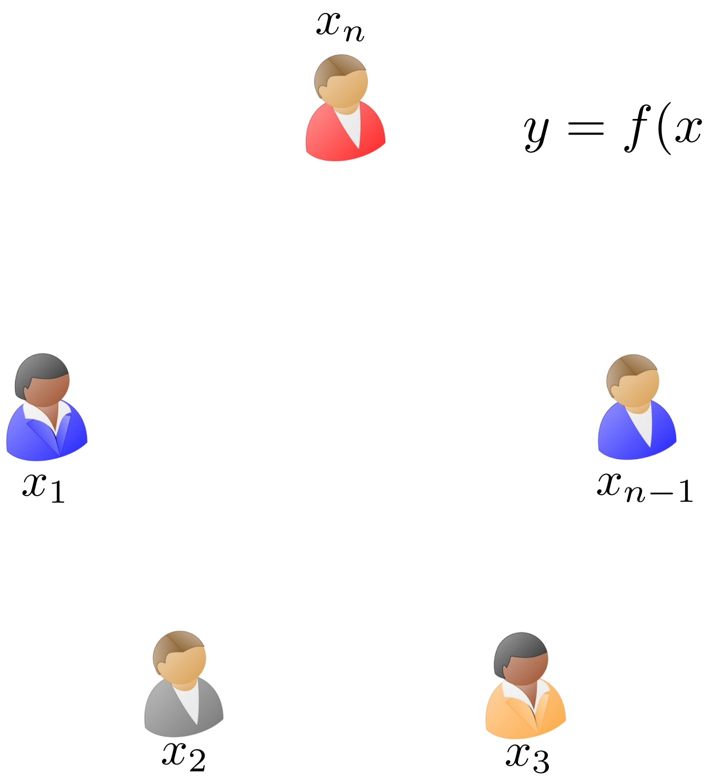

$$y = f(x_1, \ldots, x_n)$$

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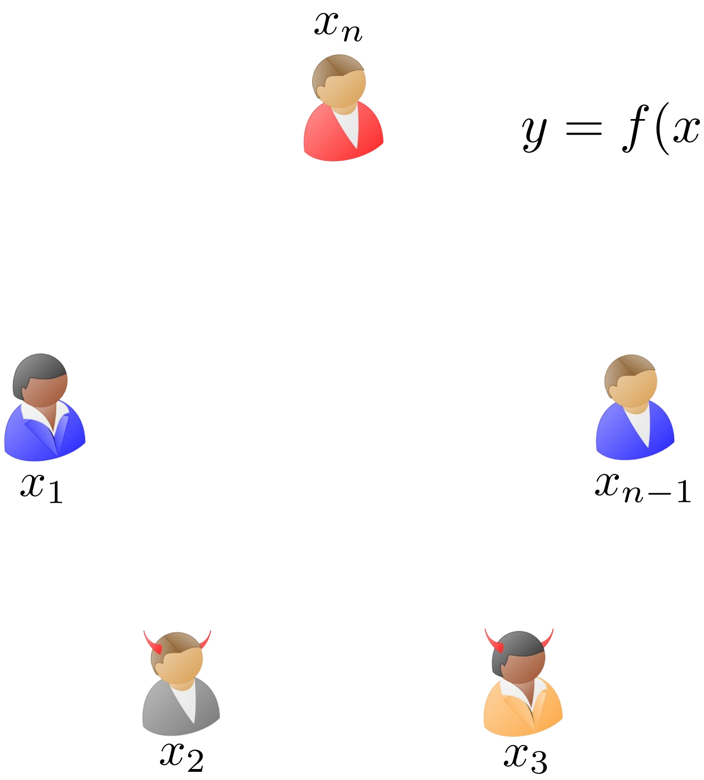

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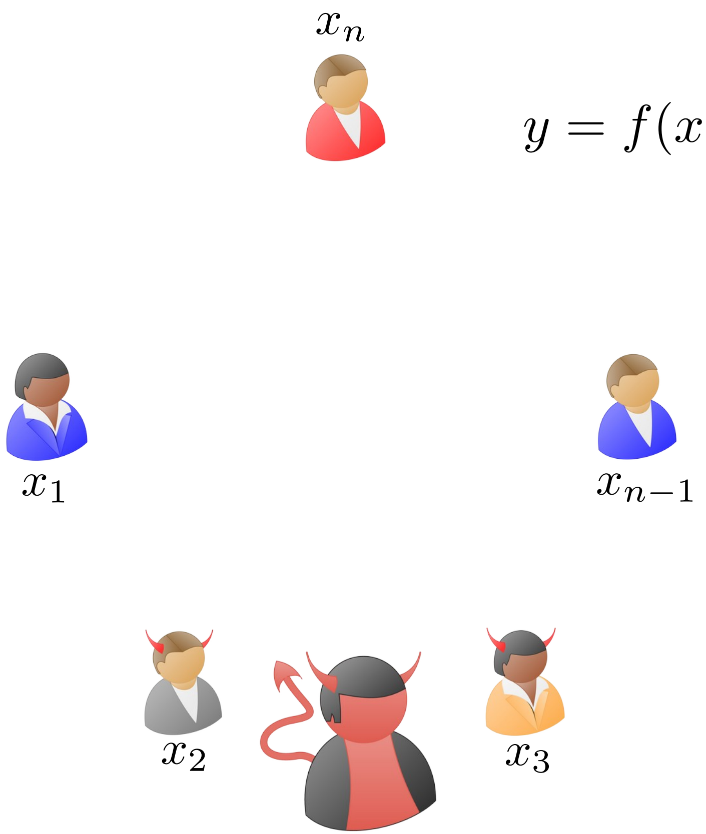

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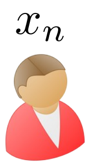

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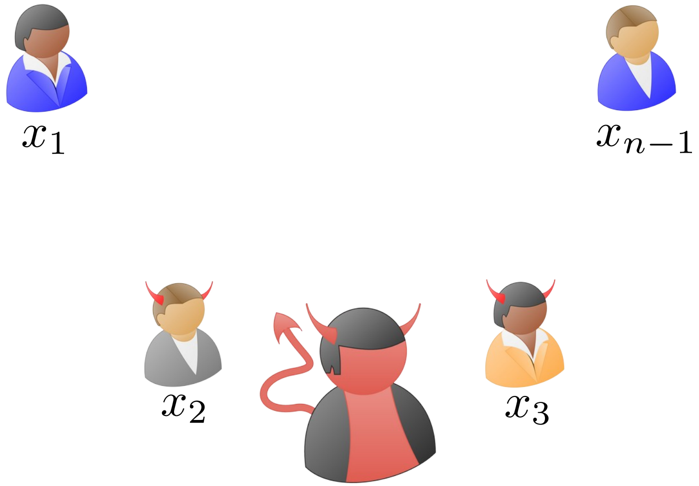
- Privacy



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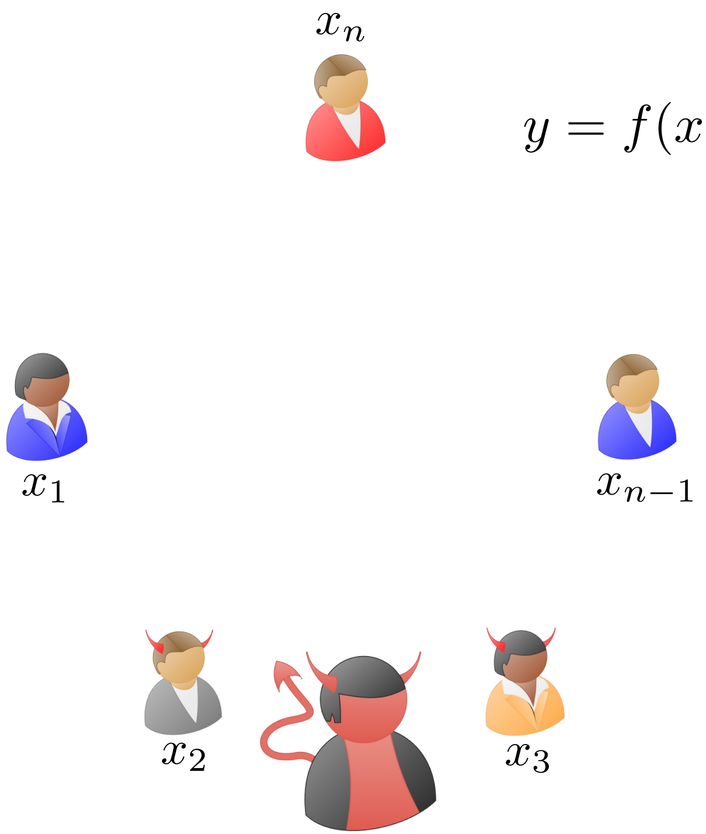

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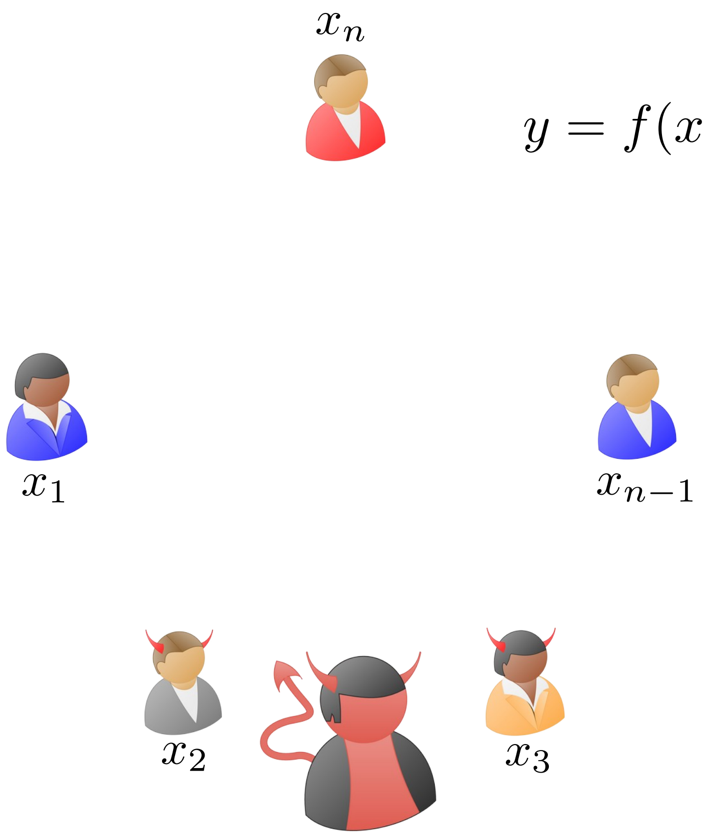

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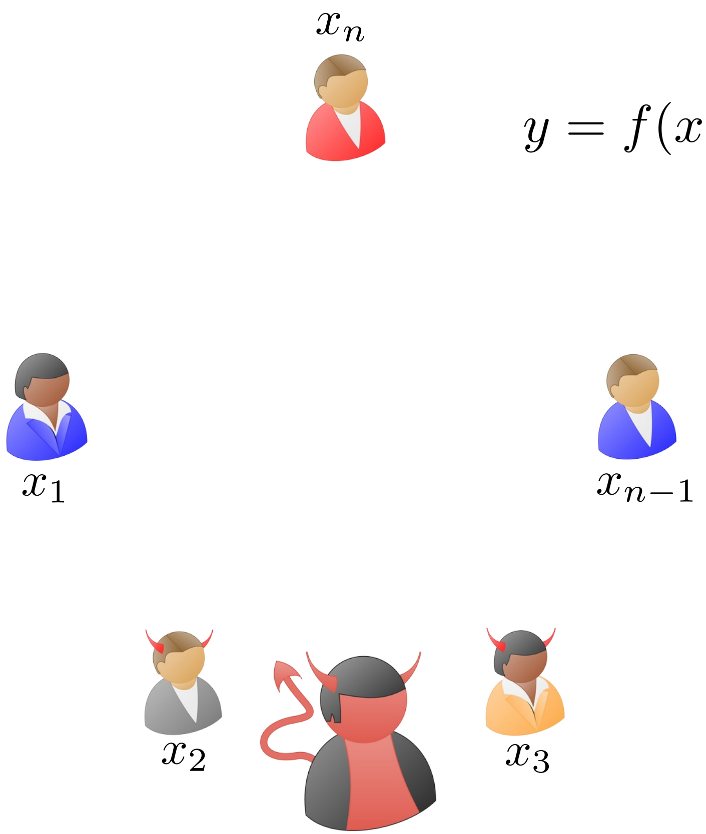

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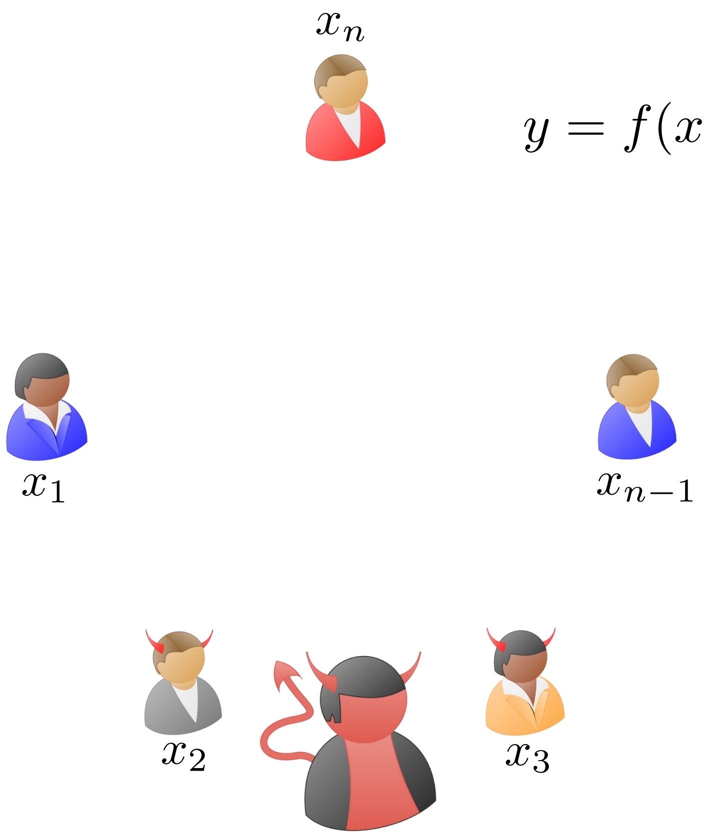

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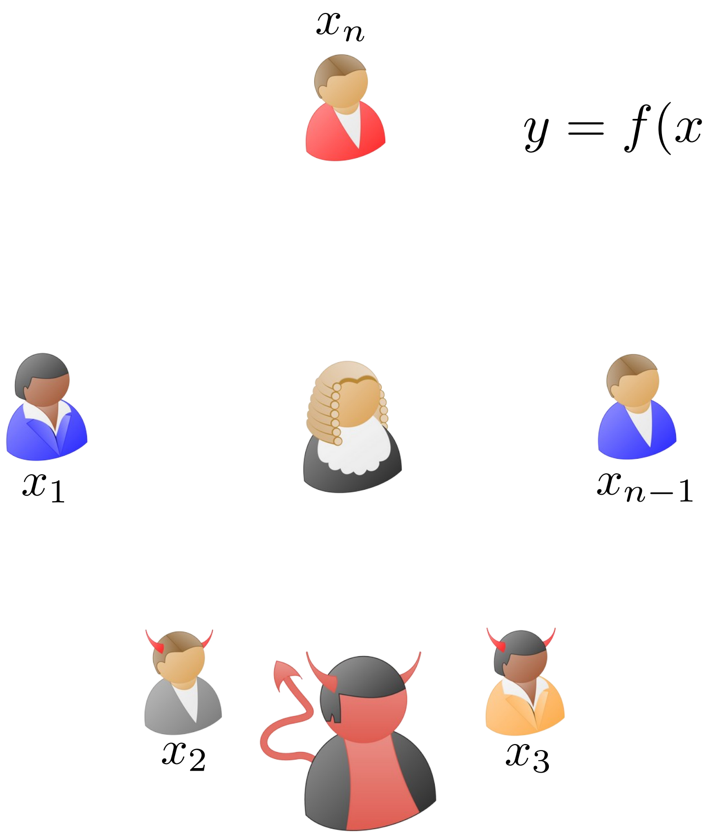

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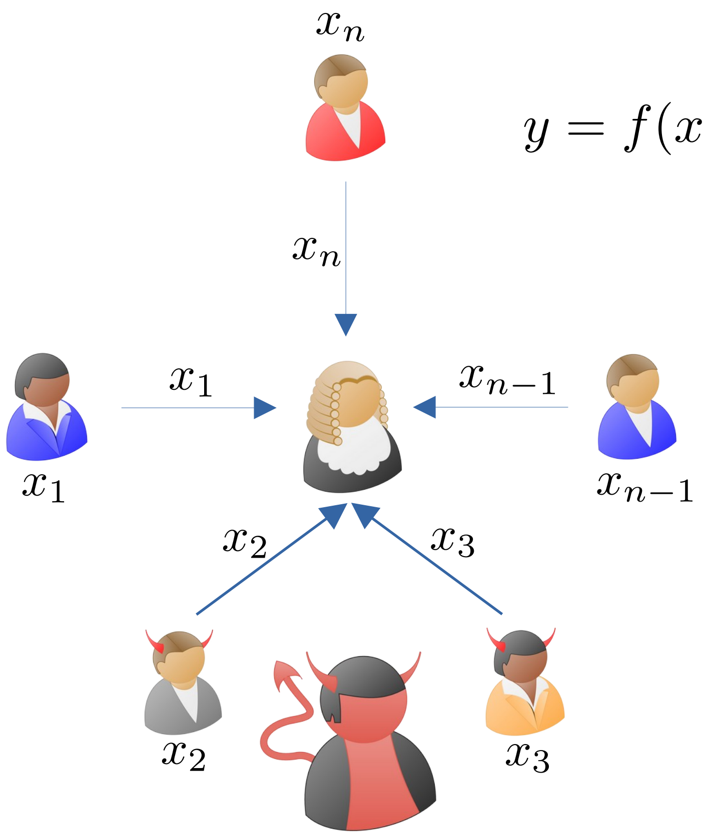

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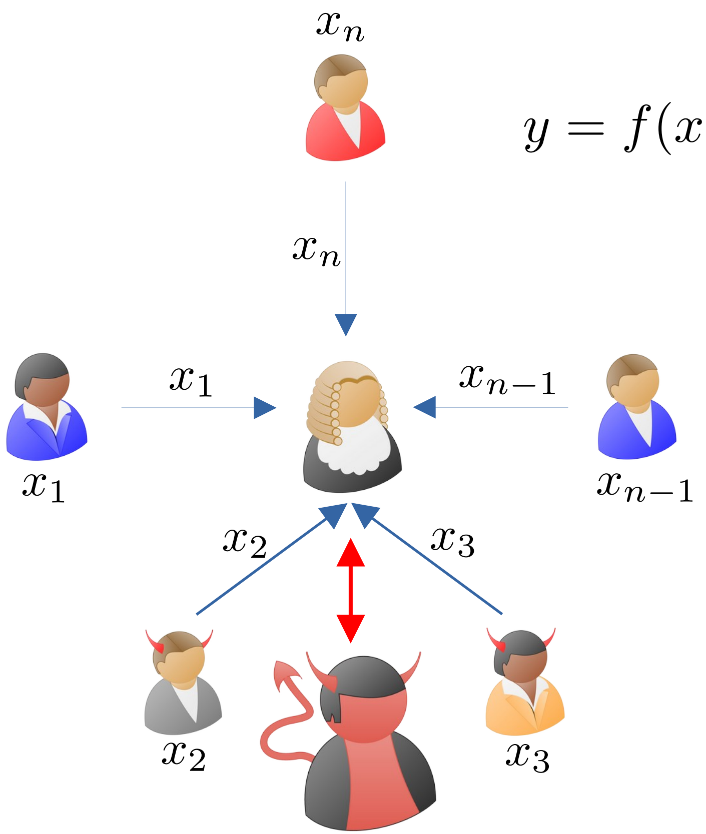

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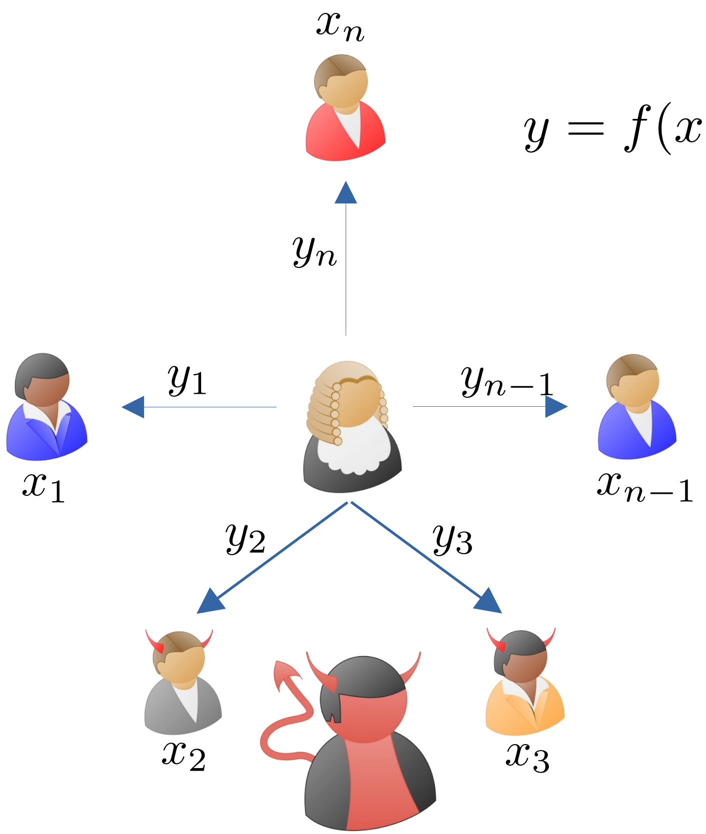

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Communication Models

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Synchronous Model

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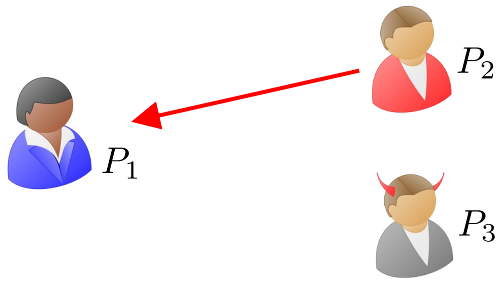

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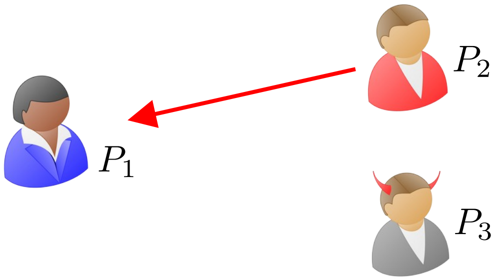

- Message Delays $< \Delta$

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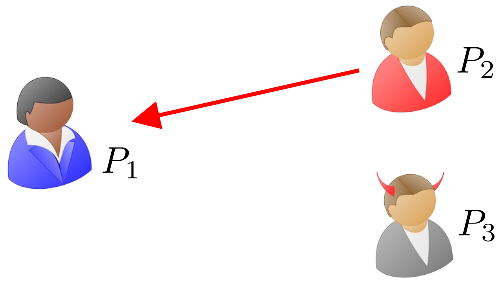

- Message Delays $< \Delta$
- Synchronized Clocks

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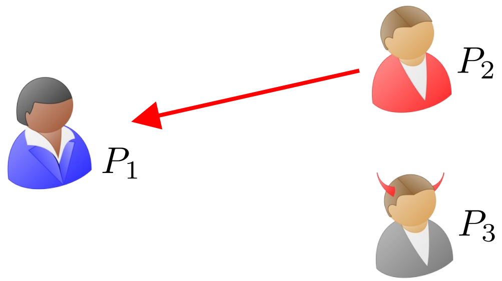

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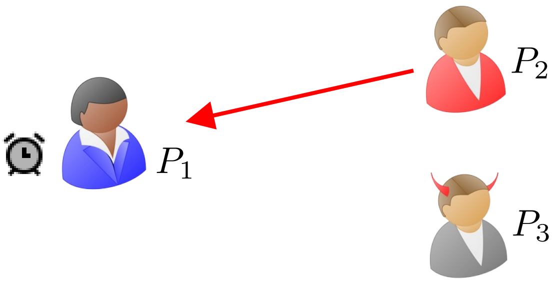

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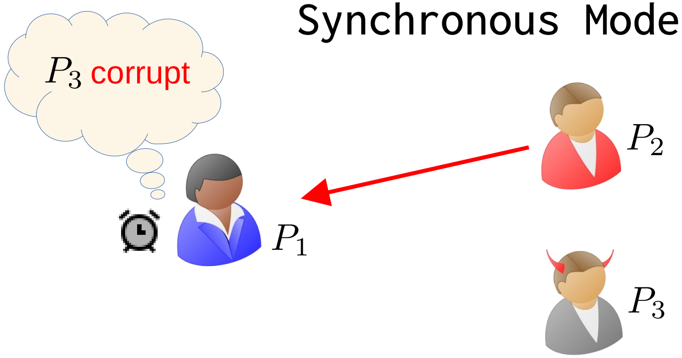

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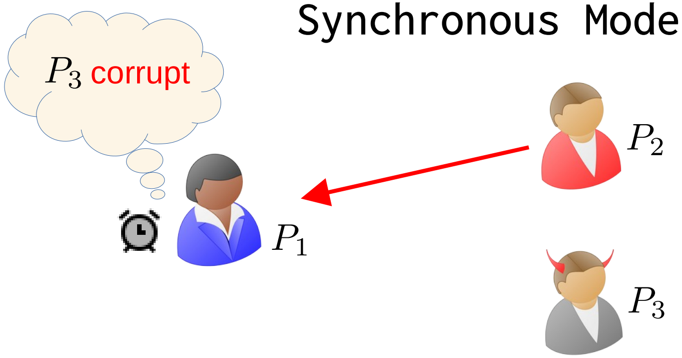

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Asynchronous Model [BCG93]

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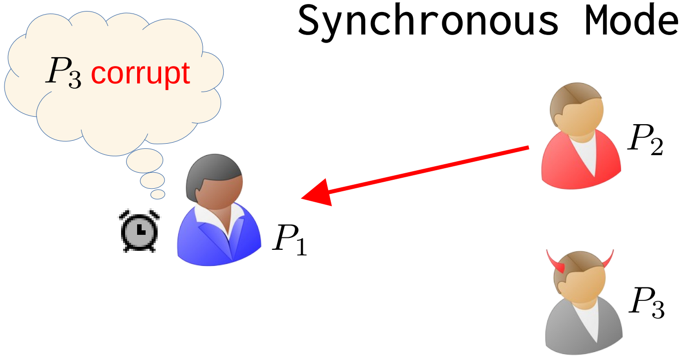

