Fluid MPC: Secure Multiparty Computation with Dynamic Participants

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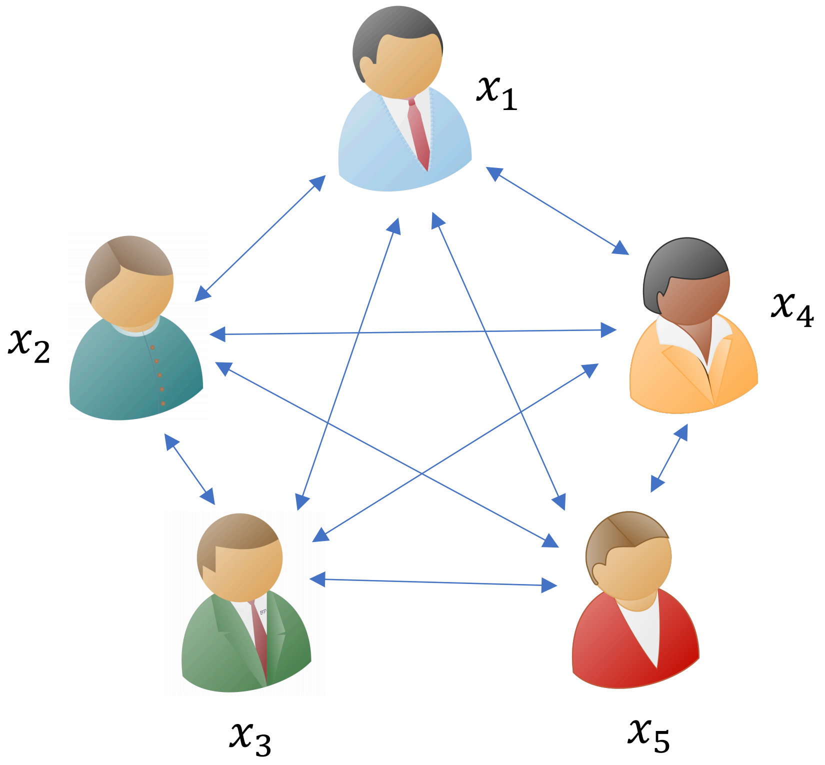
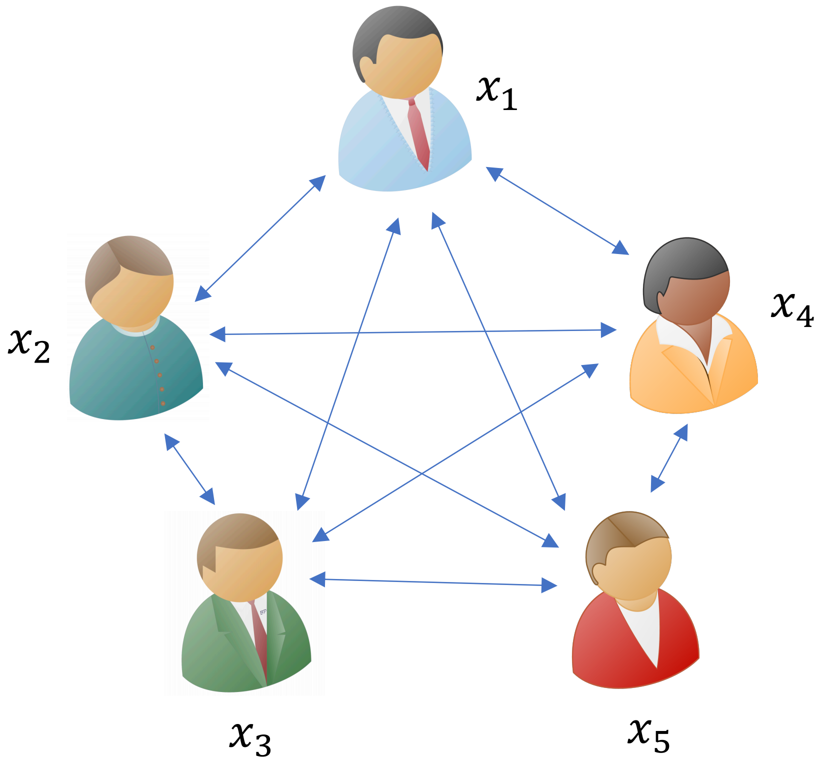
Abhishek Jain   Gabriel Kaptchuk

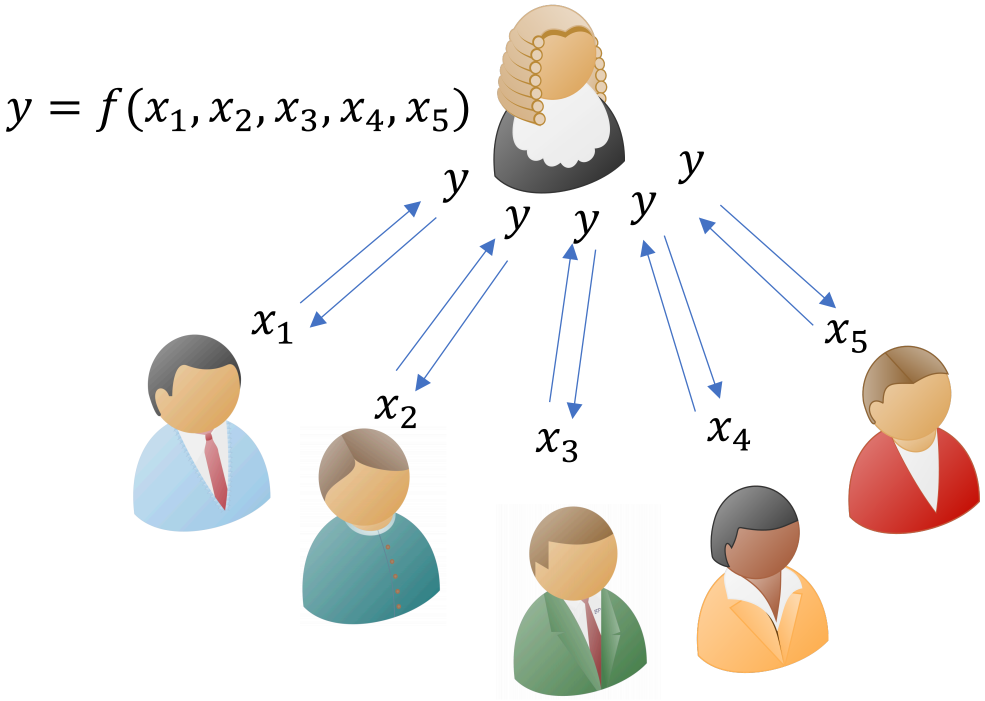
Johns Hopkins University

Secure Multiparty Computation



Secure Multiparty Computation





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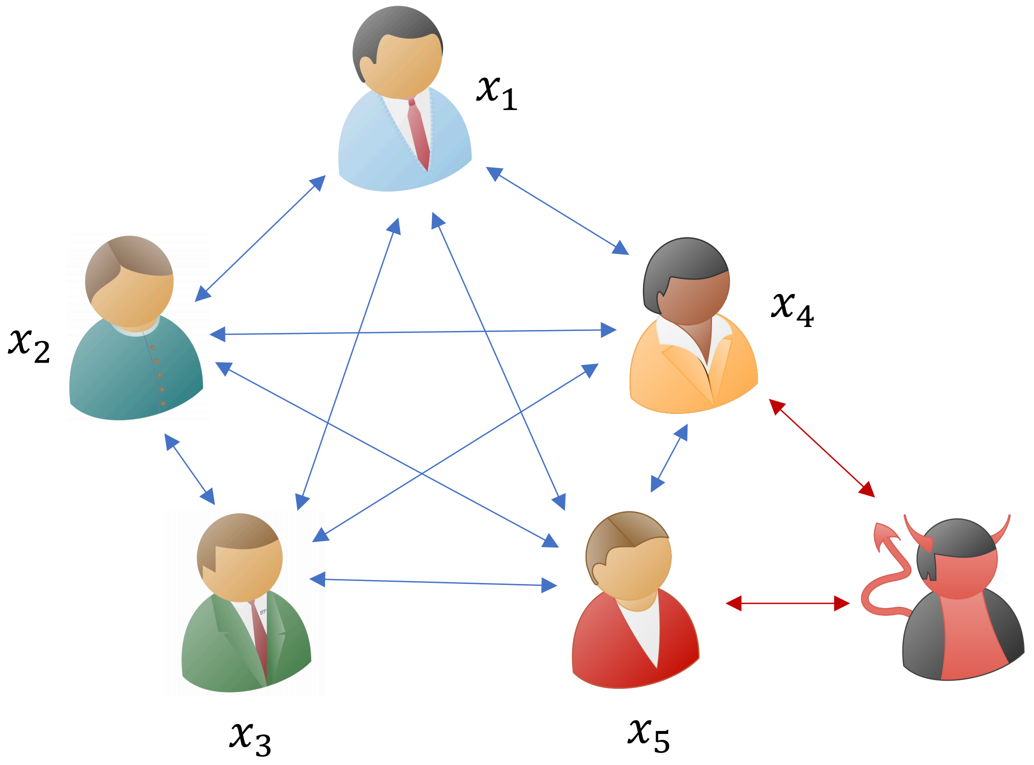

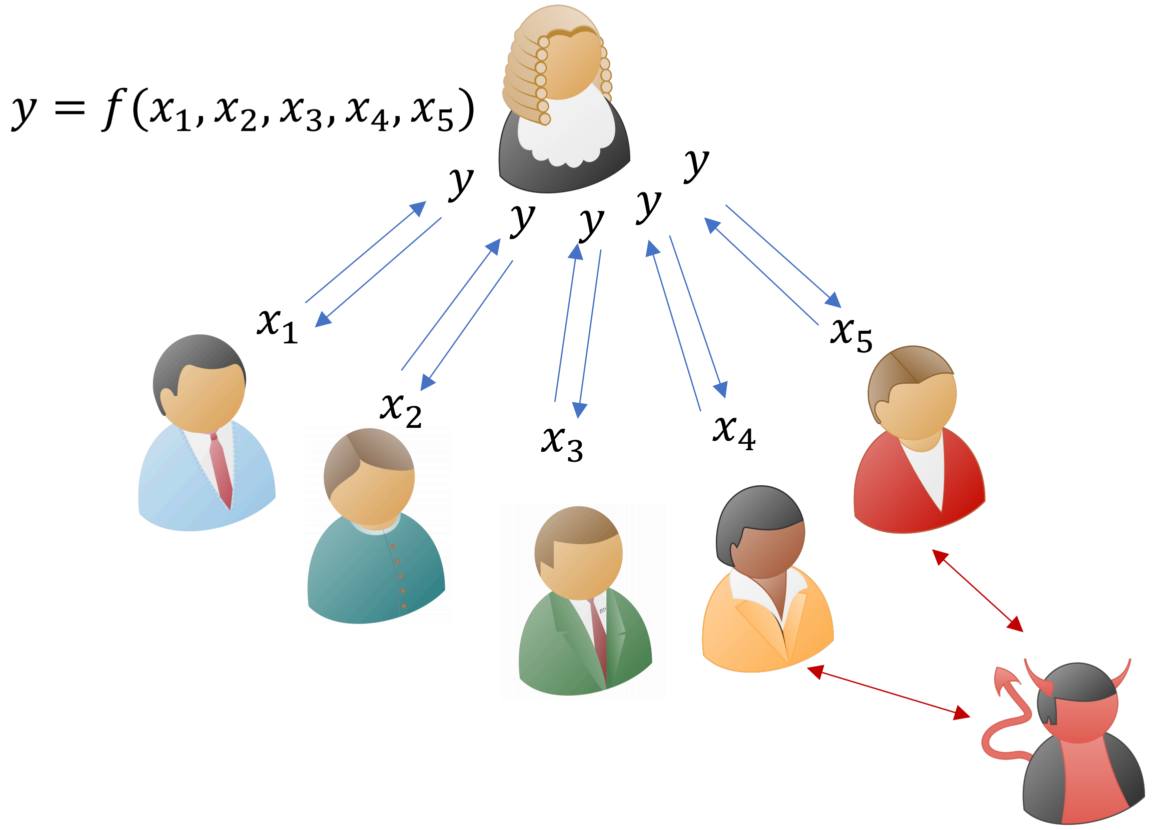

Adversary learns the same amount of information in the two scenarios

Efficient MPC and Emerging Applications

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- MPC protocols are becoming increasingly efficient.

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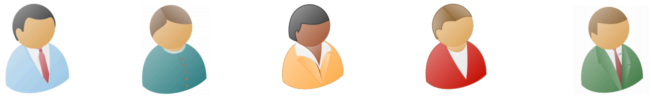
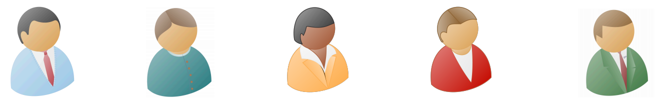
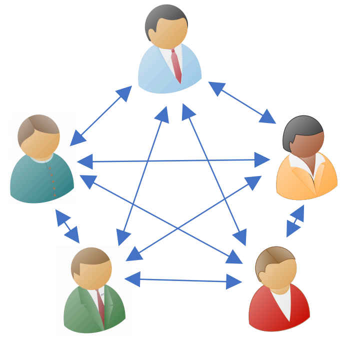
Issue: Evaluating these functionalities could take up to several hours or even days.

Prior Work: Static MPC



Prior Work: Static MPC 

Round 1



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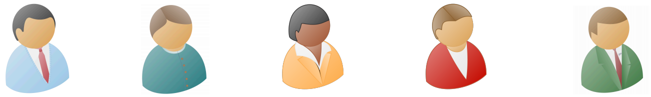
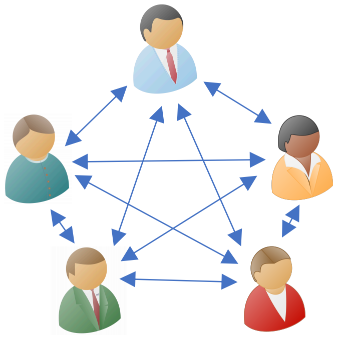
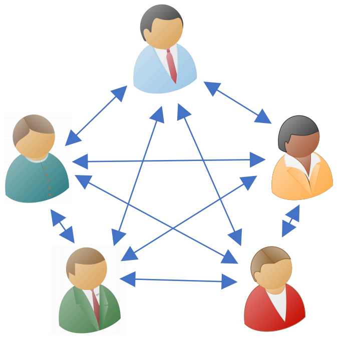


Round 1	Round 2





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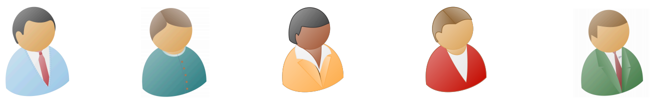
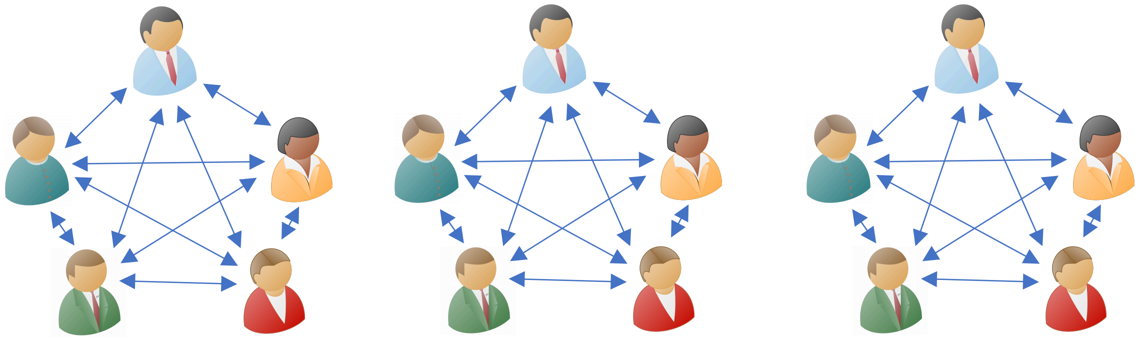


Round 1	Round 2	Round 3



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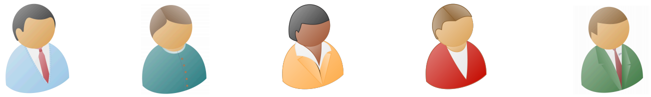

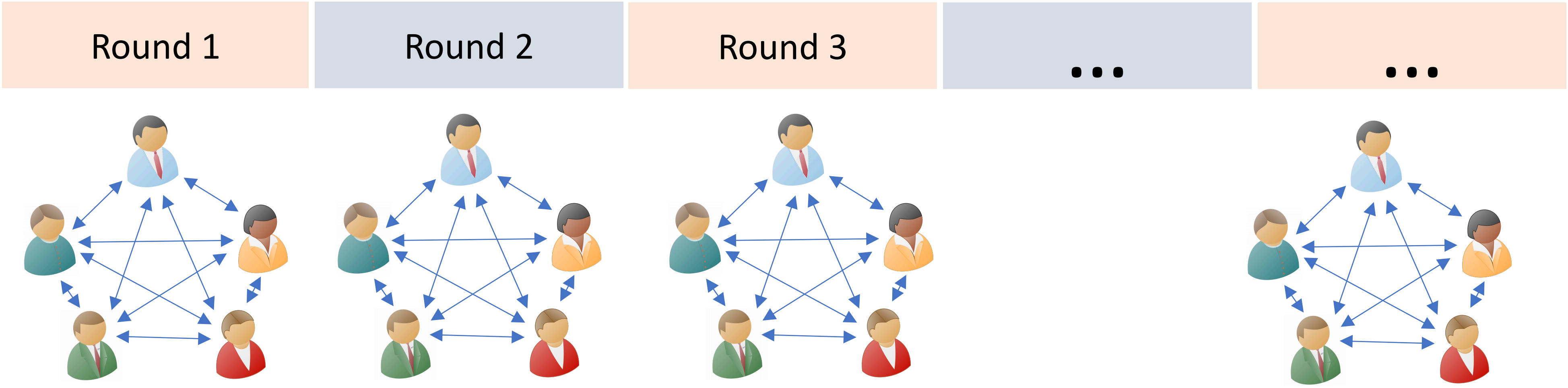

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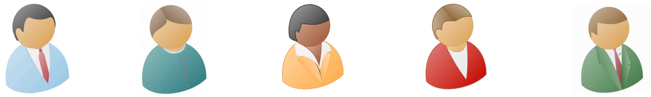

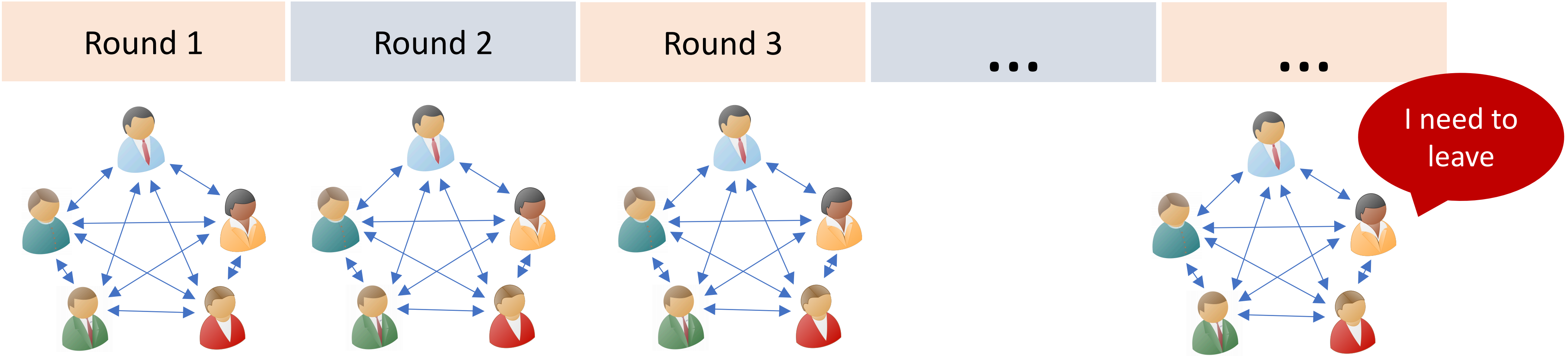

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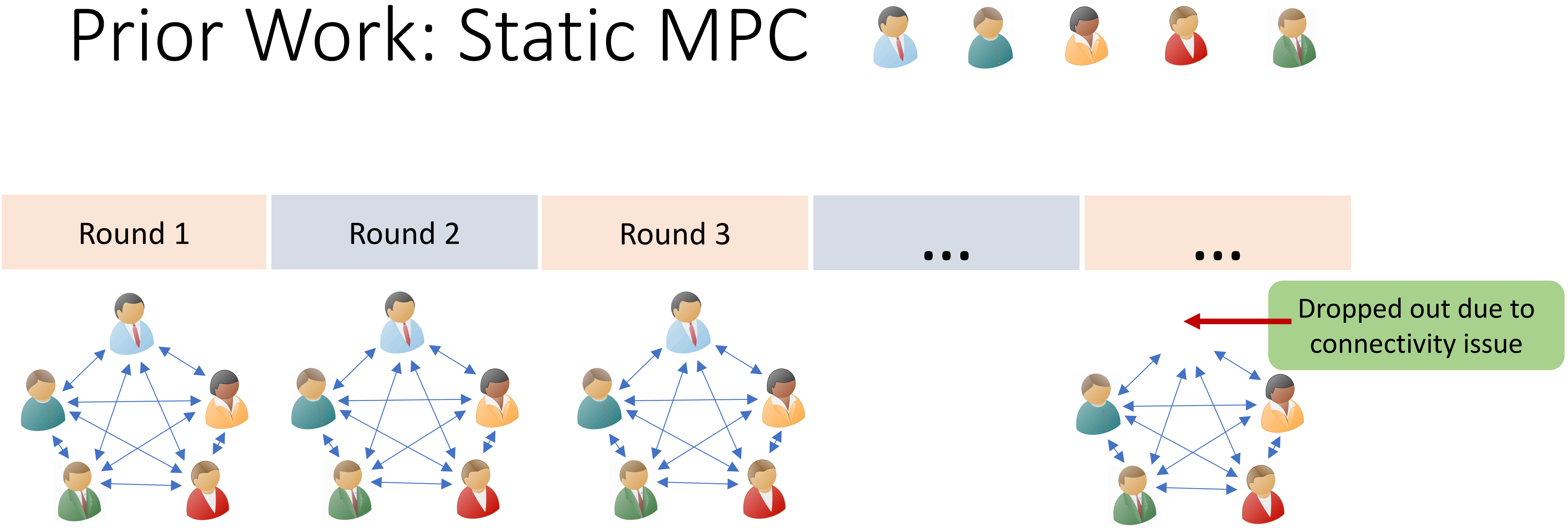

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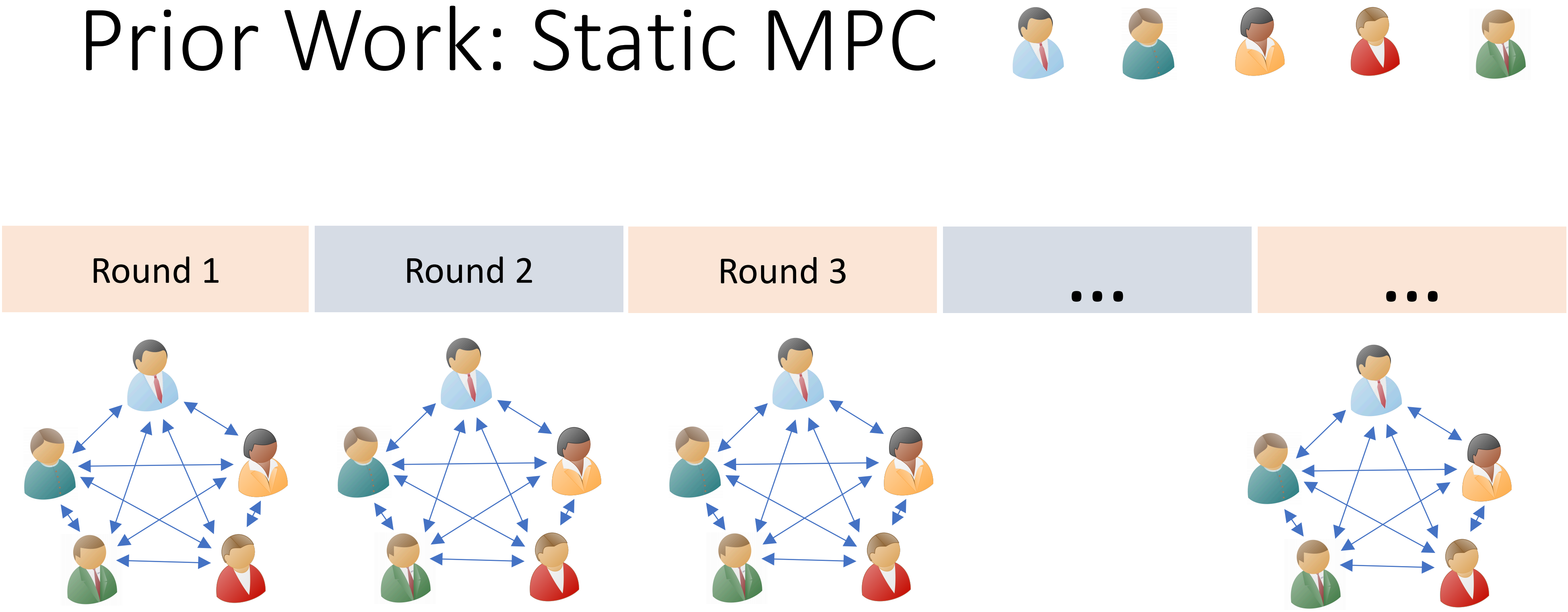
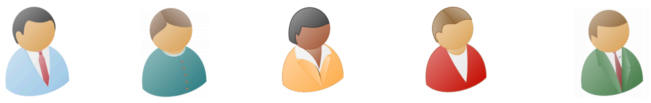
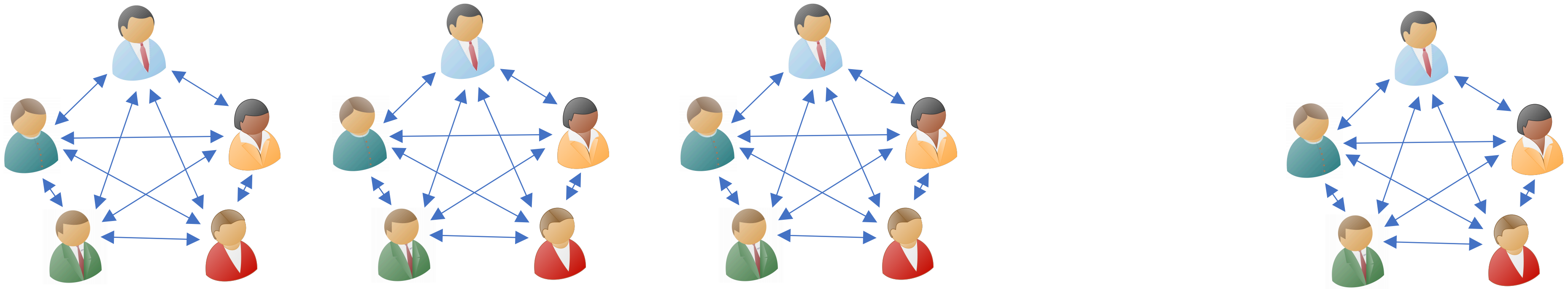


Requiring all participants to stay online throughout the computation is an unrealistic expectation.

Prior Work: Static MPC



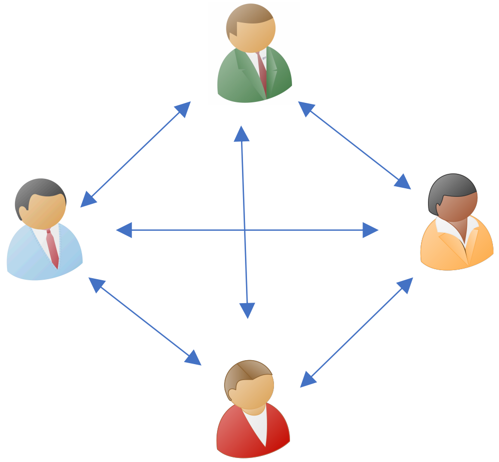
Round 1	Round 2	Round 3	…	…



Can we design MPC protocols with Dynamic Participants?

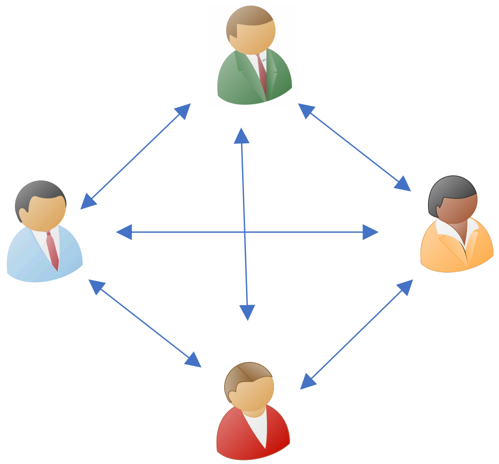
MPC with Dynamic Participants

MPC with Dynamic Participants



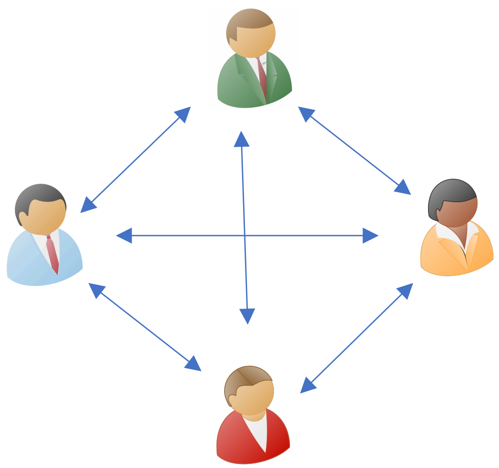
A group of parties start the computation

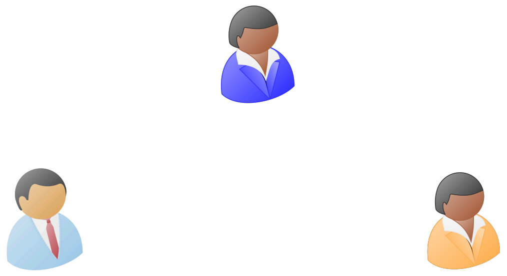
MPC with Dynamic Participants



After some time two parties have to leave

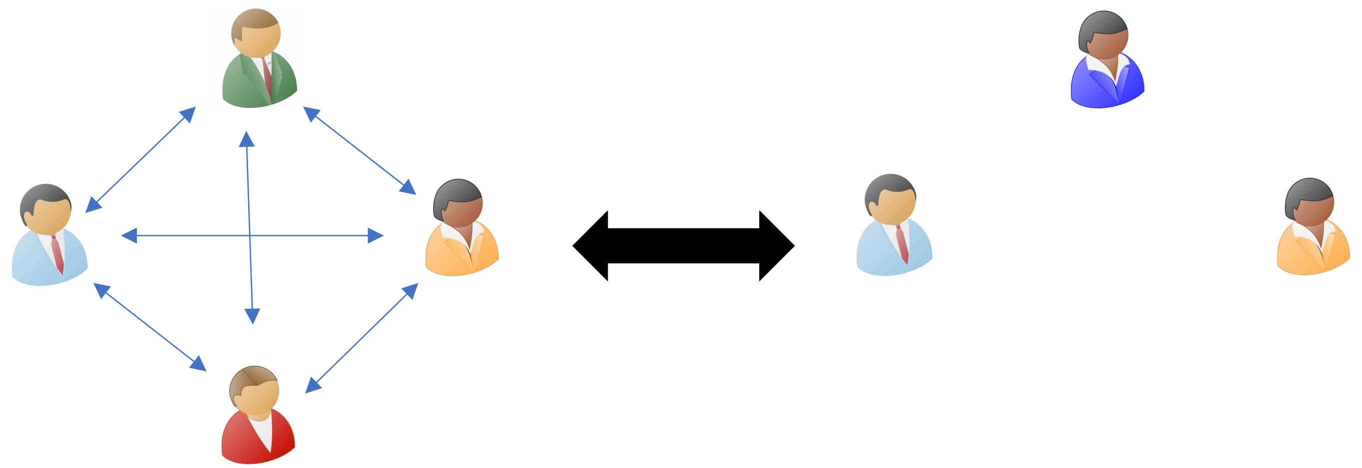
MPC with Dynamic Participants





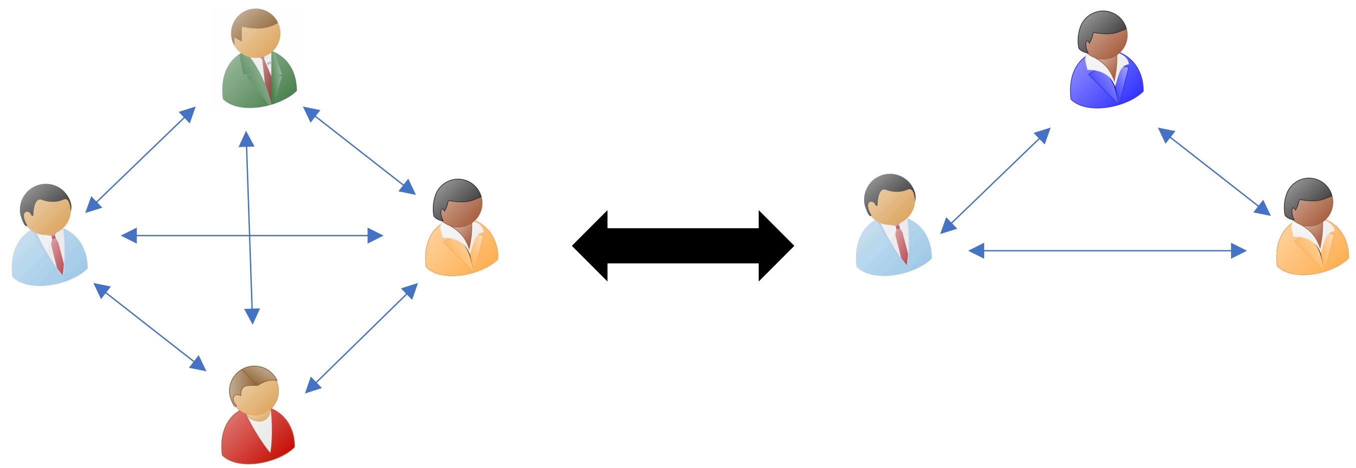
And a new party wants to join the computation

MPC with Dynamic Participants



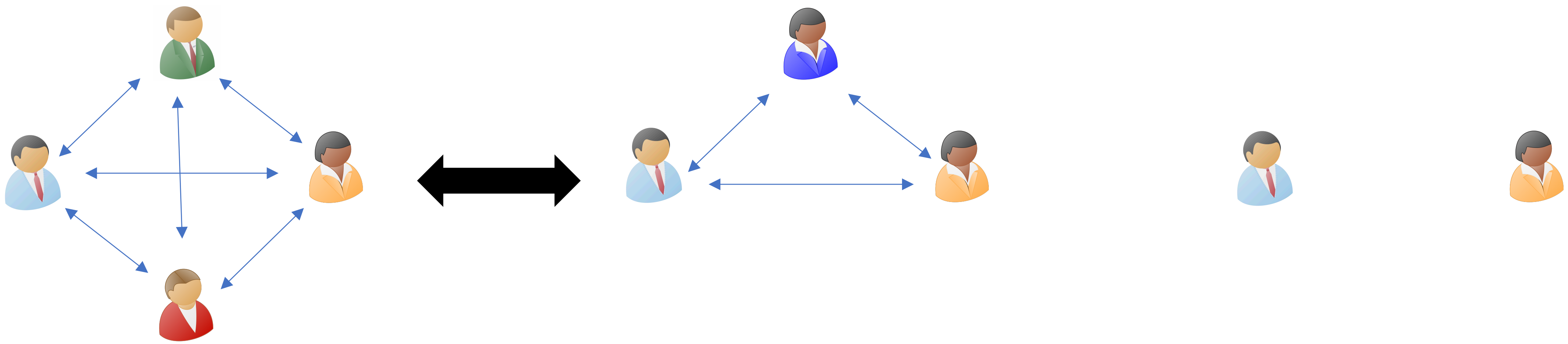
The previous group of parties securely distributes information about the computation so far, to the new group

MPC with Dynamic Participants



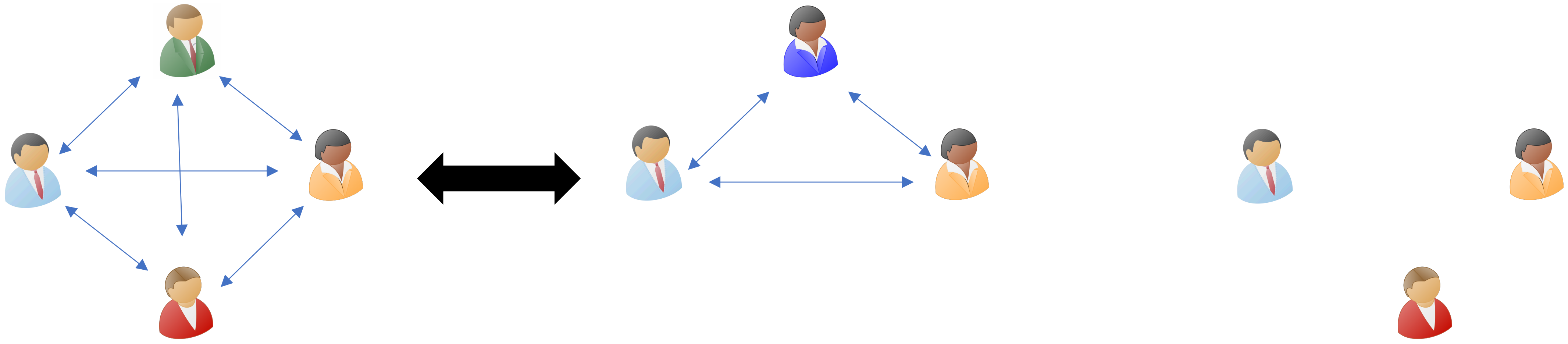
Given this information, the new group
continues with the rest of the computation

MPC with Dynamic Participants



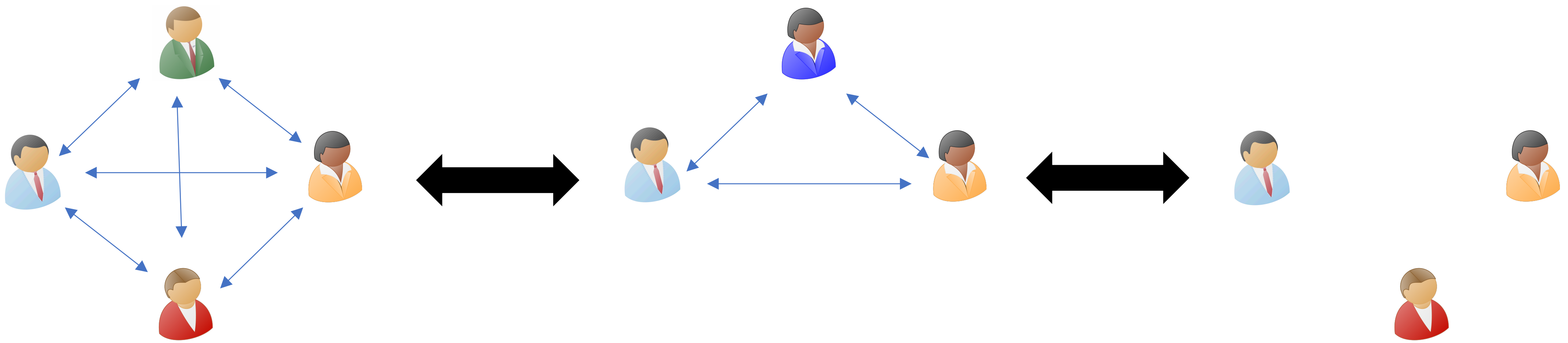
Again, after some time, a party has to leave

MPC with Dynamic Participants



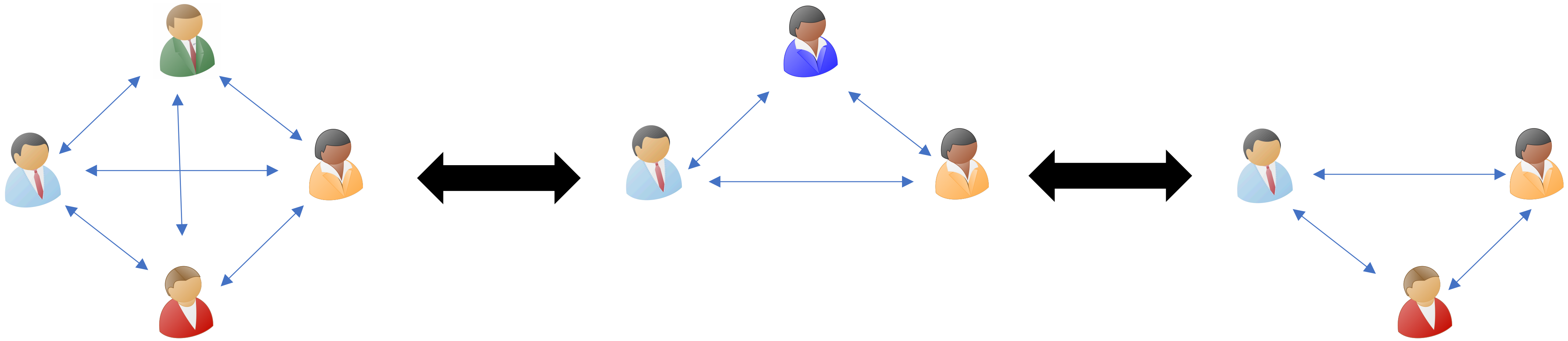
And an old party wants to re-join the computation

MPC with Dynamic Participants



This group will again securely distribute
information about the computation thus far,
with the new group of parties

MPC with Dynamic Participants



This group will continue with the rest of the computation

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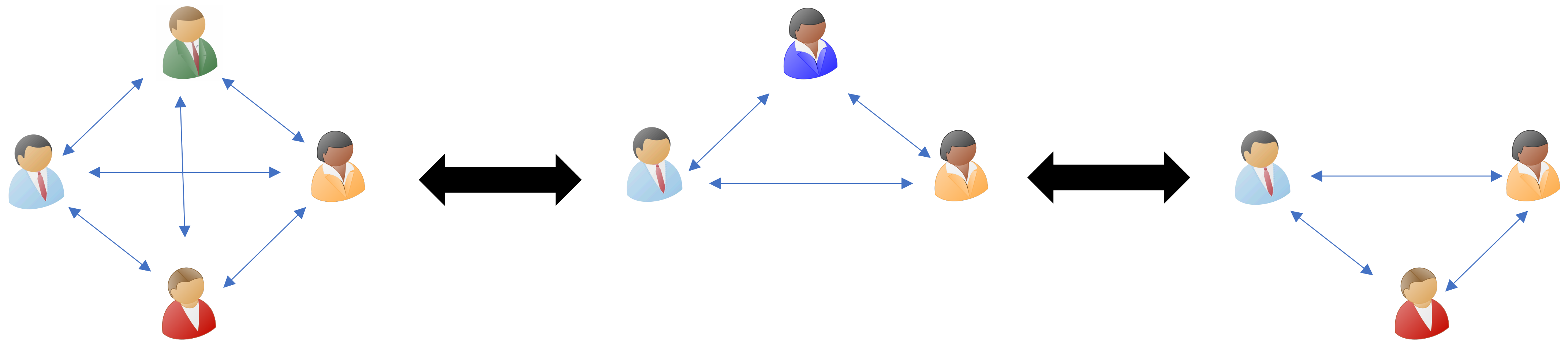

This reduces the burden of computation on individual parties

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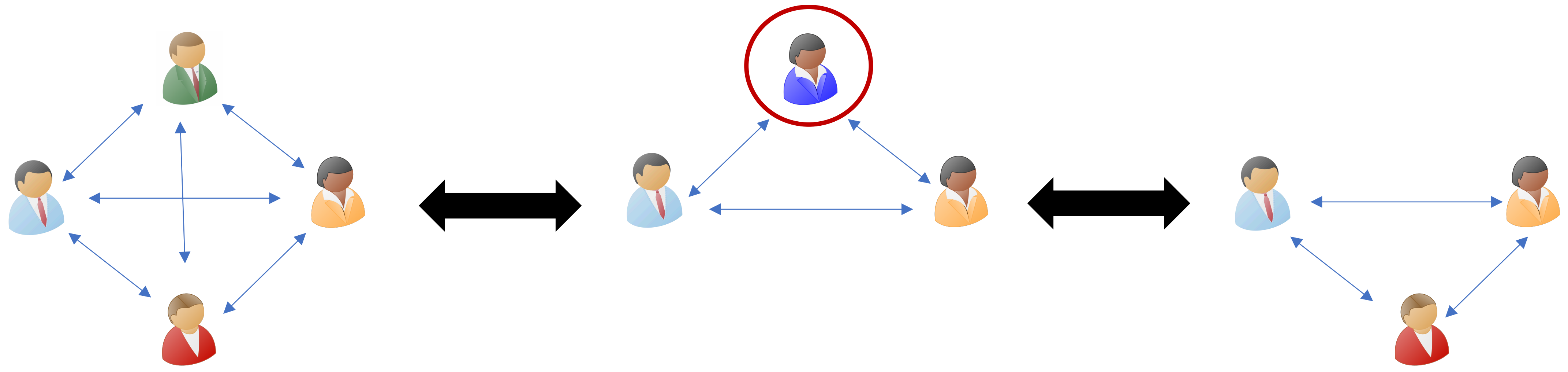

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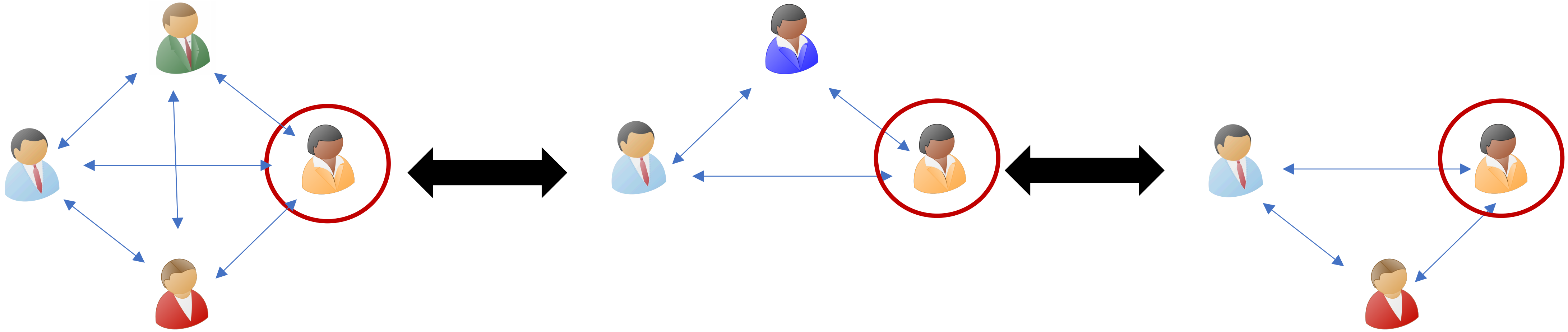
Parties with low computational resources can also participate for a small time

MPC with Dynamic Participants



This reduces the burden of computation on individual parties

While parties with more time and computational resources can help with the computation for a longer time

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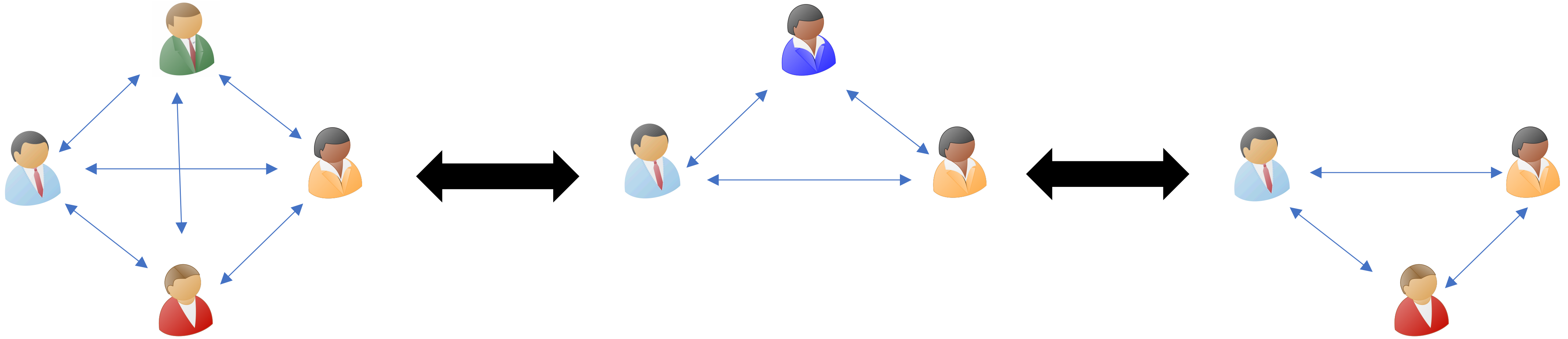
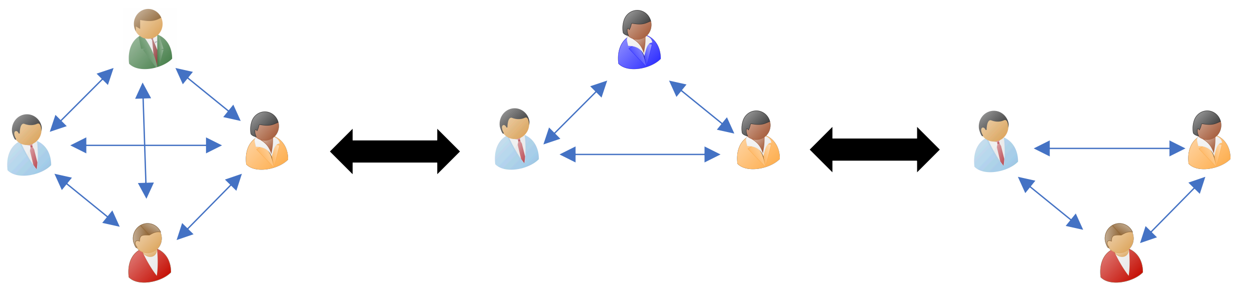


This will result in a weighted, privacy preserving distributed computing system.

MPC as a Service



MPC with Dynamic Participants

- Allows Participants to join and leave at will
- Reduces burden of computation on individual participants

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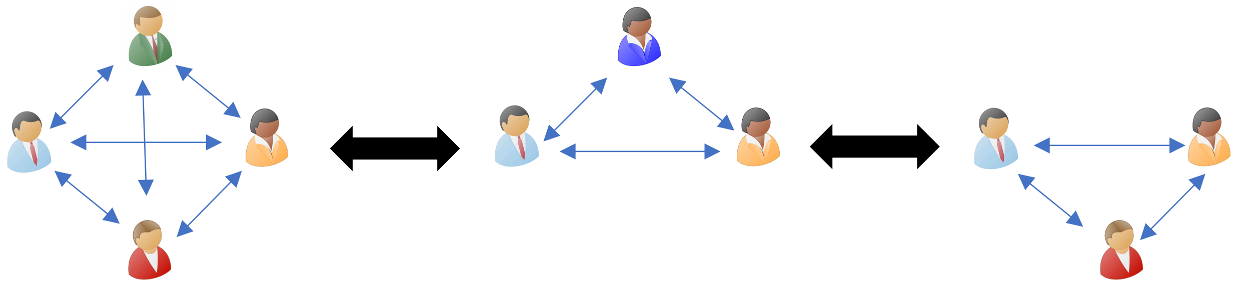

bitcoin

ETHERIUM

MPC with Dynamic Participants

Dynamic Peer-to-peer networks.

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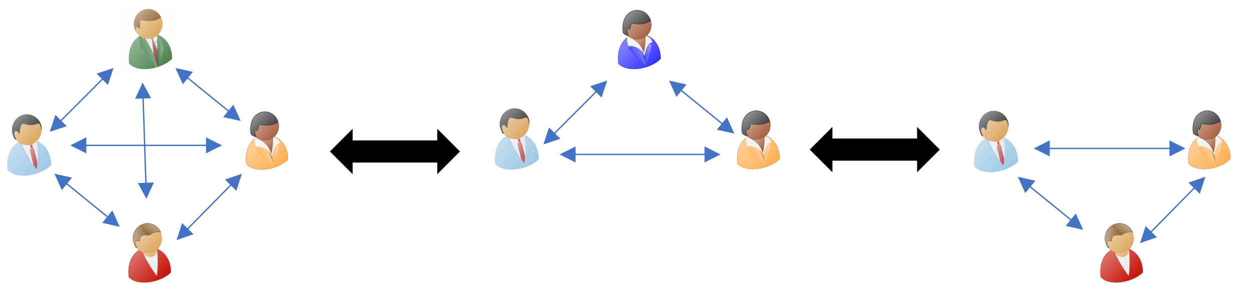

MPC with Dynamic Participants

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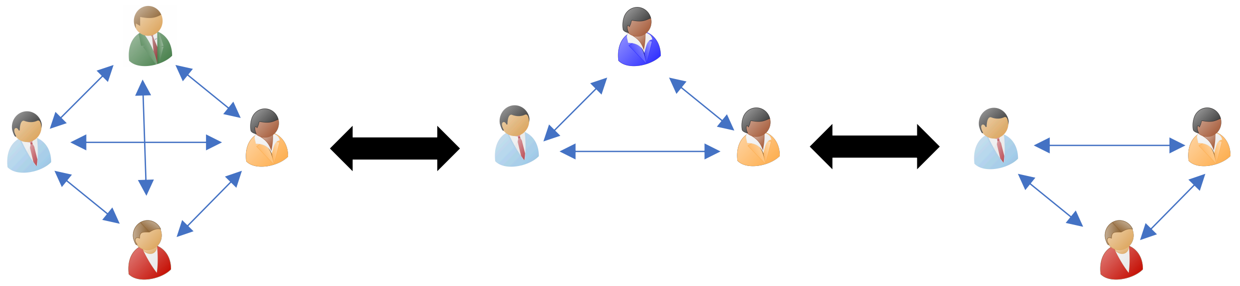
Dynamic Peer-to-peer networks.