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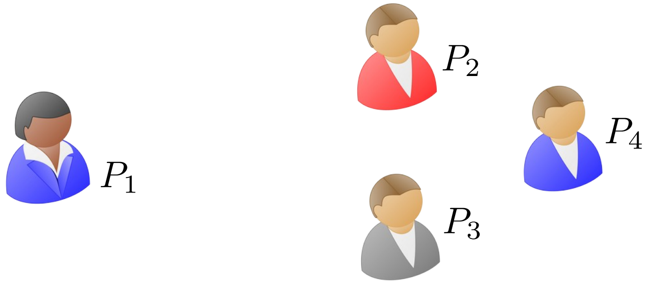

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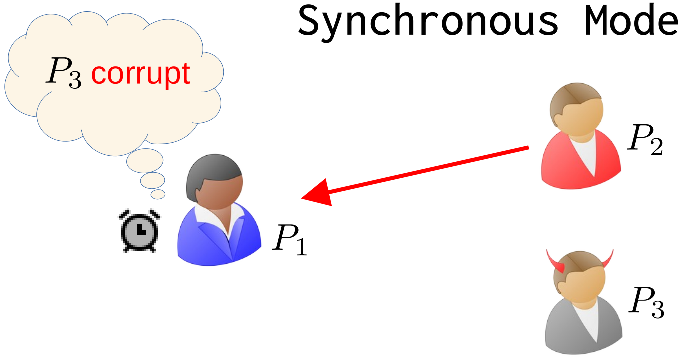

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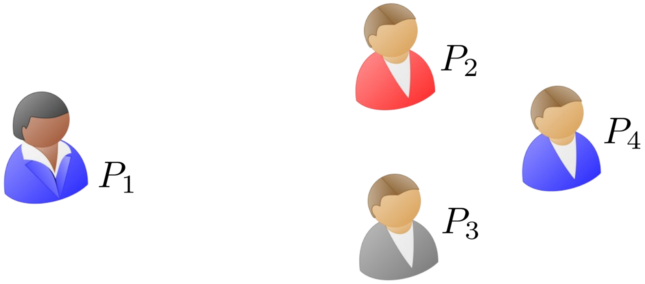

Unbounded
(finite) Delays

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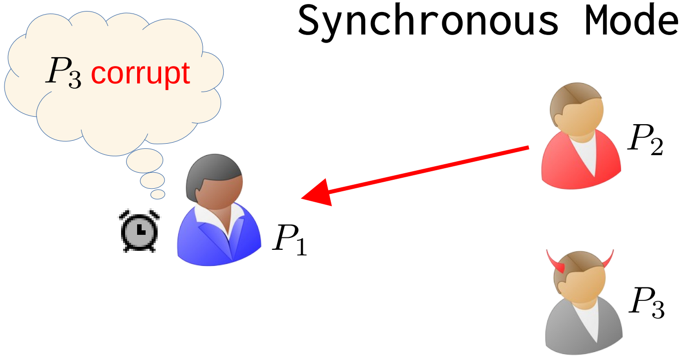

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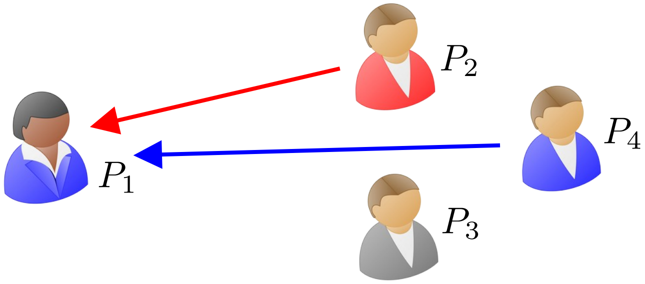

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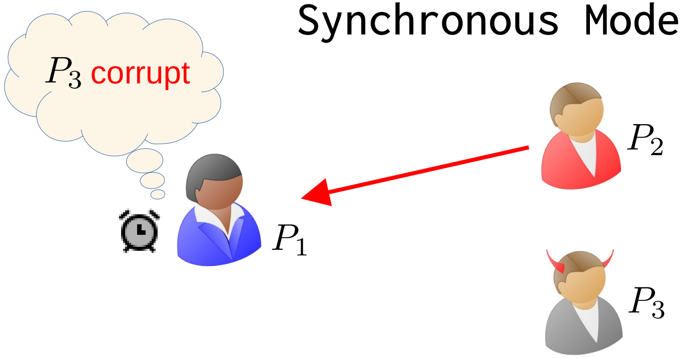

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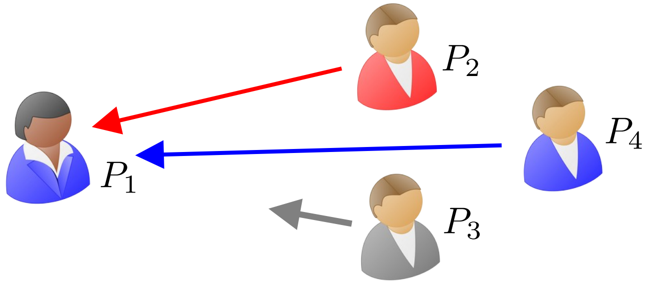

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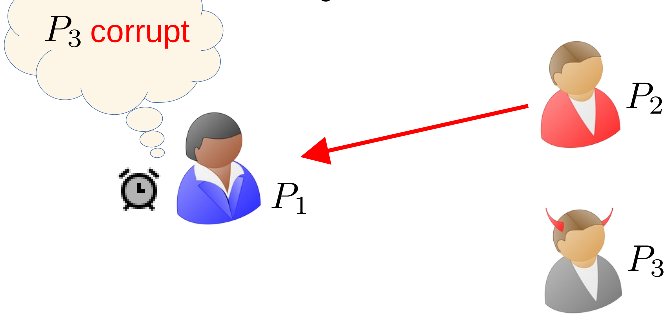

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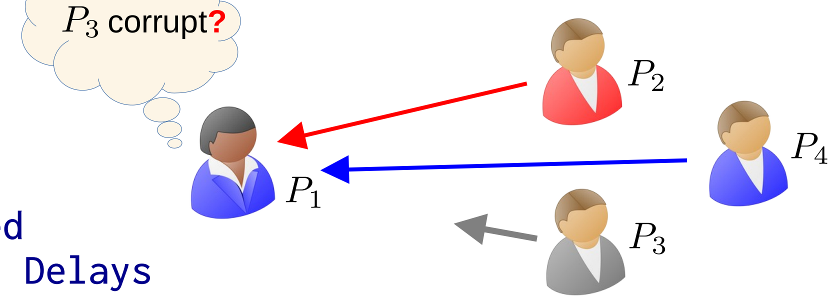

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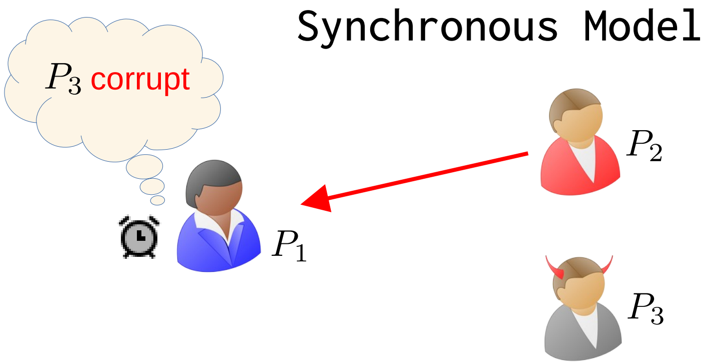

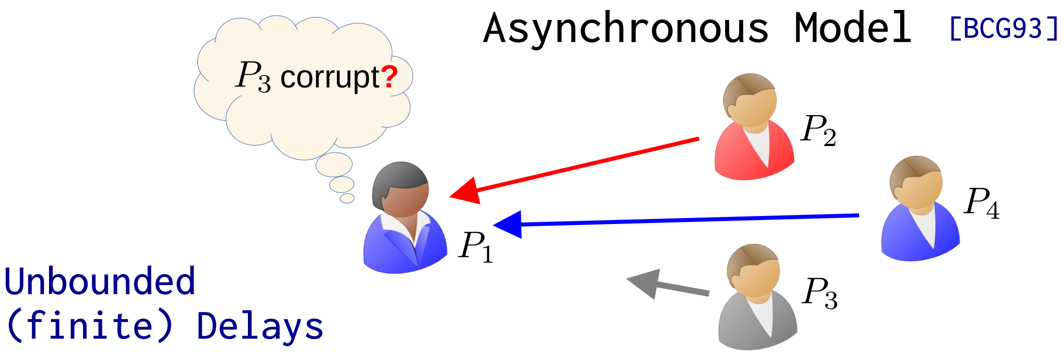

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- No Input Provision

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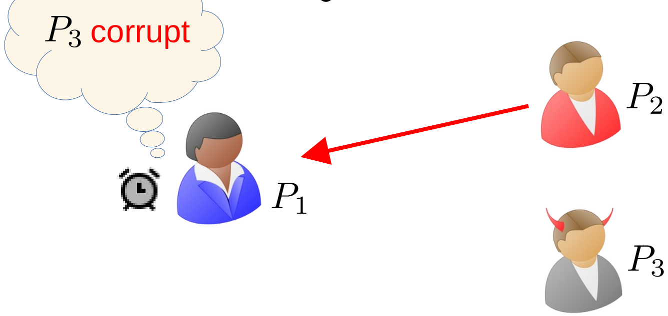

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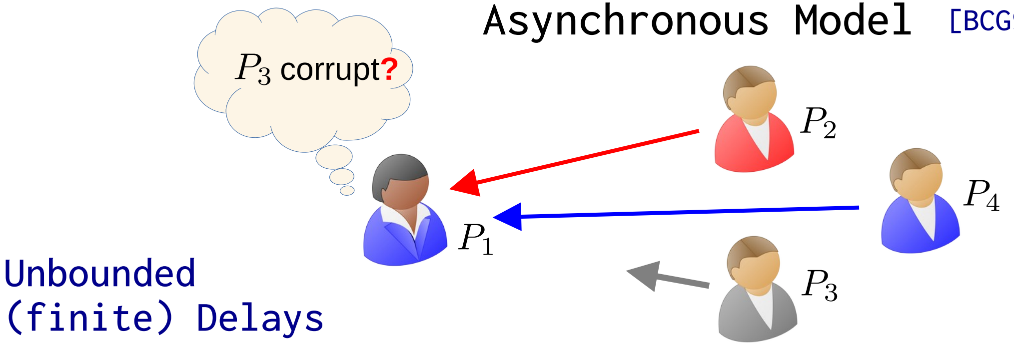

- No Input Provision $f(x_1, x_2, \cdot, x_4)$

Communication Models

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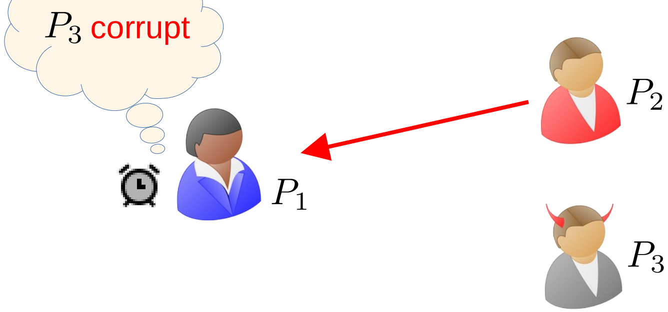

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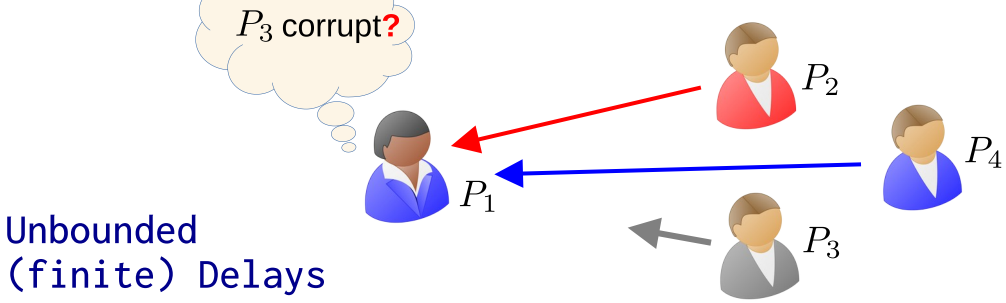
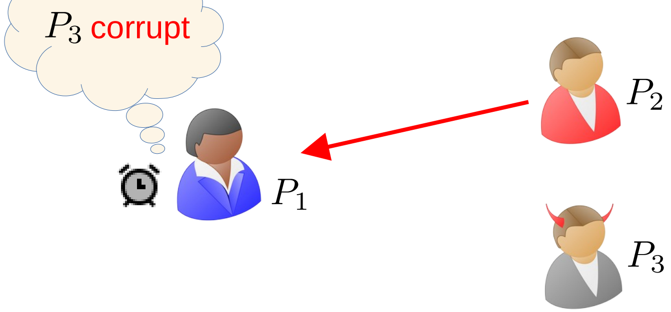


- No Input Provision $f(x_1, x_2, \cdot, x_4)$
- Worse Resilience

Communication Models

Synchronous Model



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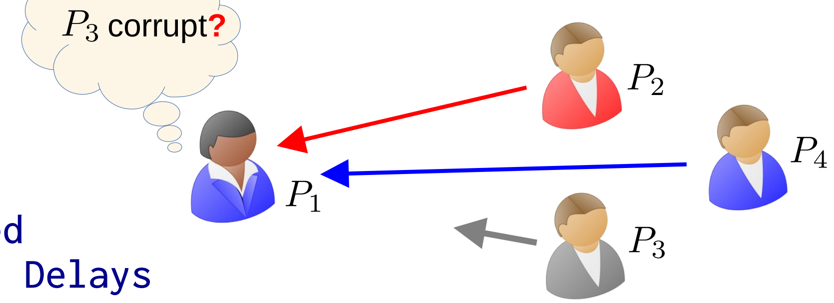

Unbounded (finite) Delays

- No Input Provision $f(x_1, x_2, \cdot, x_4)$
- Worse Resilience
- Worse Communication and Computation (Known Protocols)

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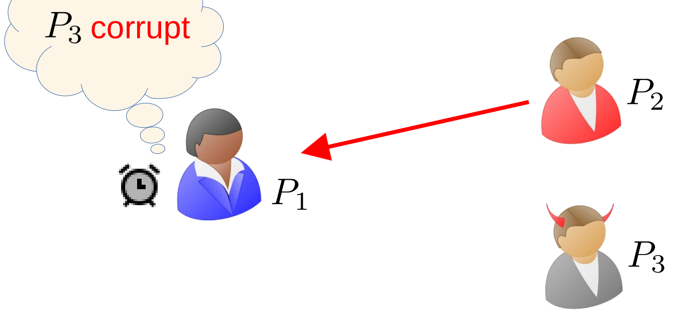

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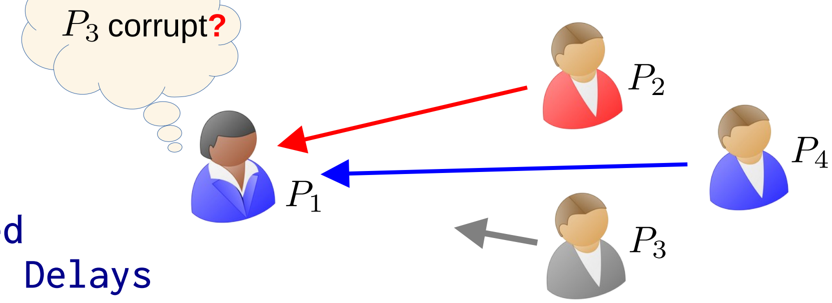

Unbounded
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- Real-World Networks

Communication Models

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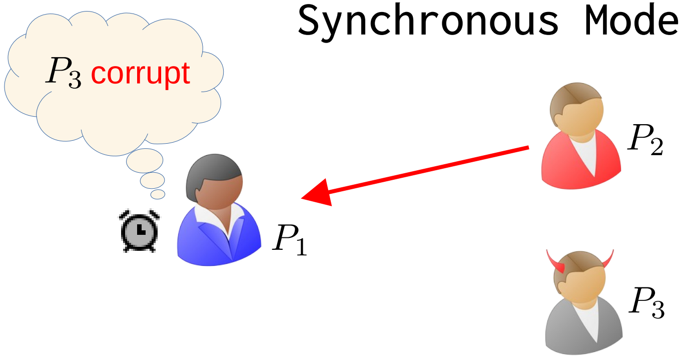

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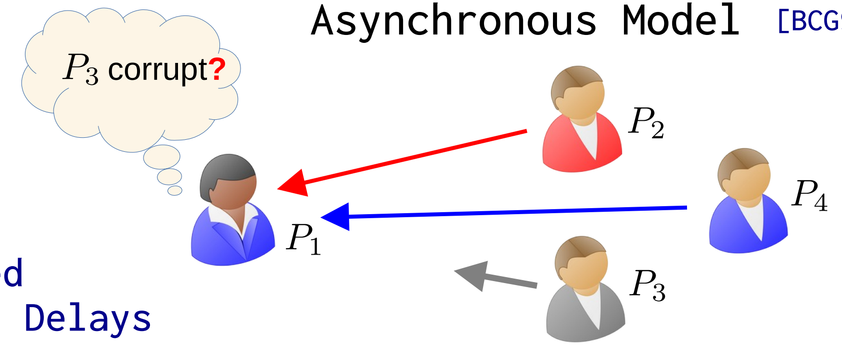

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- Worse Resilience
- Worse Communication and Computation (Known Protocols)
- Real-World Networks 
- Responsiveness 

General Adversaries

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Most MPC protocols: $t < \frac{n}{k}$

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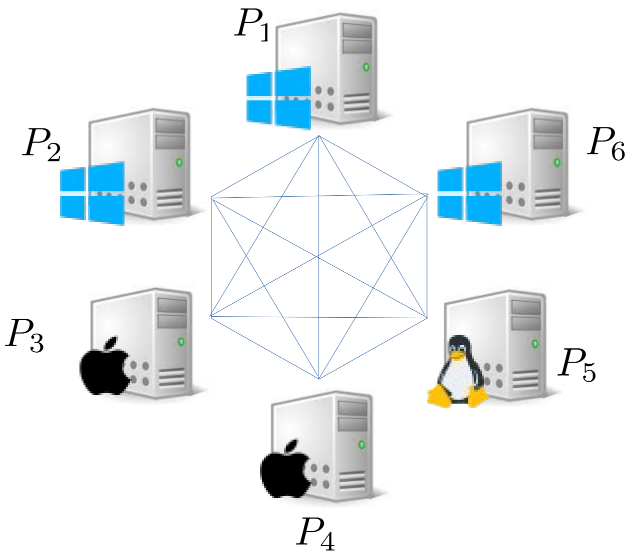

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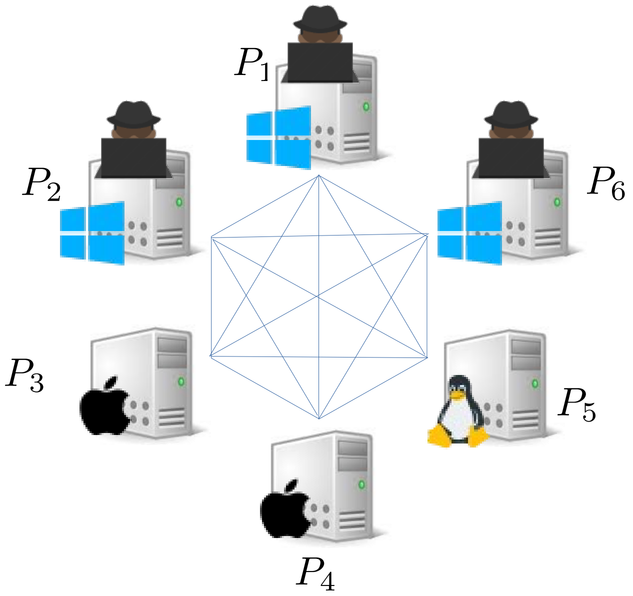

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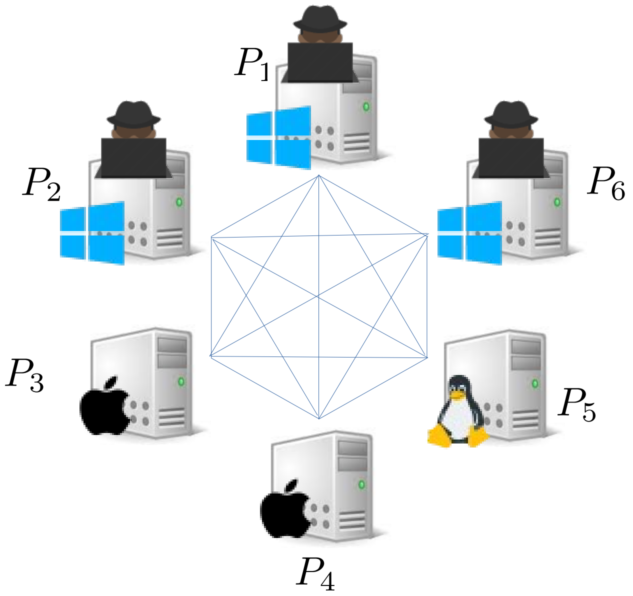

- Computational-Security

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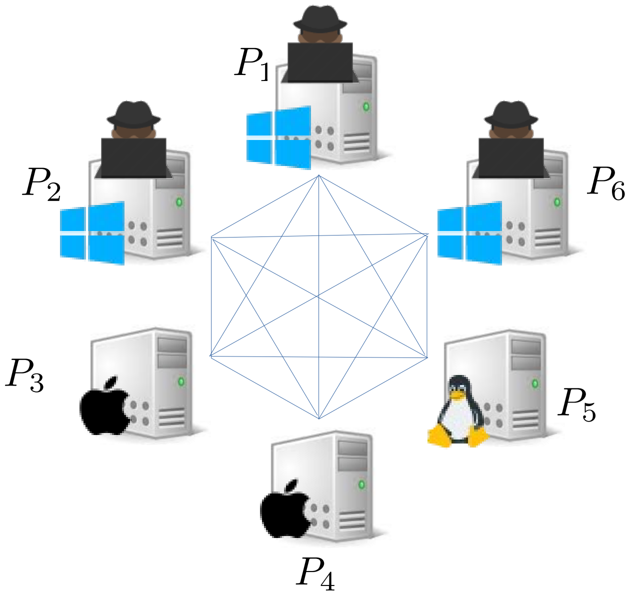

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- Guaranteed Output Delivery

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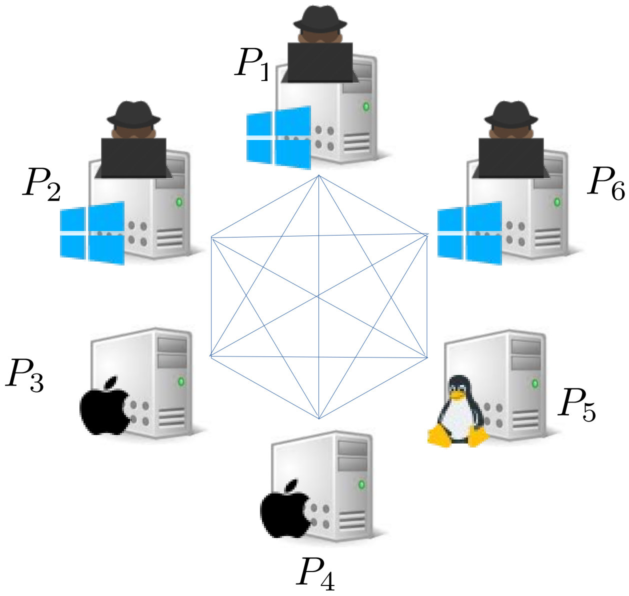

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$$t < 6/2 \implies t \leq 2$$

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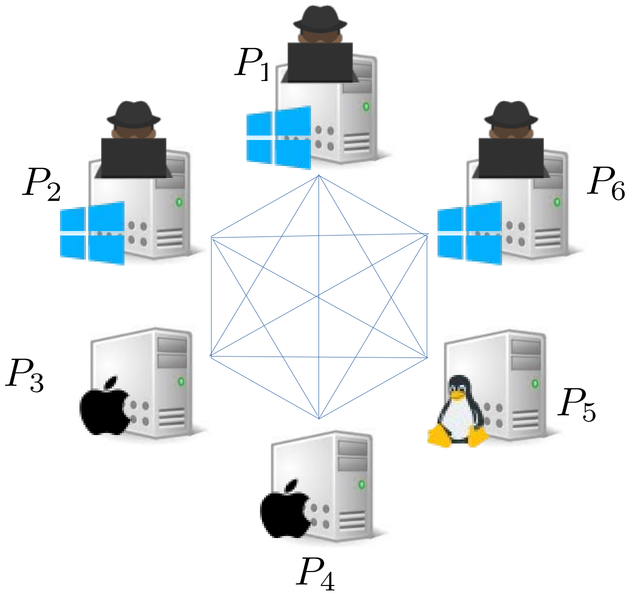

$$\mathcal{Z} = \{\{P_1, P_2, P_6\}, \{P_3, P_4\}, \{P_5\}\}$$ [HM97]

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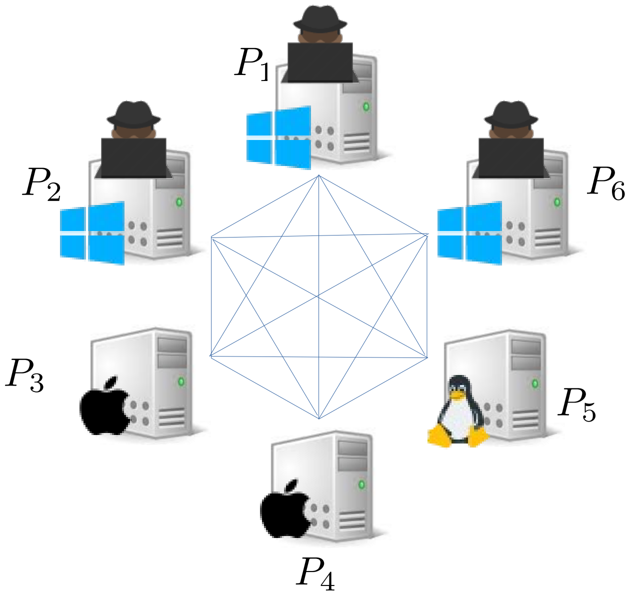

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- monotone, maximal

- Computational-Security
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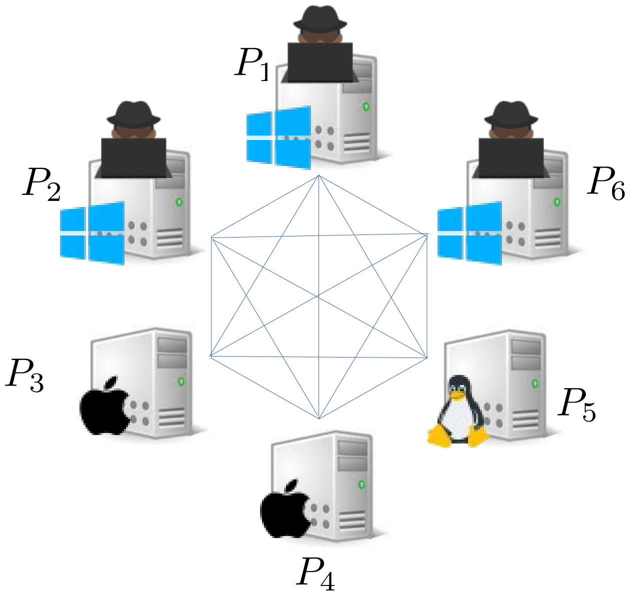

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- monotone, maximal
- Size possibly exp in n

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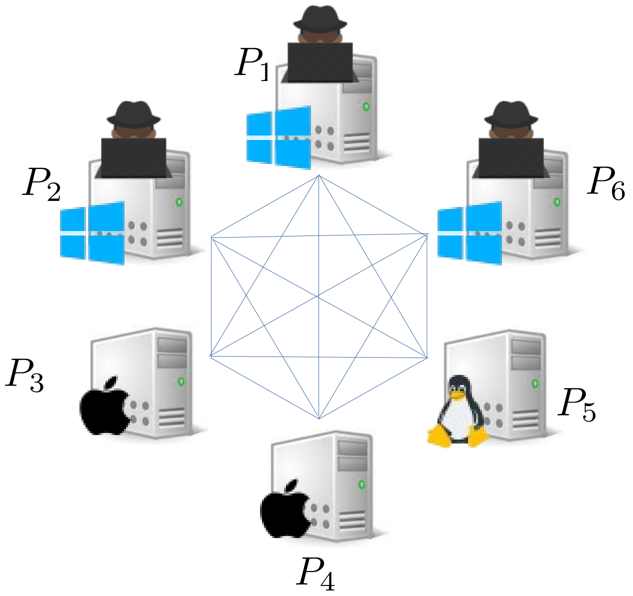

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- Increased flexibility

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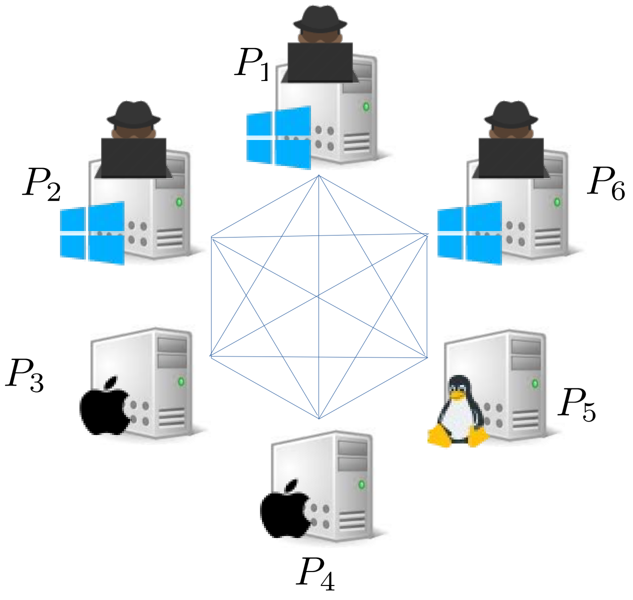

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- monotone, maximal
- Size possibly exp in n

- Increased flexibility
- Communication Complexity $|\mathcal{Z}|^{\mathcal{O}(1)}$ (Known Protocols)

- Computational-Security
- Guaranteed Output Delivery

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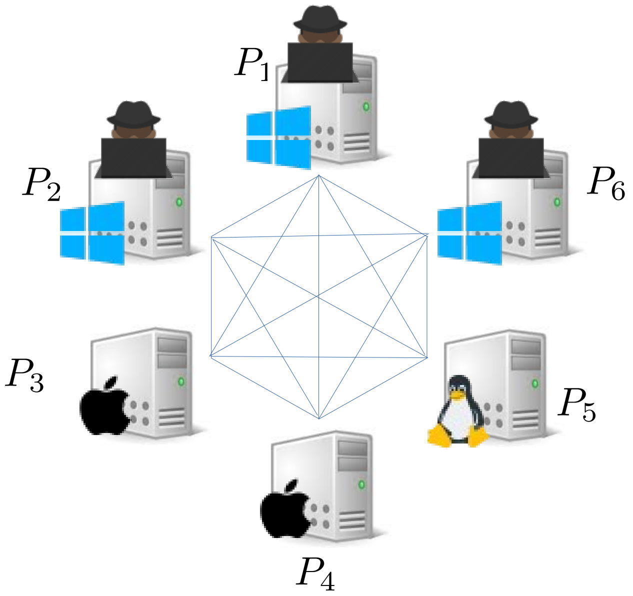
General Adversaries

Most MPC protocols: $t < \frac{n}{k}$ Can be limiting...



$$\mathcal{Z} = \{\{P_1, P_2, P_6\}, \{P_3, P_4\}, \{P_5\}\}$$ [HM97]

- monotone, maximal
- Size possibly exp in n

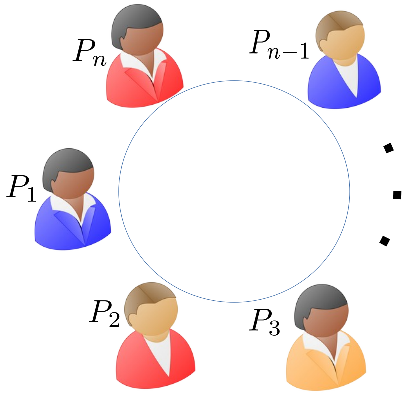
- Computational-Security
- Guaranteed Output Delivery

$$t < 6/2 \implies t \leq 2$$

- Increased flexibility
- Communication Complexity $|\mathcal{Z}|^{\mathcal{O}(1)}$ (Known Protocols)
- Computational Complexity Lower Bound $\Omega(|\mathcal{Z}|)$ [HM00]

Setting

Setting



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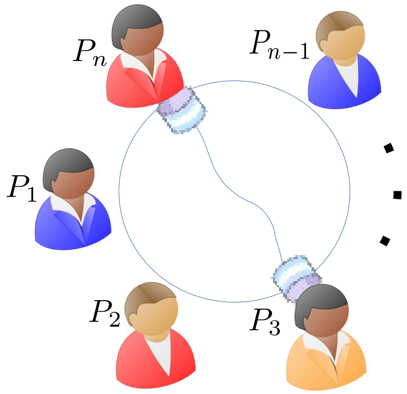

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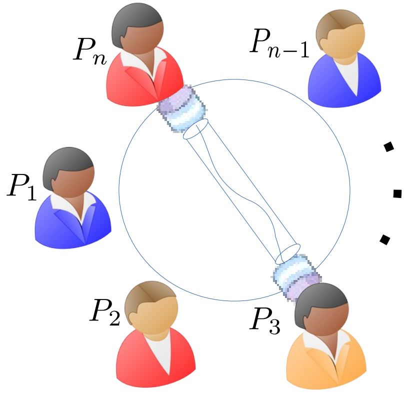

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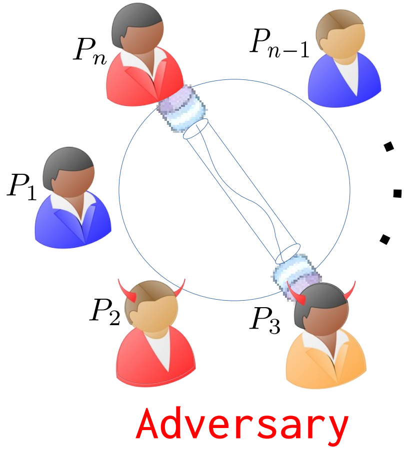

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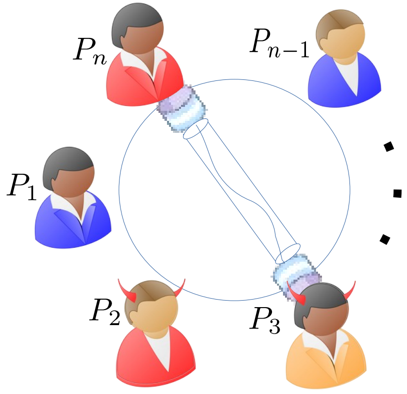
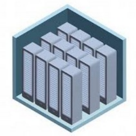


Adversary

- Computationally-Unbounded 

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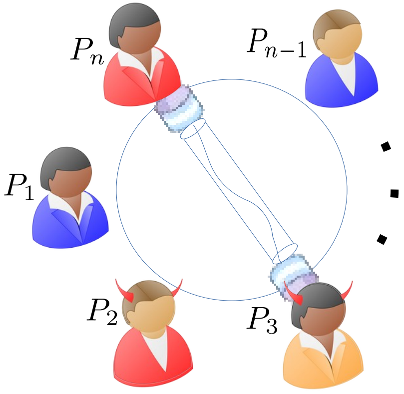
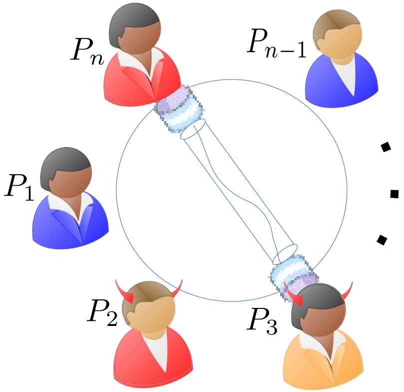


Adversary

- Computationally-Unbounded 

  Perfect-Security 0%

Setting



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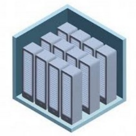
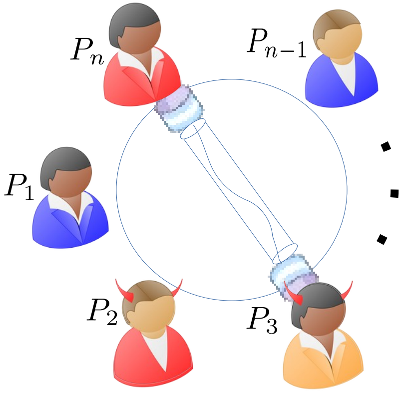
- Computationally-Unbounded 

  Perfect-Security 0%

- Malicious (Byzantine)

Setting



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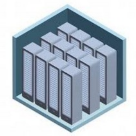
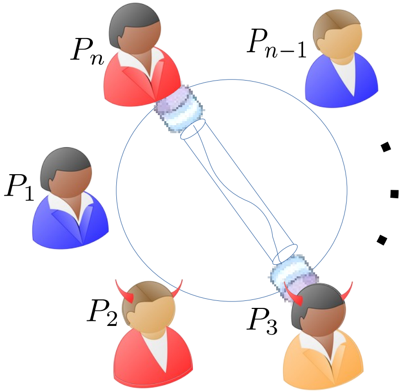
- Computationally-Unbounded 

  Perfect-Security 0% 

- Malicious (Byzantine)  

- Message Scheduler 

Setting



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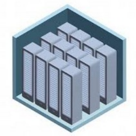
- Computationally-Unbounded 

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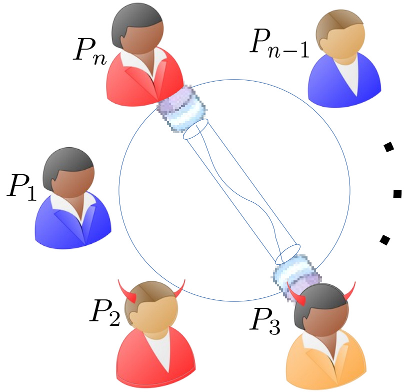
Adversary Structure $\mathcal{Z} = \{\ldots, Z_i, \ldots\}$

Setting



Adversary

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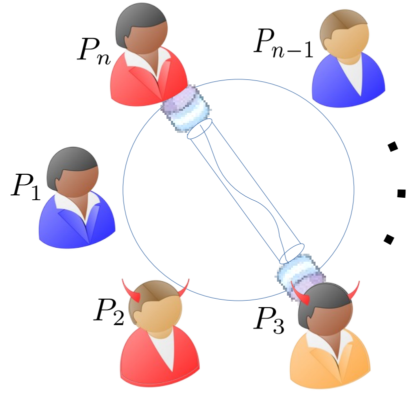
Adversary Structure $\mathcal{Z} = \{\ldots, Z_i, \ldots\}$

Requires $\mathcal{Q}^{(4)}$
[KSR02]

Setting



Adversary

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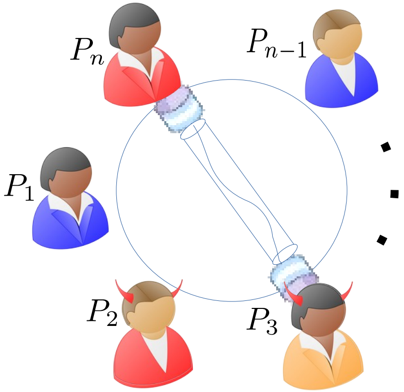
[KSR02]

Partyset $\mathcal{P}$

Setting



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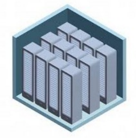
- Computationally-Unbounded 

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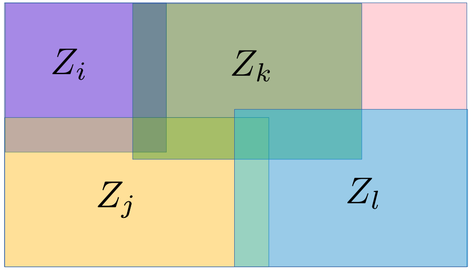

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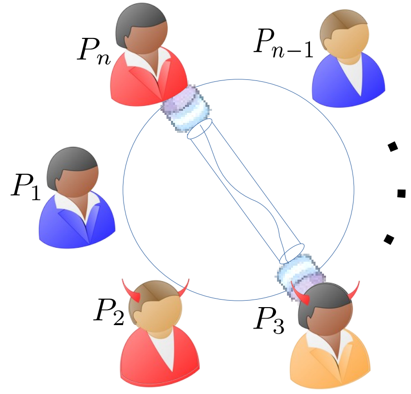
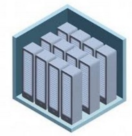


Adversary

$f(x_1, x_2, x_3, x_4)$

- Computationally-Unbounded 

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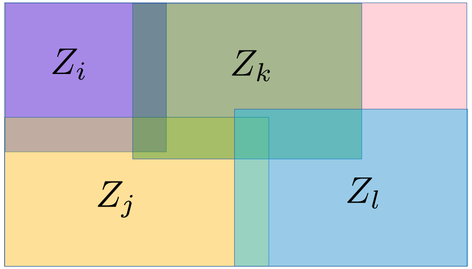

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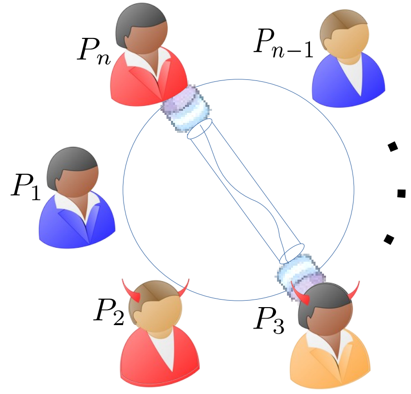

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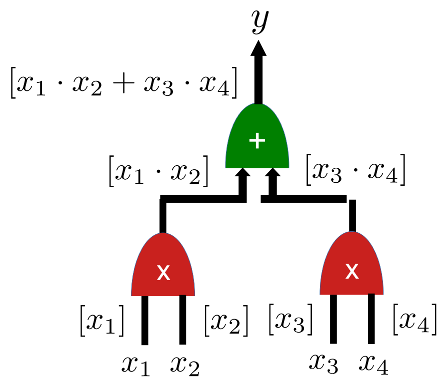
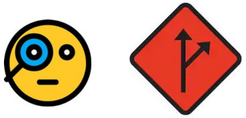


Arithmetic Circuit over Field/Ring

- Computationally-Unbounded 

  Perfect-Security 0%

- Malicious (Byzantine) 

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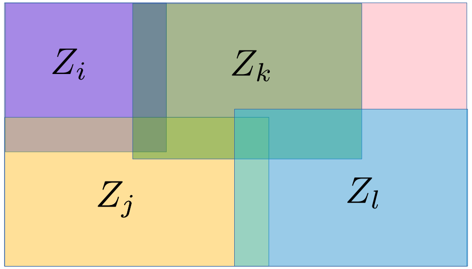

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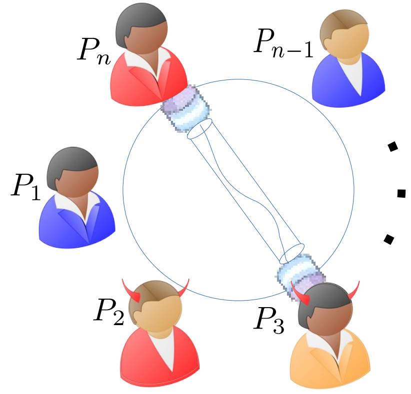

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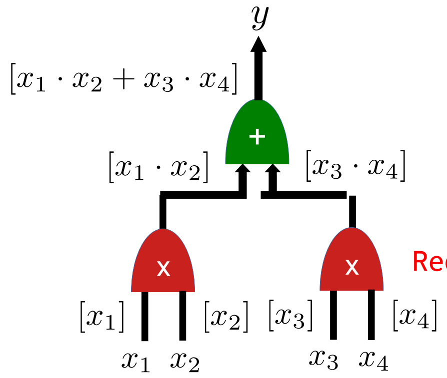

Requires Interaction

Arithmetic Circuit over Field/Ring

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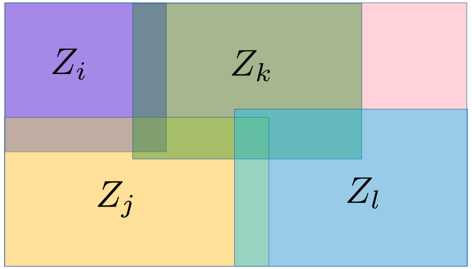

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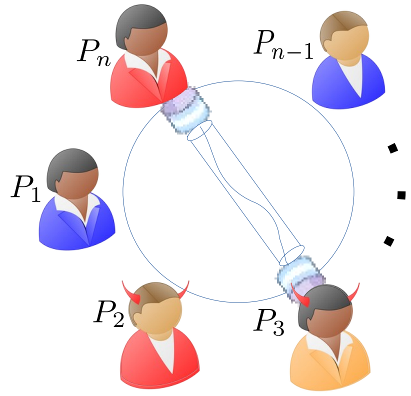

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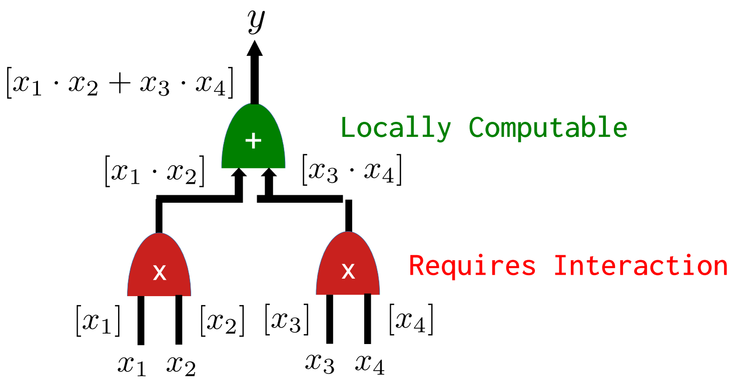

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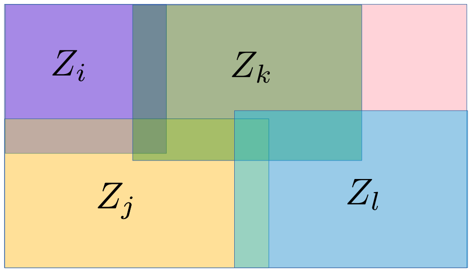

Work on General Adversaries

Work on General Adversaries

Synchronous Model

Work on General Adversaries

Synchronous Model

- [HM97, HM00]
  Feasibility Results

Work on General Adversaries

Synchronous Model

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  Feasibility Results

- [CDD+99, CDM00, FHM99, Mau02, SS99]
  Polynomial (in $|\mathcal{Z}|$) complexities

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- [KSR02]
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Asynchronous Model

- [KSR02]
  - Perfect-Security Setting
  - MSP-based AVSS Protocol

Work on General Adversaries

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  - AMPC Protocol ⚠️

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Asynchronous Model

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- Our Work

Work on General Adversaries

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Asynchronous Model

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  - Perfectly-Secure Additive SS-based ([Mau02]) AVSS Protocol

Work on General Adversaries

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  - ABA Protocol (Generalization of [CR93])

Flaw in [KSR02]

Flaw in [KSR02]

Player Elimination Framework [HMP00]

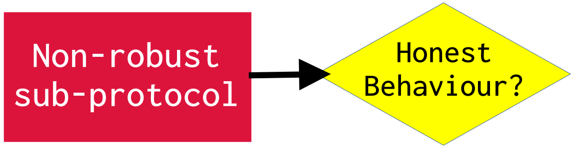
Flaw in [KSR02]

Player Elimination Framework [HMP00]

Non-robust sub-protocol

Flaw in [KSR02]

Player Elimination Framework [HMP00]



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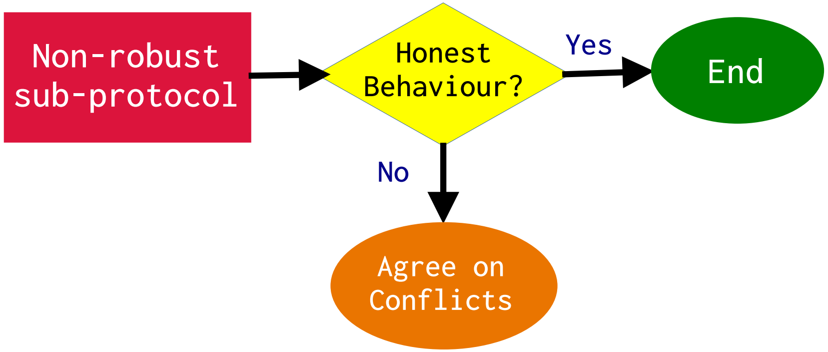

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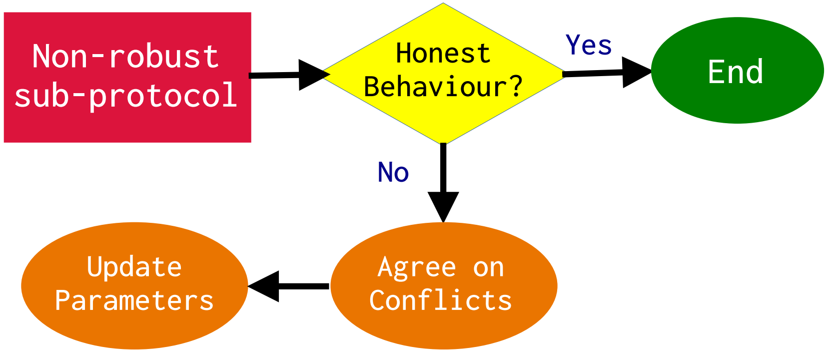

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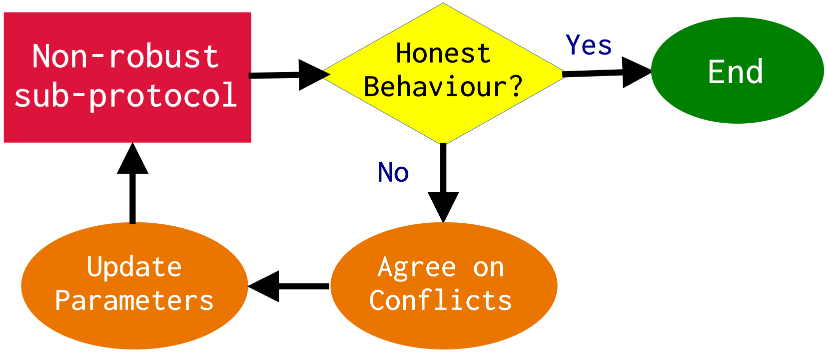

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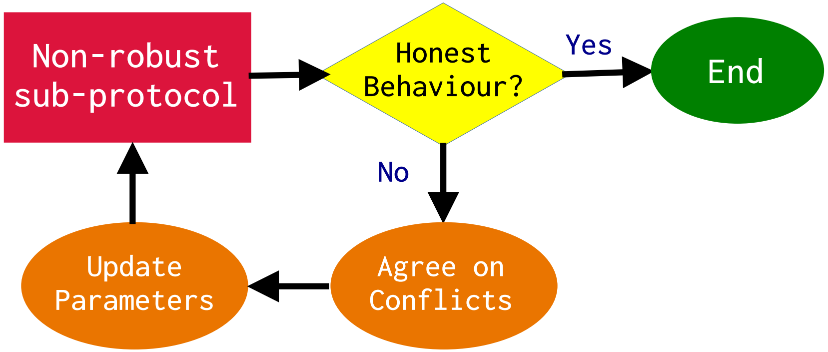
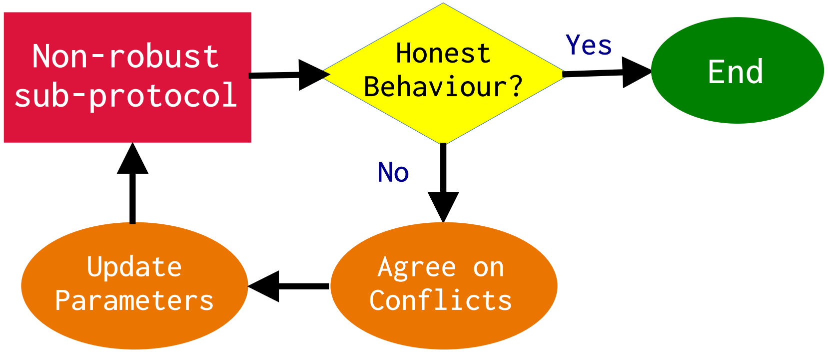


Example Execution

Flaw in [KSR02]

Player Elimination Framework [HMP00]



Example Execution

Partyset $\mathcal{P} = \{P_1, P_2, P_3, P_4, P_5, P_6, P_7\}$

Flaw in [KSR02]

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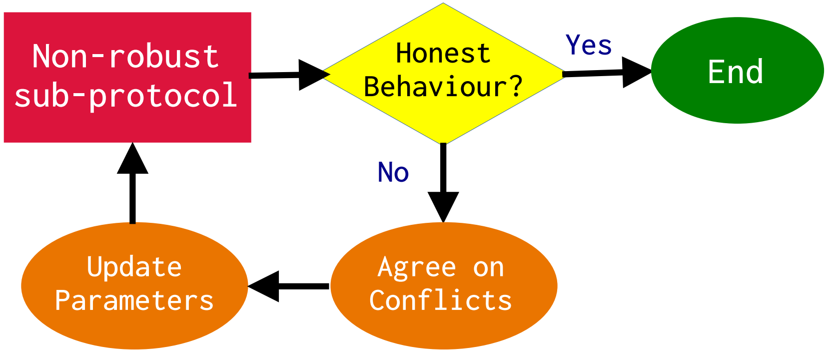