- Powered by volunteer nodes- that can come and go as they wish.
- Very Successful!

MPC as a Service



ETHERIUM

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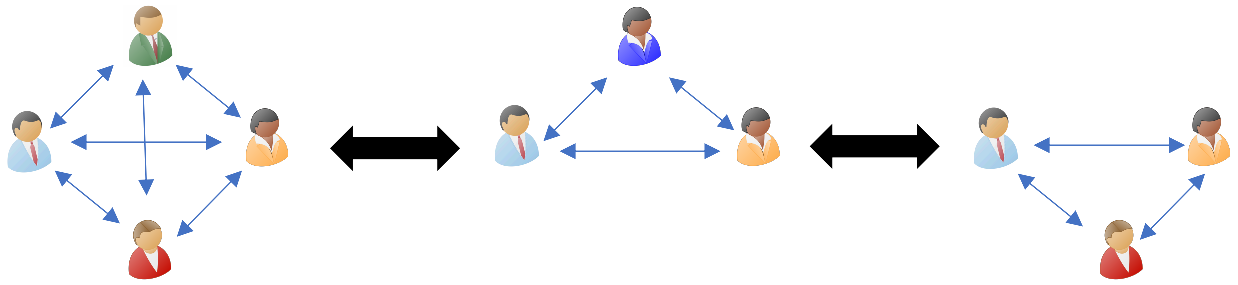
Compatible with each other

MPC as a Service



MPC with Dynamic Participants

+

ETHERIUM

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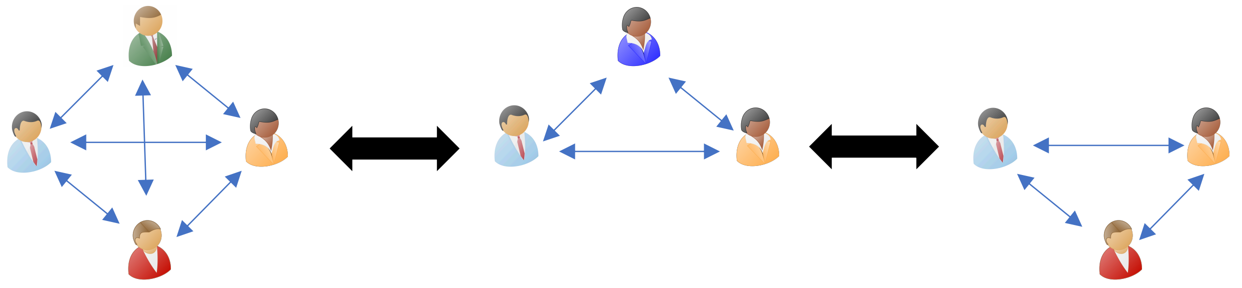

ETHERIUM

MPC with Dynamic Participants

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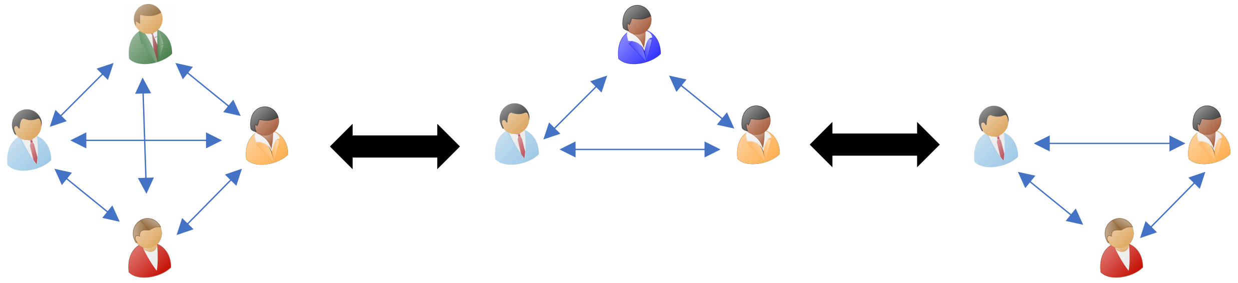

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ETHERIUM

MPC with Dynamic Participants

Dynamic Peer-to-peer networks.

Volunteer networks capable of private computation.

MPC-as-a-service framework - anyone can volunteer to participate irrespective of their computational power or availability.

Clients can delegate computations to such services.

Player Replaceability

- Byzantine Agreement [Mic17, CM19] : After every round, the current set of players can be replaced by new ones.

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- Blockchains [GHMVZ17]: This idea is used in the design of Algorand.
  - Helps mitigate targeted attacks on chosen participants after their identity is revealed.

Related Work

- Proactive MPC [OY91]
    - Static participants
    - Mobile adversaries

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- Proactive MPC [OY91]
  - Static participants
  - Mobile adversaries
- Secret Sharing with dynamic participants [GKMPS20, BGGHKLRR20]
  - Computational setting
  - Guaranteed output delivery

Our Contributions

Fluid MPC: A formal model for MPC with dynamic participants

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- security with abort
- $2\times$ communication complexity
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Implementation of our maliciously secure protocol based on BGW

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Fluid MPC Model

Modeling Dynamic Computation

- Client-server model
- Clients delegate computation to volunteer servers

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Input Stage

Clients pre-process
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Input Stage	Execution Stage
Clients pre-process their inputs and hand them to the servers	Dynamic servers participate to compute the function

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- Client-server model
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Input Stage	Execution Stage	Output Stage
Clients pre-process their inputs and hand them to the servers	Dynamic servers participate to compute the function	Clients reconstruct the output of the function

Modeling Execution Stage

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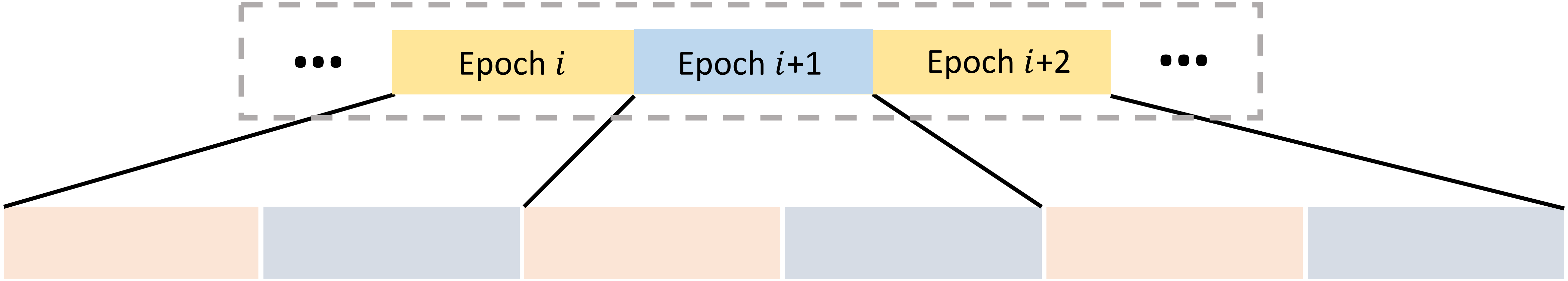

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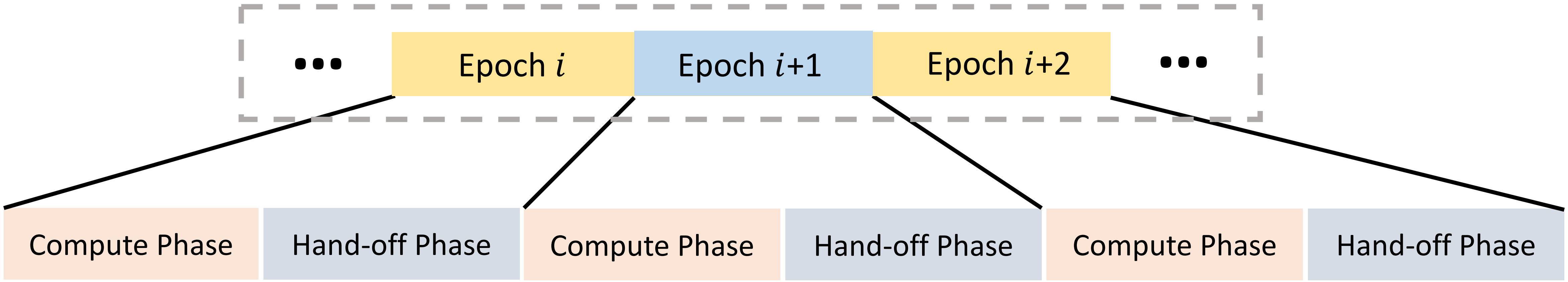

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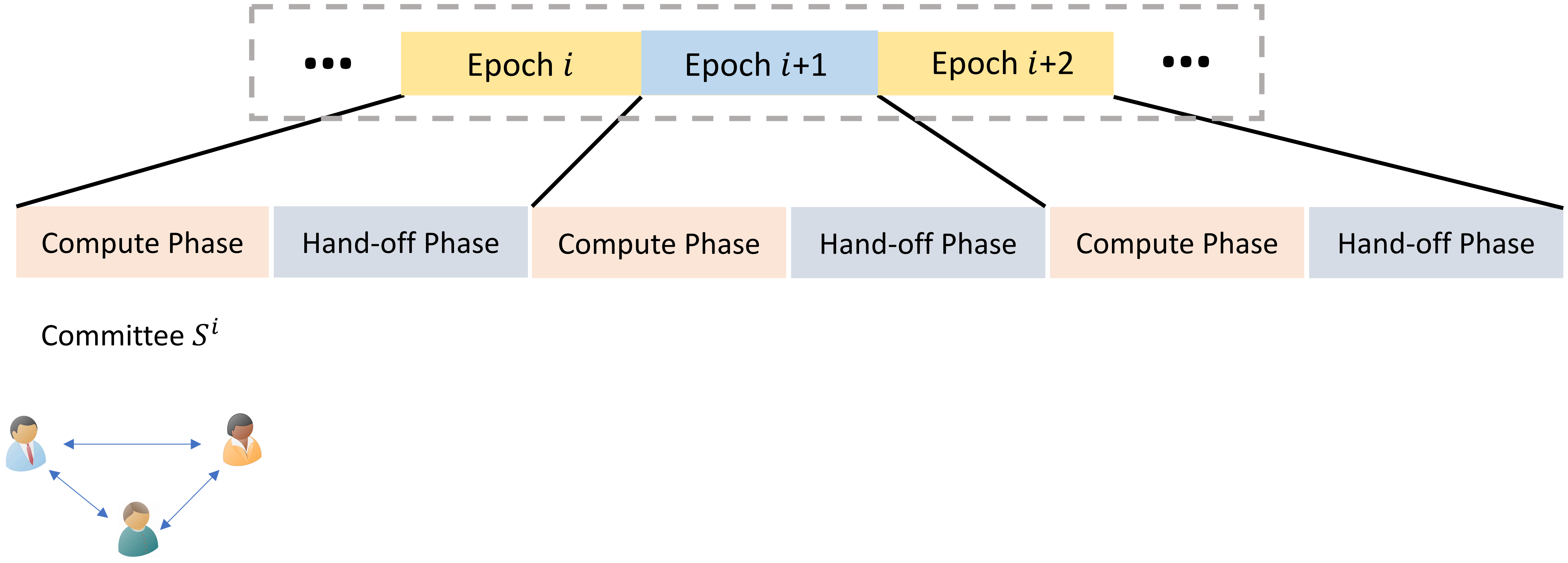

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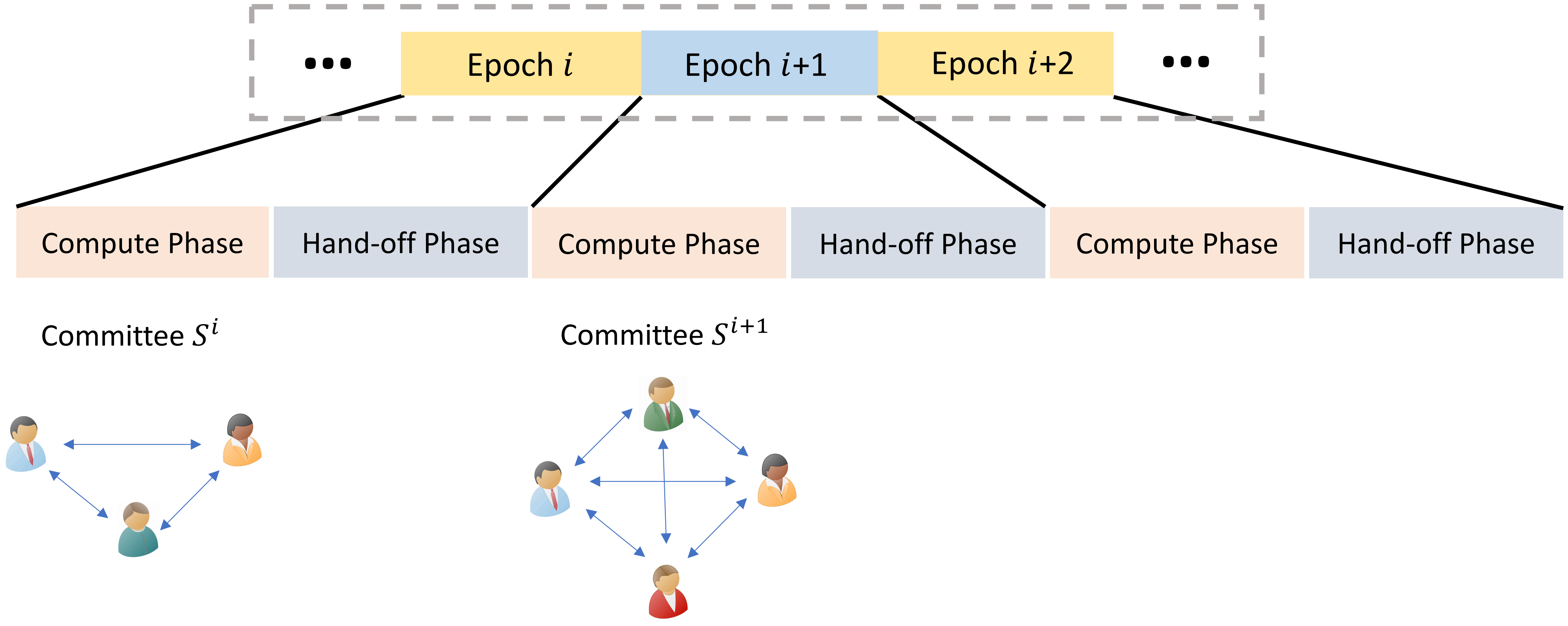

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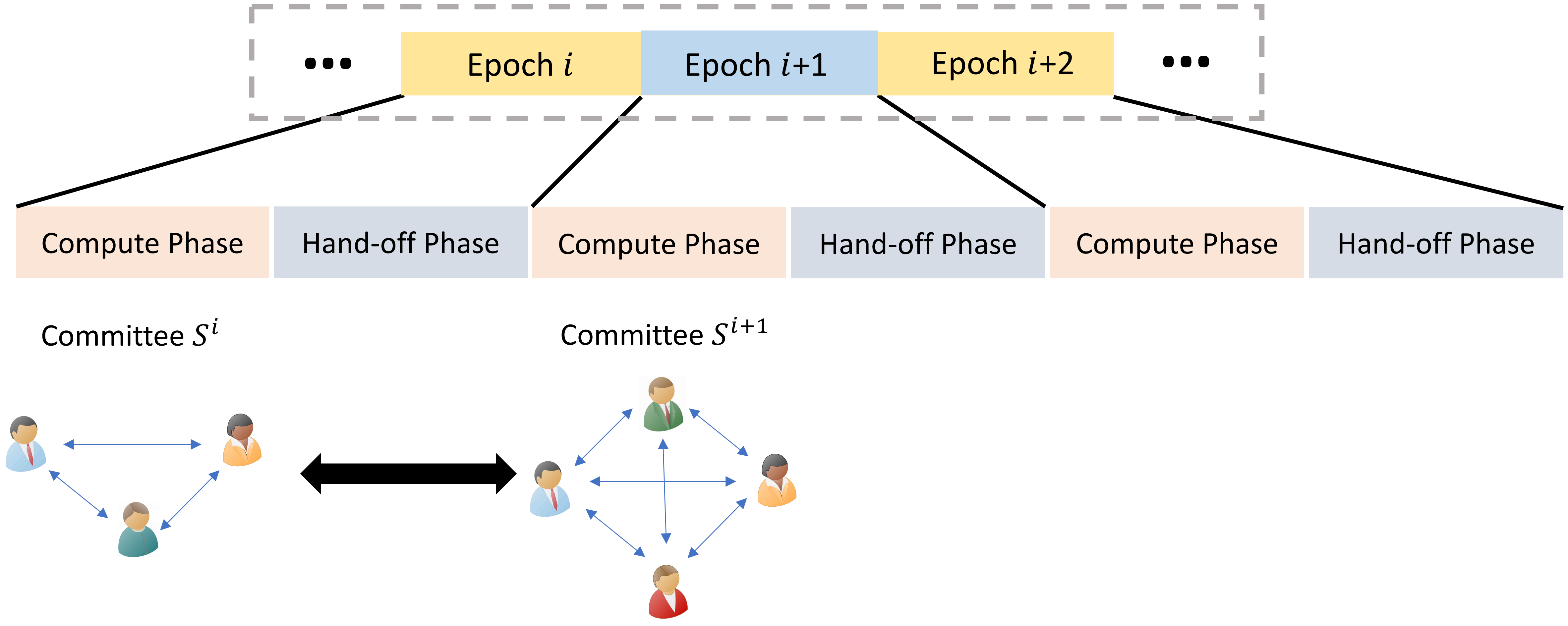

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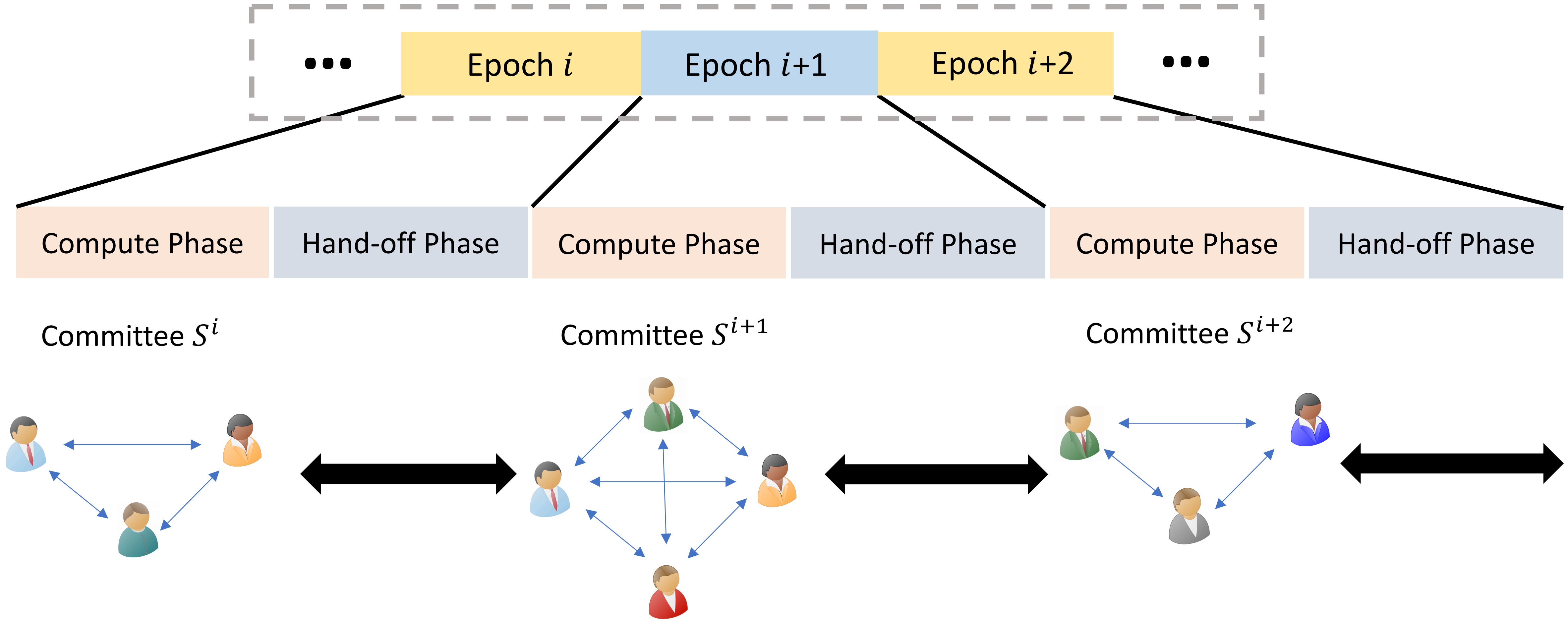

Corruption Threshold

- Clients: Honest Majority or Dishonest majority
- Servers: Honest Majority or Dishonest majority

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Our Choice

- Honest majority of clients
- Honest majority of servers in each committee

Fluid MPC Protocol

Committee Selection/Corruption

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Protocol Execution given these Committees

Fluid MPC Protocol

Committee Selection/Corruption

Protocol Execution given these Committees

Fluid MPC Protocol

Committee Selection/Corruption

- Committee Formation
- Committee Corruption
- Effect of Committee Corruption on Prior Epochs

Protocol Execution given these Committees

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Committee Selection/Corruption

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Protocol Execution given these Committees

Committees: When are they formed?

Static Committee Formation: Committee for each epoch is known at the start of the protocol or the execution stage.

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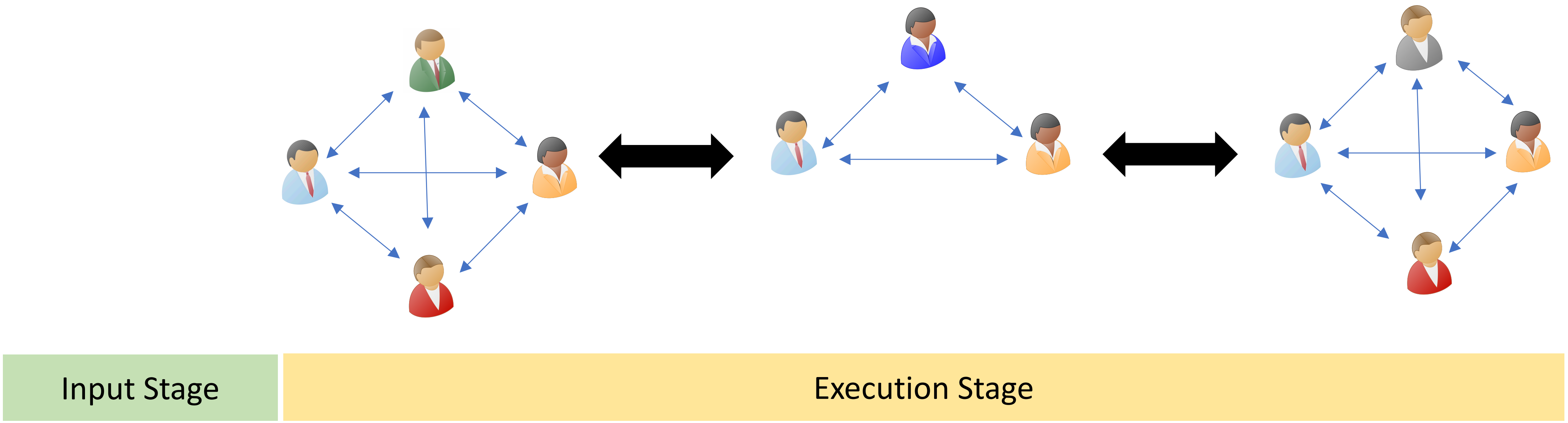

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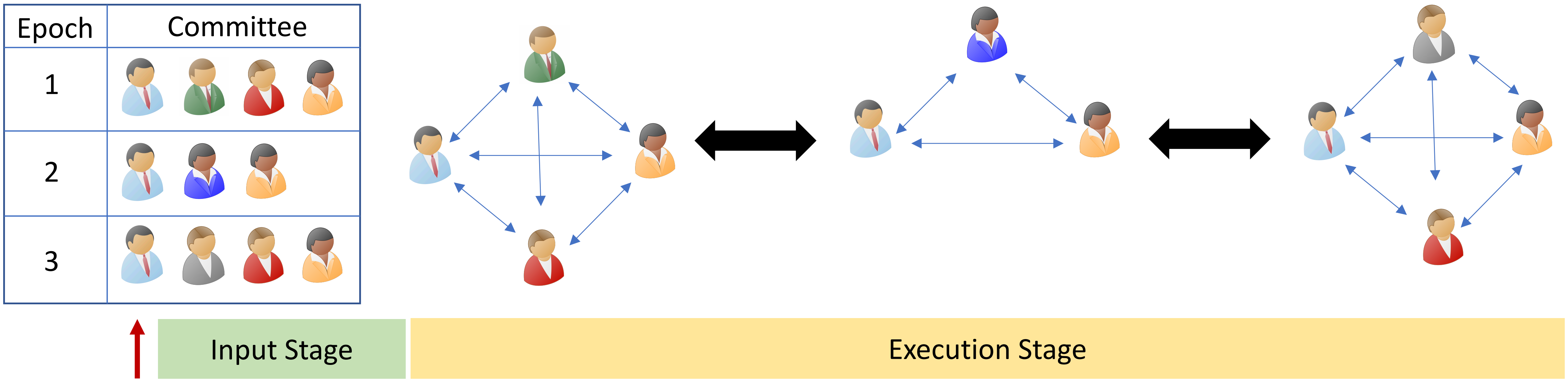

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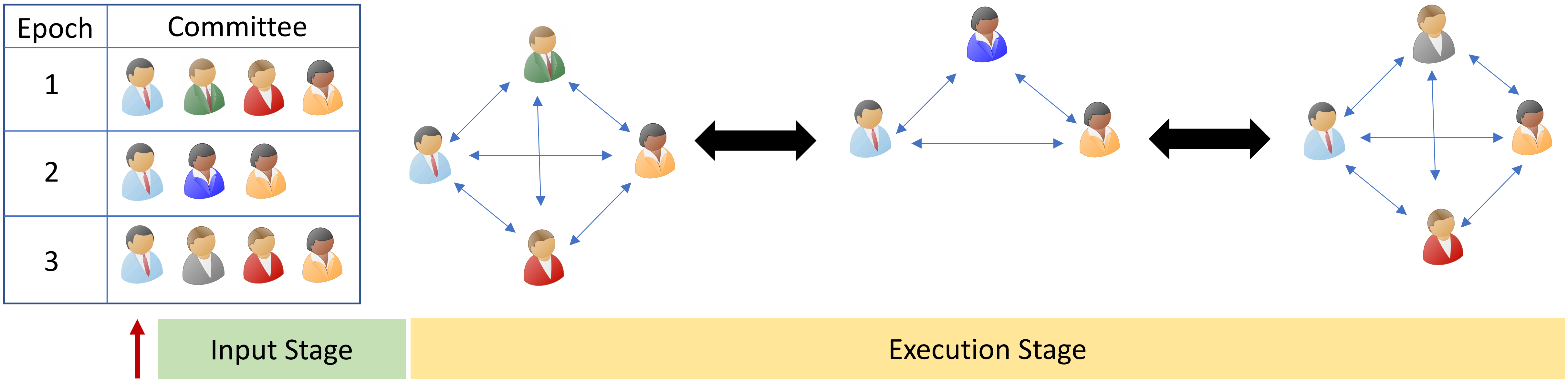

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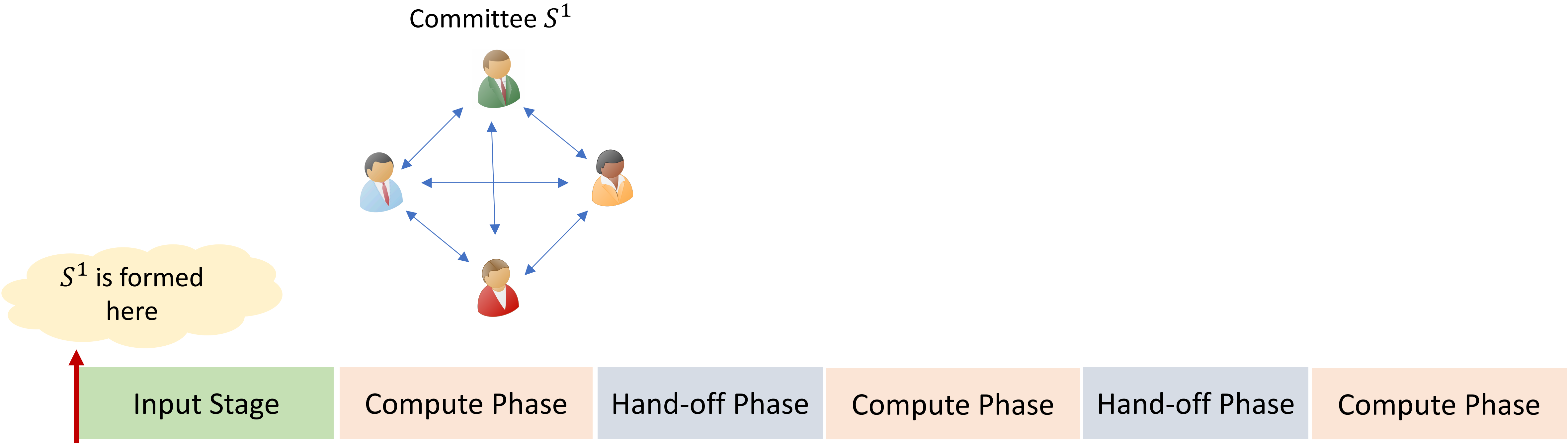
Too Restrictive!