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Adversary Structure satisfying $\mathcal{Q}^{(4)}$

Flaw in [KSR02]

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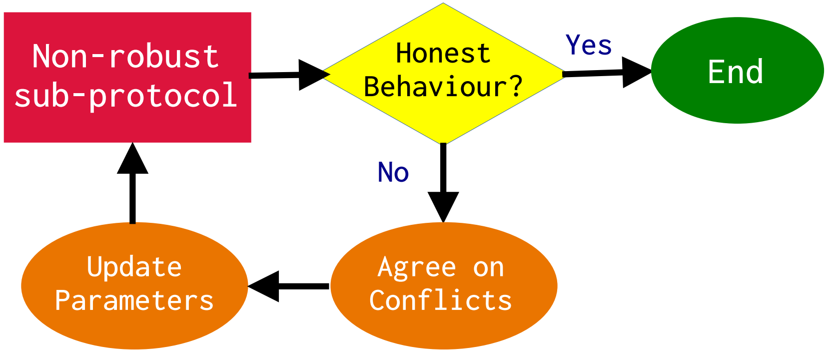


Example Execution

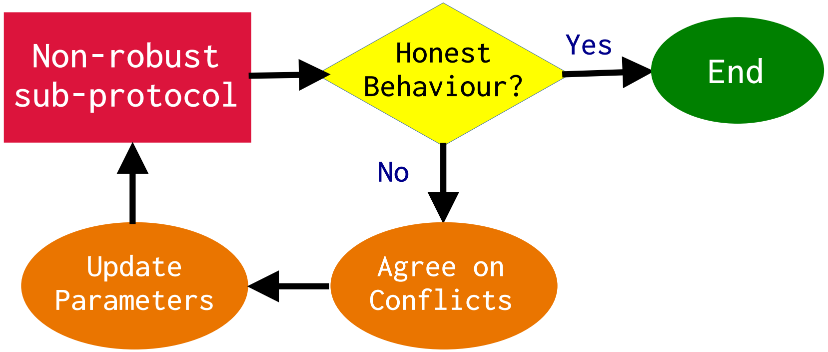
Partyset $\mathcal{P} = \{P_1, P_2, P_3, P_4, P_5, P_6, P_7\}$

Adversary Structure satisfying $\mathcal{Q}^{(4)}$

$$\mathcal{Z} = \{\{P_1, P_2\}, \{P_1, P_3\}, \{P_1, P_4\}, \{P_1, P_5, P_6\}, \{P_7\}\}$$

Flaw in [KSR02]

Player Elimination Framework [HMP00]



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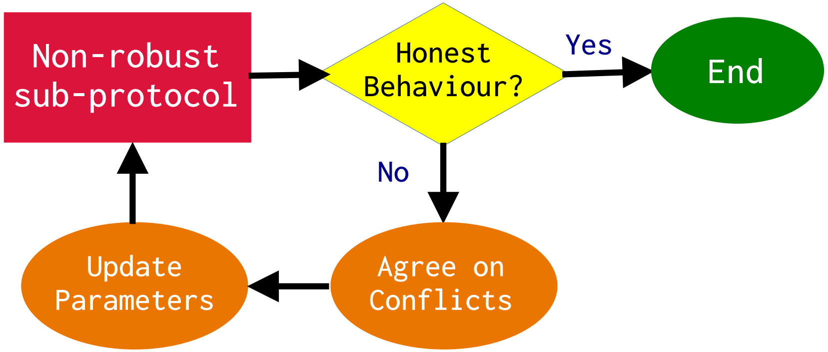
Conflict Set

$\{P_1, P_2, P_7\}$

Flaw in [KSR02]

Player Elimination Framework [HMP00]



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Conflict Set

$\{P_1, P_2, P_7\}$ Choice of Adversary

Flaw in [KSR02]

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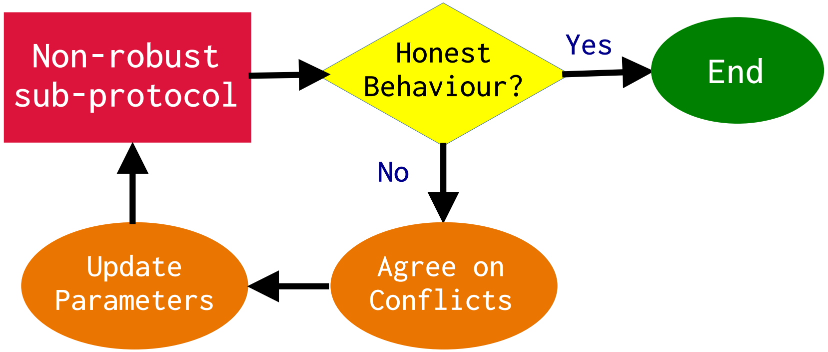

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Conflict Set

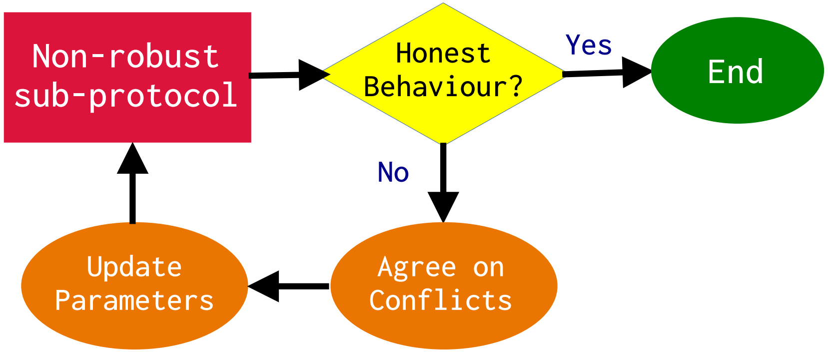
$\{P_1, P_2, P_7\}$ Choice of Adversary

Updated Parameters

$\mathcal{P} = \{P_3, P_4, P_5, P_6\}$

Flaw in [KSR02]

Player Elimination Framework [HMP00]



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Conflict Set

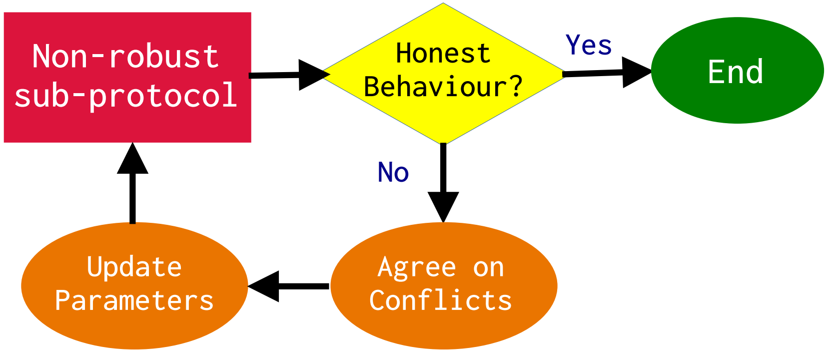
$\{P_1, P_2, P_7\}$ Choice of Adversary

Updated Parameters

$\mathcal{P} = \{P_3, P_4, P_5, P_6\}$ $\mathcal{Z}$ remains same

Flaw in [KSR02]

Player Elimination Framework [HMP00]



Example Execution

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Adversary Structure satisfying $\mathcal{Q}^{(4)}$

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Conflict Set

$\{P_1, P_2, P_7\}$ Choice of Adversary

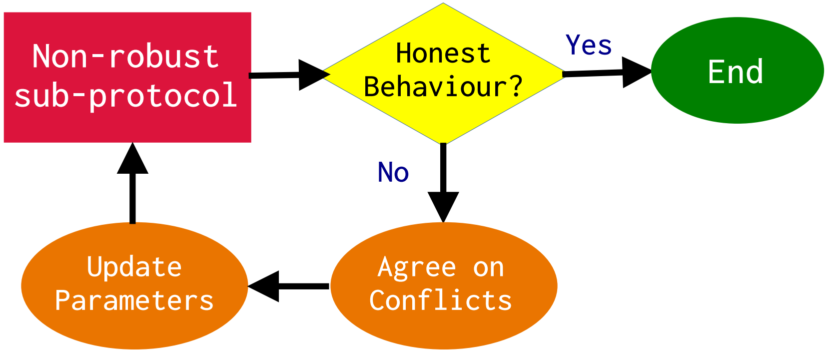
Updated Parameters

$\mathcal{P} = \{P_3, P_4, P_5, P_6\}$ $\mathcal{Z}$ remains same

$$\mathcal{P} \subseteq \{P_1, P_3\} \cup \{P_1, P_4\} \cup \{P_1, P_5, P_6\}$$

Flaw in [KSR02]

Player Elimination Framework [HMP00]



Example Execution

Partyset $\mathcal{P} = \{P_1, P_2, P_3, P_4, P_5, P_6, P_7\}$

Adversary Structure satisfying $\mathcal{Q}^{(4)}$

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Conflict Set

$\{P_1, P_2, P_7\}$ Choice of Adversary

Updated Parameters

$\mathcal{P} = \{P_3, P_4, P_5, P_6\}$ $\mathcal{Z}$ remains same

$\mathcal{P} \subseteq \{P_1, P_3\} \cup \{P_1, P_4\} \cup \{P_1, P_5, P_6\}$ $\mathcal{Q}^{(3)}$ Fails

Verifiable Secret-Sharing

Verifiable Secret-Sharing

Dealer

Verifiable Secret-Sharing

Dealer 

Secret s

Verifiable Secret-Sharing

Dealer 

Secret $\boxed{s}$

$\downarrow$

$\boxed{s^{(1)}}$, $\cdots$, $\boxed{s^{(q)}}$ $\quad q = |\mathcal{Z}|$

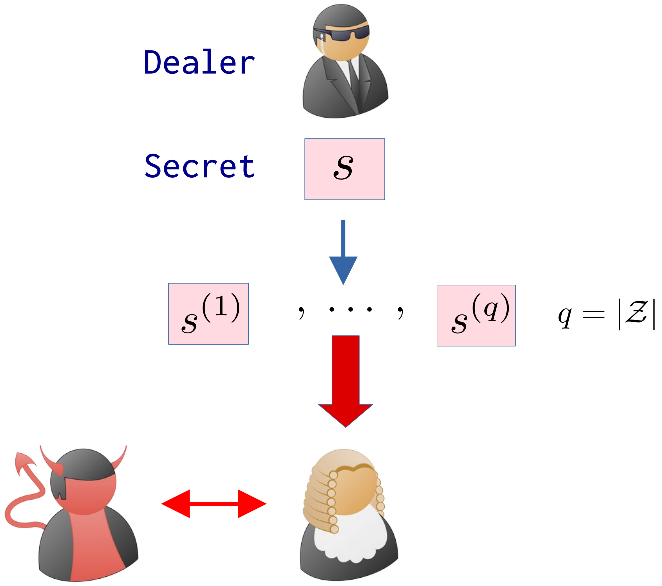
Verifiable Secret-Sharing

Dealer 

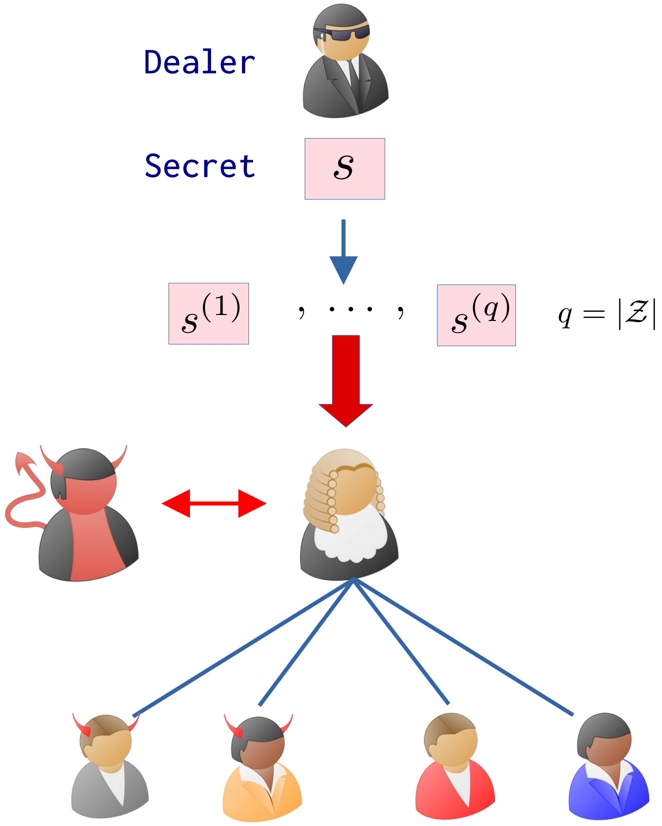
Secret $\boxed{s}$

$$\boxed{s^{(1)}}\;, \cdots,\; \boxed{s^{(q)}} \qquad q = |\mathcal{Z}|$$

Verifiable Secret-Sharing



Verifiable Secret-Sharing



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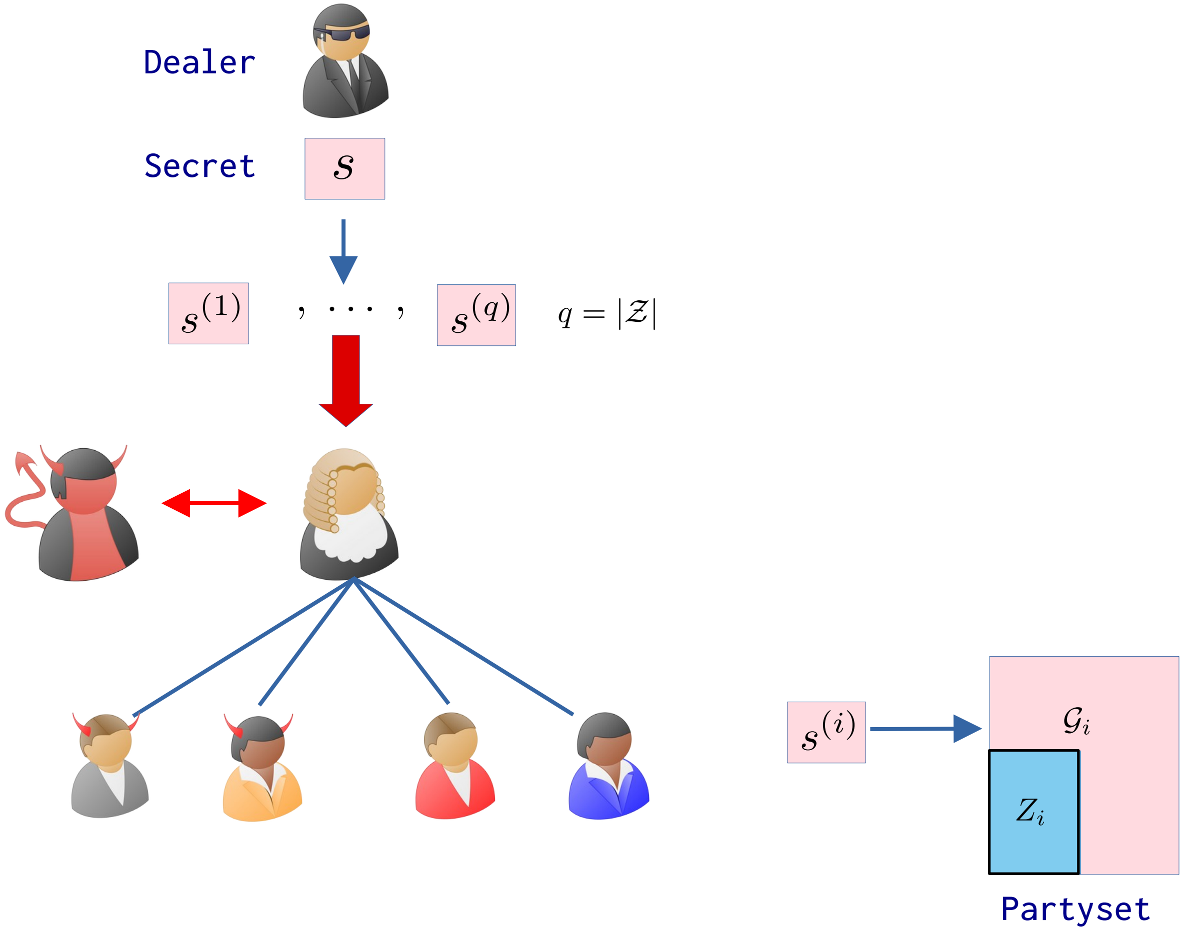
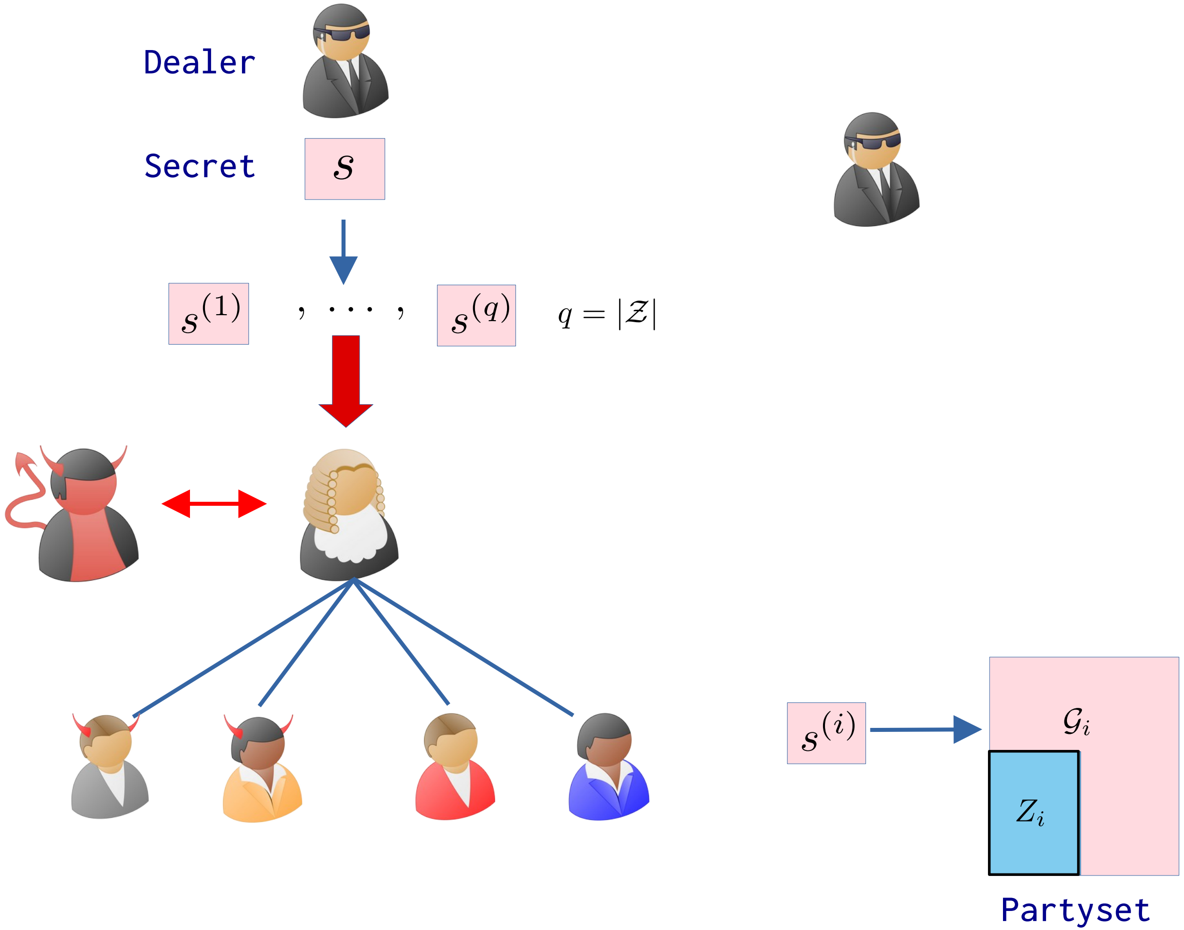


Verifiable Secret-Sharing



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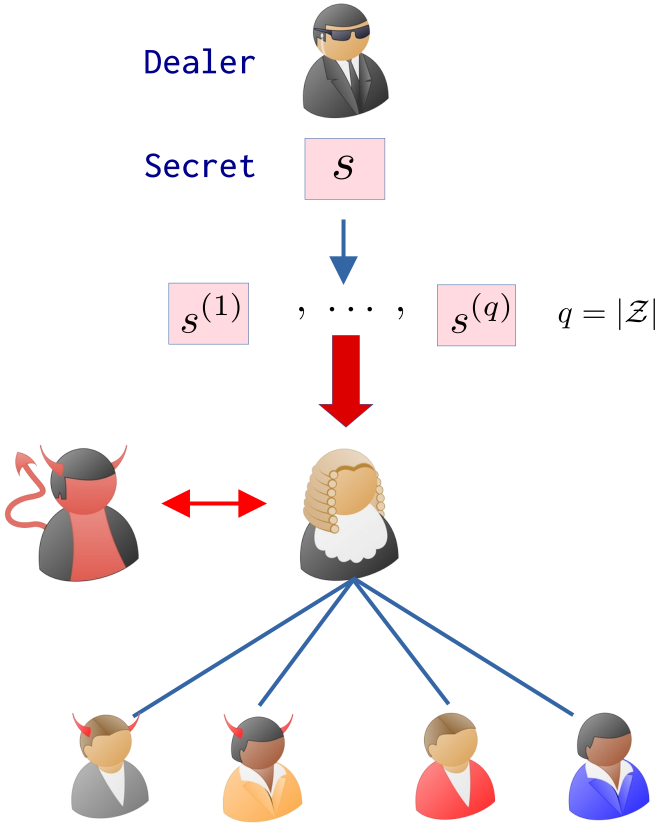
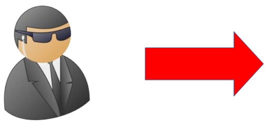
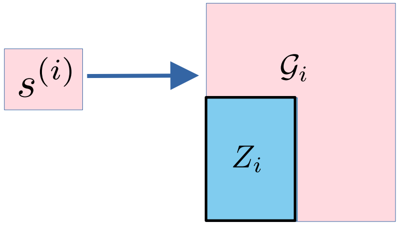




s is shared



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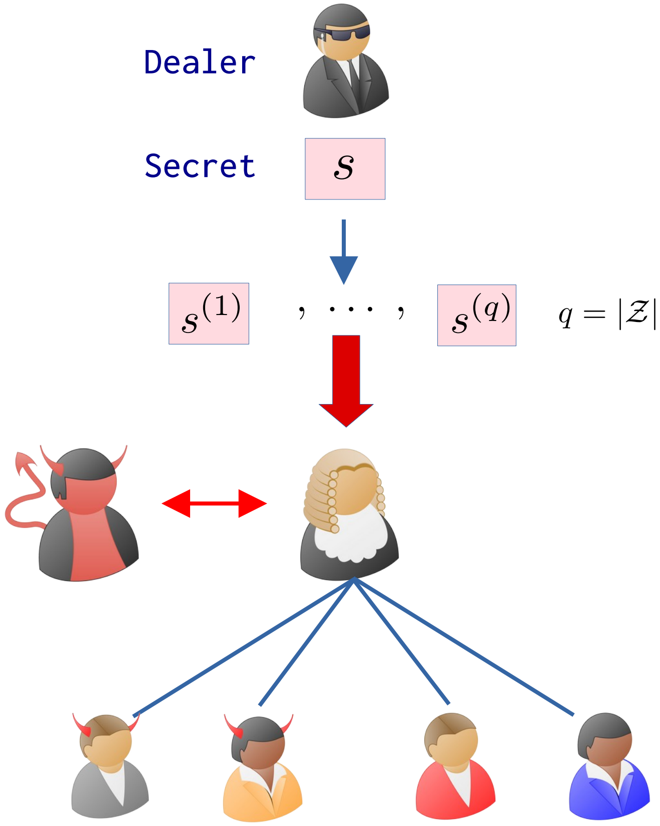

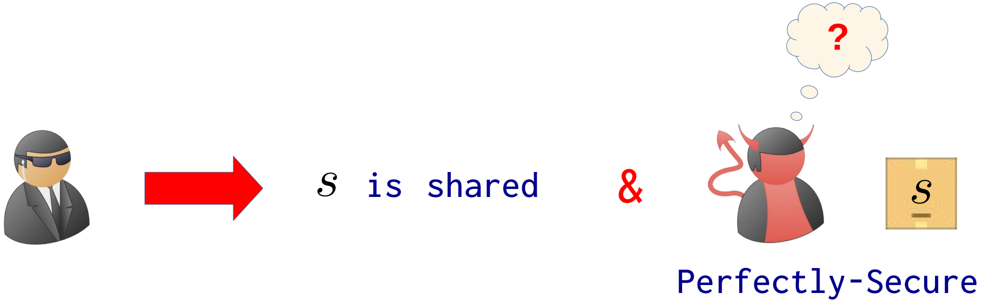

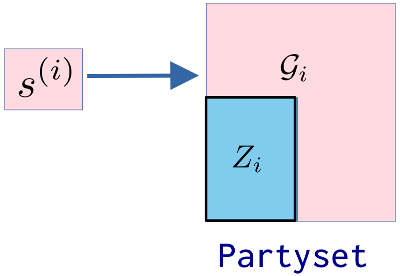

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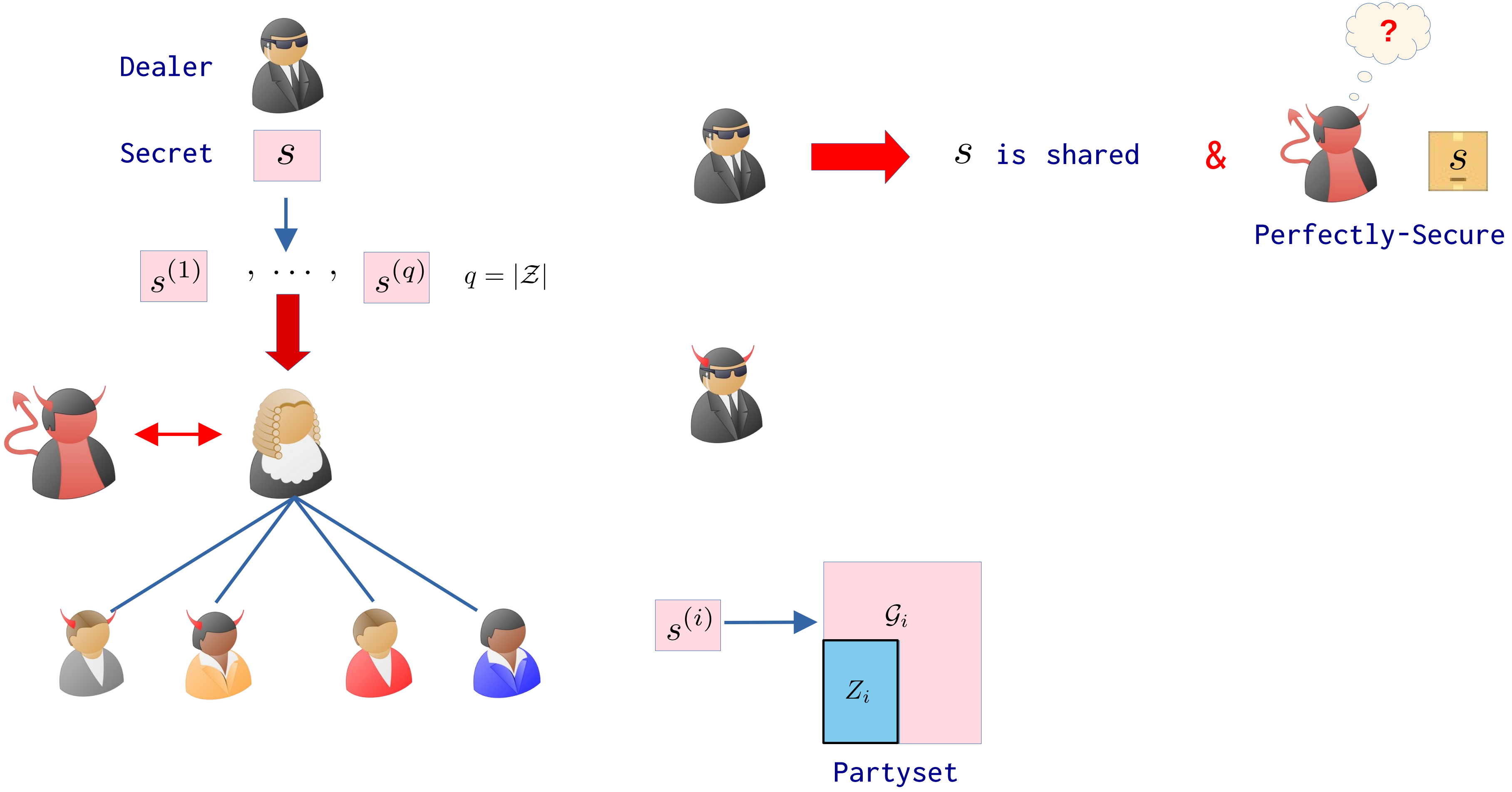

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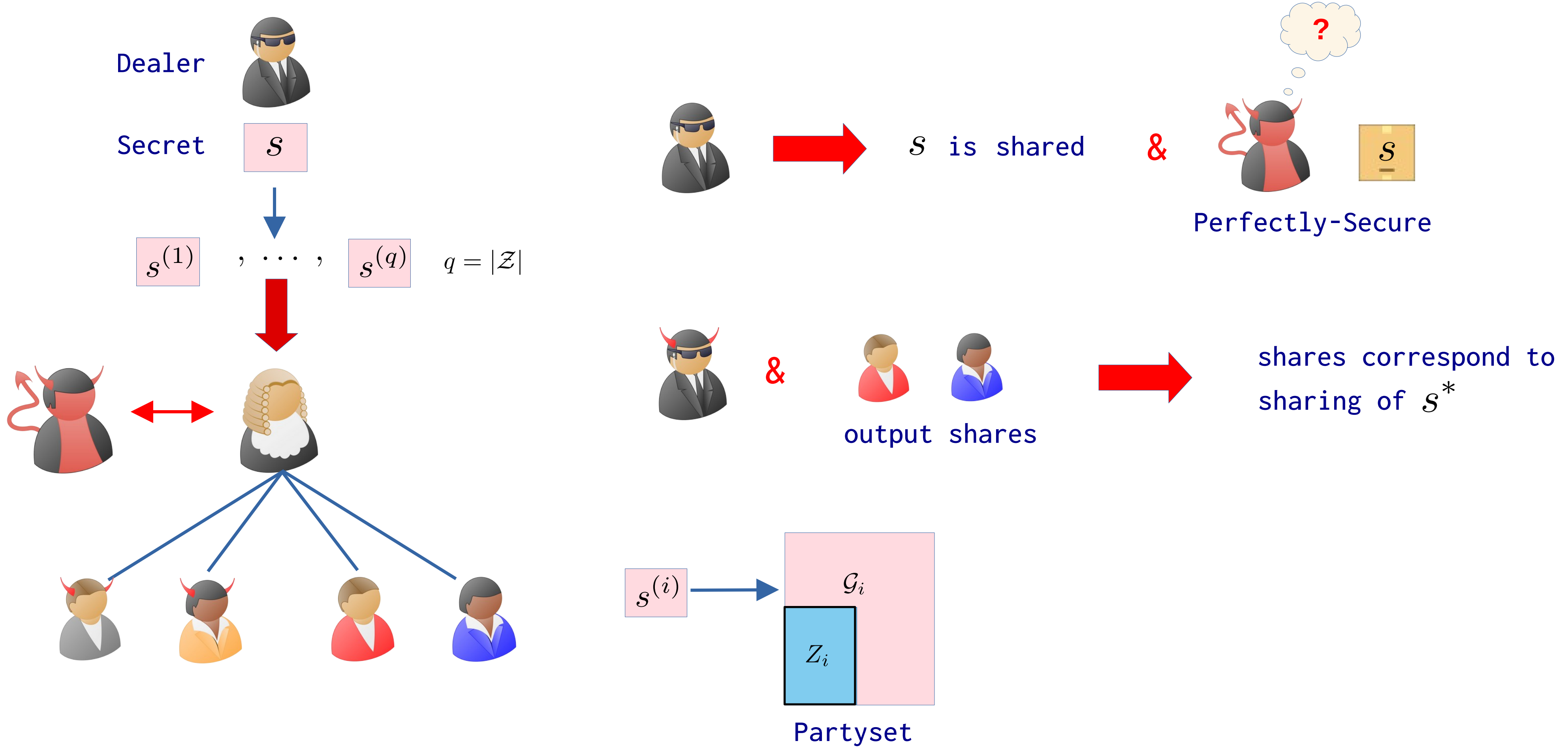

Verifiable Secret-Sharing

Verifiable Secret-Sharing

Verifiable Secret-Sharing

$$\mathcal{Z} = \{\boxed{\{P_1, P_2\}}, \boxed{\{P_1, P_3\}}, \boxed{\{P_1, P_4\}}, \boxed{\{P_1, P_5, P_6\}}, \boxed{\{P_7\}}\}$$

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Dealer

Verifiable Secret-Sharing

$\mathcal{Z} = \{\{P_1, P_2\}, \{P_1, P_3\}, \{P_1, P_4\}, \{P_1, P_5, P_6\}, \{P_7\}\}$

Secret

s

Dealer

Verifiable Secret-Sharing

$\mathcal{Z} = \{\{P_1, P_2\}, \{P_1, P_3\}, \{P_1, P_4\}, \{P_1, P_5, P_6\}, \{P_7\}\}$

Secret

s

Dealer

$$s^{(1)} + s^{(2)} + s^{(3)} + \cdots + s^{(q)}$$

$q = |\mathcal{Z}|$

Verifiable Secret-Sharing

$$\mathcal{Z} = \{\{P_1, P_2\}, \{P_1, P_3\}, \{P_1, P_4\}, \{P_1, P_5, P_6\}, \{P_7\}\}$$

Dealer

Secret

$$\boxed{s} = \boxed{s^{(1)}} + \boxed{s^{(2)}} + \boxed{s^{(3)}} + \cdots + \boxed{s^{(q)}}$$

$$q = |\mathcal{Z}|$$

Verifiable Secret-Sharing

$\mathcal{Z} = \{\{P_1, P_2\}, \{P_1, P_3\}, \{P_1, P_4\}, \{P_1, P_5, P_6\}, \{P_7\}\}$

Dealer

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Verifiable Secret-Sharing

$\mathcal{Z} = \{\{P_1, P_2\}, \{P_1, P_3\}, \{P_1, P_4\}, \{P_1, P_5, P_6\}, \{P_7\}\}$

Dealer

Secret

$$s = s^{(1)} + s^{(2)} + s^{(3)} + \cdots + s^{(q)}$$

$q = |\mathcal{Z}|$

P_2, P_3
P_5, P_6, P_7

$\{P_1, P_4\}$

Verifiable Secret-Sharing

$\mathcal{Z} = \{\{P_1, P_2\}, \{P_1, P_3\}, \{P_1, P_4\}, \{P_1, P_5, P_6\}, \{P_7\}\}$

$s^{(1)}$

$+$

$s^{(2)}$

[Mau02]

Secret

$+$

s $=$ $s^{(3)}$ $\Rightarrow$ P_2, P_3
P_5, P_6, P_7

$+$

$\{P_1, P_4\}$

$\vdots$

$+$

$s^{(q)}$

Dealer

$q = |\mathcal{Z}|$

Verifiable Secret-Sharing

$\mathcal{Z} = \{\{P_1, P_2\}, \{P_1, P_3\}, \{P_1, P_4\}, \{P_1, P_5, P_6\}, \{P_7\}\}$

Dealer

Secret

$$s = s^{(1)} + s^{(2)} + s^{(3)} + \cdots + s^{(q)}$$

$q = |\mathcal{Z}|$

[Mau02]

P_2, P_3
P_5, P_6, P_7

$\{P_1, P_4\}$

$s^{(3)} \rightarrow$ one-time pad

Verifiable Secret-Sharing

$$\mathcal{Z} = \{\{P_1, P_2\}, \{P_1, P_3\}, \{P_1, P_4\}, \{P_1, P_5, P_6\}, \{P_7\}\}$$

Dealer

Secret

$$s = s^{(1)} + s^{(2)} + s^{(3)} + \cdots + s^{(q)}$$

$q = |\mathcal{Z}|$

[Mau02]

P_2, P_3
P_5, P_6, P_7

$\{P_1, P_4\}$

$s^{(3)} \rightarrow$ one-time pad

Non-adversary sets

$\downarrow$

$s^{(1)}, \ldots, s^{(q)}$

Verifiable Secret-Sharing

$$\mathcal{Z} = \{\{P_1, P_2\}, \{P_1, P_3\}, \{P_1, P_4\}, \{P_1, P_5, P_6\}, \{P_7\}\}$$

Dealer

Secret

$$s = s^{(1)} + s^{(2)} + s^{(3)} + \cdots + s^{(q)}$$

$q = |\mathcal{Z}|$

[Mau02]

P_2, P_3
P_5, P_6, P_7

$\{P_1, P_4\}$

$s^{(3)} \rightarrow$ one-time pad

Non-adversary sets

$\downarrow$

$s^{(1)}, \ldots, s^{(q)}$

?

Verifiable Secret-Sharing

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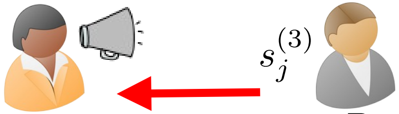

$s_i^{(3)}$ P_i $\longleftarrow$ $s_j^{(3)}$ P_j

Dealer

Secret

$$s = s^{(1)} + s^{(2)} + s^{(3)} + \cdots + s^{(q)}$$

$q = |\mathcal{Z}|$

[Mau02]

P_2, P_3
P_5, P_6, P_7

$\{P_1, P_4\}$

?

$s^{(3)} \rightarrow$ one-time pad

Non-adversary sets

$\downarrow$

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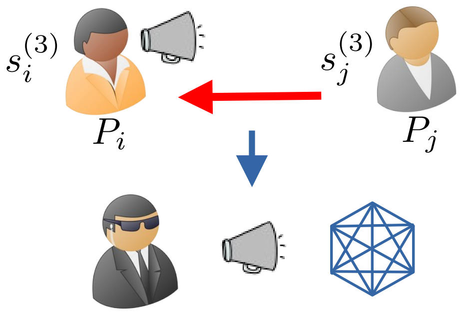

Dealer

Secret

$s = s^{(1)} + s^{(2)} + s^{(3)} + \cdots + s^{(q)}$

$q = |\mathcal{Z}|$

[Mau02]

P_2, P_3
P_5, P_6, P_7

$\{P_1, P_4\}$

?

$s^{(3)} \rightarrow$ one-time pad

Non-adversary sets

$\downarrow$

$s^{(1)}, \ldots, s^{(q)}$

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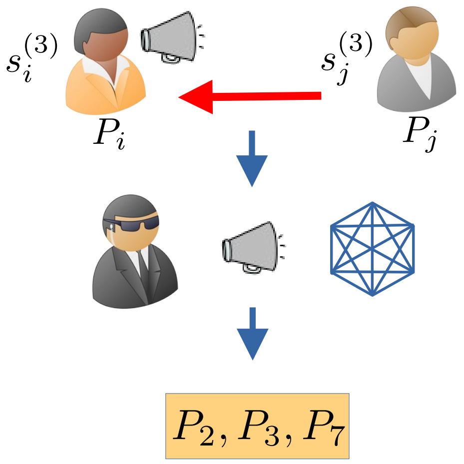

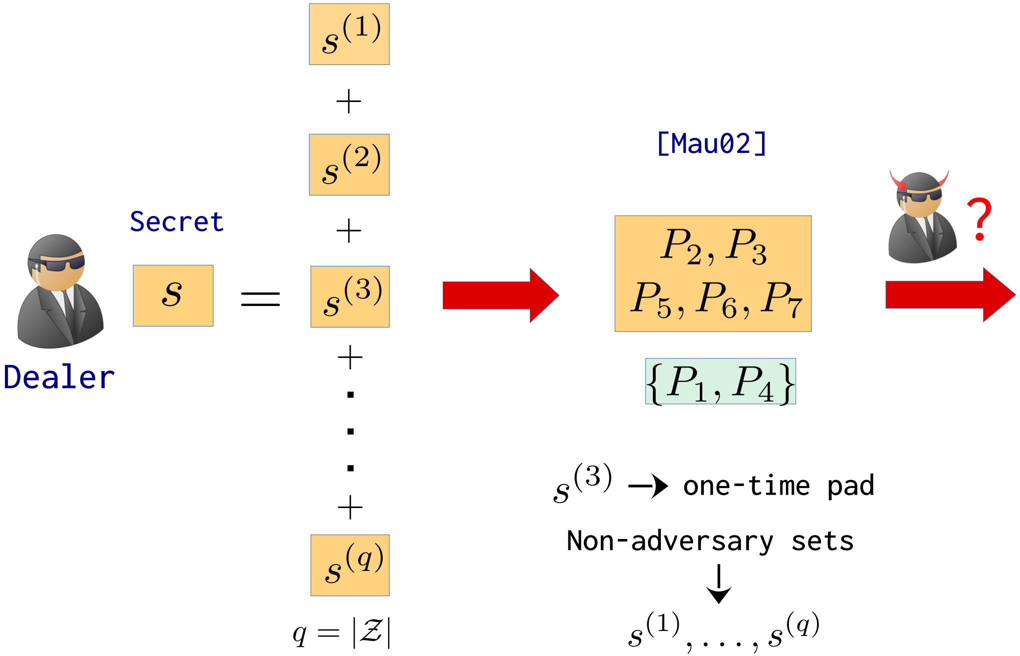

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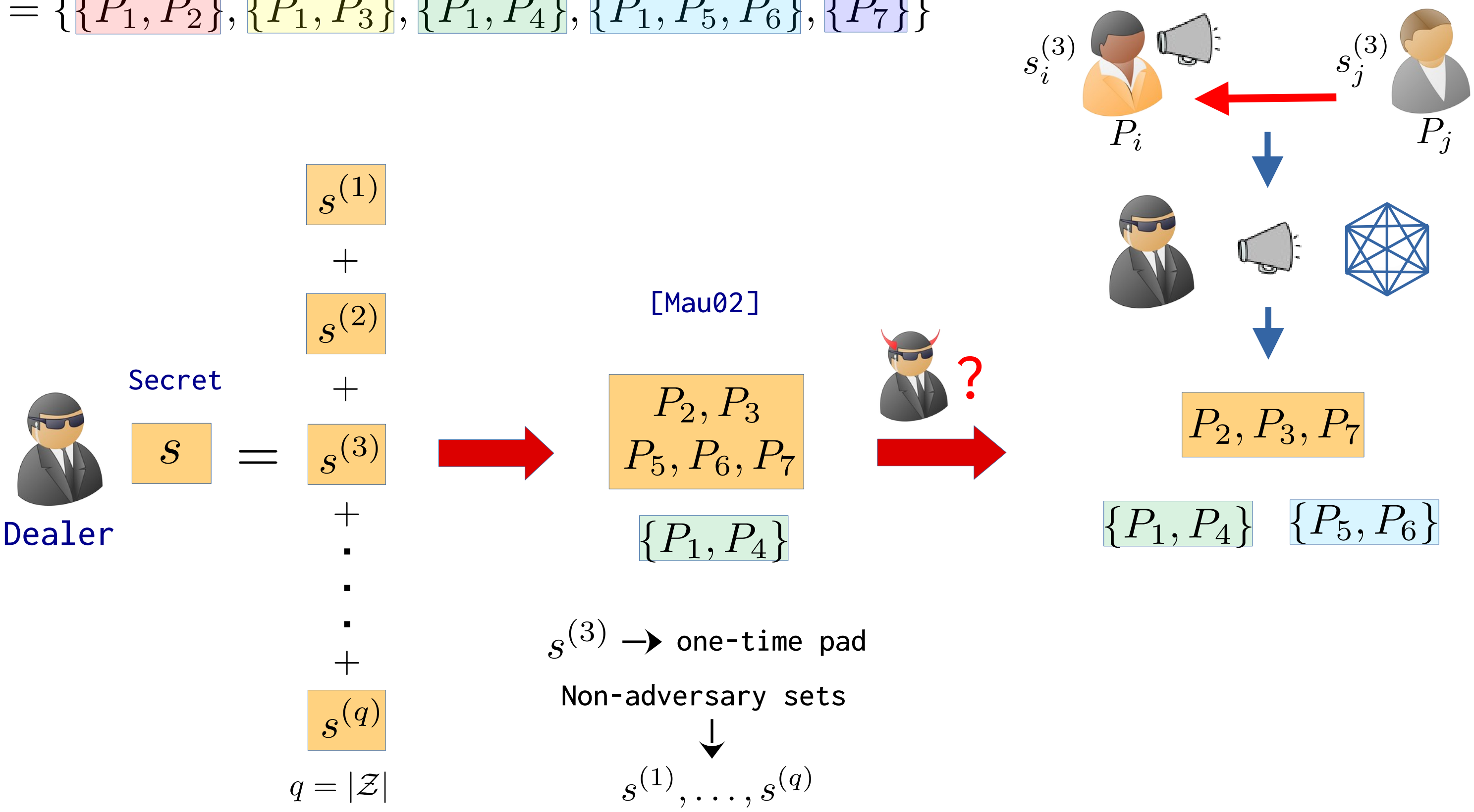
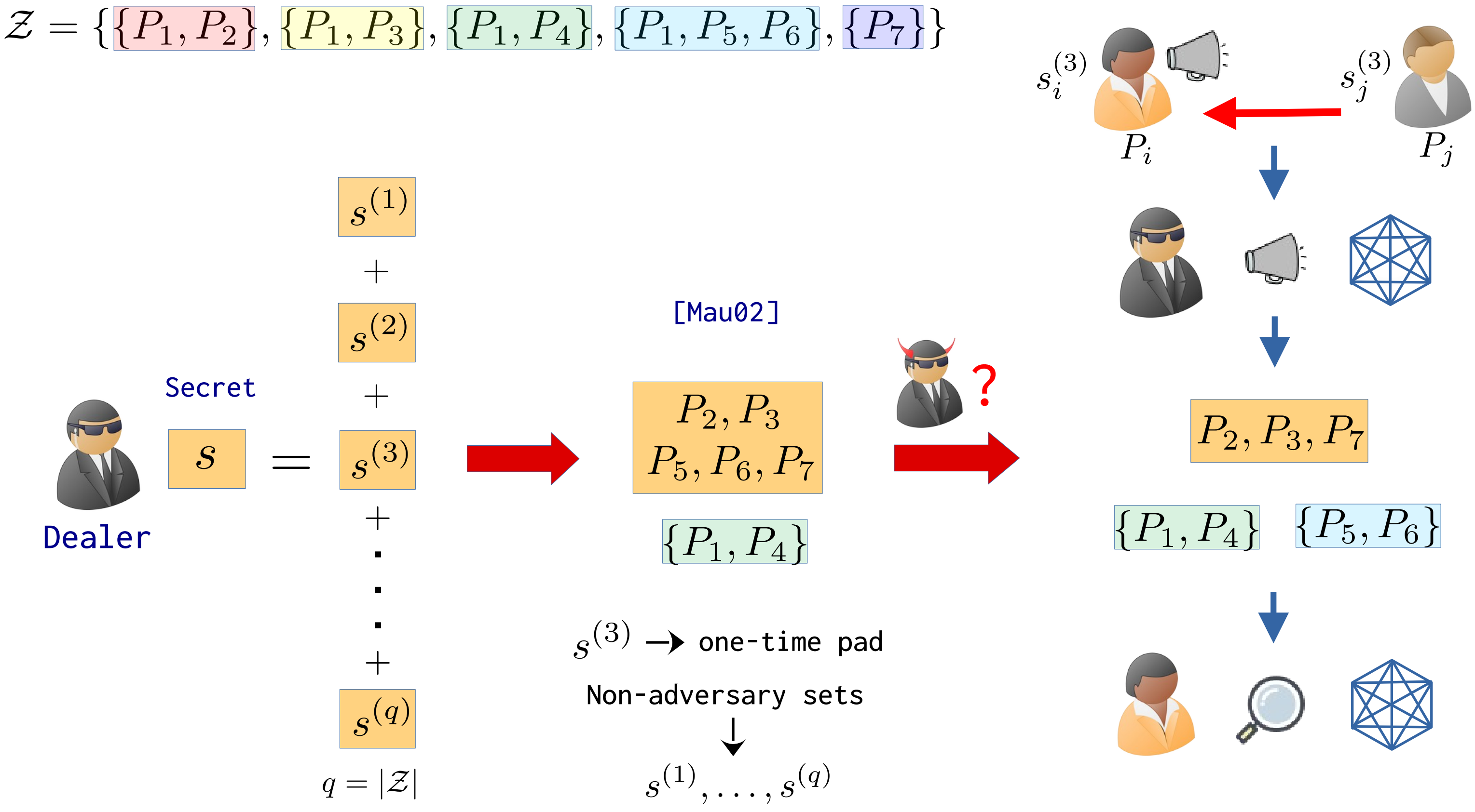


Verifiable Secret-Sharing



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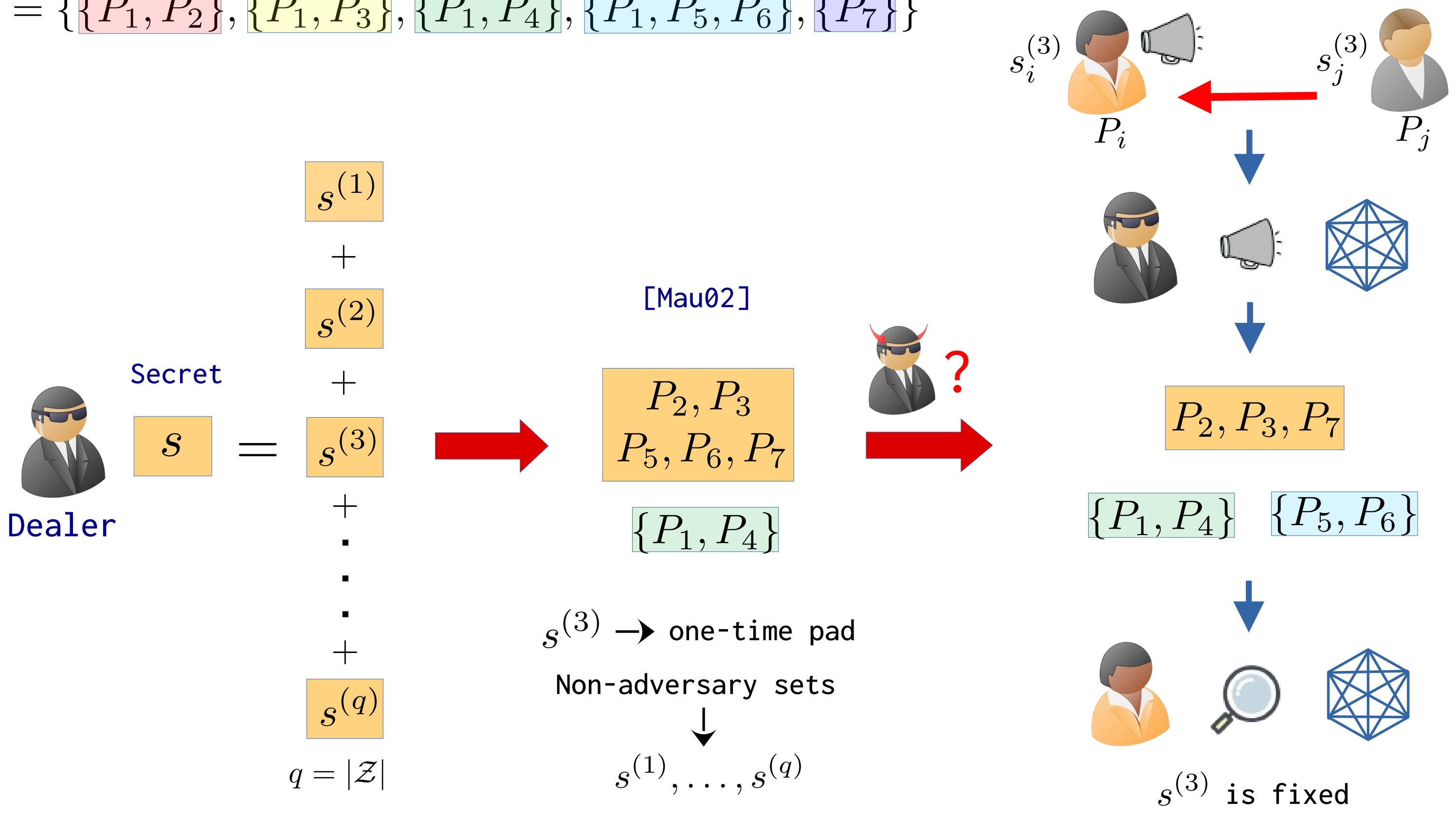