Committees: When are they formed?

On-the-fly Committee Formation: Committee for each epoch is known at the start of the hand-off phase of the previous epoch.

Committees: When are they formed?



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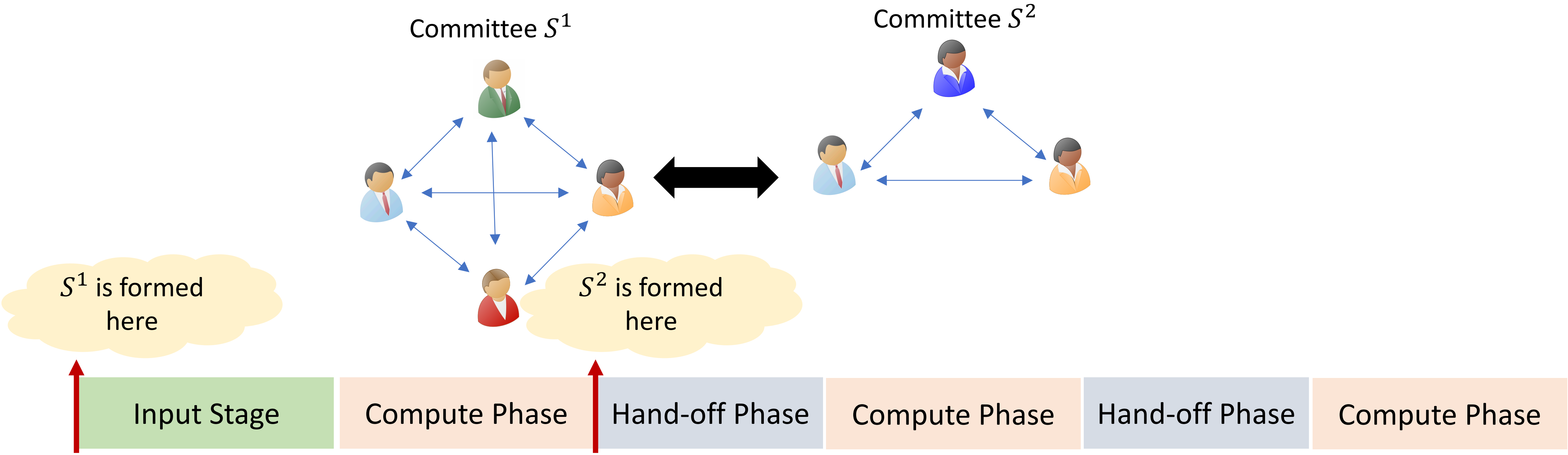

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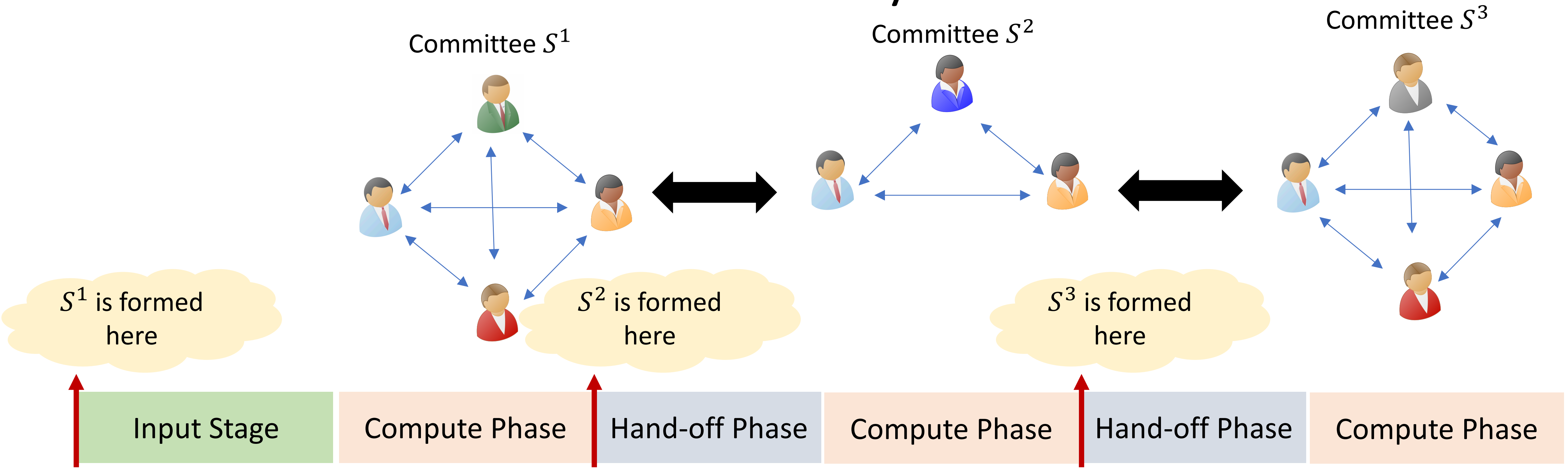

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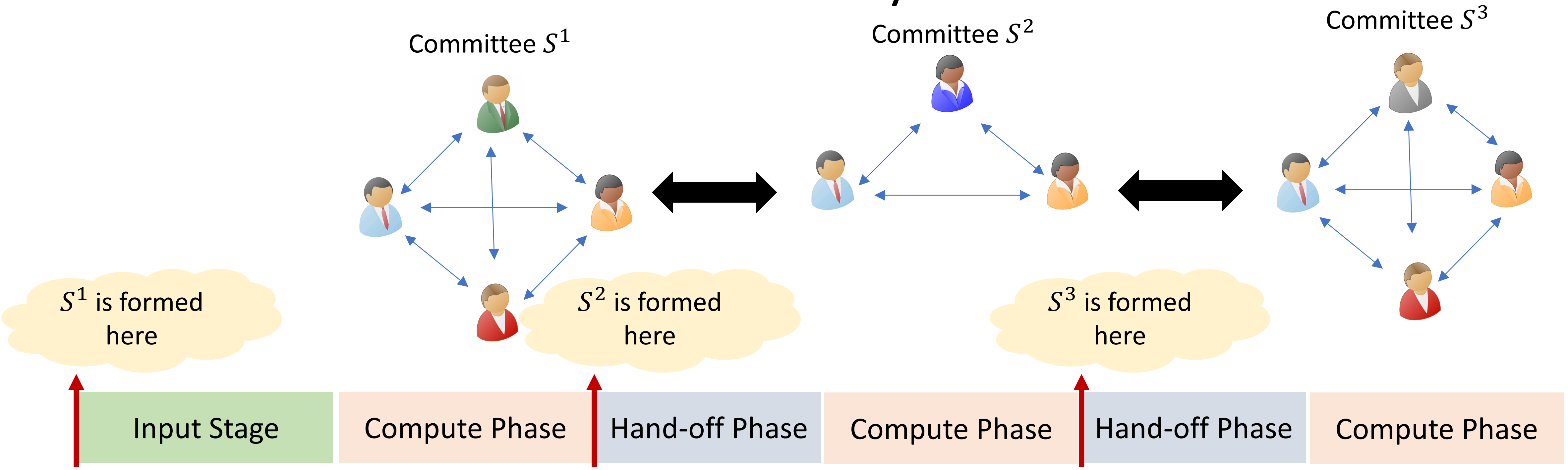
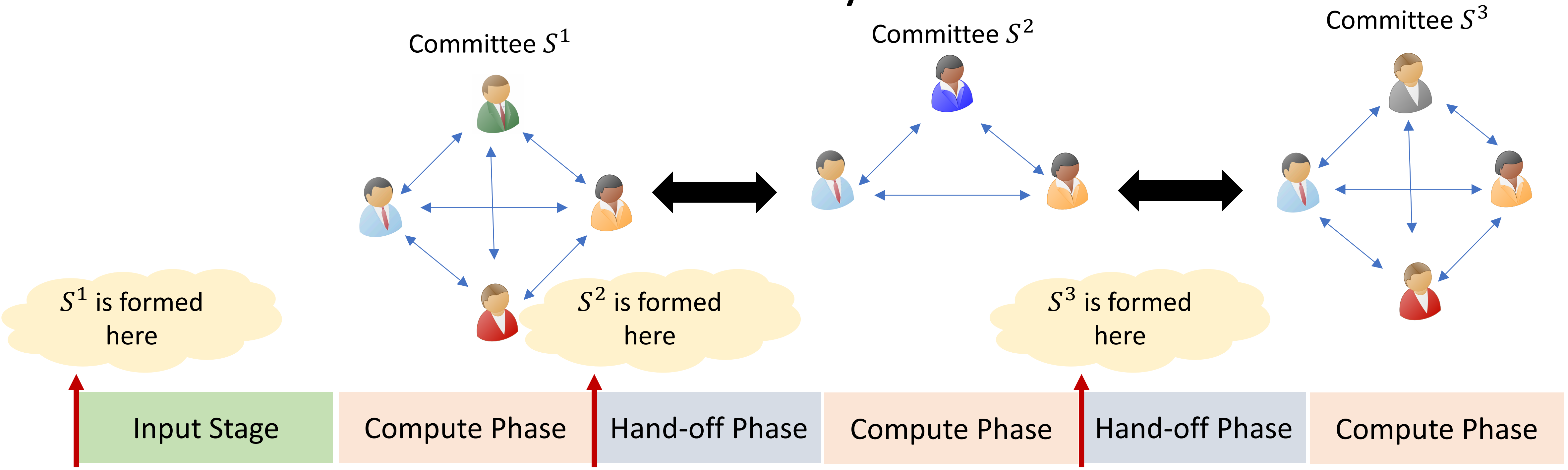


Our Choice

On-the-fly Committee Formation: Committee for each epoch is known at the start of the hand-off phase of the previous epoch.

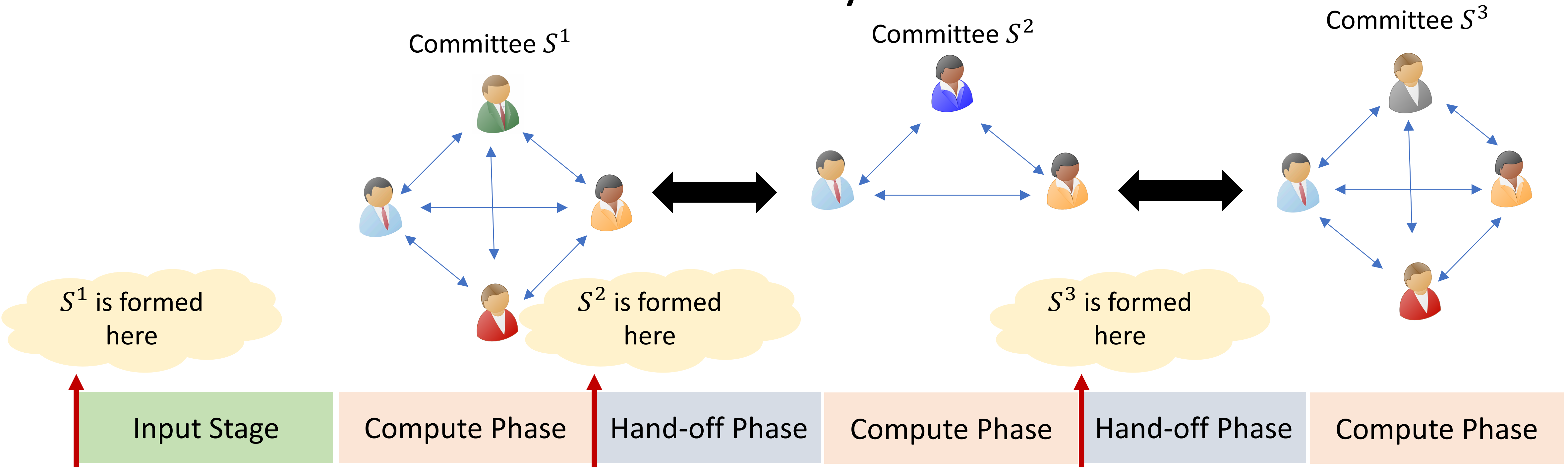
Committees: How are they formed?



On-the-fly Committee Formation:

Volunteer: Anyone who volunteers can join the computation (Corruption threshold is difficult to enforce)

Committees: How are they formed?



On-the-fly Committee Formation:

Volunteer: Anyone who volunteers can join the computation (Corruption threshold is difficult to enforce)
Elected: Anyone can nominate themself and an election process decides which nominees will participate (e.g., [BGGHKLRR20, GHMNY20] uses proof-of-stake blockchains)

Fluid MPC Protocol

Committee Selection/Corruption

Committee Formation

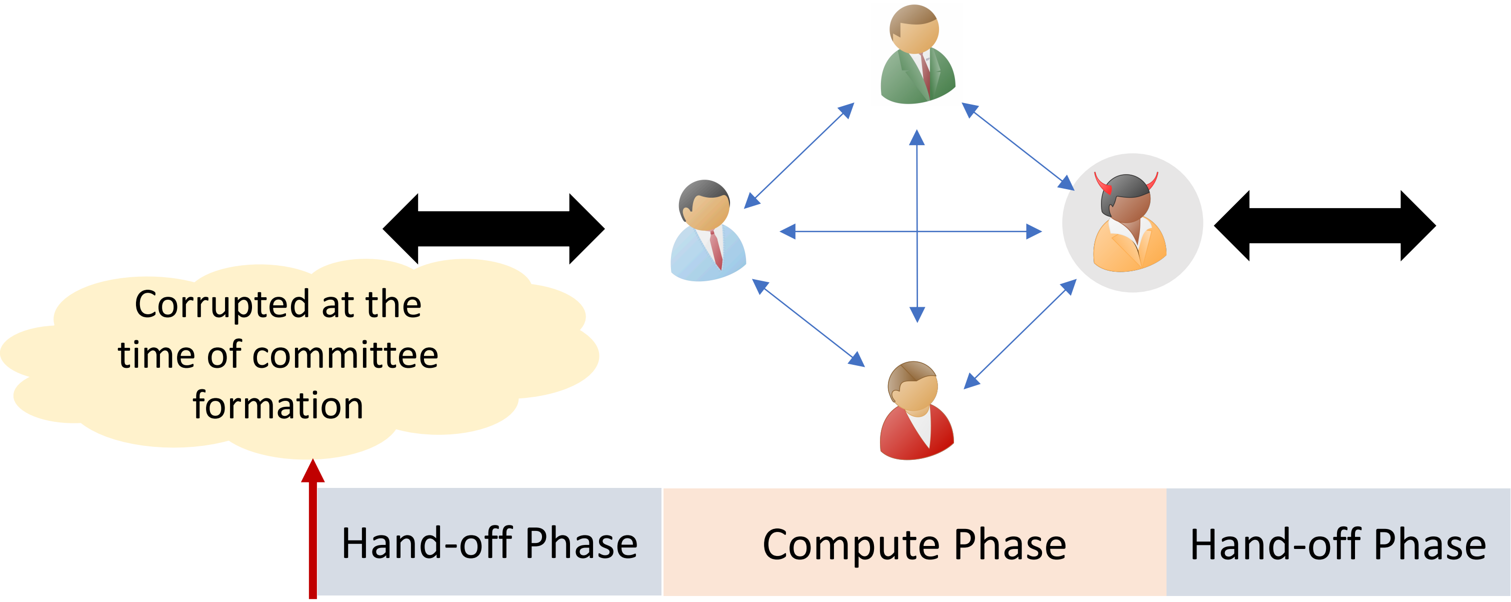
Committee Corruption

Effect of Committee Corruption on Prior Epochs

Protocol Execution given these Committees

Committee Corruption

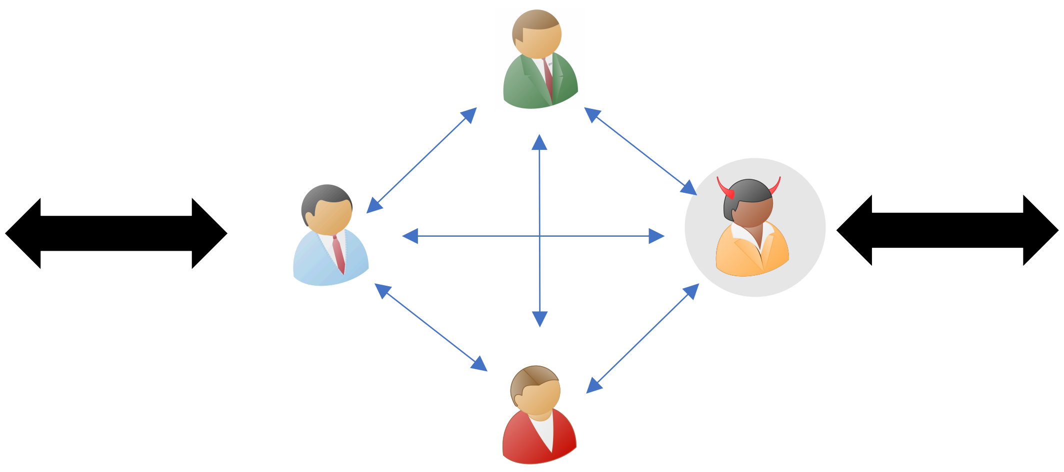
When can a server be corrupted?



Static Corruption

Committee Corruption

When can a server be corrupted?

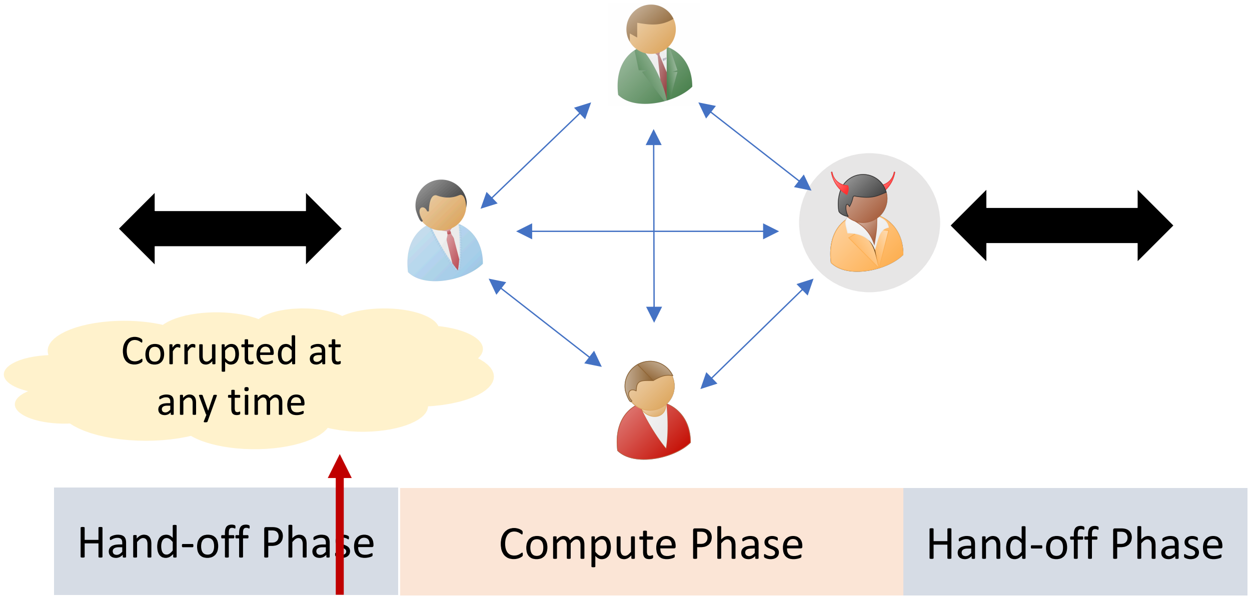


Hand-off Phase	Compute Phase	Hand-off Phase

Adaptive Corruption

Committee Corruption

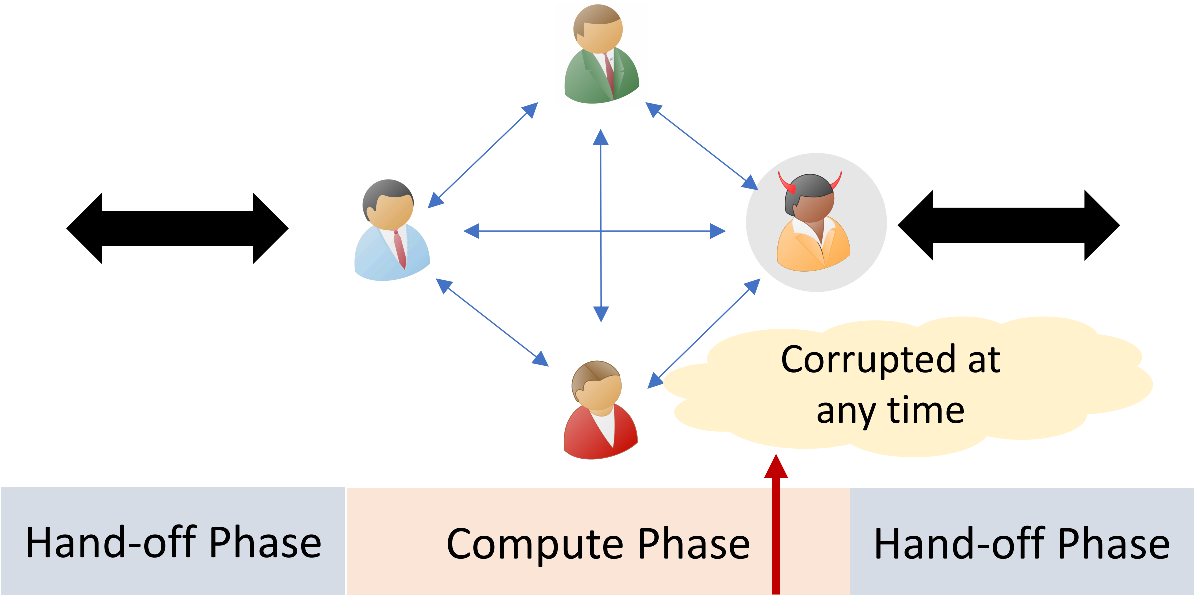
When can a server be corrupted?



Adaptive Corruption

Committee Corruption

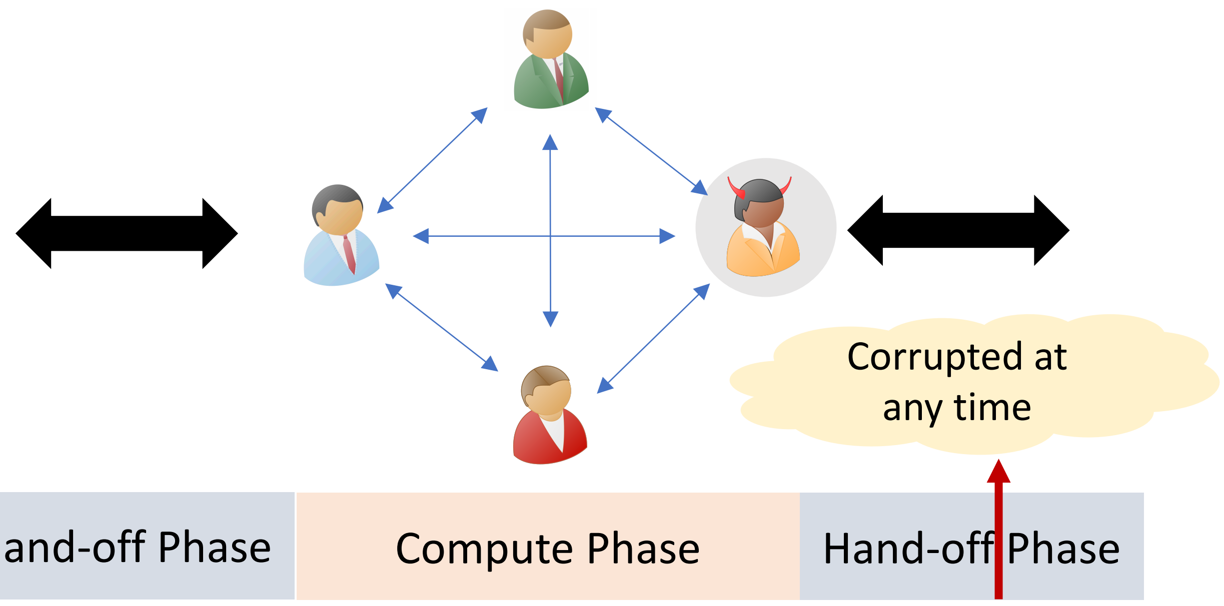
When can a server be corrupted?



Adaptive Corruption

Committee Corruption

When can a server be corrupted?



Adaptive Corruption

Committee Corruption

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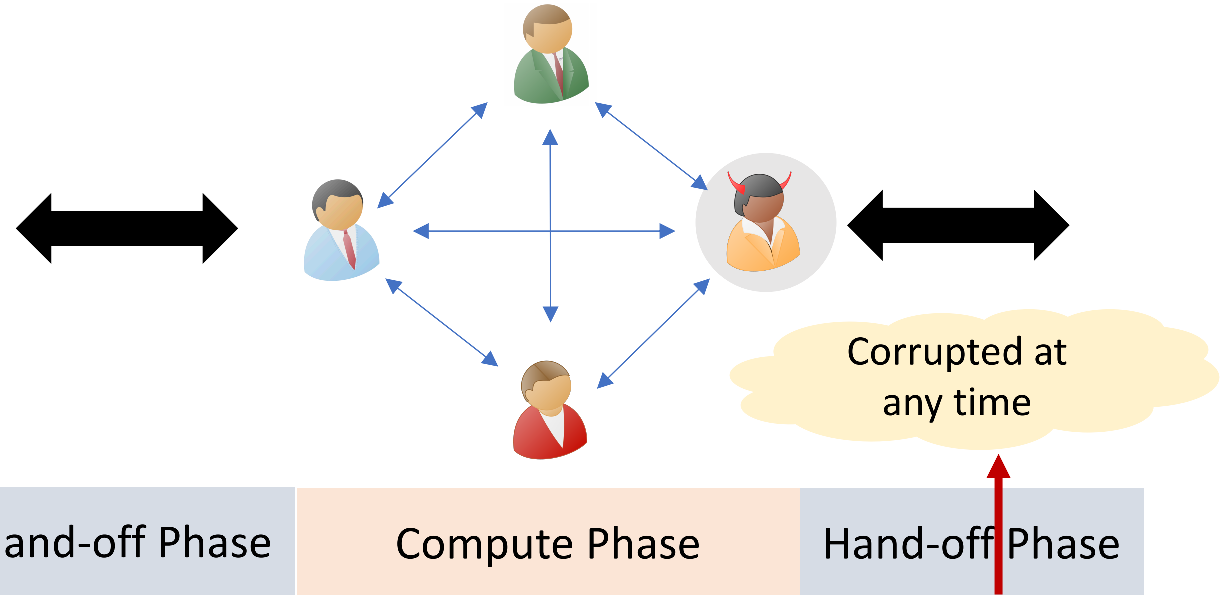


Our Choice

Adaptive Corruption

Fluid MPC Protocol

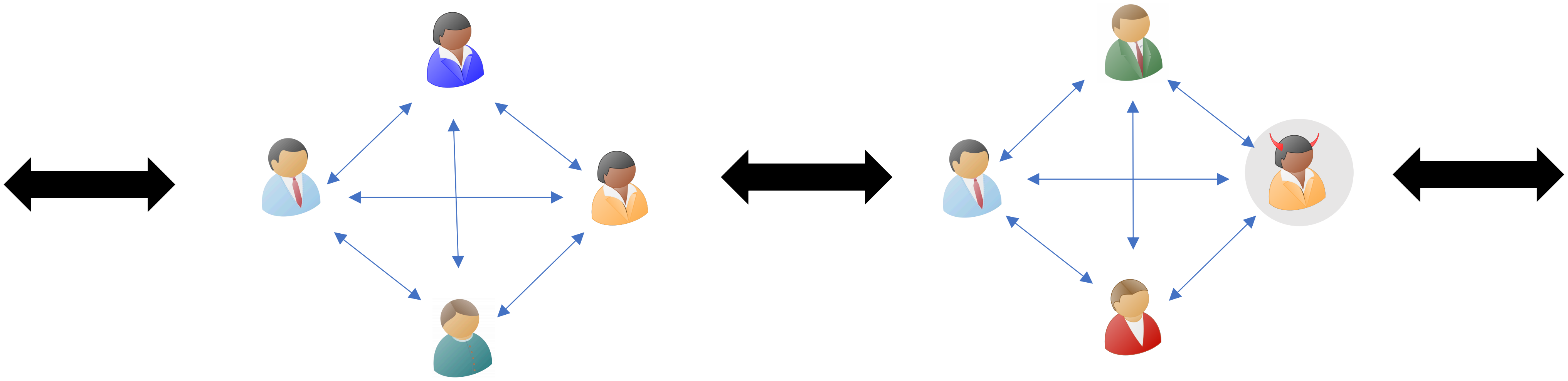
Committee Selection/Corruption

- Committee Formation
- Committee Corruption
- Effect of Committee Corruption on Prior Epochs

Protocol Execution given these Committees

Effect of Committee Corruption on Prior Epochs

What effect does corrupting a server have on the prior epochs where it participated?



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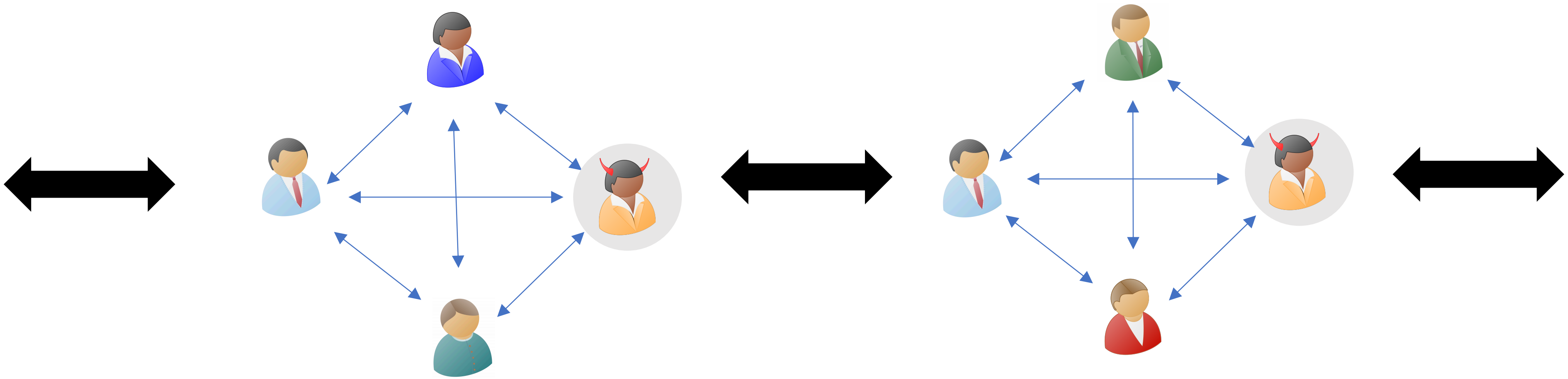

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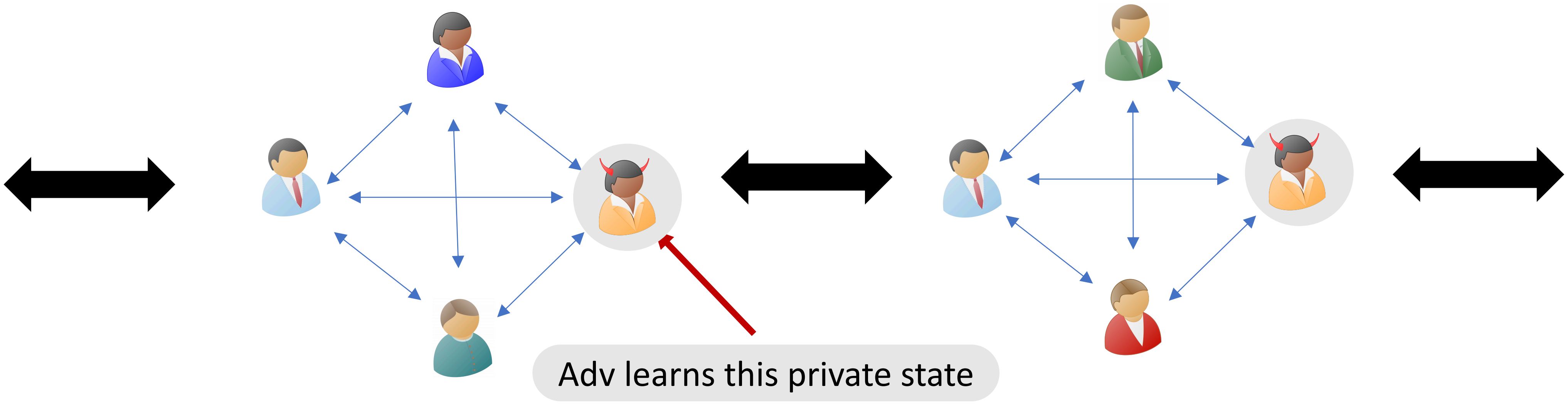

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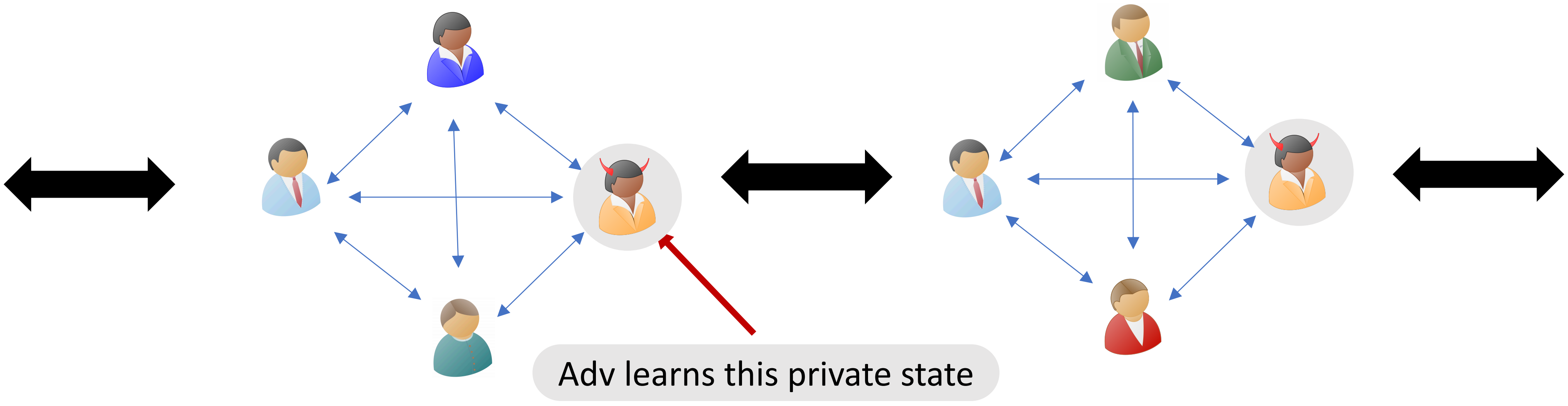

Can be prevented by only allowing disjoint committees

Effect of Committee Corruption on Prior Epochs

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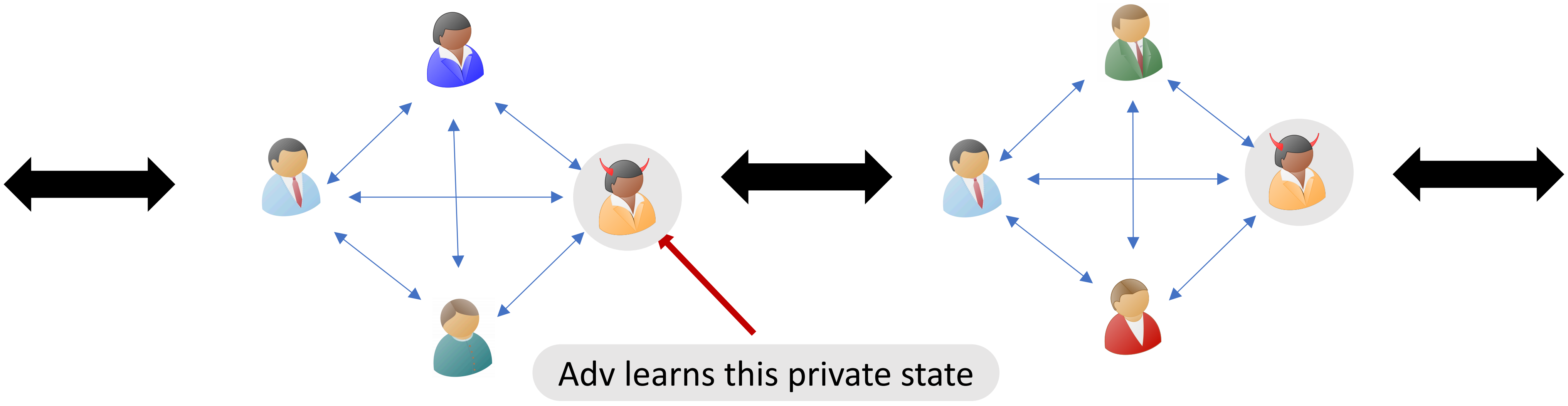
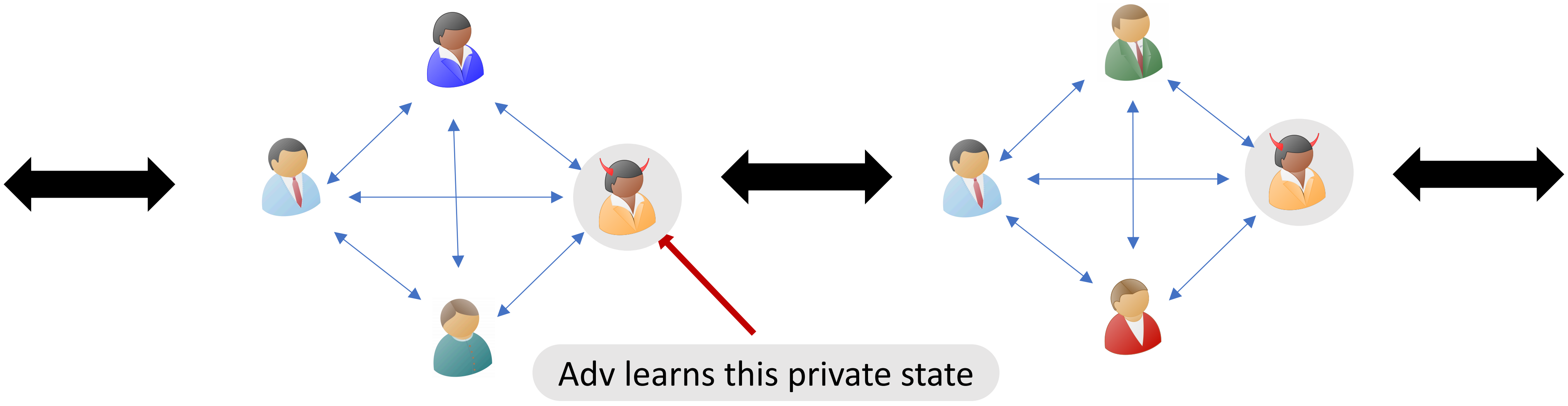


Can be prevented by only allowing disjoint committees

If there is overlap across committees, a server can only be corrupted if it does not violate the corruption threshold of prior epochs.

Effect of Committee Corruption on Prior Epochs

What effect does corrupting a server have on the prior epochs where it participated?



Can be prevented by only allowing disjoint committees

If there is overlap across committees, a server can only be corrupted if it does not violate the corruption threshold of prior epochs.

Similar to being passively corrupted in prior epochs

Fluid MPC Protocol

Committee Selection/Corruption

- Committee Formation
- Committee Corruption
- Effect of Committee Corruption on Prior Epochs

Protocol Execution given these Committees

Fluid MPC Protocol

- Committee Selection/Corruption
  - Committee Formation
  - Committee Corruption
  - Effect of Committee Corruption on Prior Epochs

- Protocol Execution given these Committees
  - Requirements/Challenges
  - Semi-Honest
  - Malicious

Fluid MPC Protocol

- Committee Selection/Corruption
  - Committee Formation
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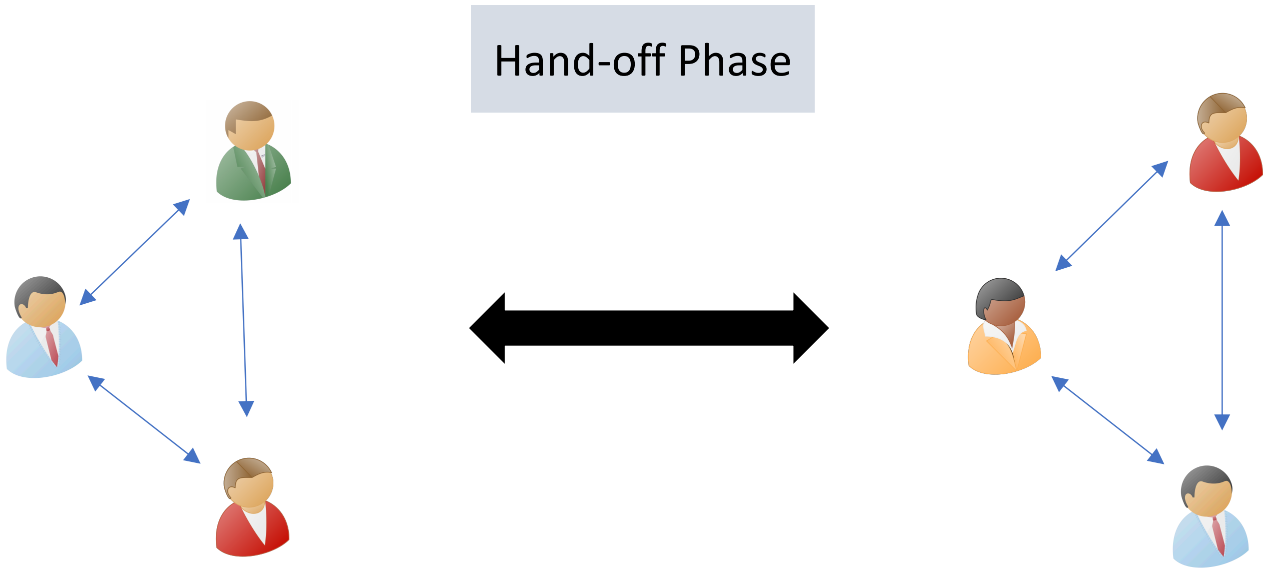
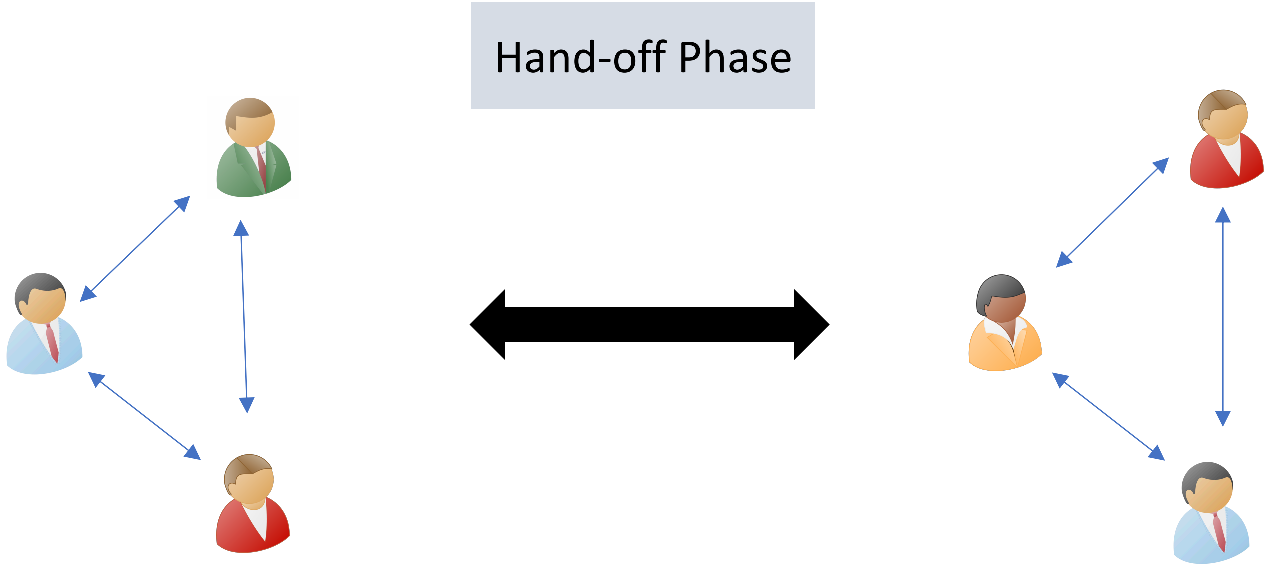
Requirements: Small State Complexity



Since states need to be transferred after every epoch, state complexity has a direct effect on communication complexity

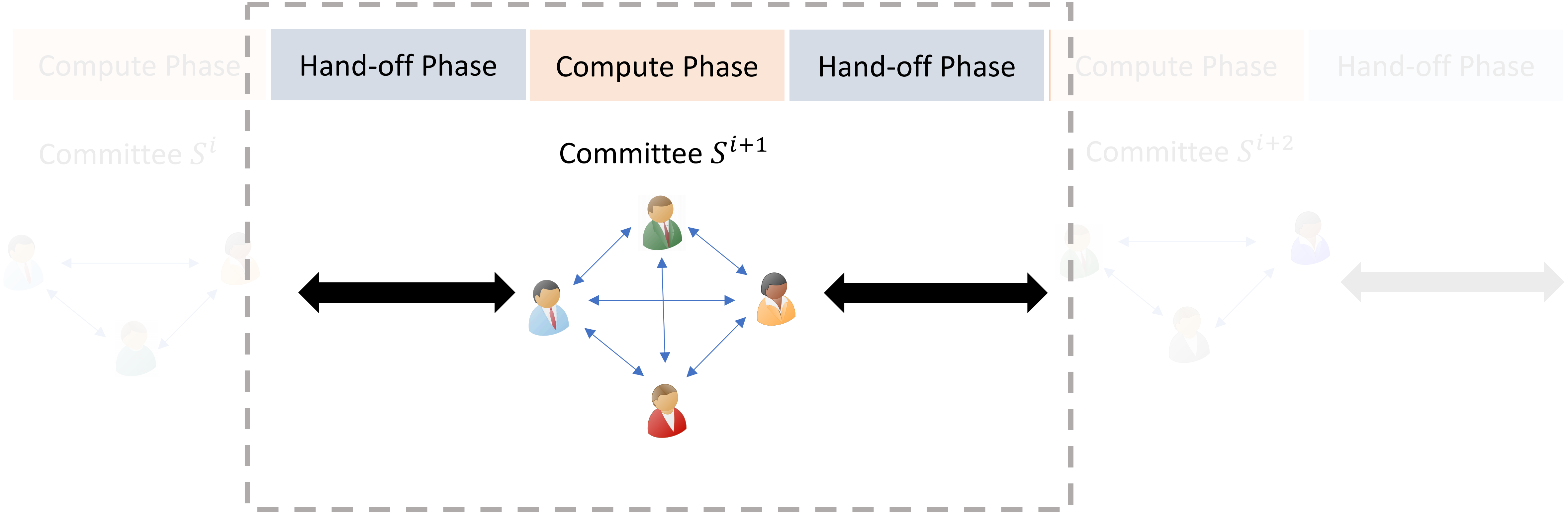
Requirements: Small State Complexity



Since states need to be transferred after every epoch, state complexity has a direct effect on communication complexity

State size of each party should be independent of the depth of the circuit

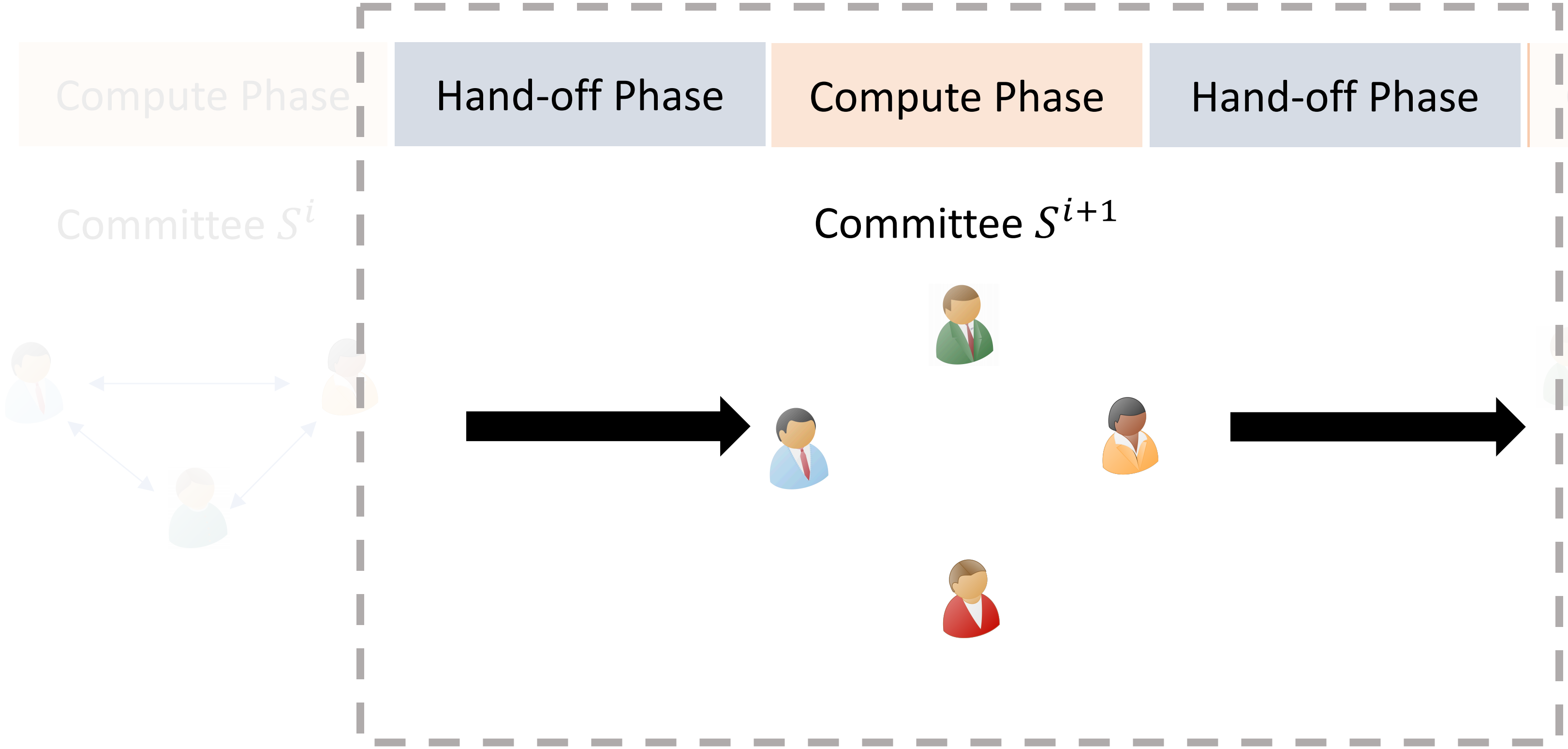
Requirements: High Fluidity



Fluidity is the minimum commitment a server needs to make for participating in the protocol.