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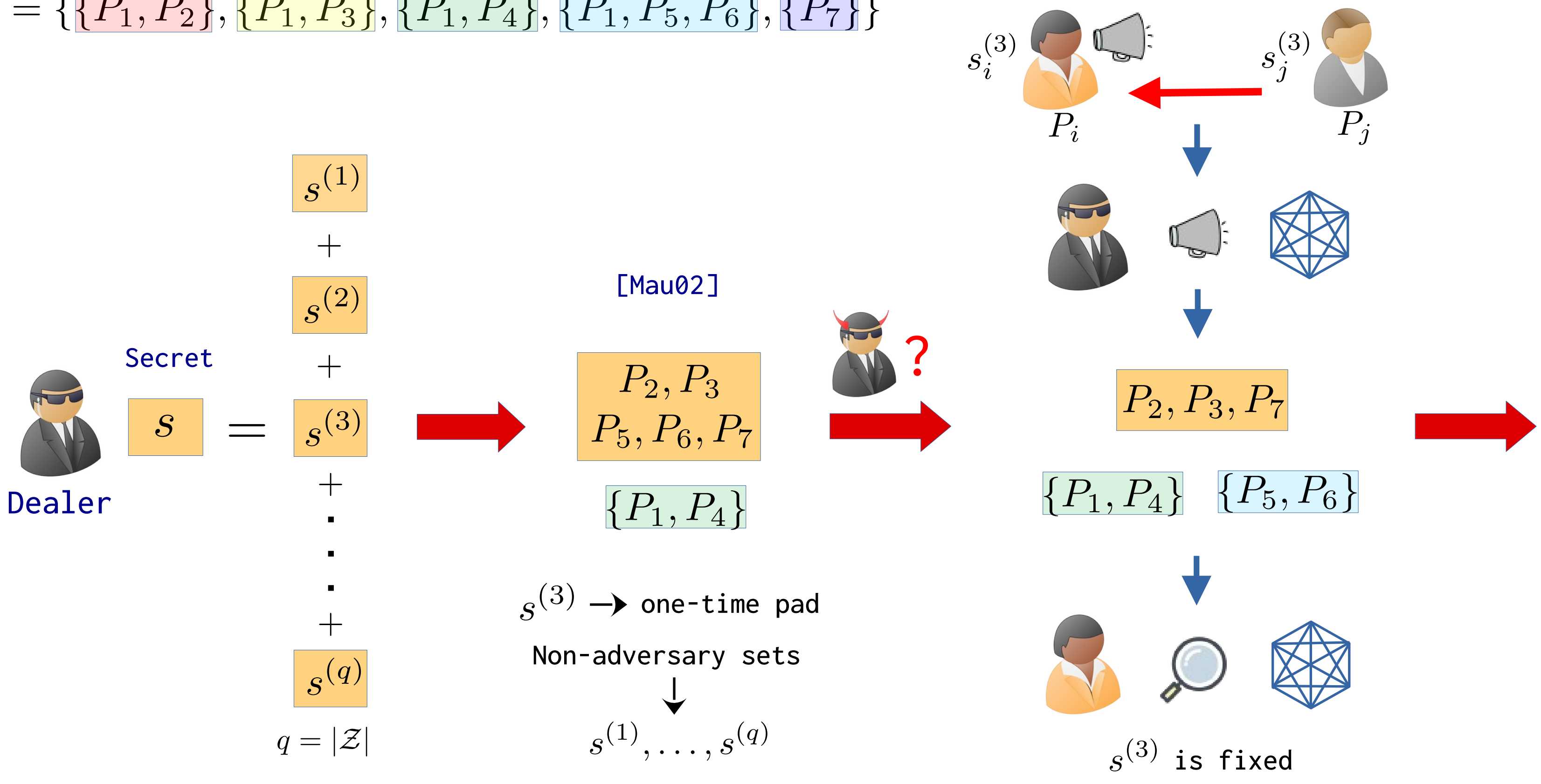

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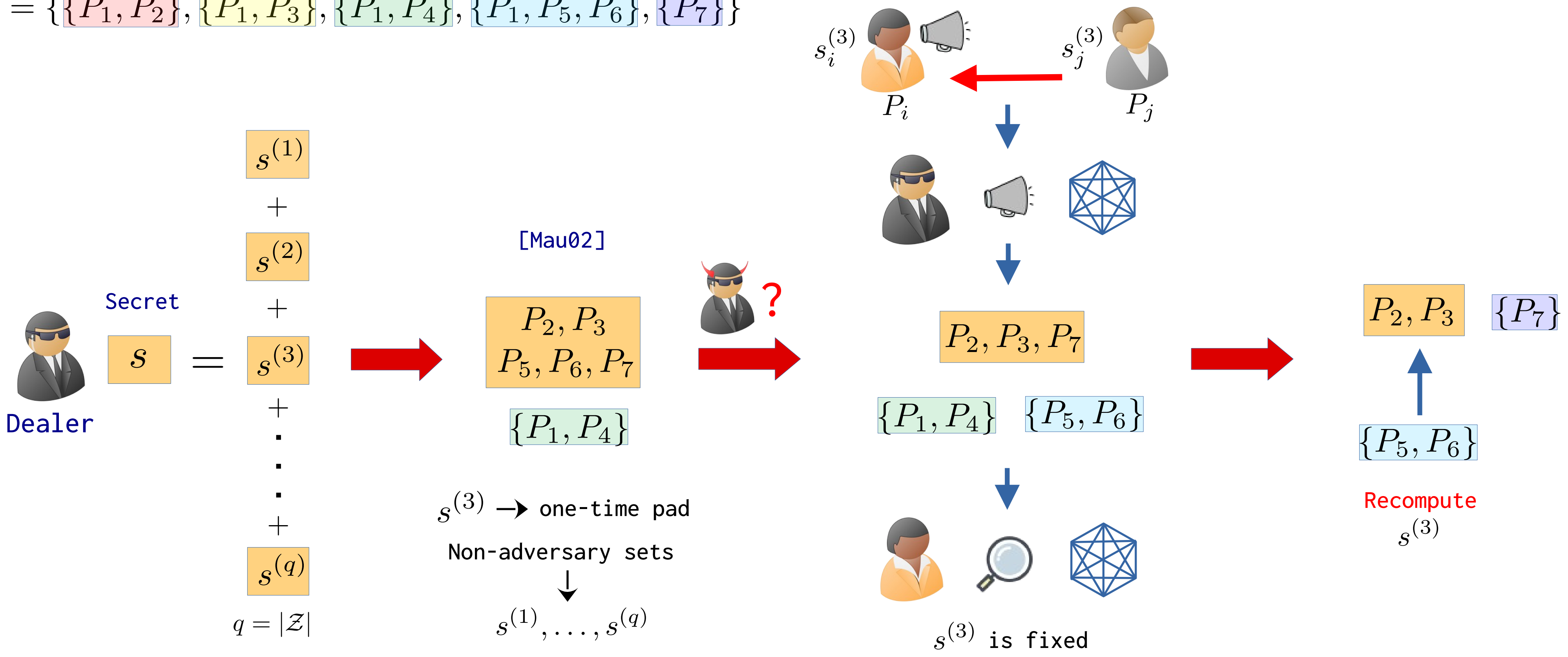

Verifiable Secret-Sharing

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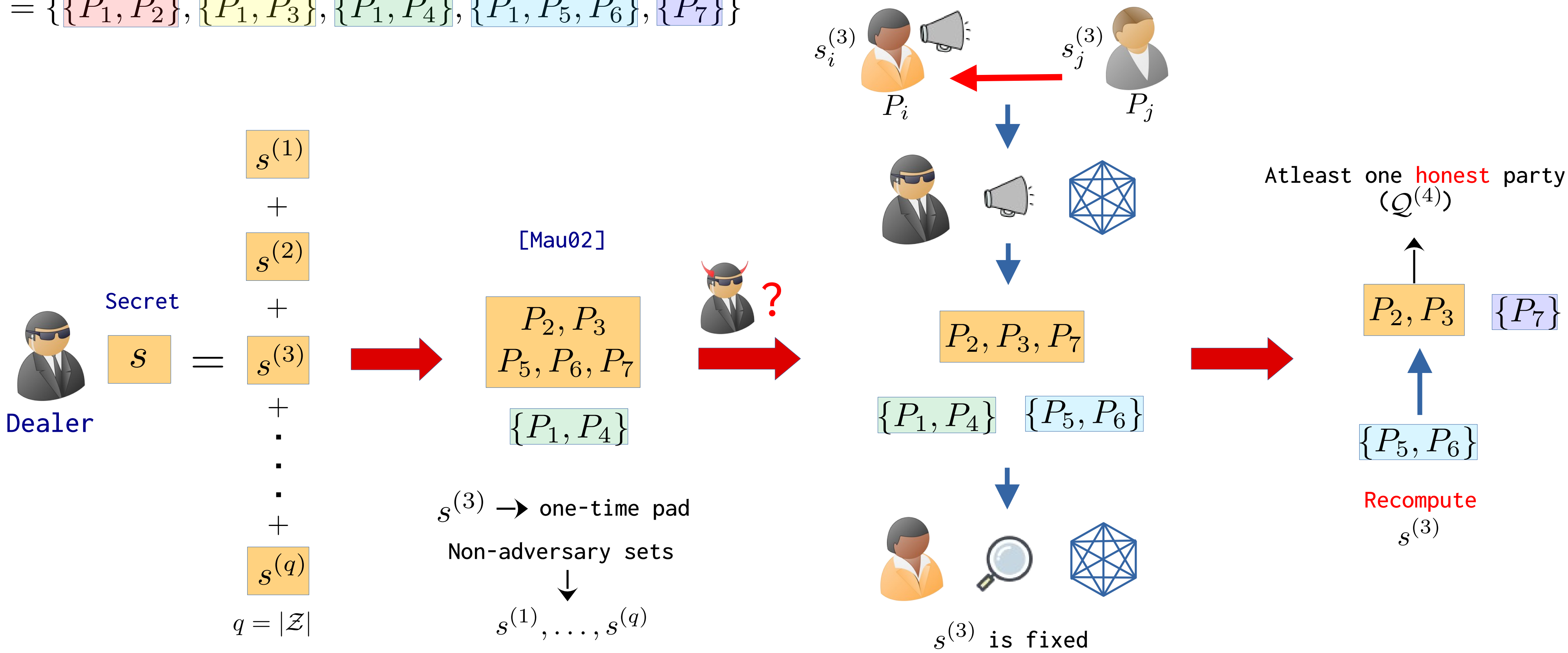

Asynchronous Byzantine Agreement (ABA)

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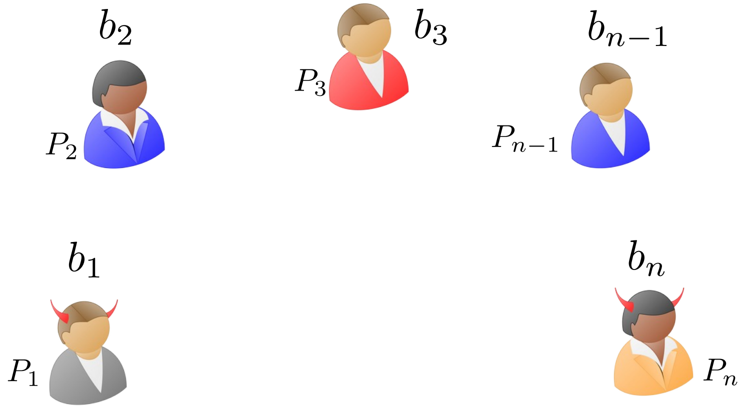
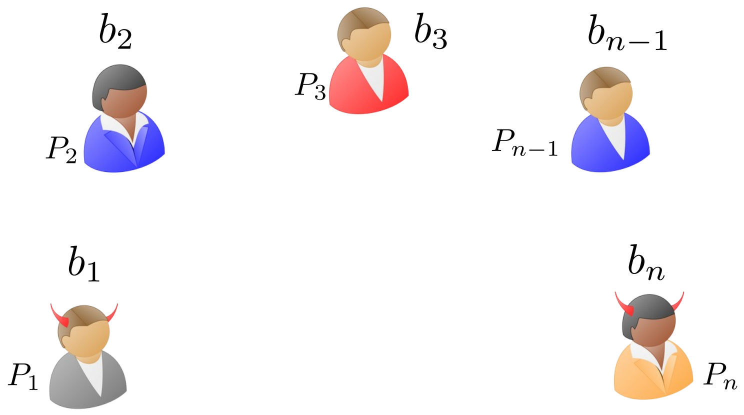


Asynchronous Byzantine Agreement (ABA)

Agree on a common bit



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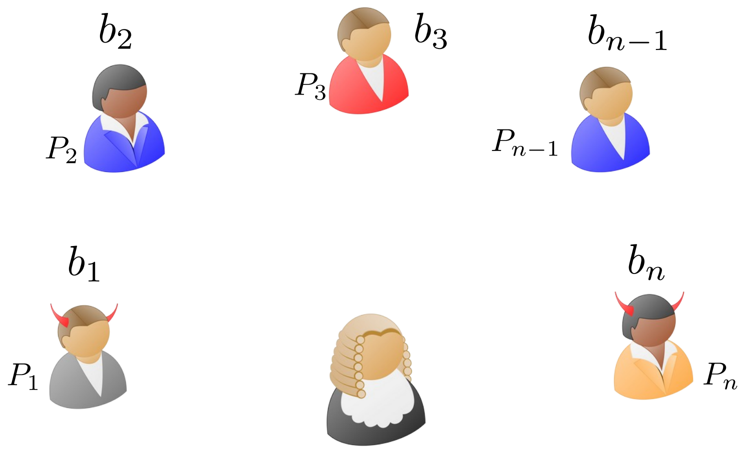

Asynchronous Byzantine Agreement (ABA)

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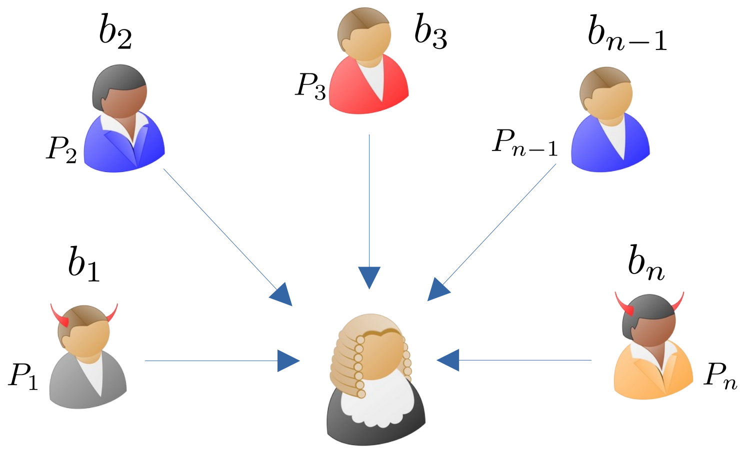

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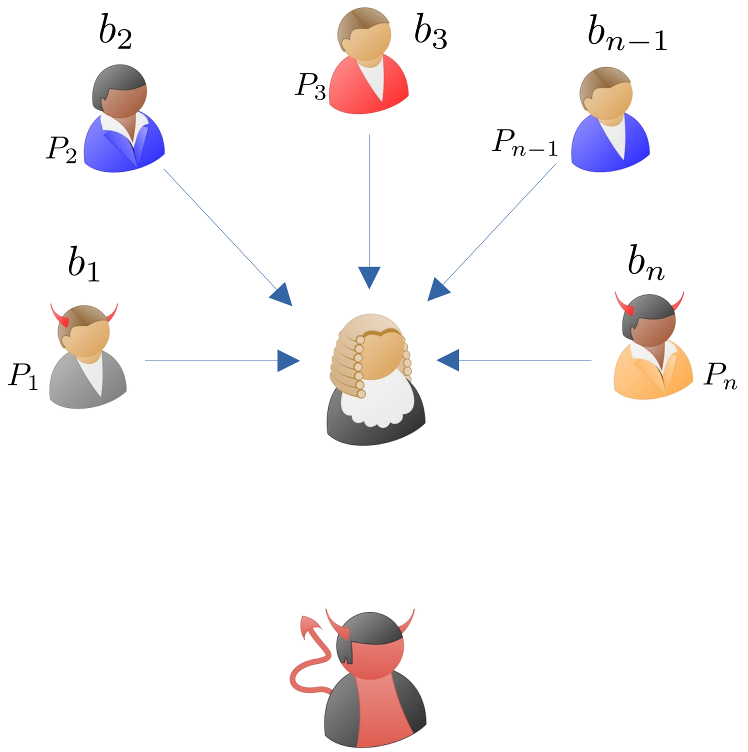

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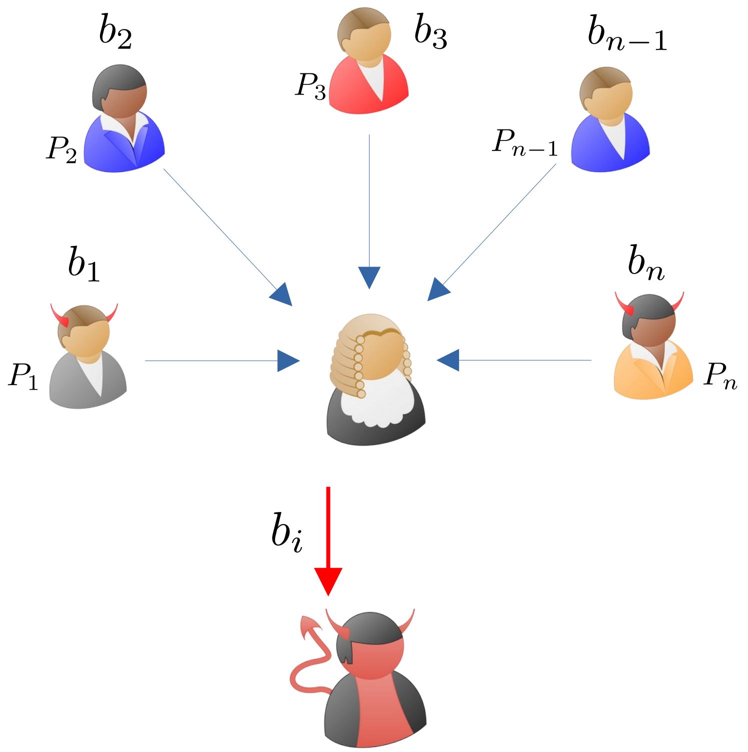
Agree on a common bit



Asynchronous Byzantine Agreement (ABA)

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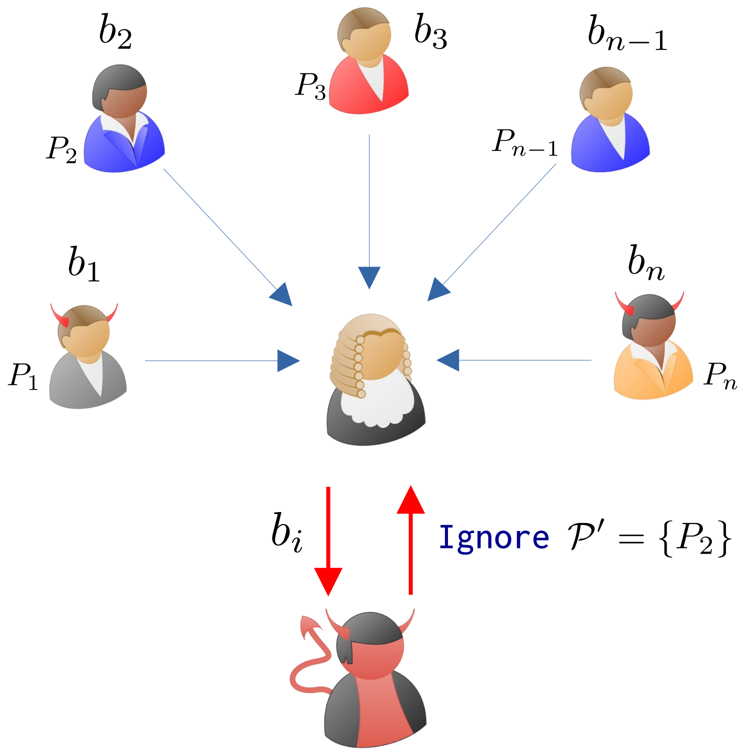

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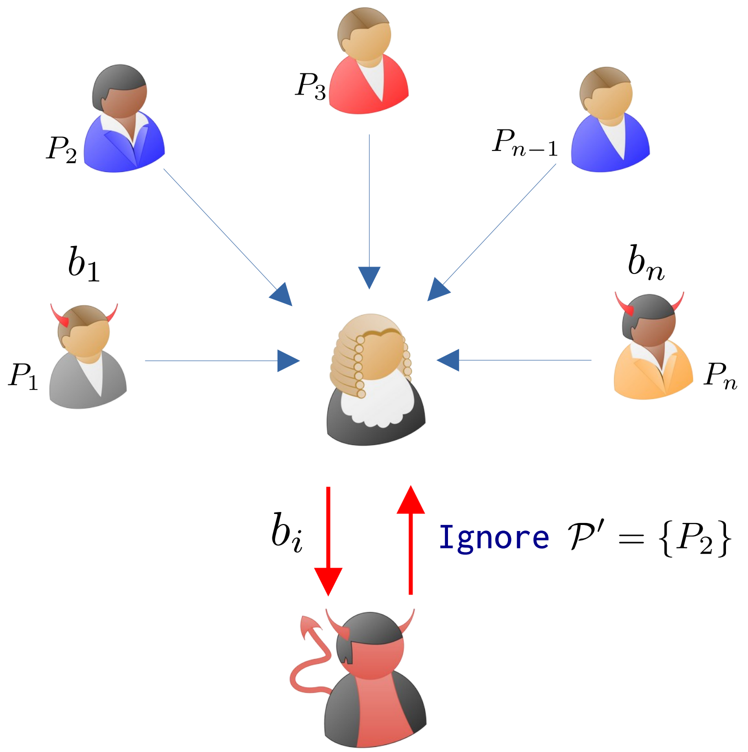
Agree on a common bit



Asynchronous Byzantine Agreement (ABA)

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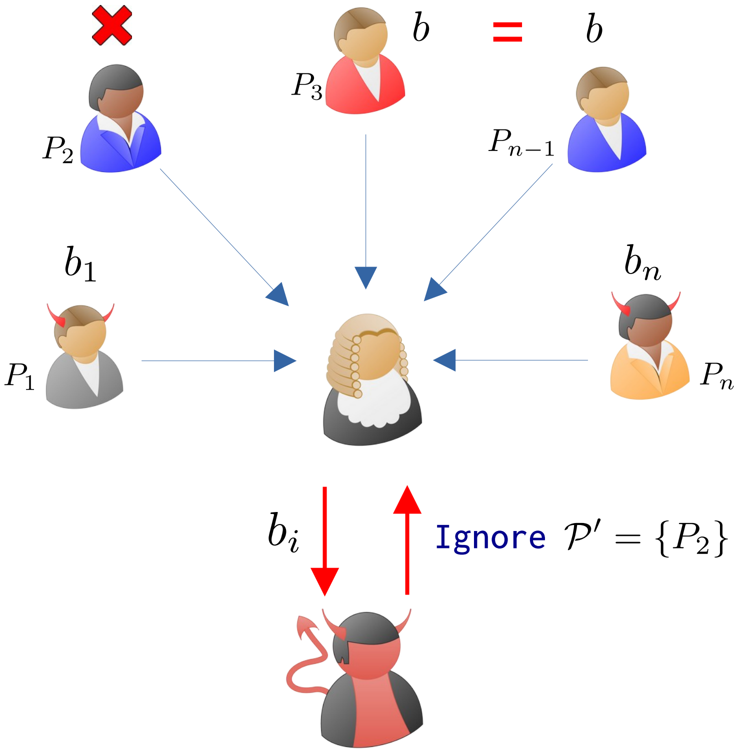

Asynchronous Byzantine Agreement (ABA)

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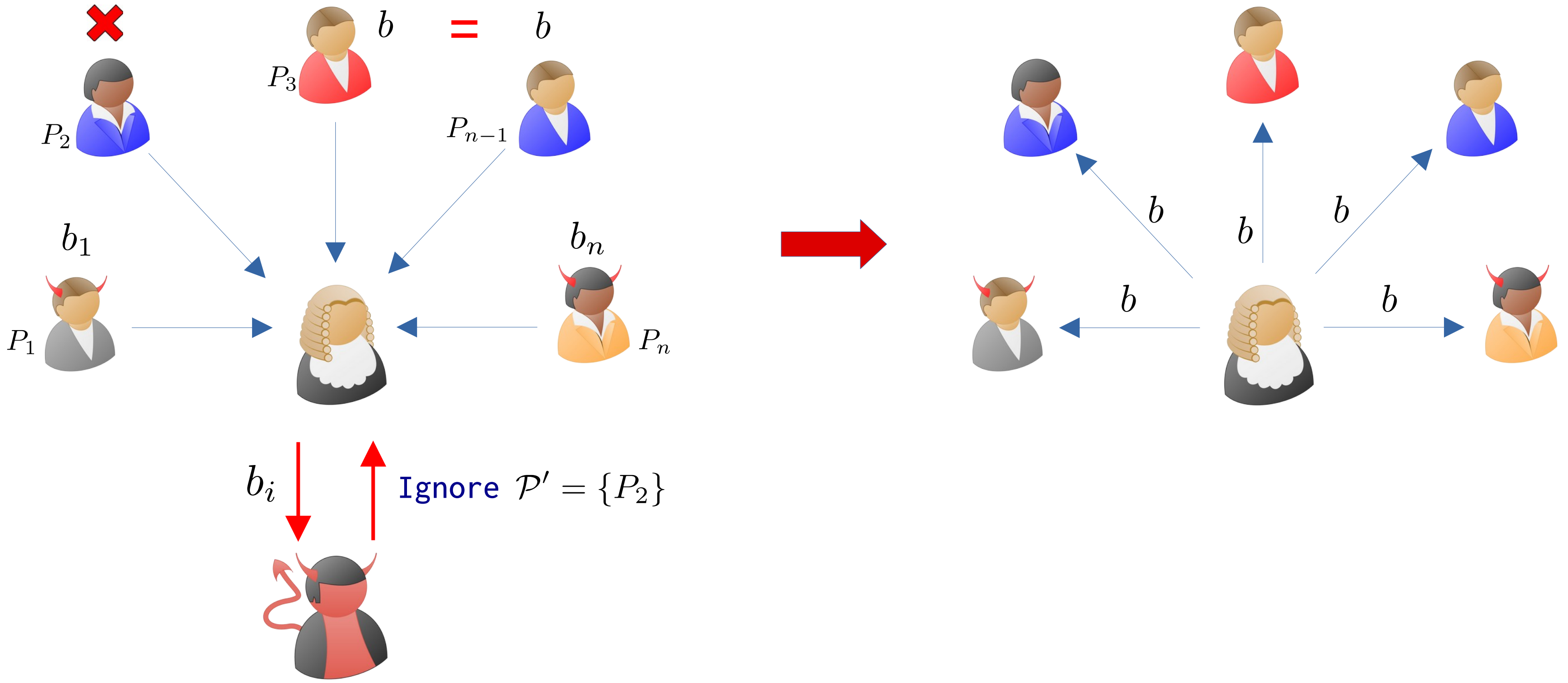