Measured by the number of rounds in an epoch

Maximal Fluidity



Essentially, each party is only required to communicate in one round

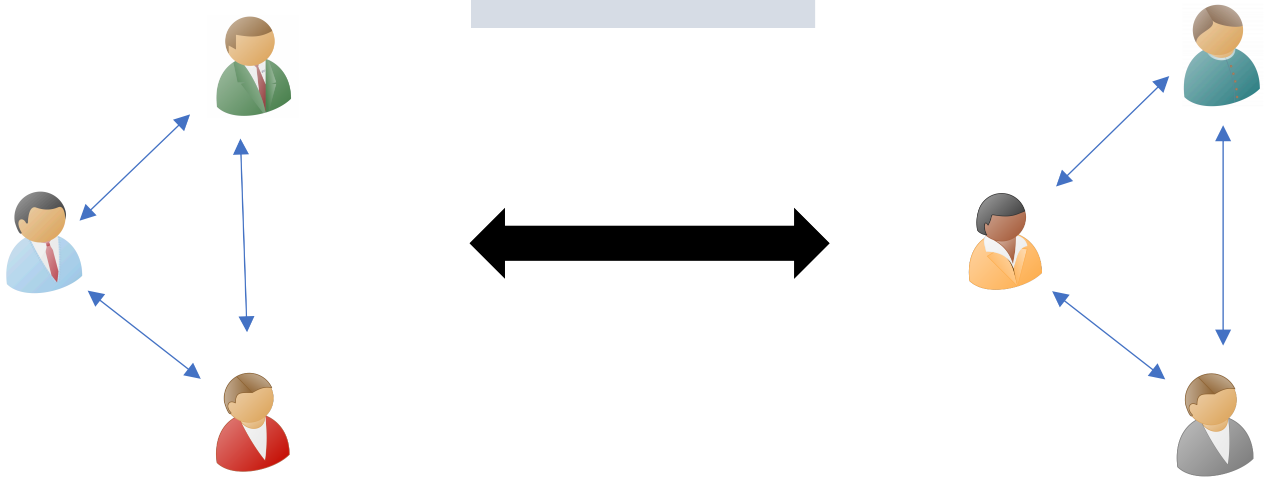
Silent compute phase

1 Round of unidirectional hand-off phase

1 round epoch

Requirements: Secure State Transfer

Hand-off Phase



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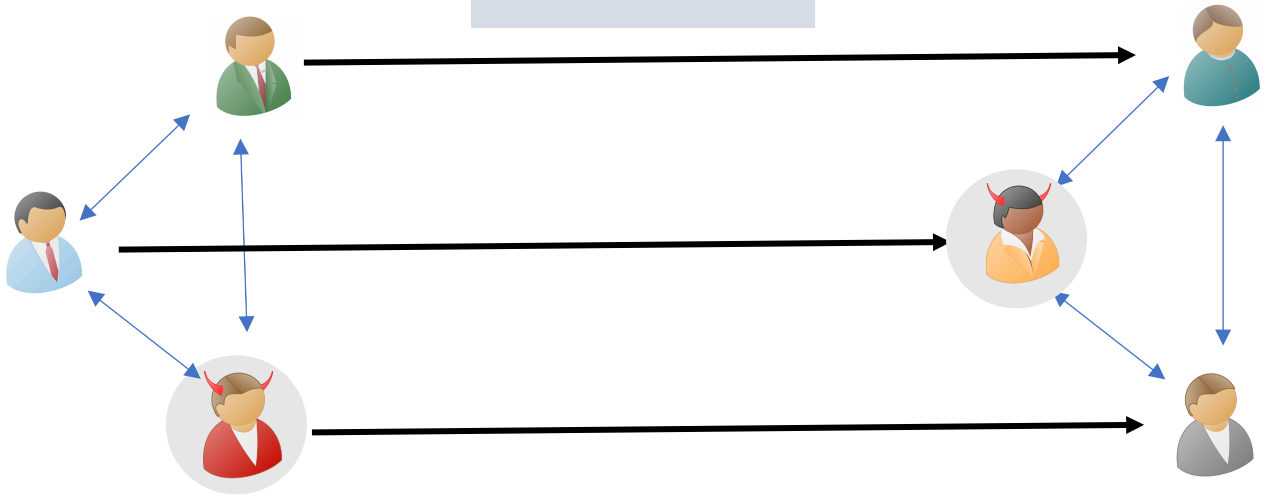
Hand-off Phase



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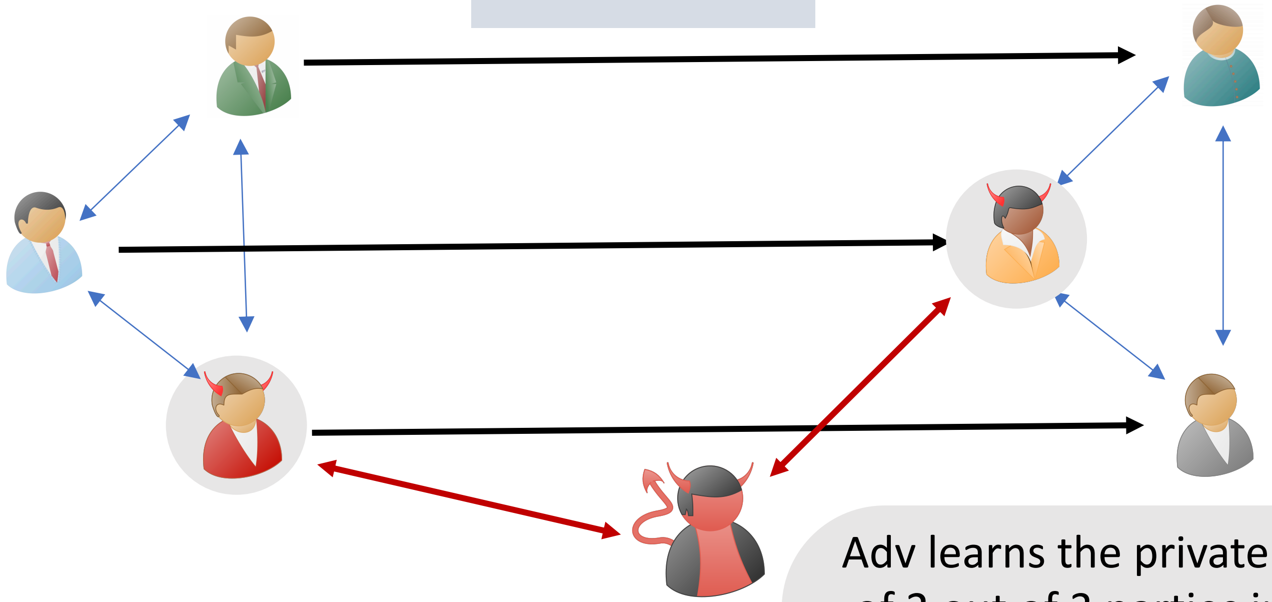
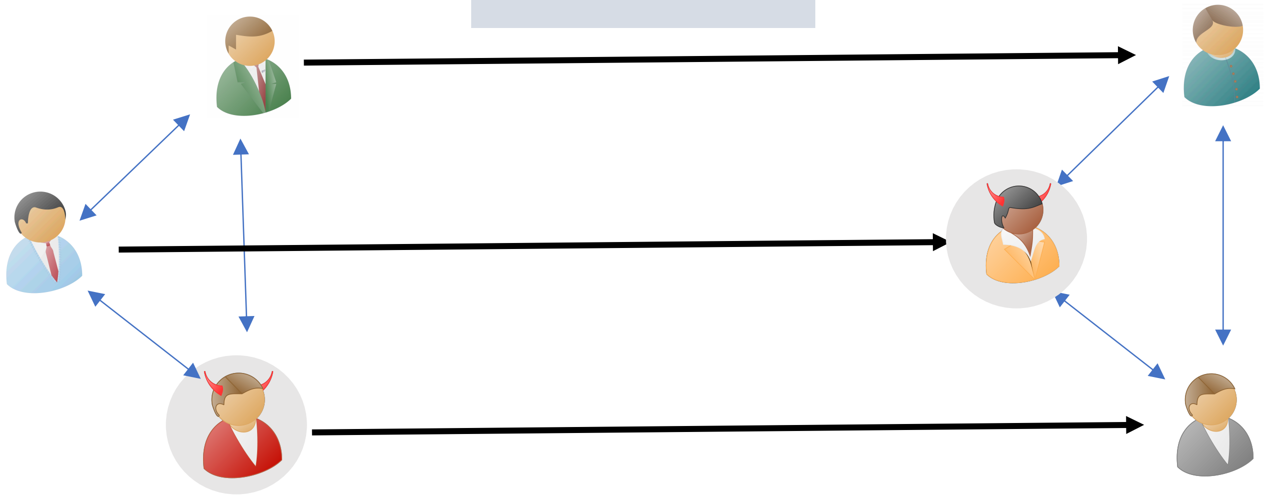


Adv learns the private state of 2 out of 3 parties in the first committee

Requirements: Secure State Transfer

Hand-off Phase



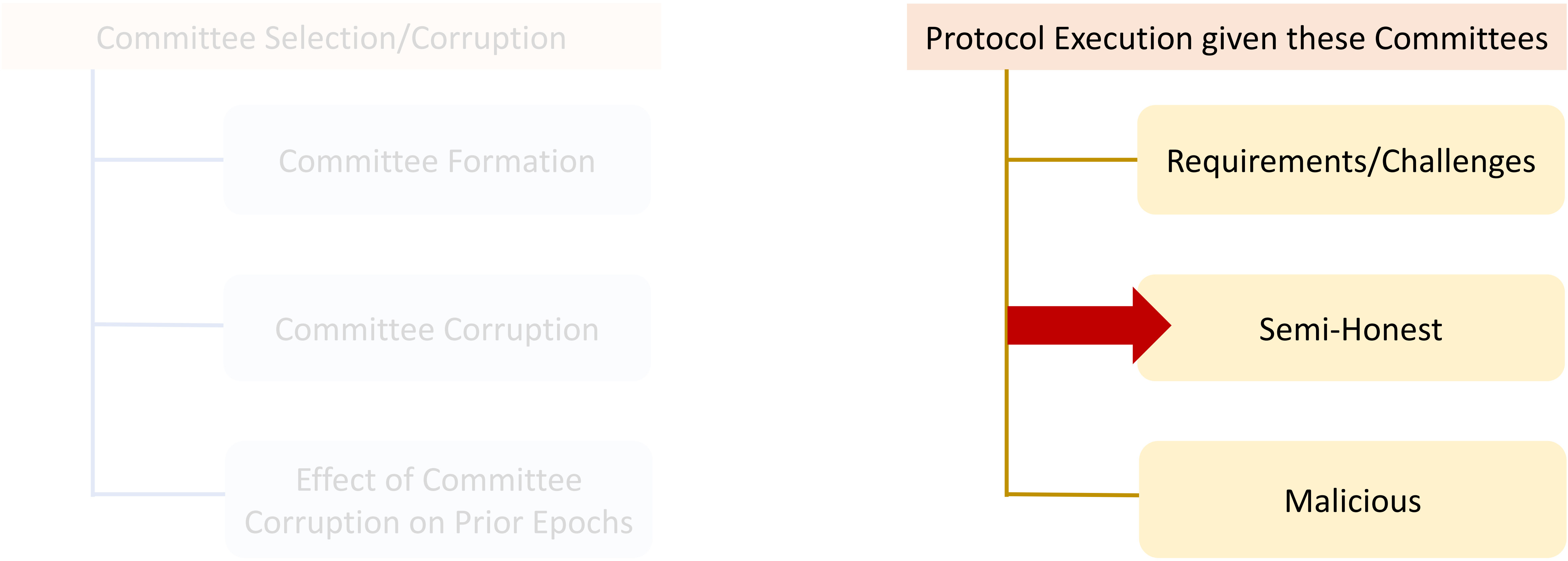
This naïve way handing-off states between committees in a one-to-one manner could break privacy.

Need a secure state transferring mechanism

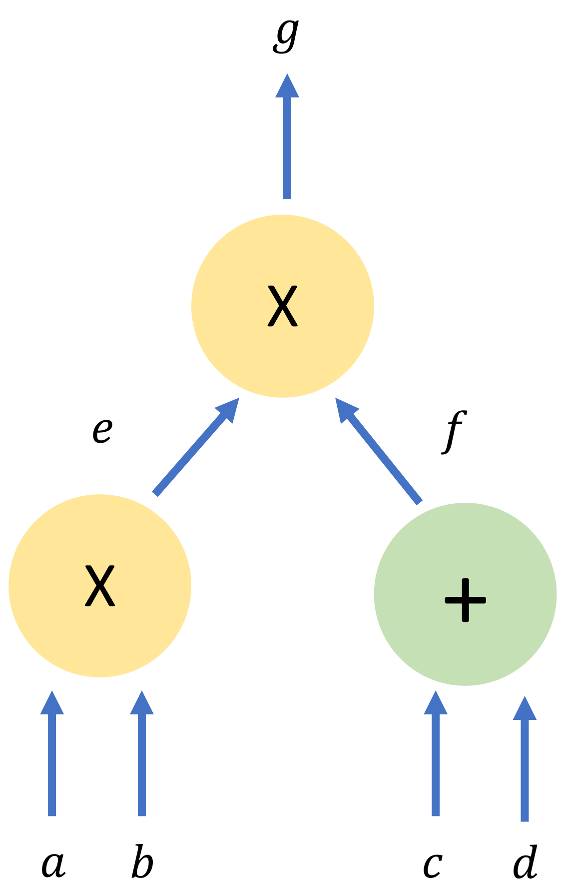
Requirements: Checklist

- ❑ Max Fluidity
- ❑ Small State Size
- ❑ Secure State Transfer

Fluid MPC Protocol



Semi-honest BGW



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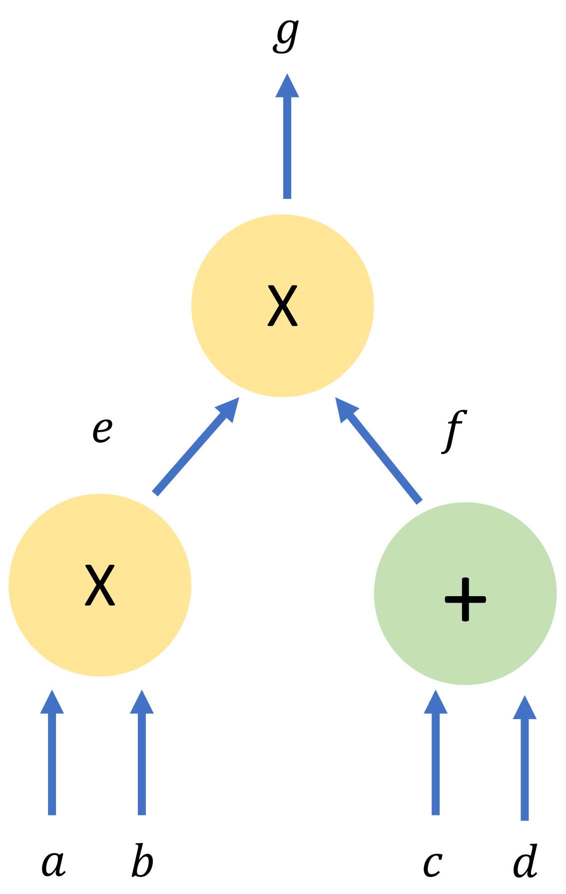
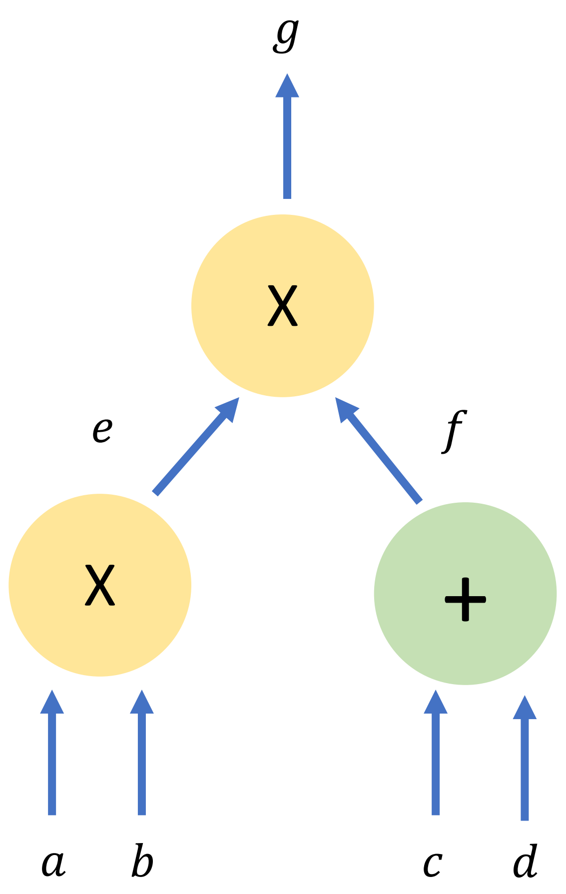
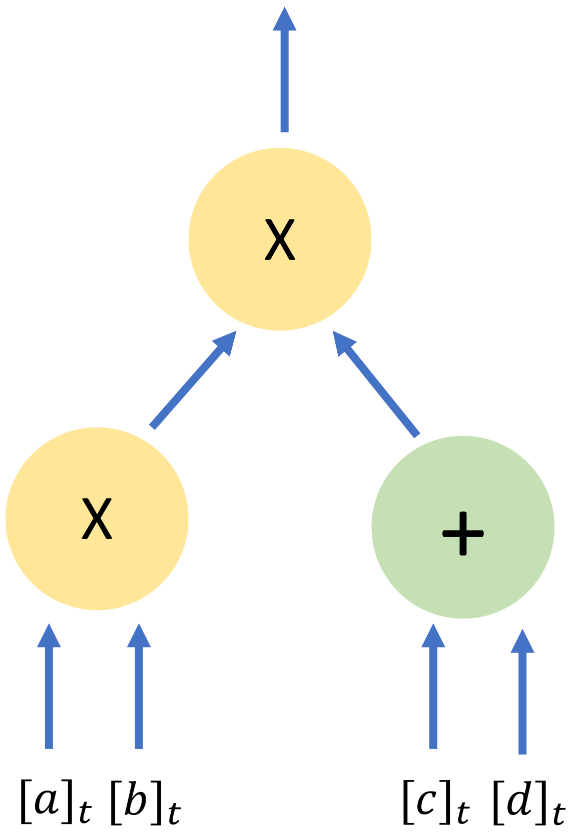


Gate-by-Gate evaluation on secret shared inputs

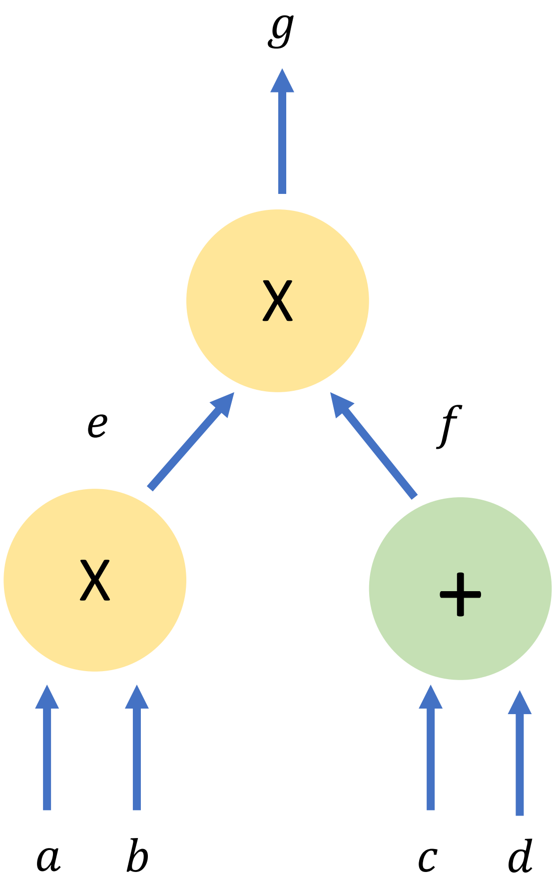
Semi-honest BGW



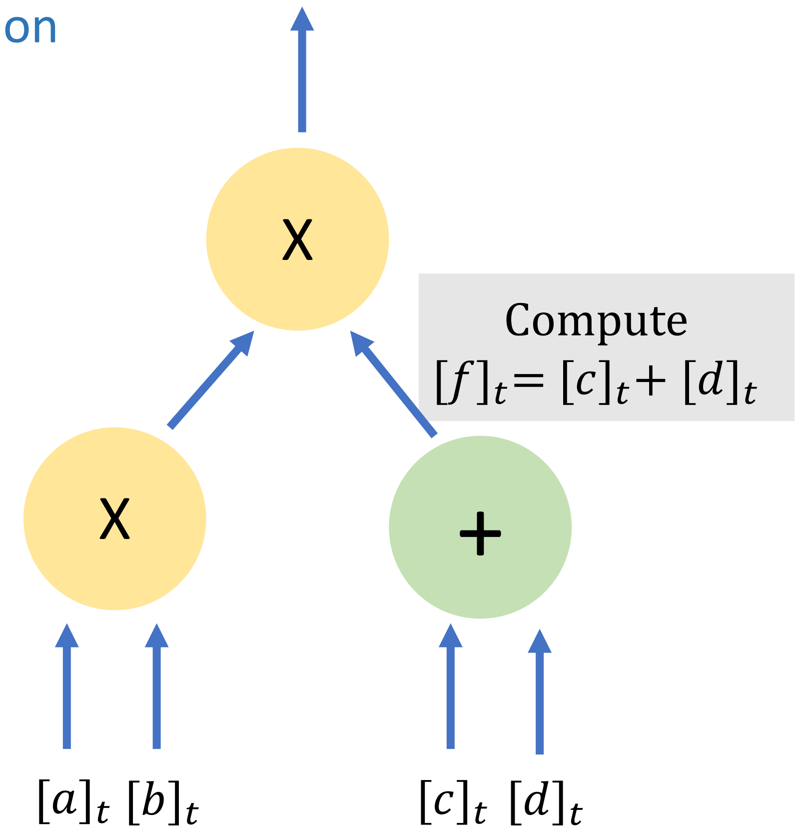


Input sharing: t-out-of-n shares of inputs

Semi-honest BGW



Gate-by-Gate Evaluation



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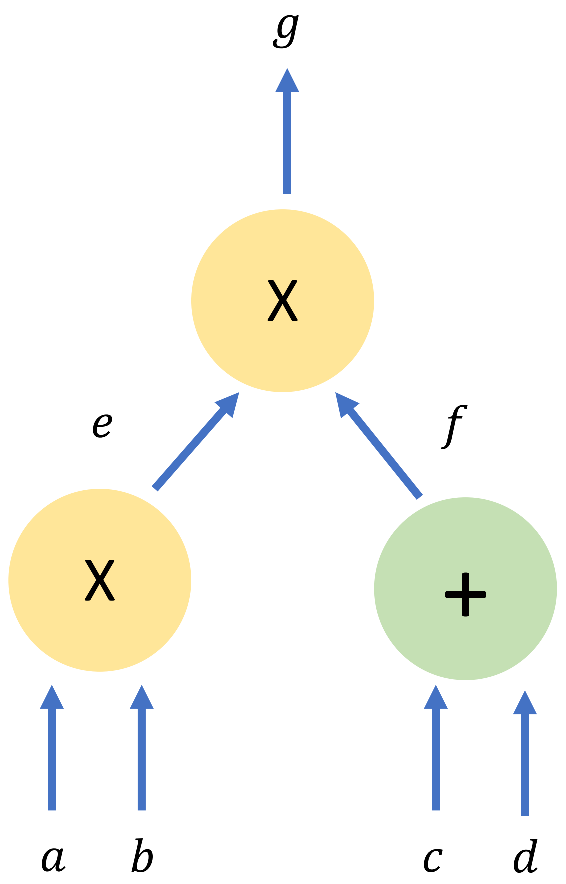
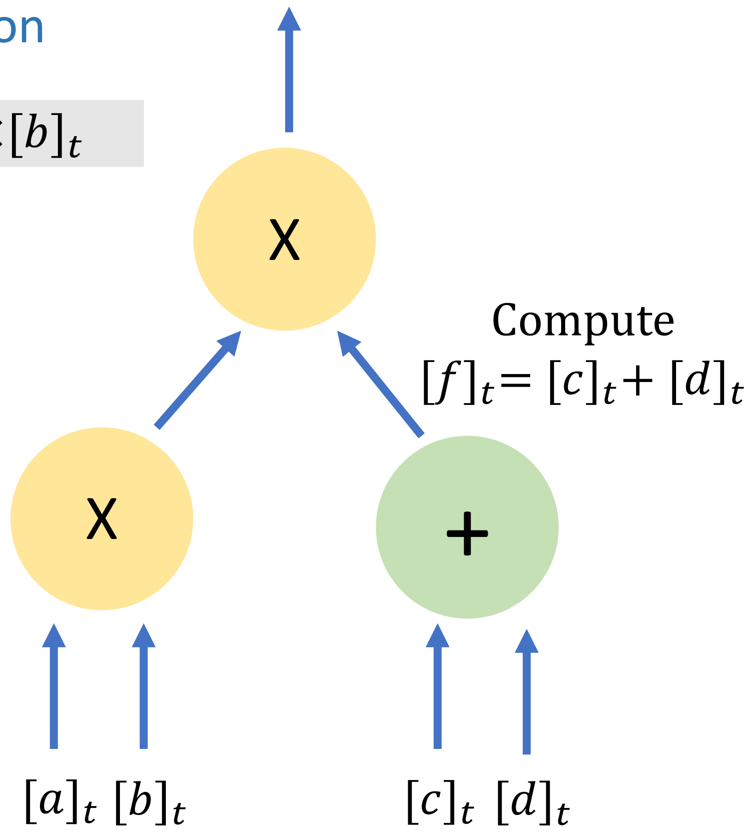