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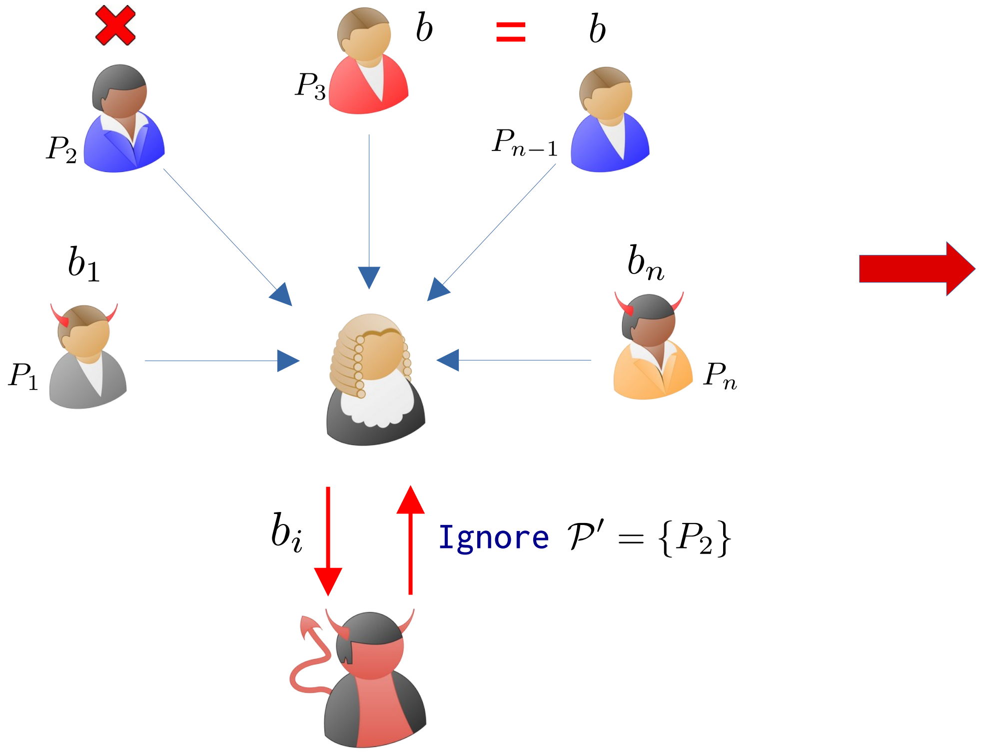

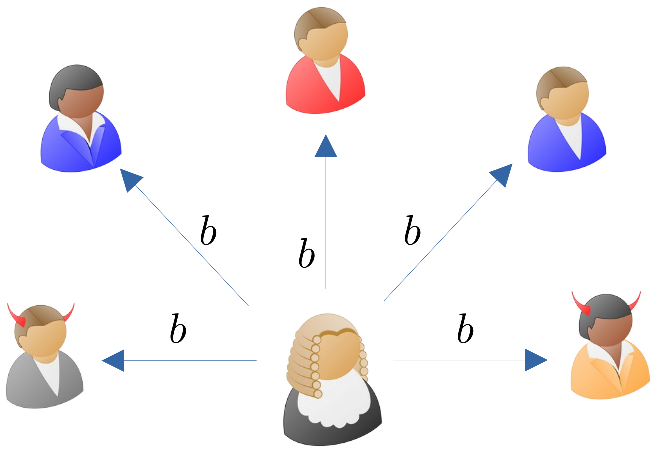

Validity

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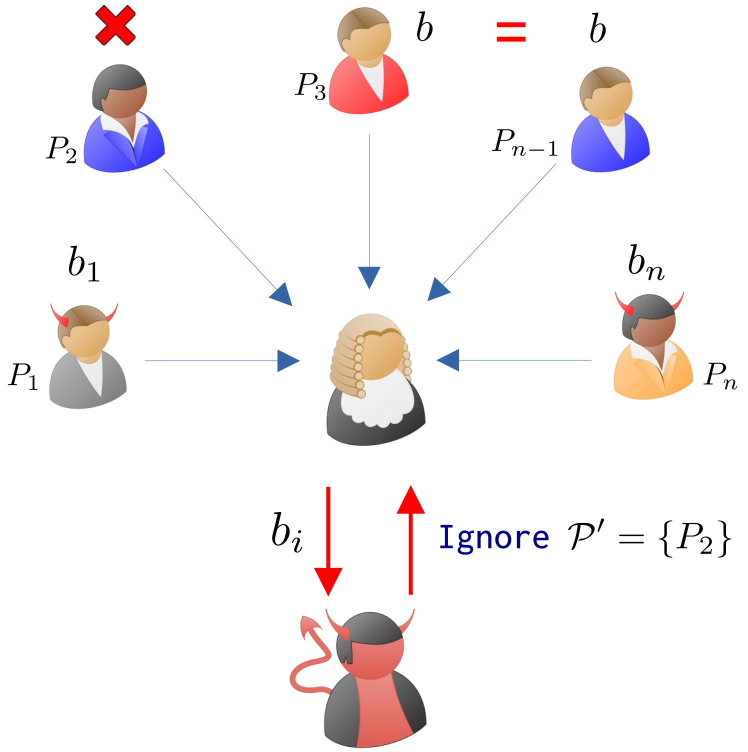

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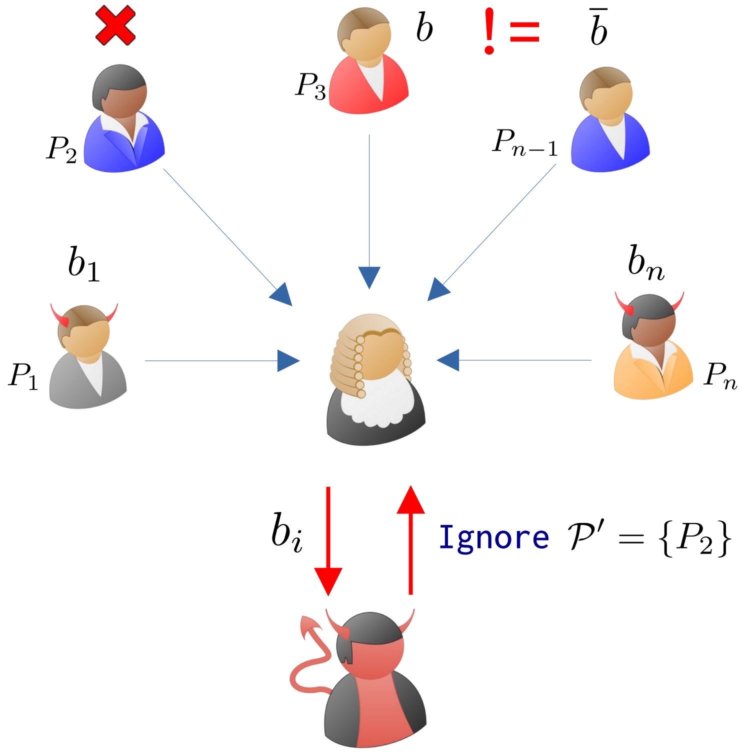

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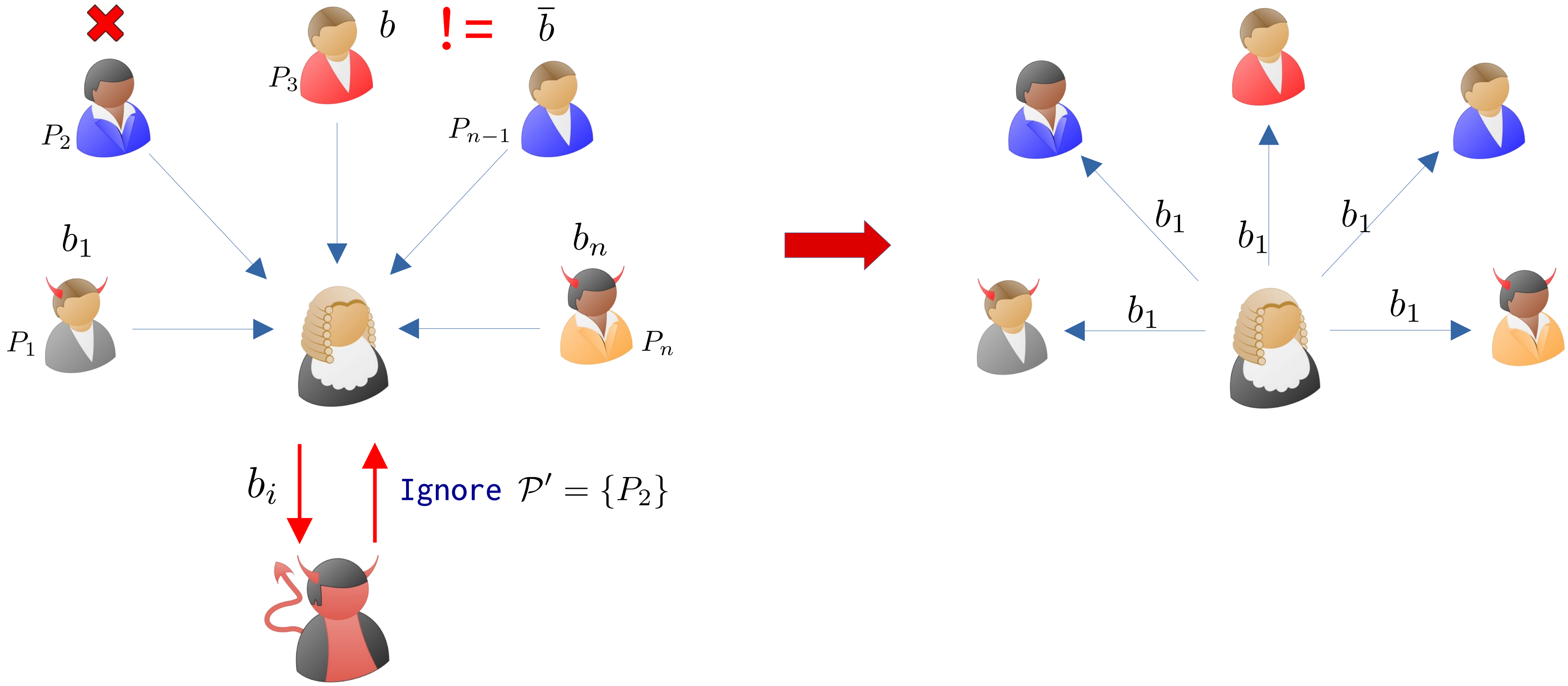

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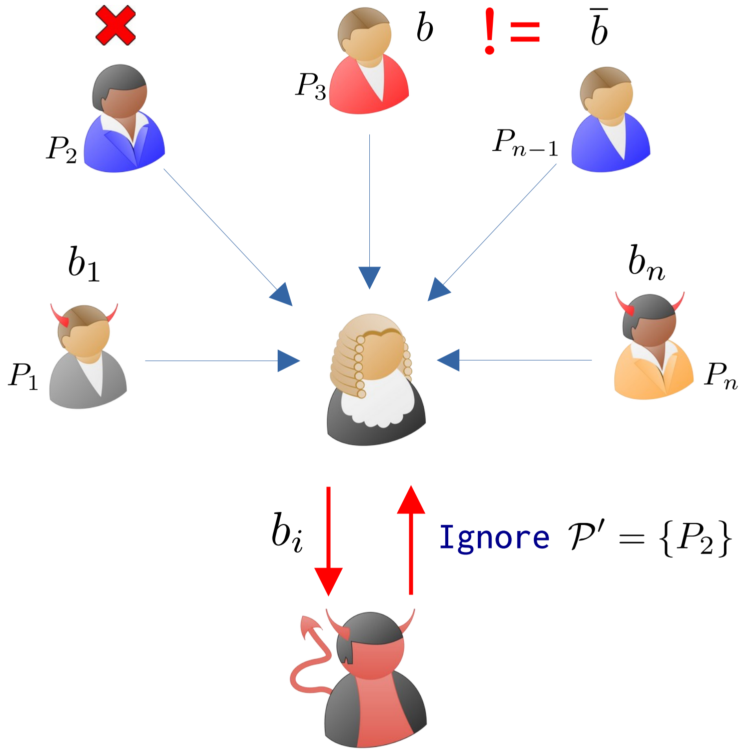

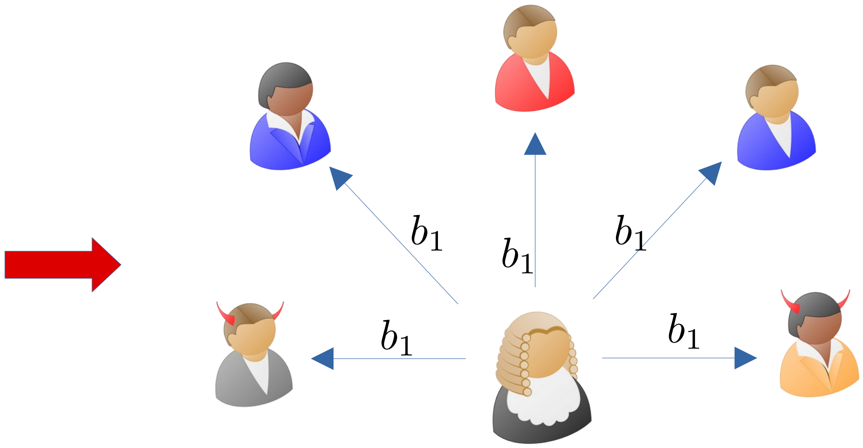

Agreement

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AVSS

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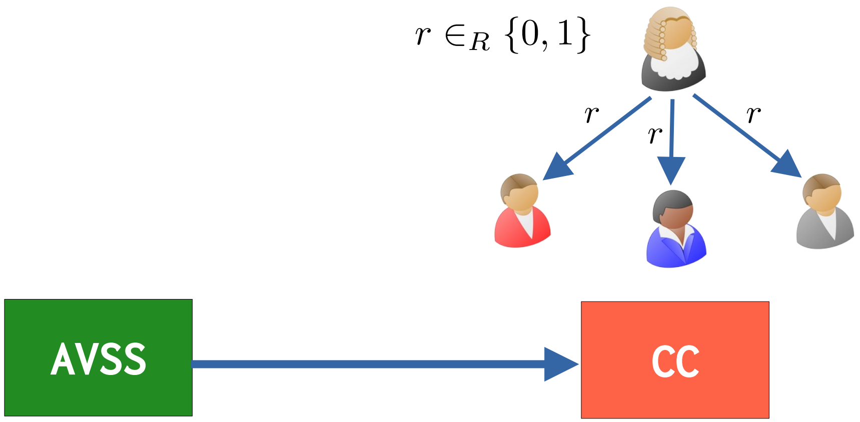

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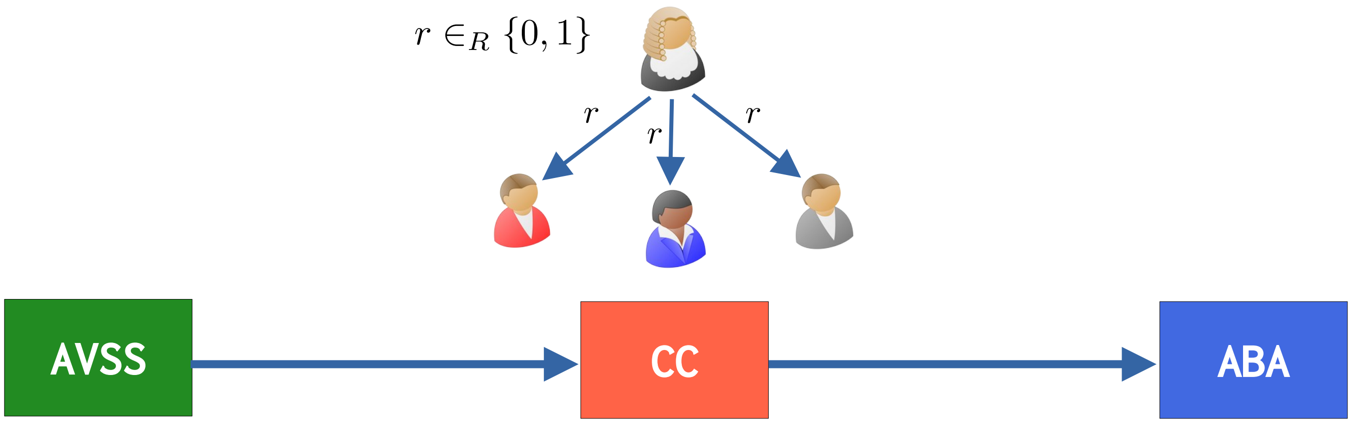

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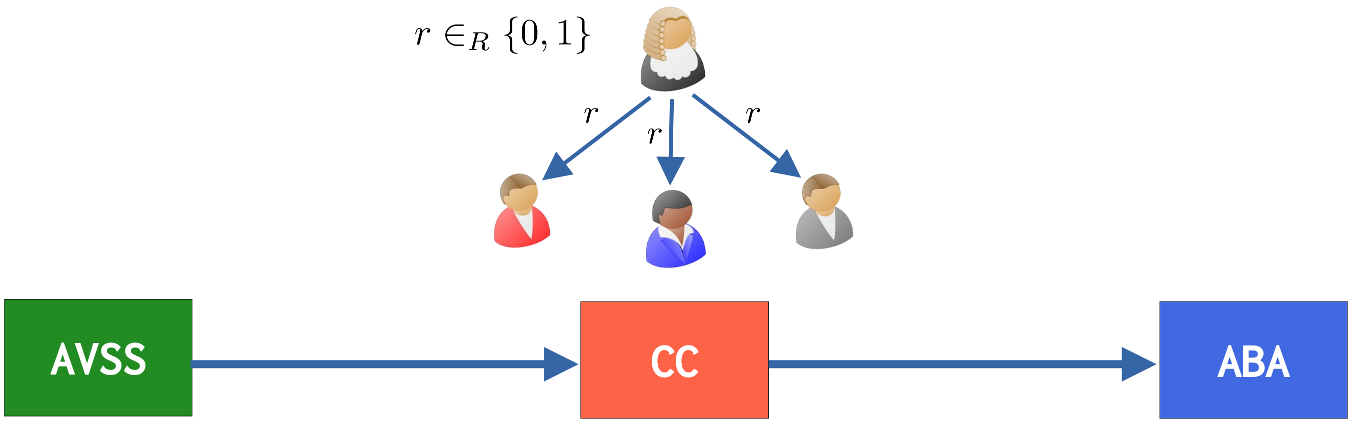

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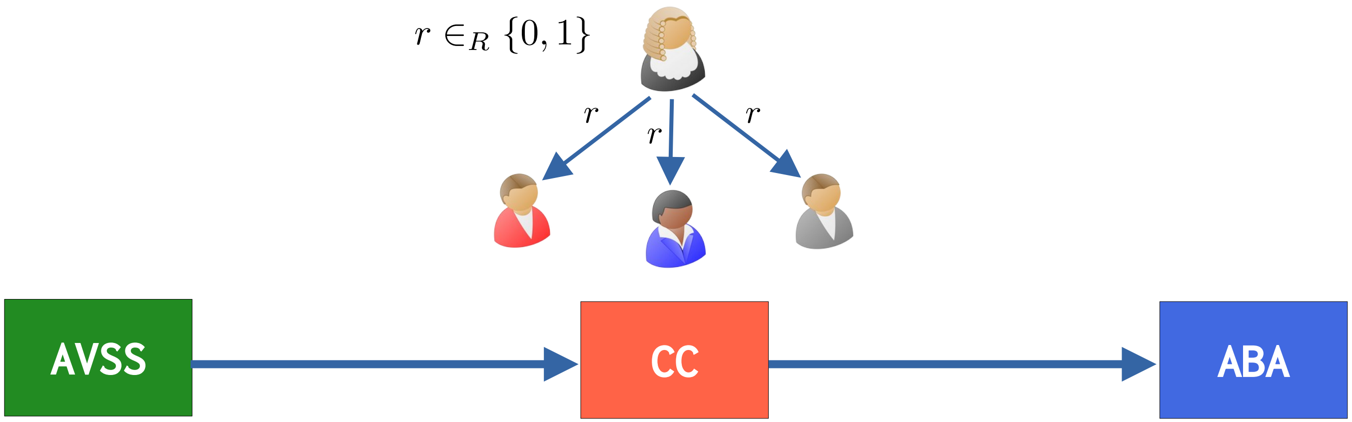

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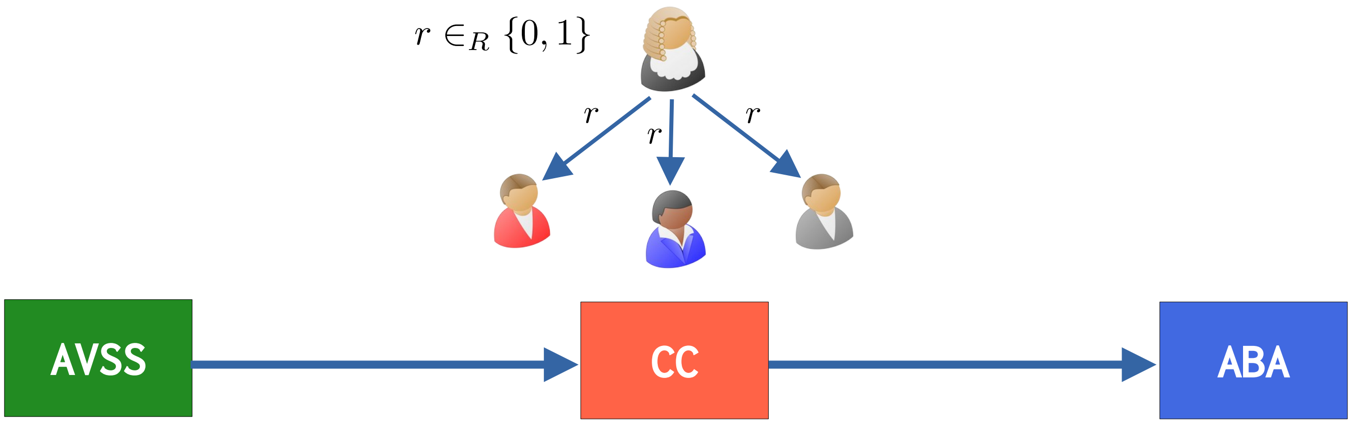

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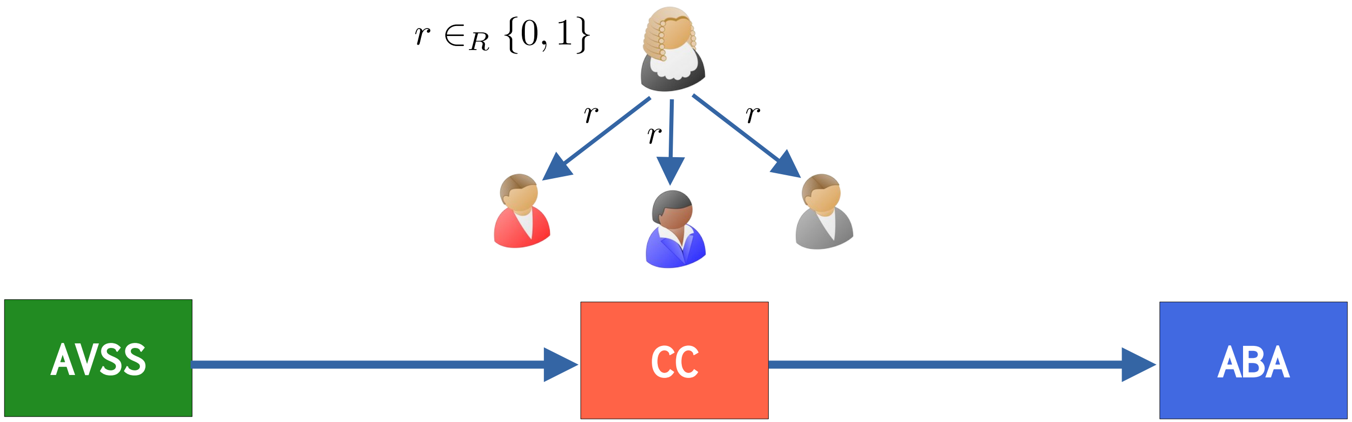

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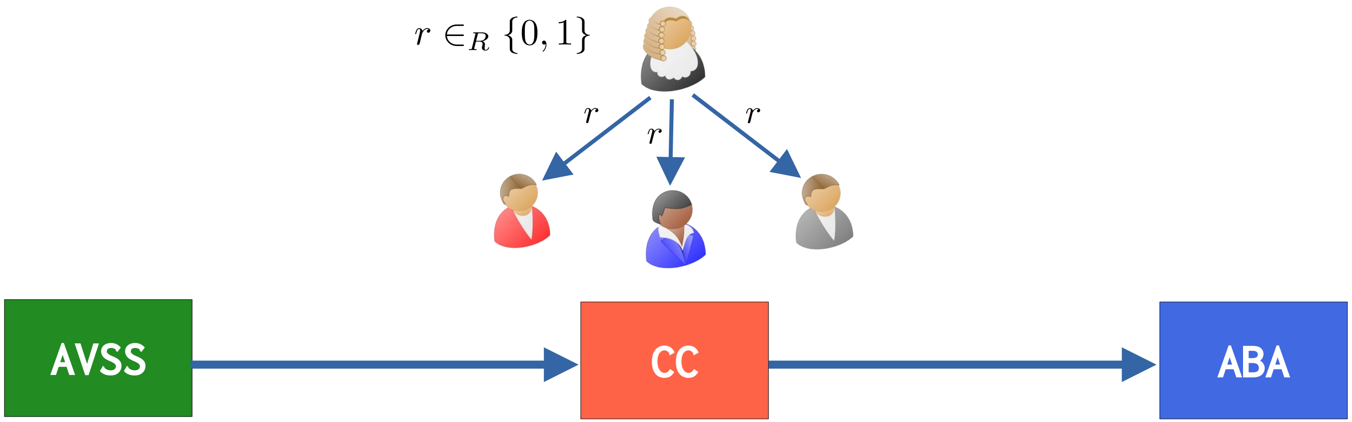

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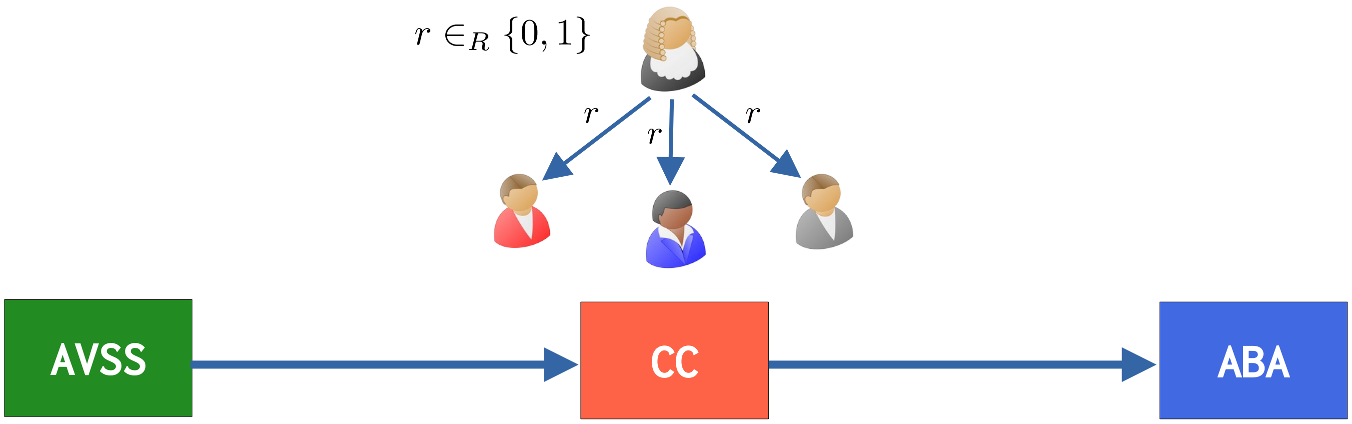