Gate-by-Gate Evaluation

Compute $[e]_{2t} = [a]_t \times [b]_t$



Input sharing: t-out-of-n shares of inputs

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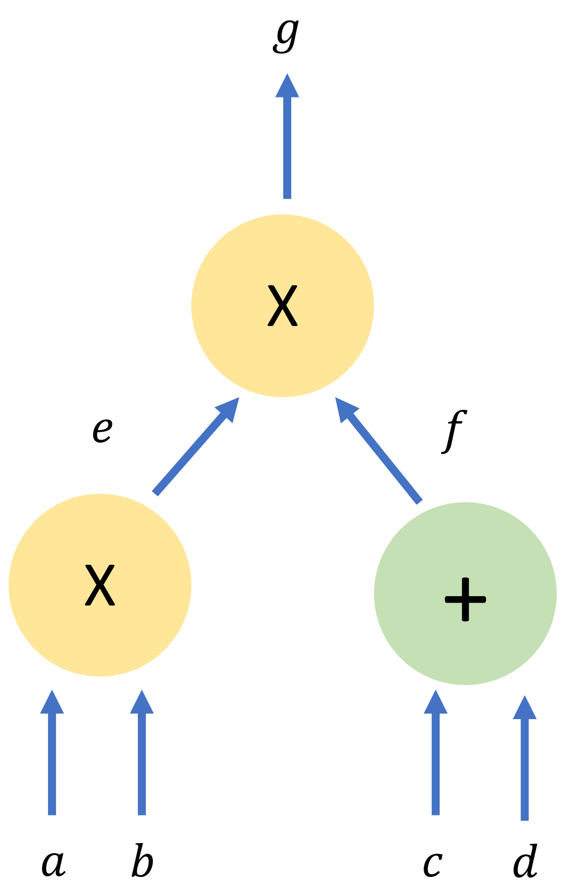
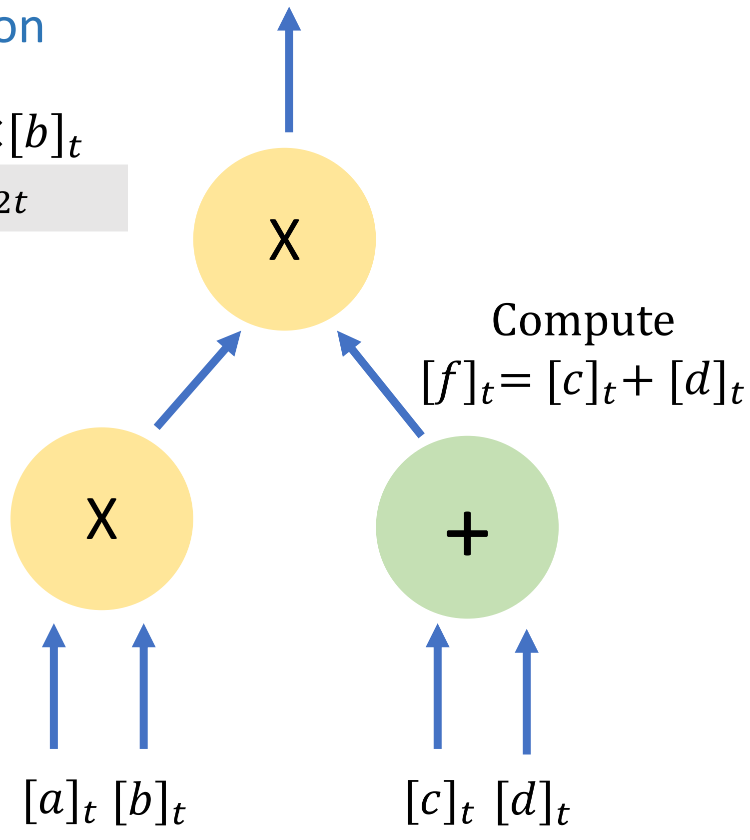


Gate-by-Gate Evaluation

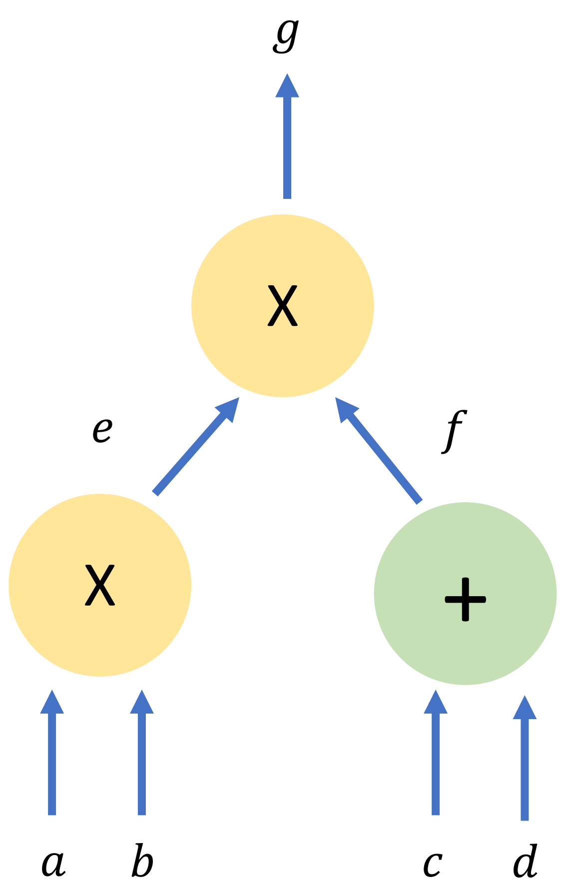
Compute $[e]_{2t} = [a]_t \times [b]_t$

$[[e]_{2t}]_t \leftarrow [e]_{2t}$



Input sharing: t-out-of-n shares of inputs

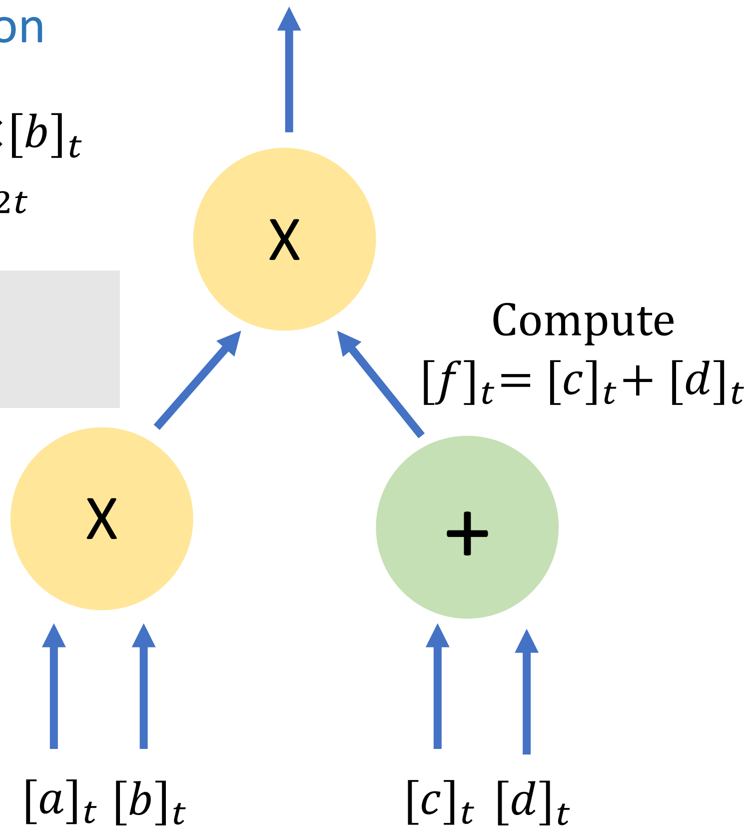
Semi-honest BGW



Gate-by-Gate Evaluation

Compute $[e]_{2t} = [a]_t \times [b]_t$
$[[e]_{2t}]_t \leftarrow [e]_{2t}$

Exchange $[[e]_{2t}]_t$
(Shares of Shares)



Input sharing: t-out-of-n shares of inputs

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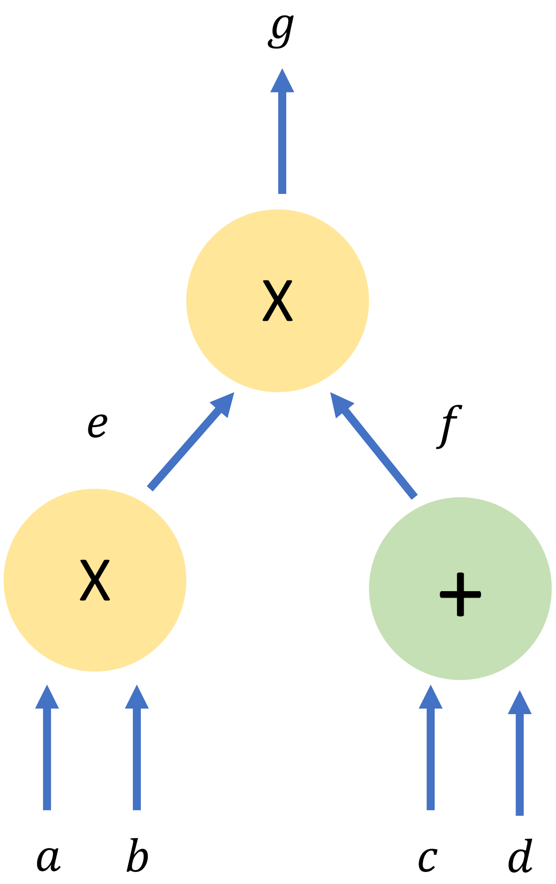

Gate-by-Gate Evaluation

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$[[e]_{2t}]_t \leftarrow [e]_{2t}$

Exchange $[[e]_{2t}]_t$
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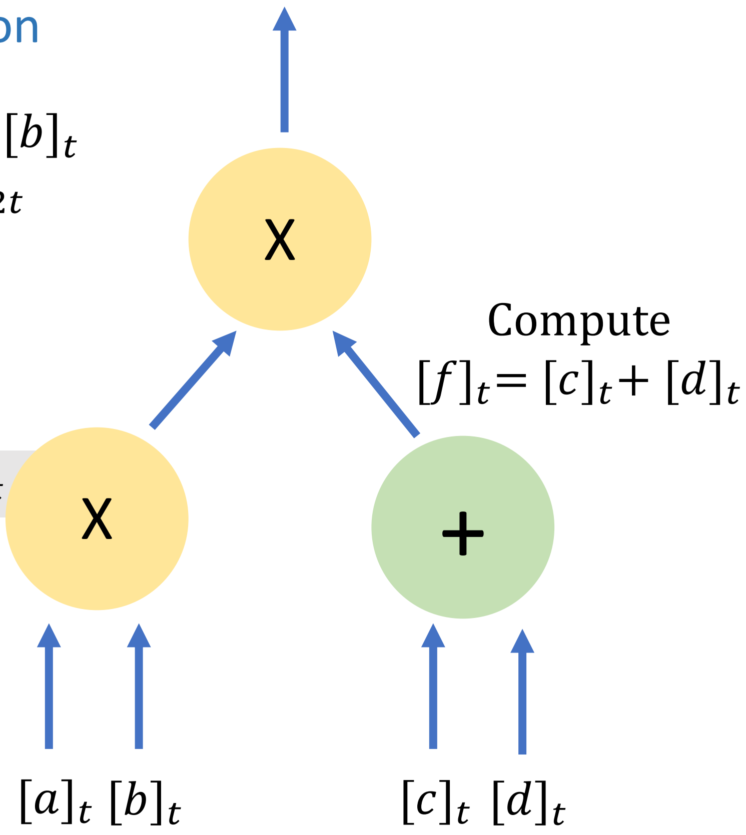
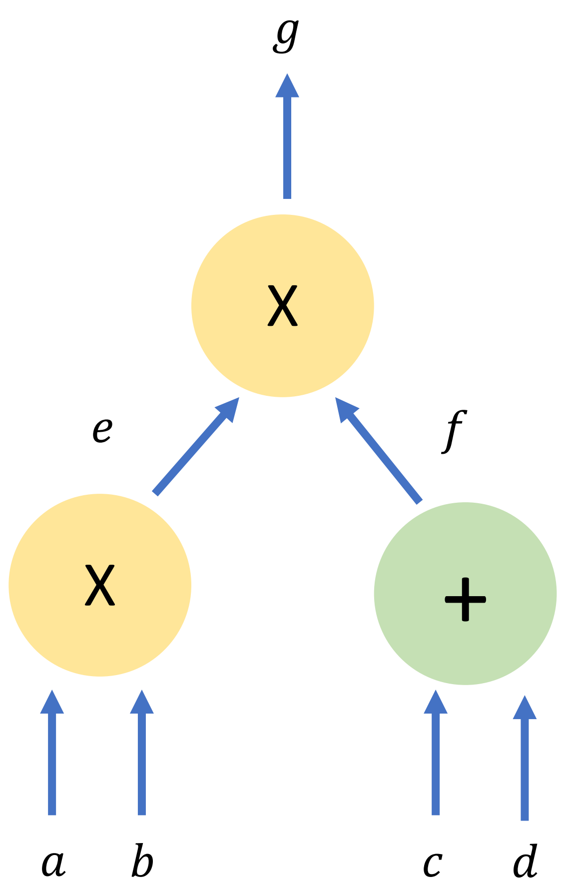
Compute $[e]_t \leftarrow [[e]_{2t}]_t$



Input sharing: t-out-of-n shares of inputs

Semi-honest BGW



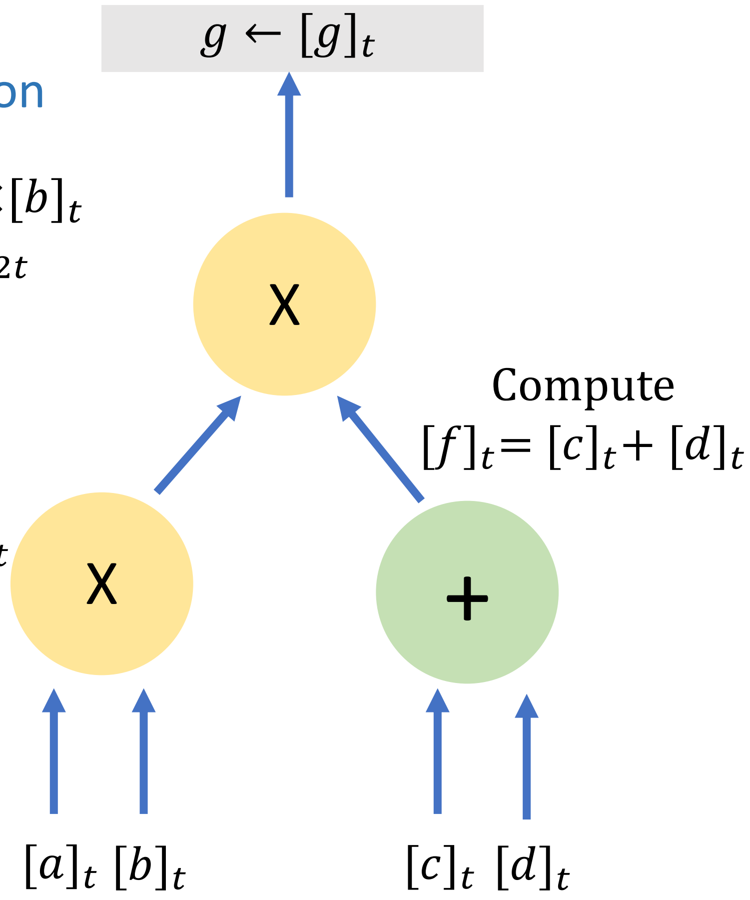
Output Reconstruction

Gate-by-Gate Evaluation

Compute $[e]_{2t} = [a]_t \times [b]_t$
$[[e]_{2t}]_t \leftarrow [e]_{2t}$

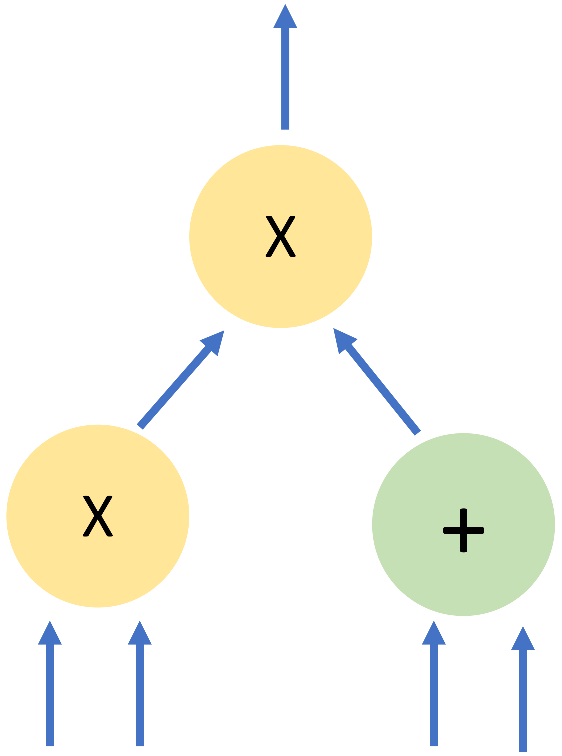
Exchange $[[e]_{2t}]_t$
(Shares of Shares)

Compute $[e]_t \leftarrow [[e]_{2t}]_t$

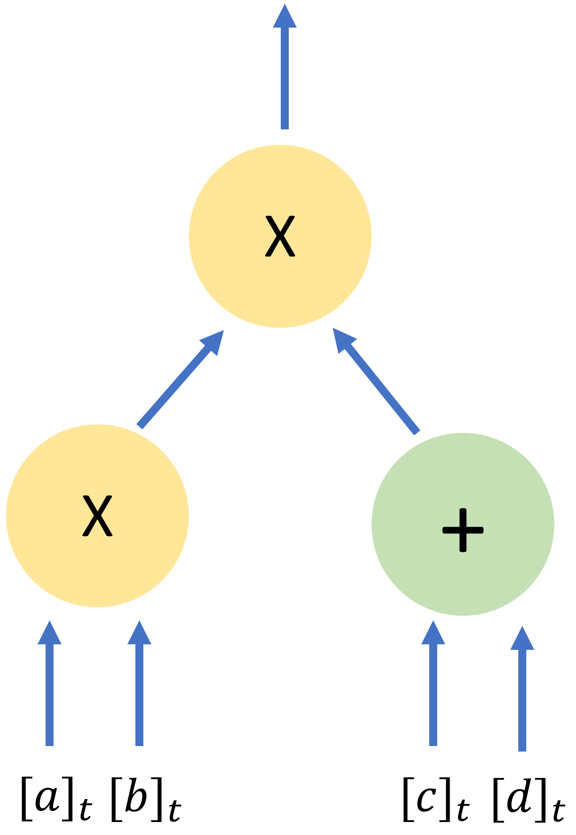


Input sharing: t-out-of-n shares of inputs

Semi-honest Fluid-BGW



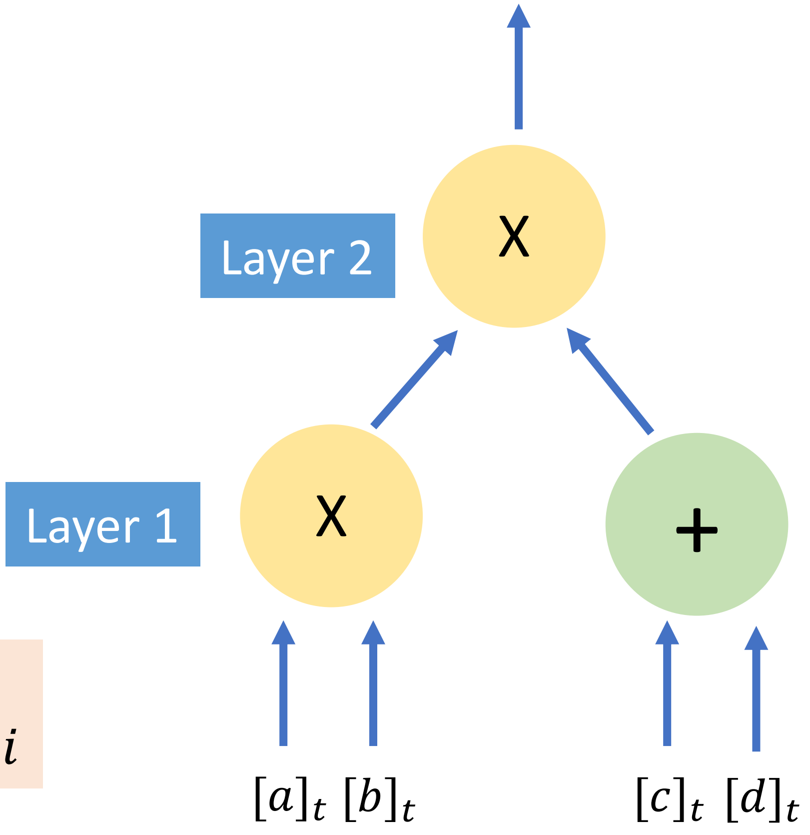
Semi-honest Fluid-BGW



Input Phase: Clients send t-out-of-n shares of inputs to the first committee

Semi-honest Fluid-BGW

Execution Stage



Layer-wise computations
Committee i computes layer i

Input Phase: Clients send t-out-of-n shares of inputs to the first committee

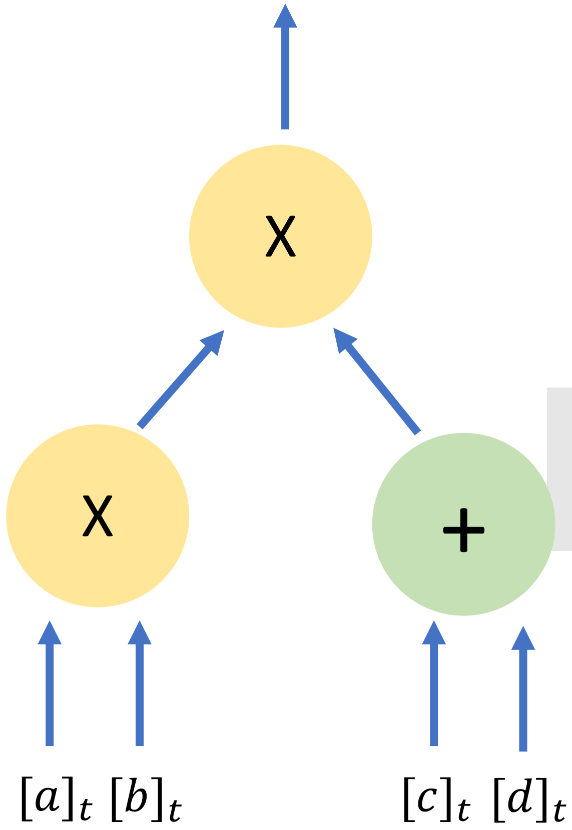
Semi-honest Fluid-BGW

Execution Stage

Computation Phase of Epoch 2 : $[e]_t \leftarrow [[e]_{2t}]_t$

Handoff Phase $[[e]_{2t}]_t$

Computation Phase of Epoch 1 : $[e]_{2t} = [a]_t \times [b]_t$
$[[e]_{2t}]_t \leftarrow [e]_{2t}$



Computation Phase of Epoch 2 : $[f]_t \leftarrow [[f]_t]_t$

Handoff Phase $[[f]_t]_t$

Computation Phase of Epoch 1 : $[f]_t = [c]_t + [d]_t$
$[[f]_t]_t \leftarrow [f]_t$

Input Phase: Clients send t-out-of-n shares of inputs to the first committee

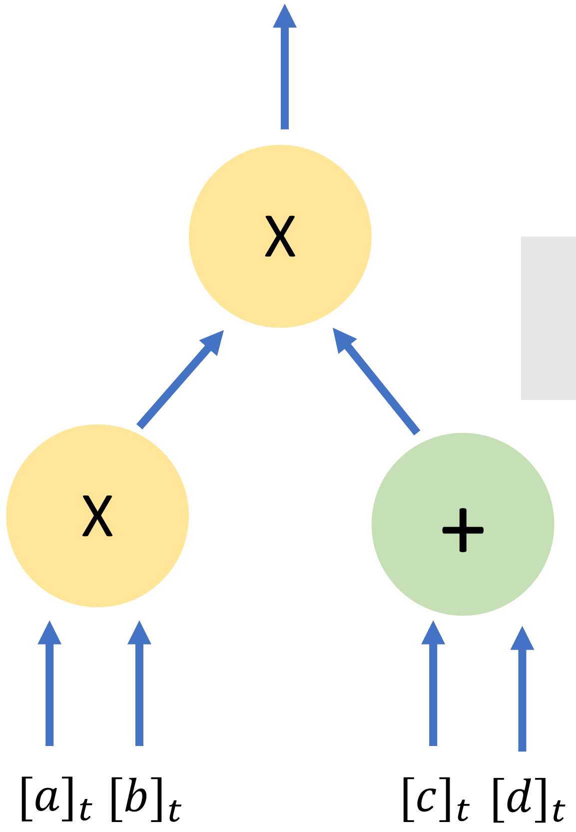
Semi-honest Fluid-BGW

Execution Stage

Computation Phase of Epoch 2: $[e]_t \leftarrow [[e]_{2t}]_t$

Handoff Phase: $[[e]_{2t}]_t$

Computation Phase of Epoch 1: $[e]_{2t} = [a]_t \times [b]_t$, $[[e]_{2t}]_t \leftarrow [e]_{2t}$



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Handoff Phase: $[[f]_t]_t$

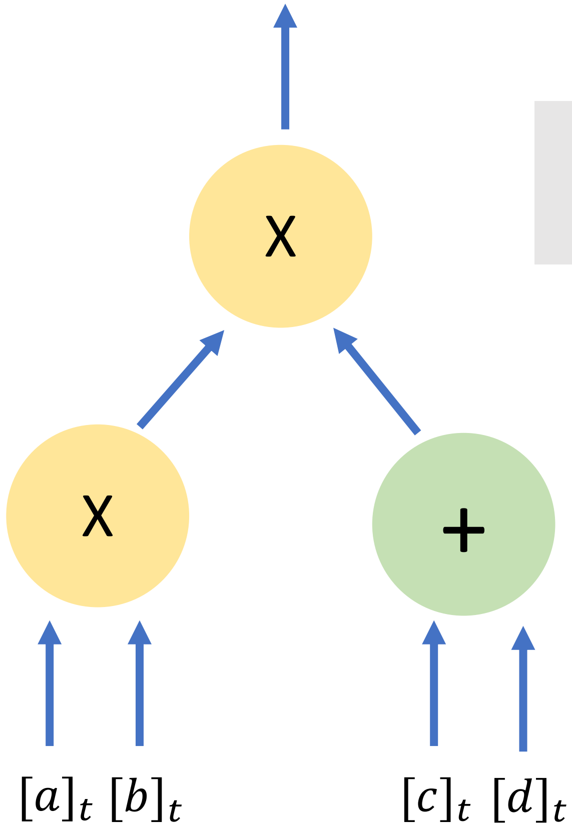
Computation Phase of Epoch 1: $[f]_t = [c]_t + [d]_t$, $[[f]_t]_t \leftarrow [f]_t$

Input Phase: Clients send t-out-of-n shares of inputs to the first committee

Semi-honest Fluid-BGW

Execution Stage

Computation Phase : of Epoch 2	$[e]_t \leftarrow [[e]_{2t}]_t$
Handoff Phase	$[[e]_{2t}]_t$
Computation Phase : of Epoch 1	$[e]_{2t} = [a]_t \times [b]_t$ $[[e]_{2t}]_t \leftarrow [e]_{2t}$

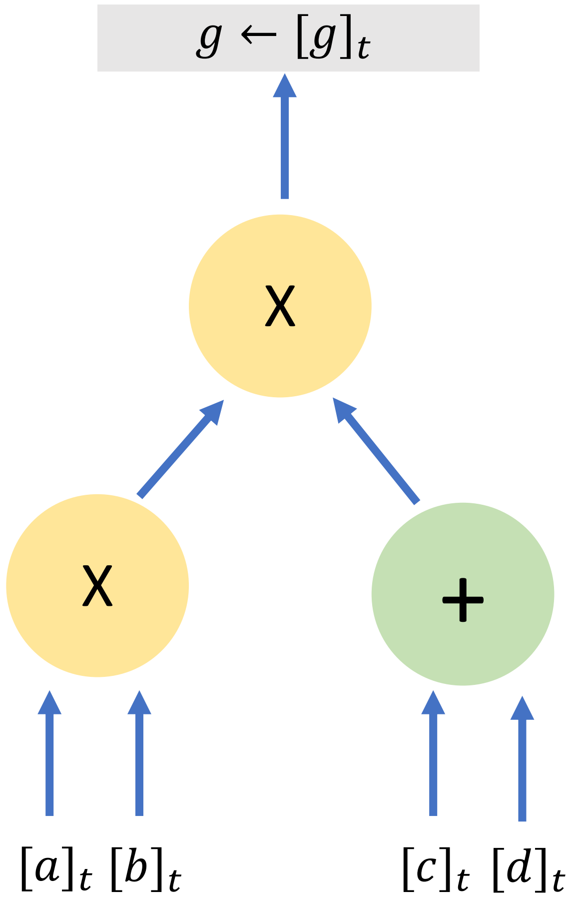


Computation Phase : of Epoch 2	$[f]_t \leftarrow [[f]_t]_t$
Handoff Phase	$[[f]_t]_t$
Computation Phase : of Epoch 1	$[f]_t = [c]_t + [d]_t$ $[[f]_t]_t \leftarrow [f]_t$