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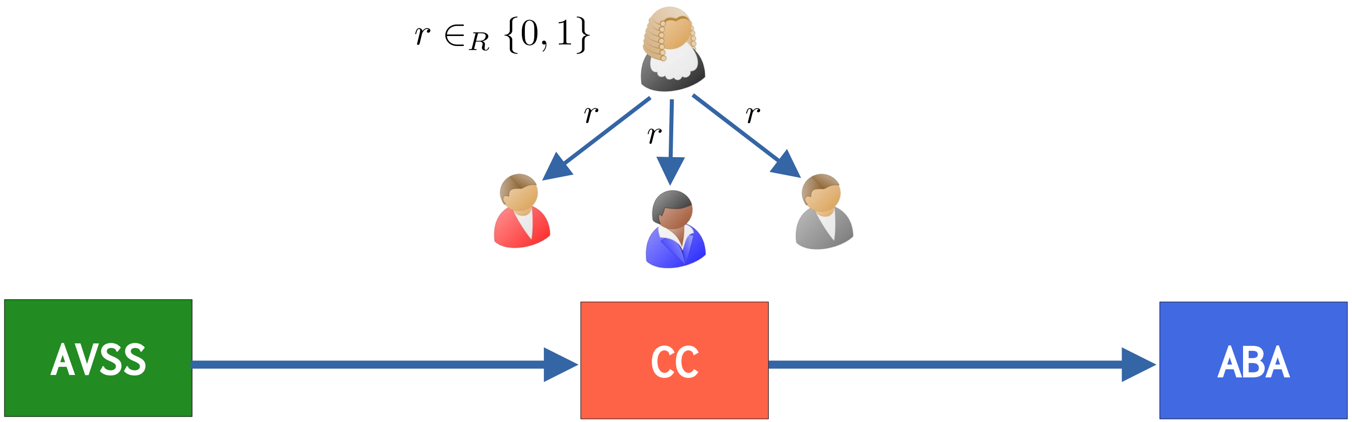

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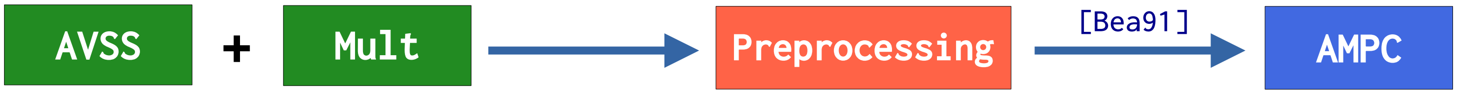

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Mult

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$[a]$ $[b]$ Mult

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P_i

$[\, a^{(1)} \cdot b^{(3)} \,]$

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P_3, P_5 P_6, P_7 $\rightarrow$ P_3, P_5 P_6

$\{P_7\}$

P_2, P_3 P_5, P_6, P_7 $\mathcal{Q}^{(3)}$

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P_3, P_5 P_6, P_7

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$[\, a^{(1)} \cdot b^{(3)} \,]$

n

ABA . . . ABA

ACS

P_3, P_5 P_6

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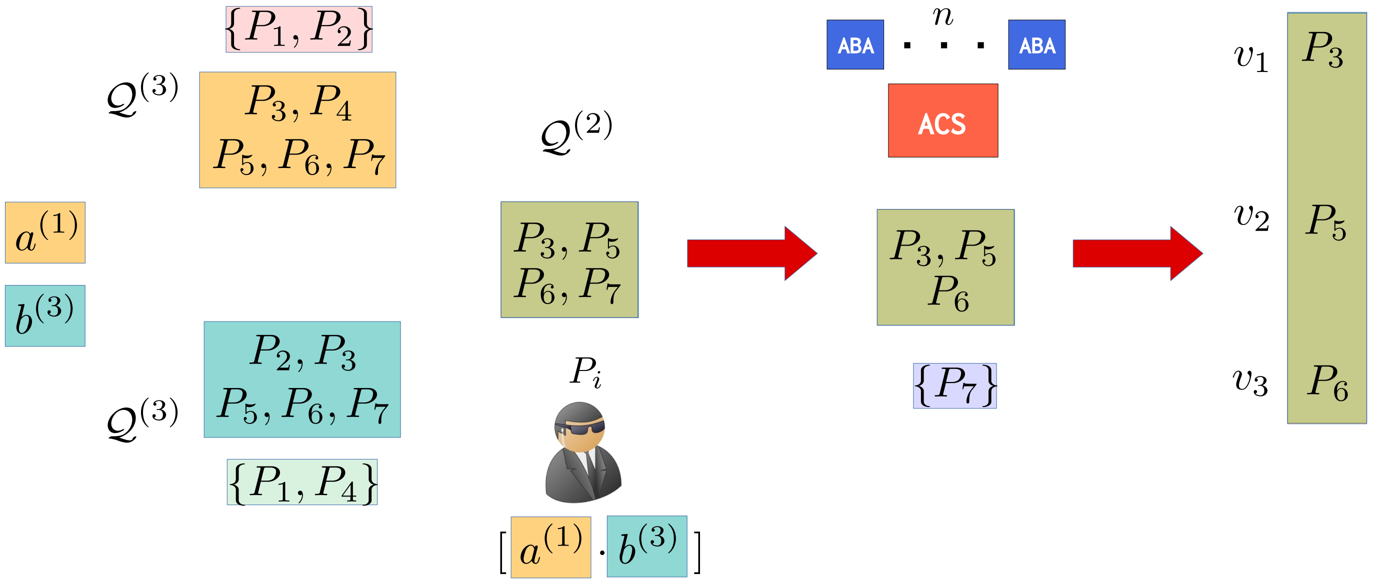

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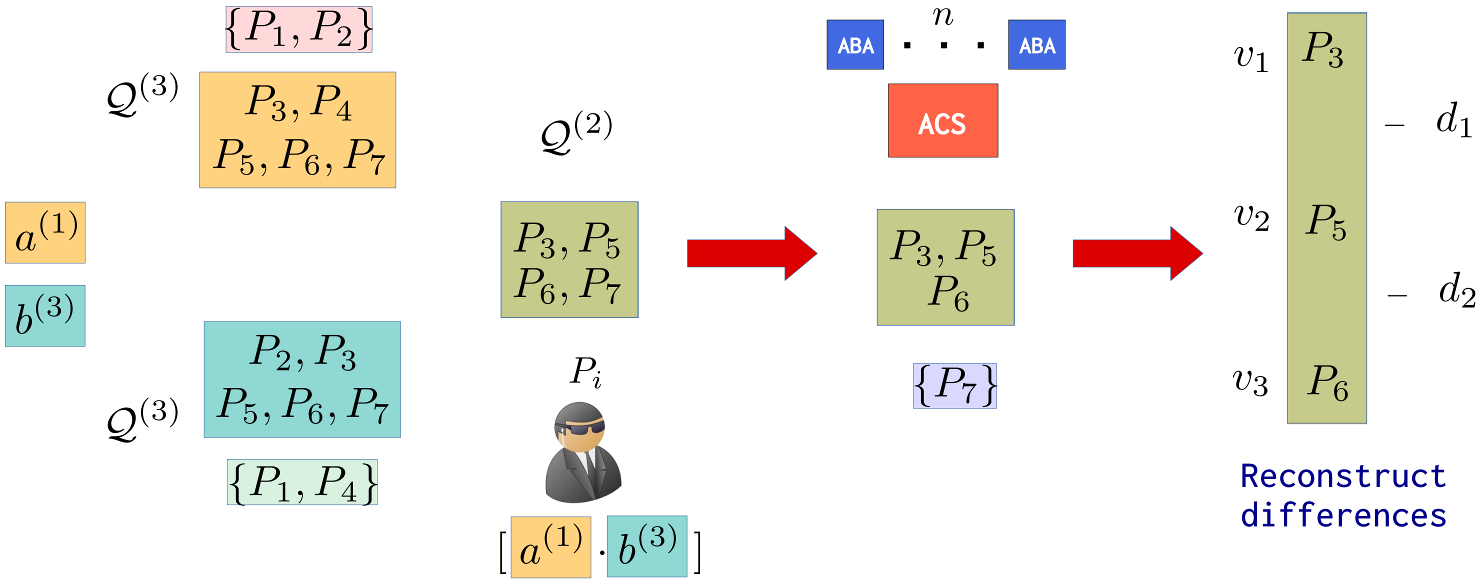

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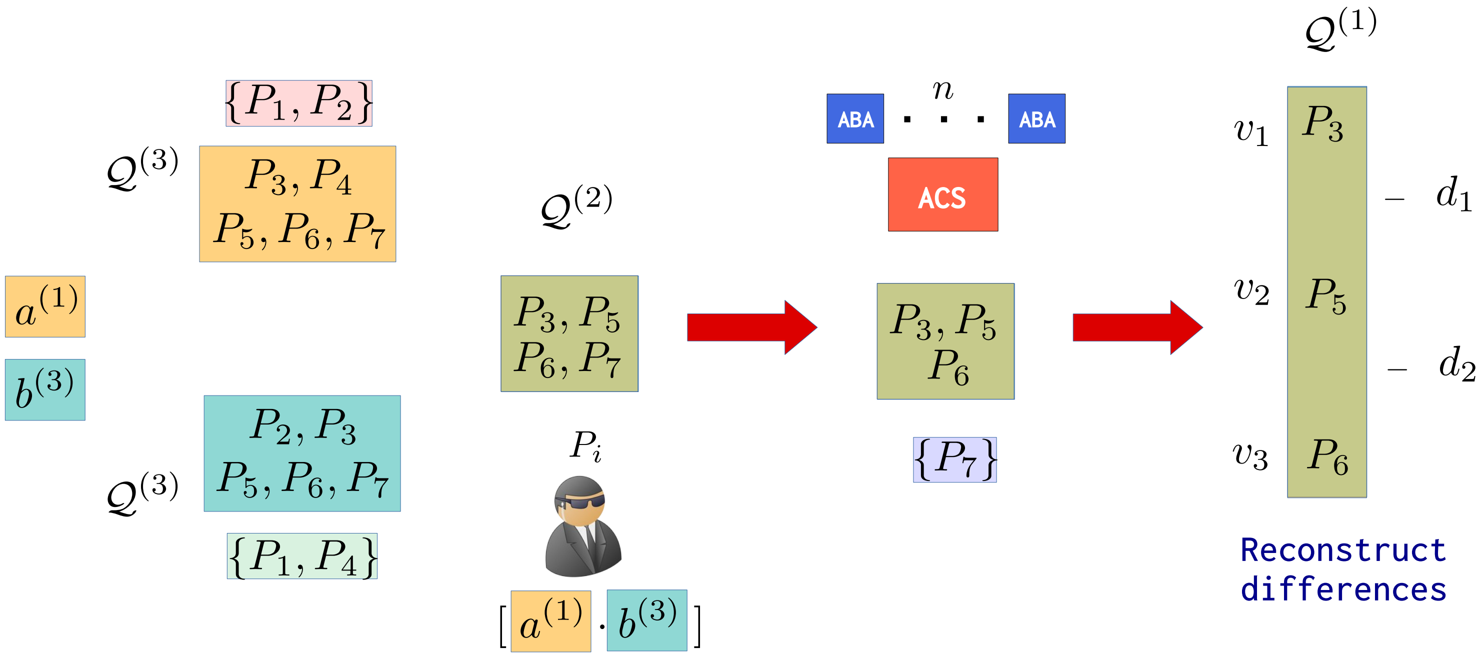

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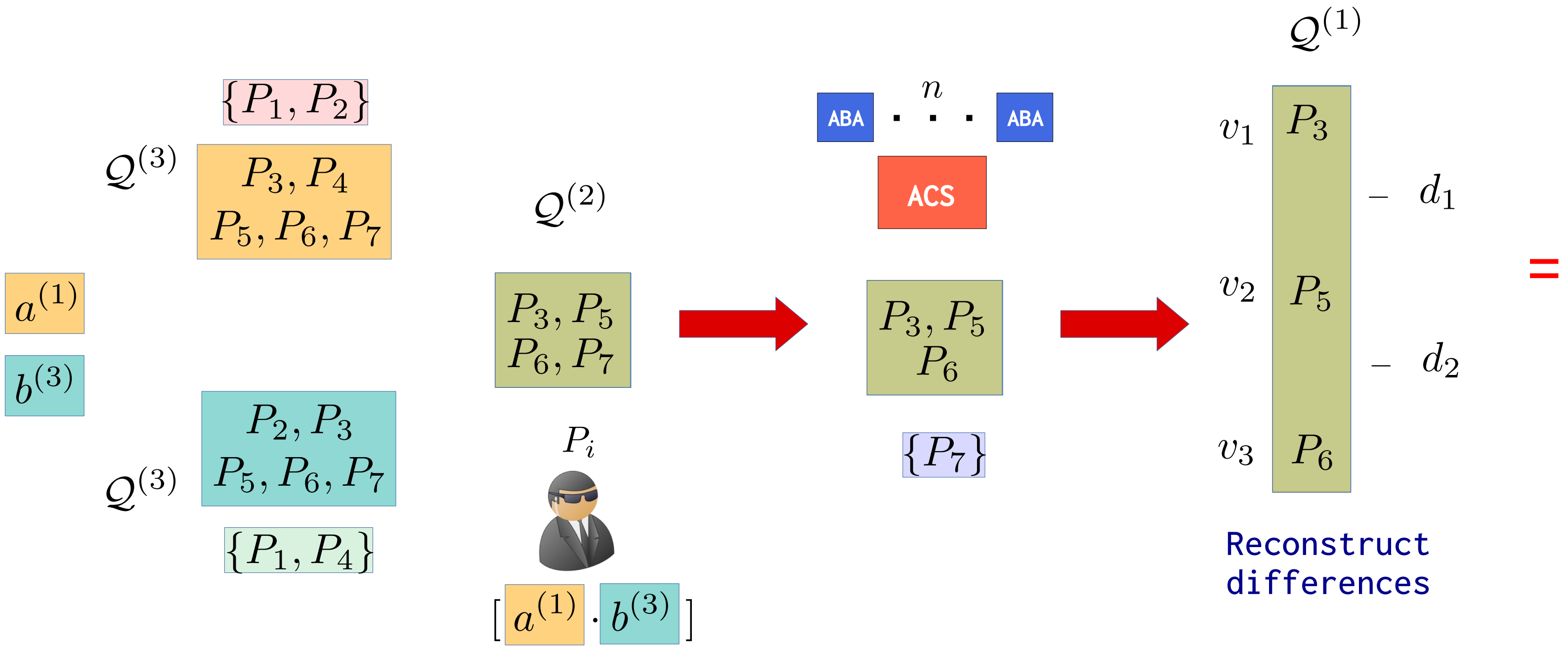

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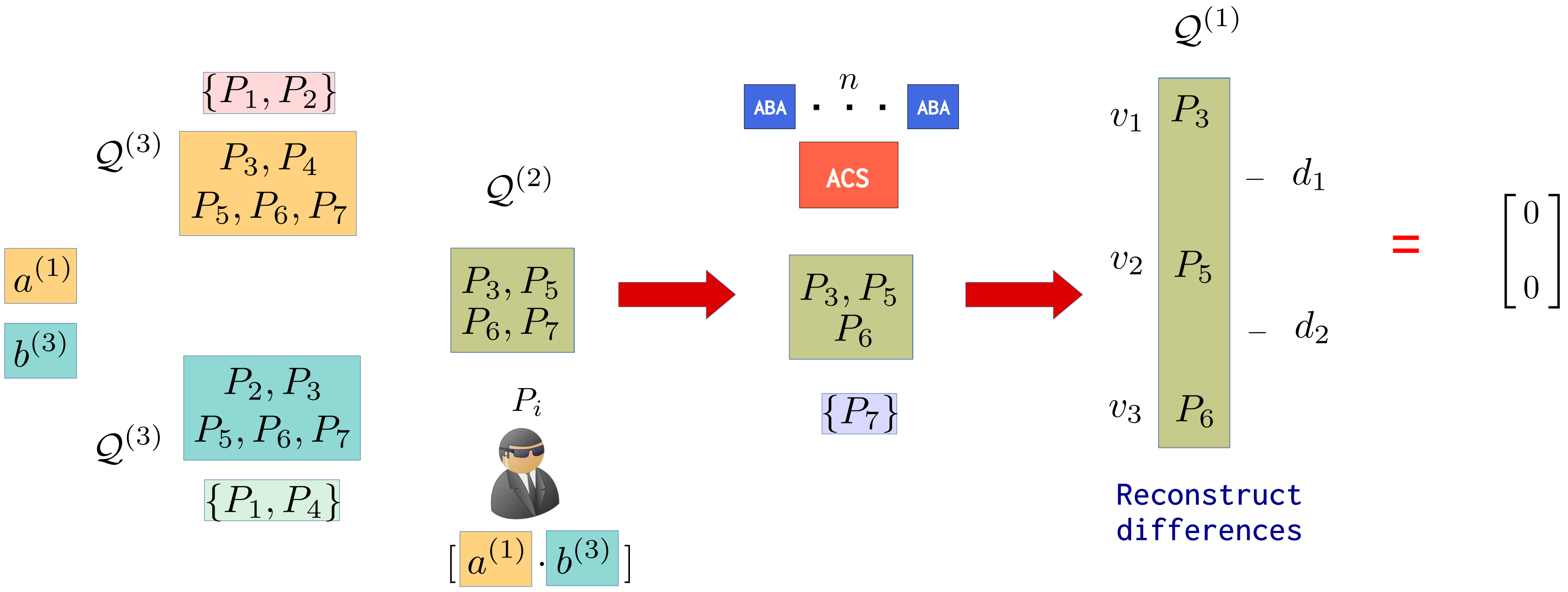

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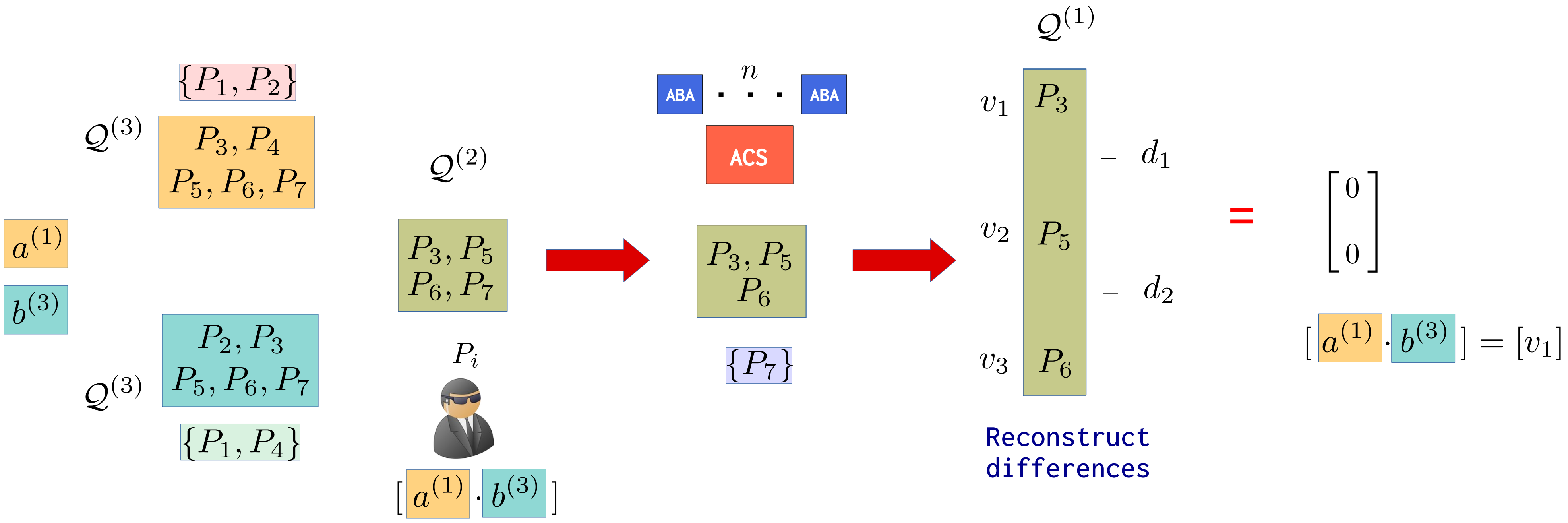

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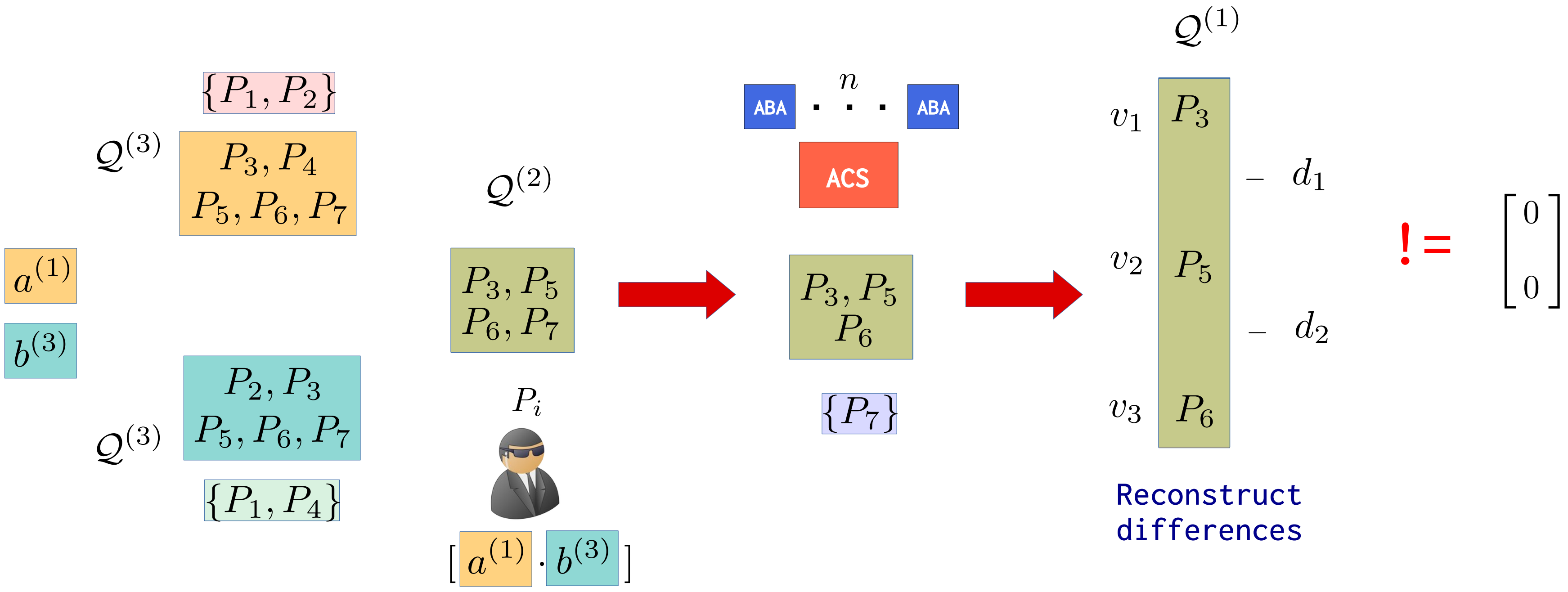

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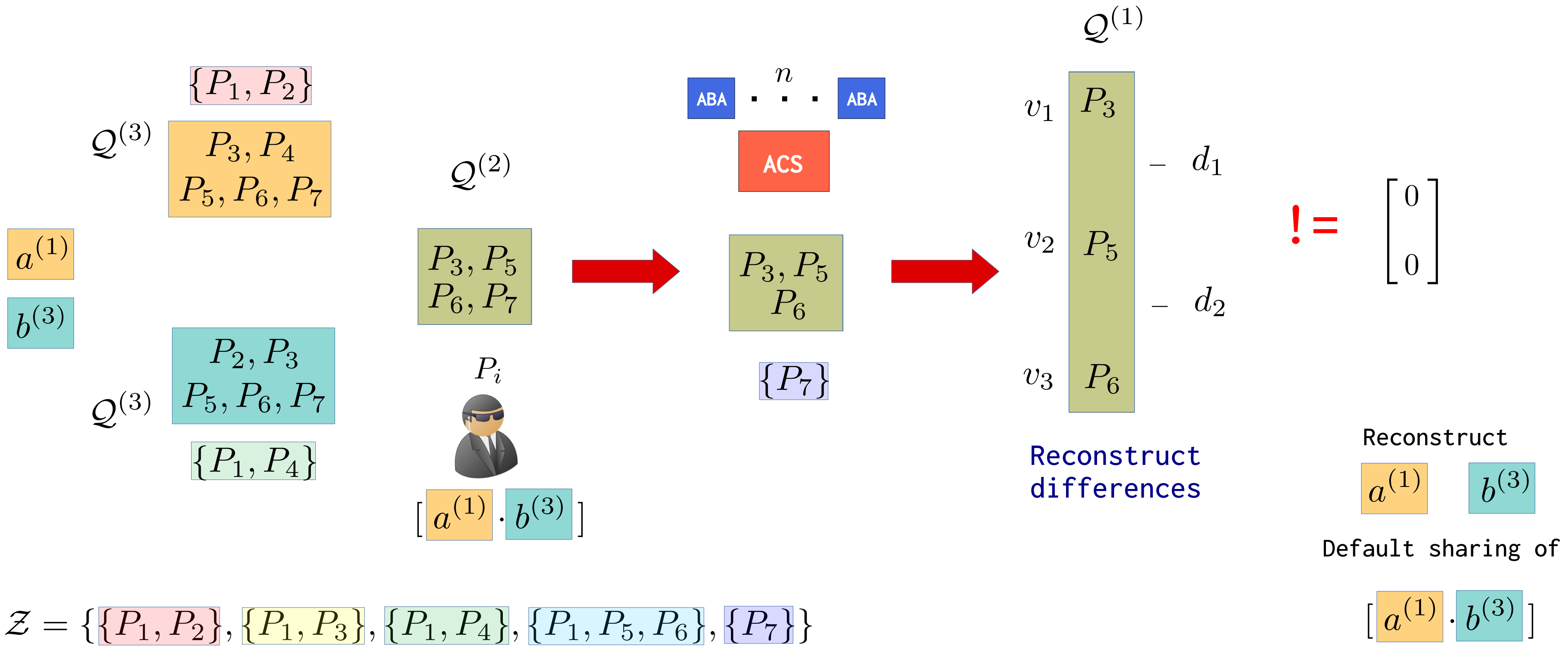

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Thanks!