Input Phase: Clients send t-out-of-n shares of inputs to the first committee

Semi-honest Fluid-BGW

Output Phase



Execution Stage

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Handoff Phase $[[e]_{2t}]_t$

Computation Phase of Epoch 1 : $[e]_{2t} = [a]_t \times [b]_t$
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Computation Phase of Epoch 2 : $[f]_t \leftarrow [[f]_t]_t$

Handoff Phase $[[f]_t]_t$

Computation Phase of Epoch 1 : $[f]_t = [c]_t + [d]_t$
$[[f]_t]_t \leftarrow [f]_t$

Input Phase: Clients send t-out-of-n shares of inputs to the first committee

Semi-honest Fluid-BGW

Output Phase

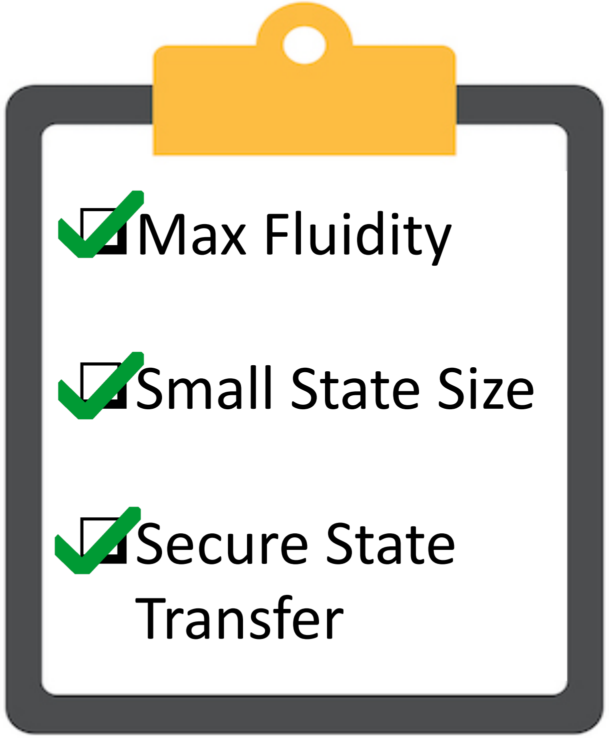
$a \leftarrow [a]_t$

Execution Stage

Computation Phase : $[e]_t \leftarrow [[e]_{2t}]_t$
of Epoch 2

Handoff Phase $[[e]_{2t}]_t$

Computation Phase : $[e]_{2t} = [a]_t \times [b$
of Epoch 1 $[[e]_{2t}]_t \leftarrow [e]_{2t}$



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Computation Phase : $[f]_t = [c]_t + [d]_t$
of Epoch 1 $[[f]_t]_t \leftarrow [f]_t$

$[a]_t$ $[b]_t$ $[c]_t$ $[d]_t$

Input Phase: Clients send t-out-of-n shares of inputs to the first committee

Fluid MPC Protocol

Committee Selection/Corruption

- Committee Formation
- Committee Corruption
- Effect of Committee Corruption on Prior Epochs

Protocol Execution given these Committees

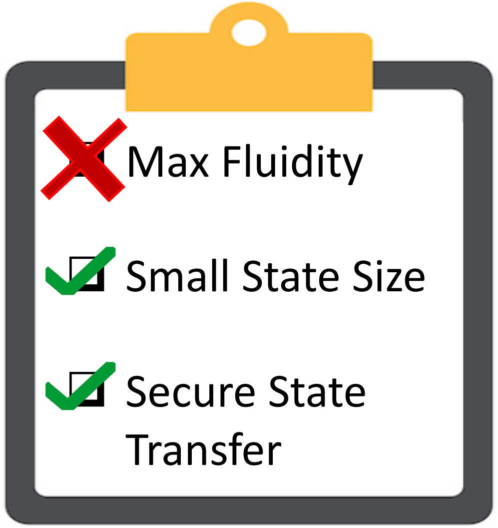
- Requirements/Challenges
- Semi-Honest
- Malicious

Shortcomings of Natural Solutions

Need to Verify Honest Behavior

Implementing a gate-by-gate check

Requires more interaction



Shortcomings of Natural Solutions

Need to Verify Honest Behavior

Implementing a gate-by-gate check

Requires more interaction

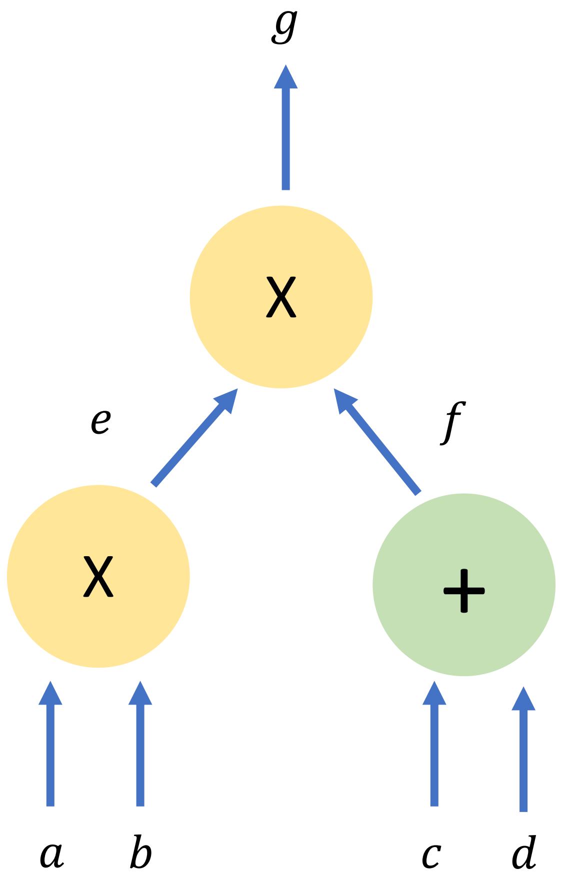
- ✗ Max Fluidity
- ✓ Small State Size
- ✓ Secure State Transfer

Using NIZKs

May require access to all prior rounds

- ✓ Max Fluidity
- ✗ Small State Size
- ✓ Secure State Transfer

Additive Attack Paradigm [GIPST14]



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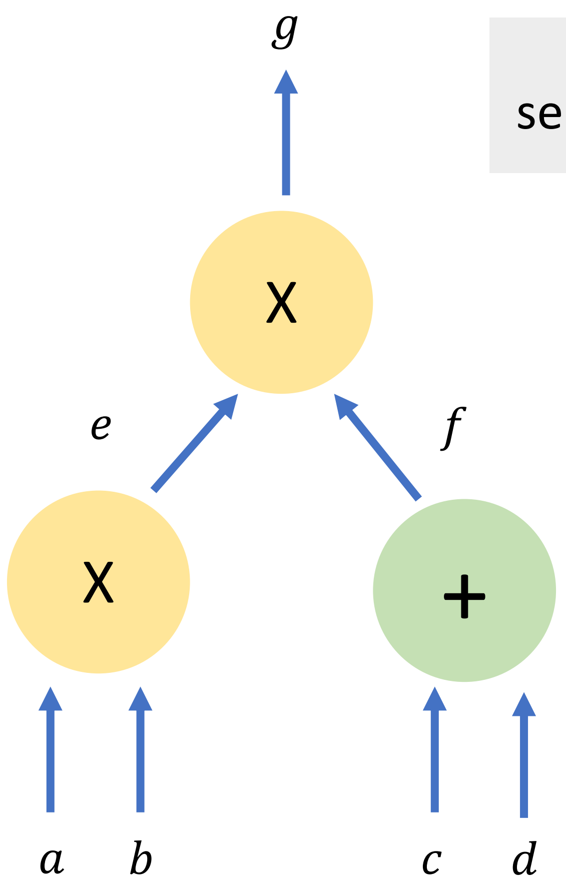

Most secret sharing based semi-honest protocols are secure against malicious adversaries up to additive attacks:

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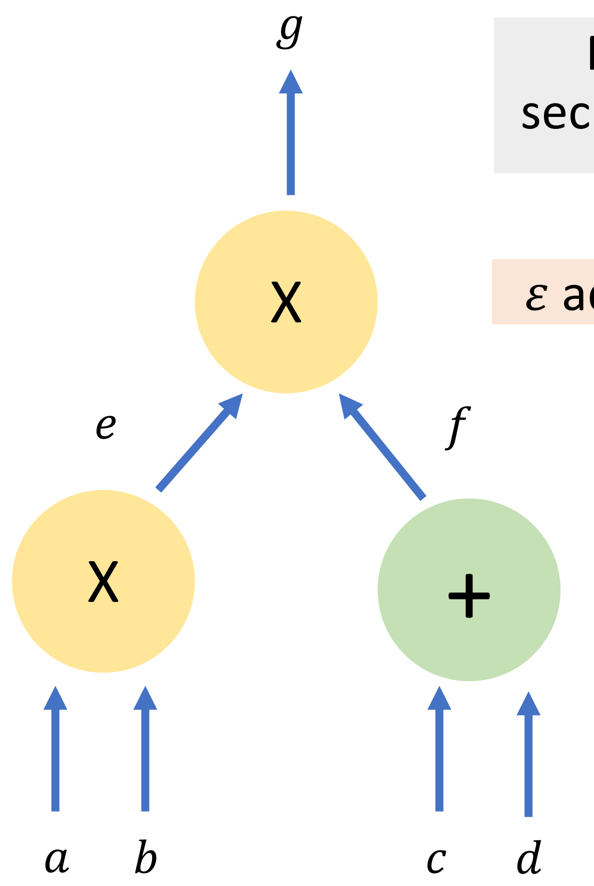
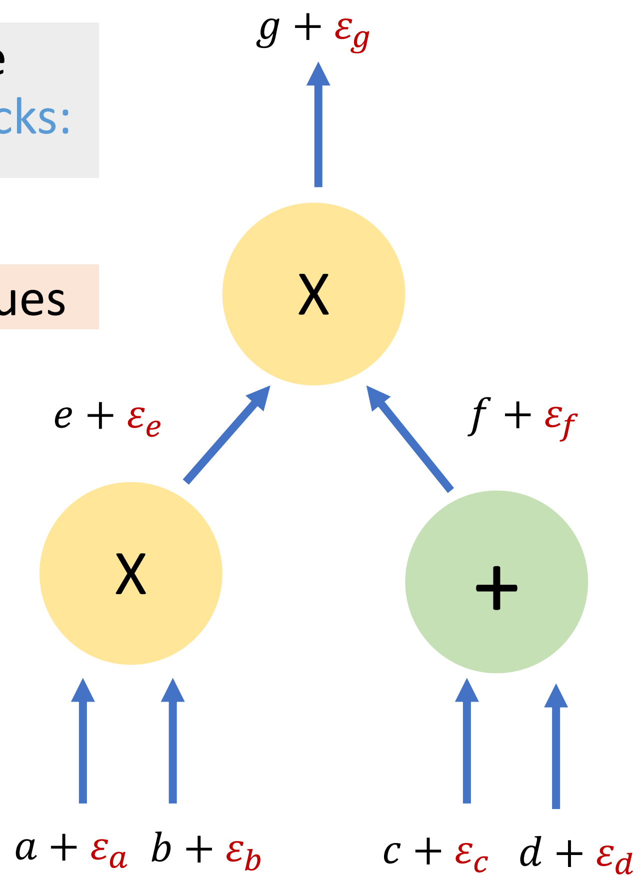


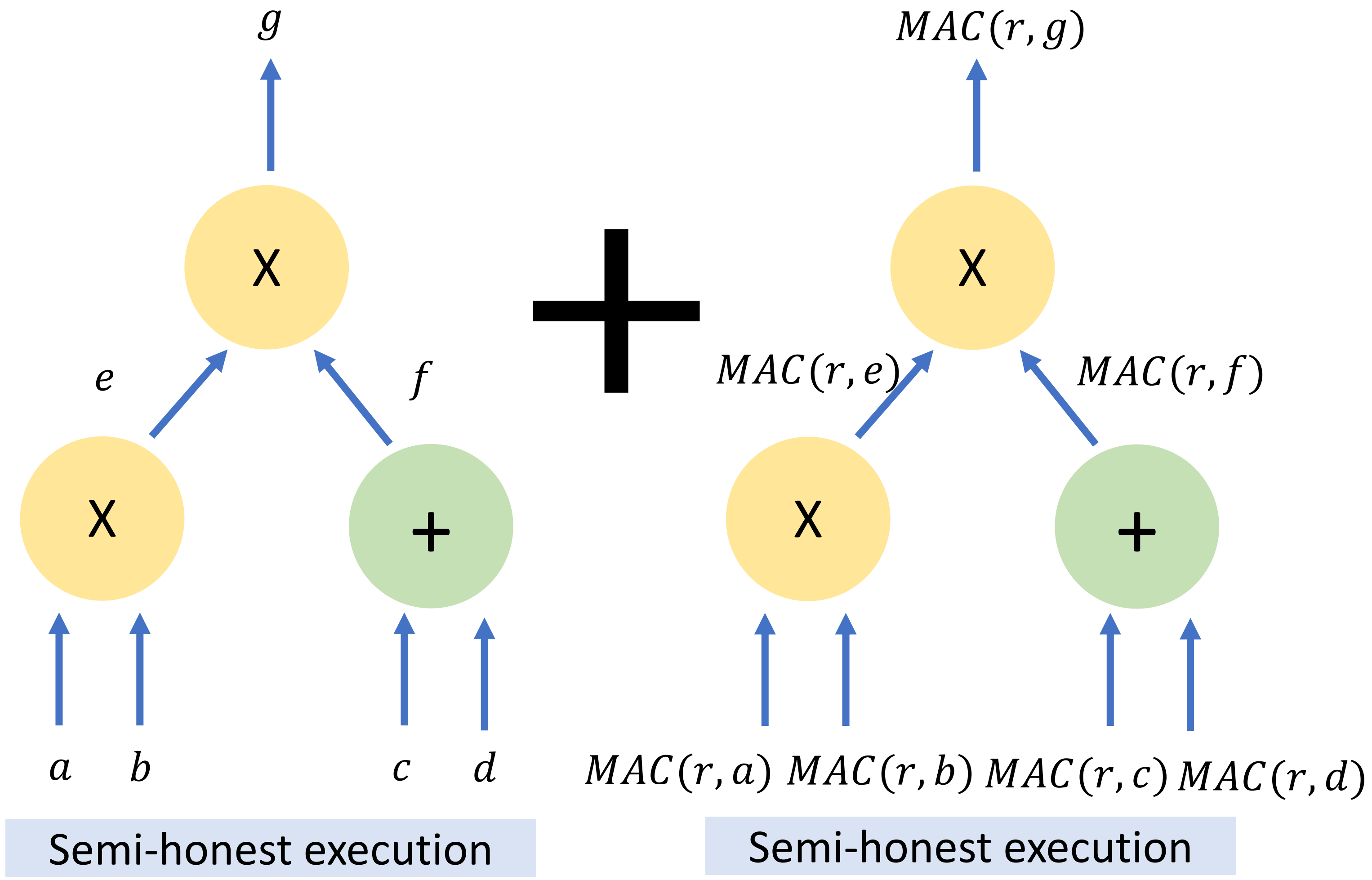
Most secret sharing based semi-honest protocols are secure against malicious adversaries up to additive attacks:

ε additive errors are independent of the actual wire values



Efficient Maliciously Secure Protocols [DPSZ12,CGHIKLN18]

Modern efficient maliciously secure protocols rely on this additive attack paradigm.



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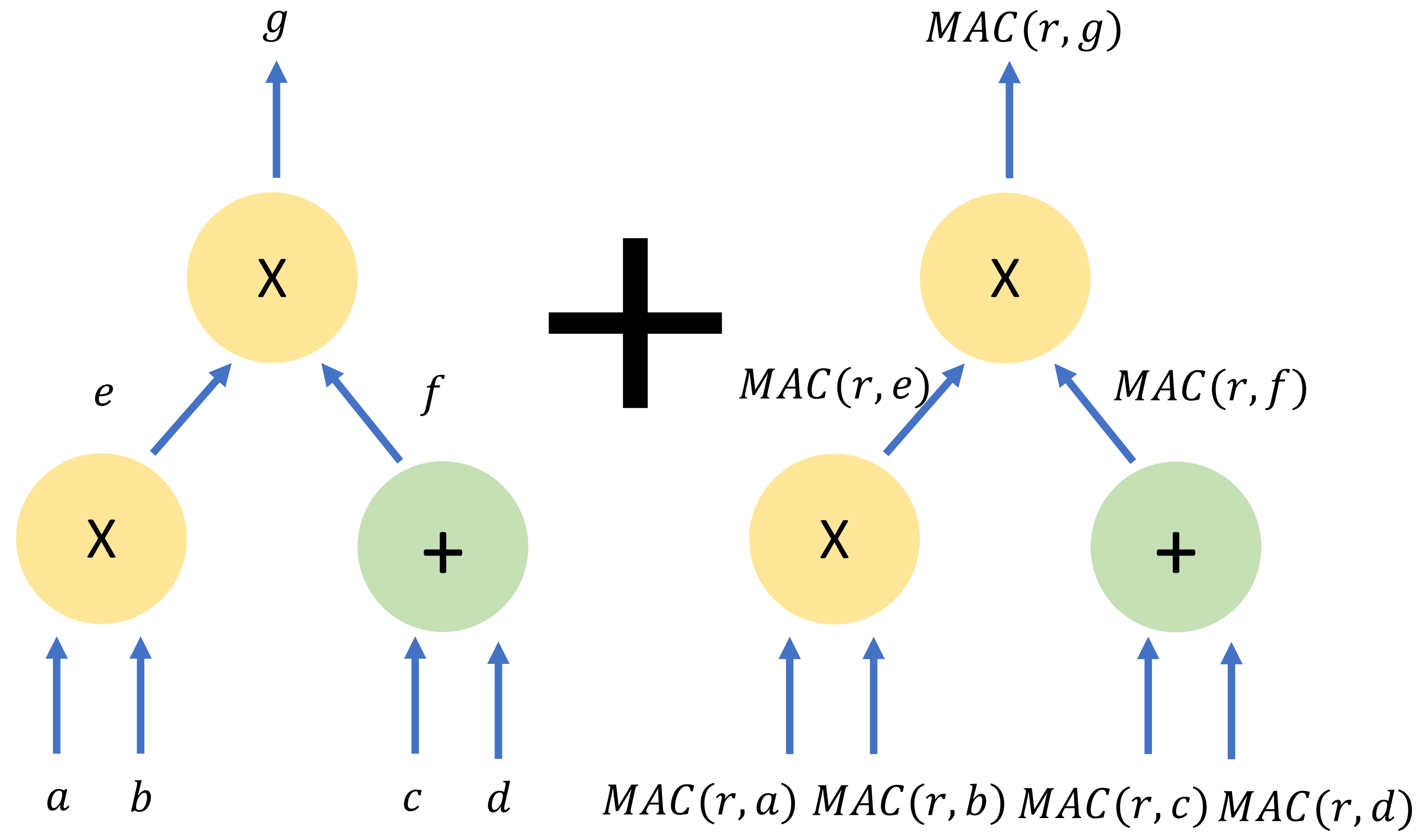

Semi-honest execution

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Check validity of all the MACs at the end

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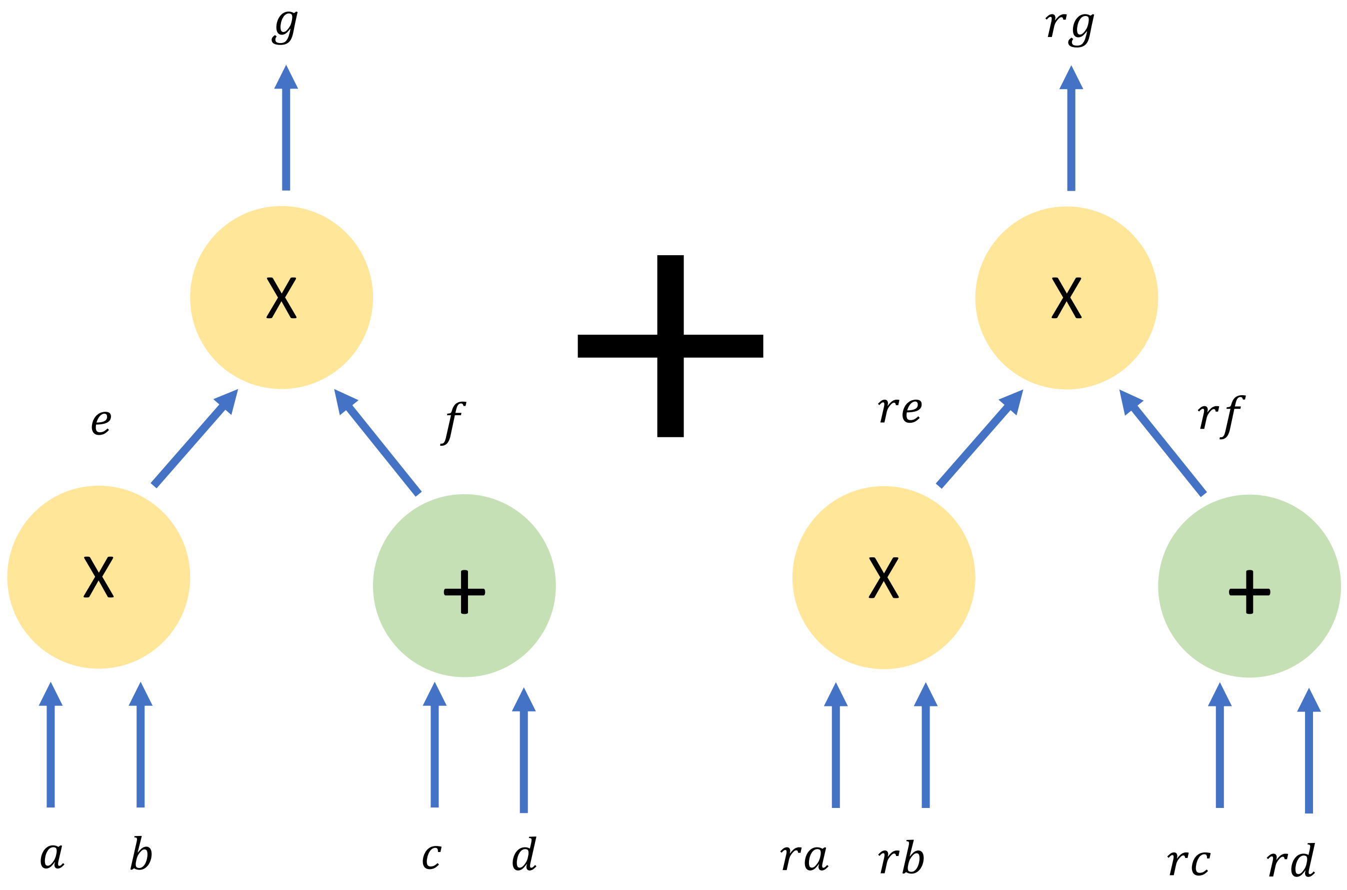

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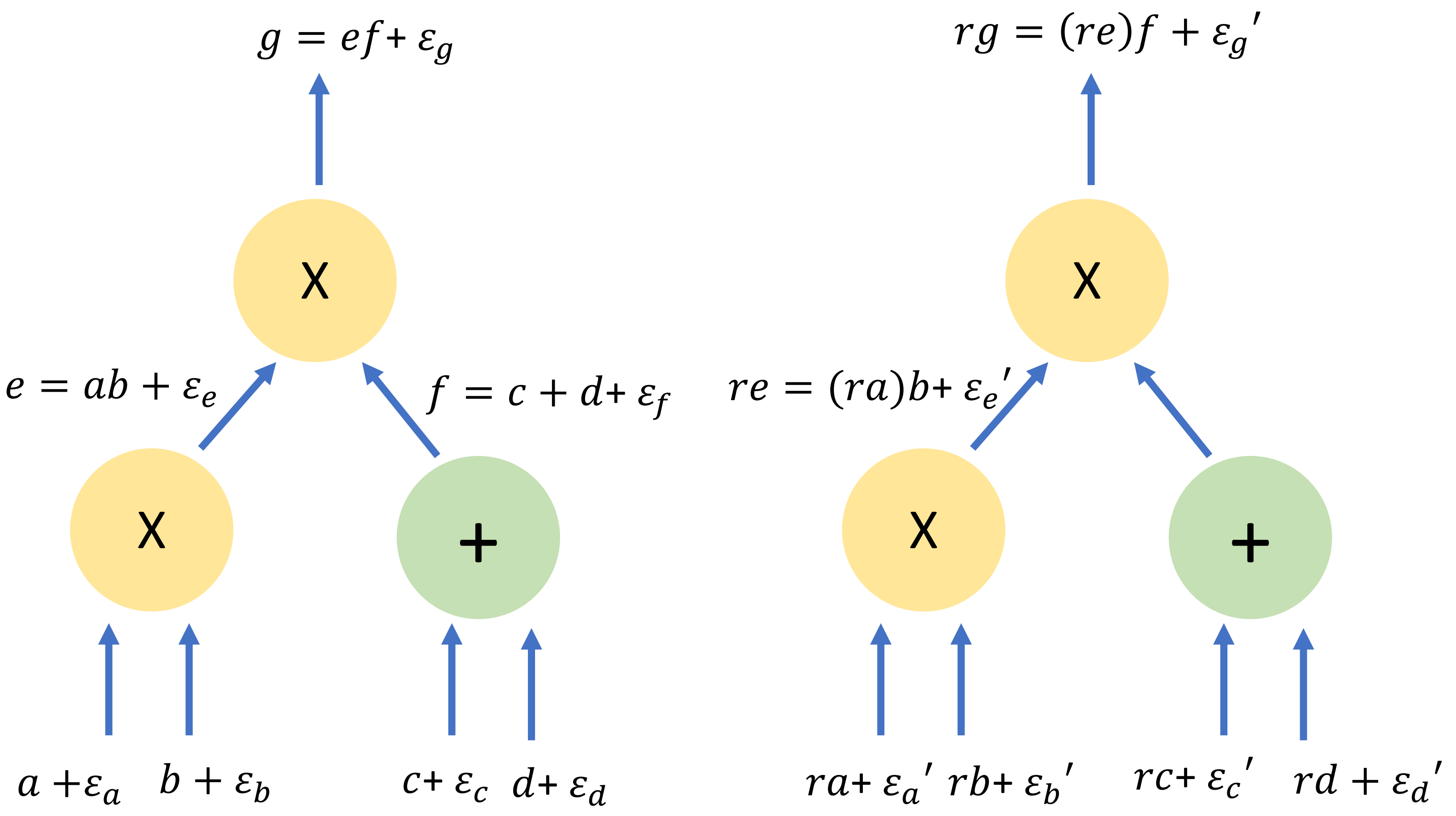

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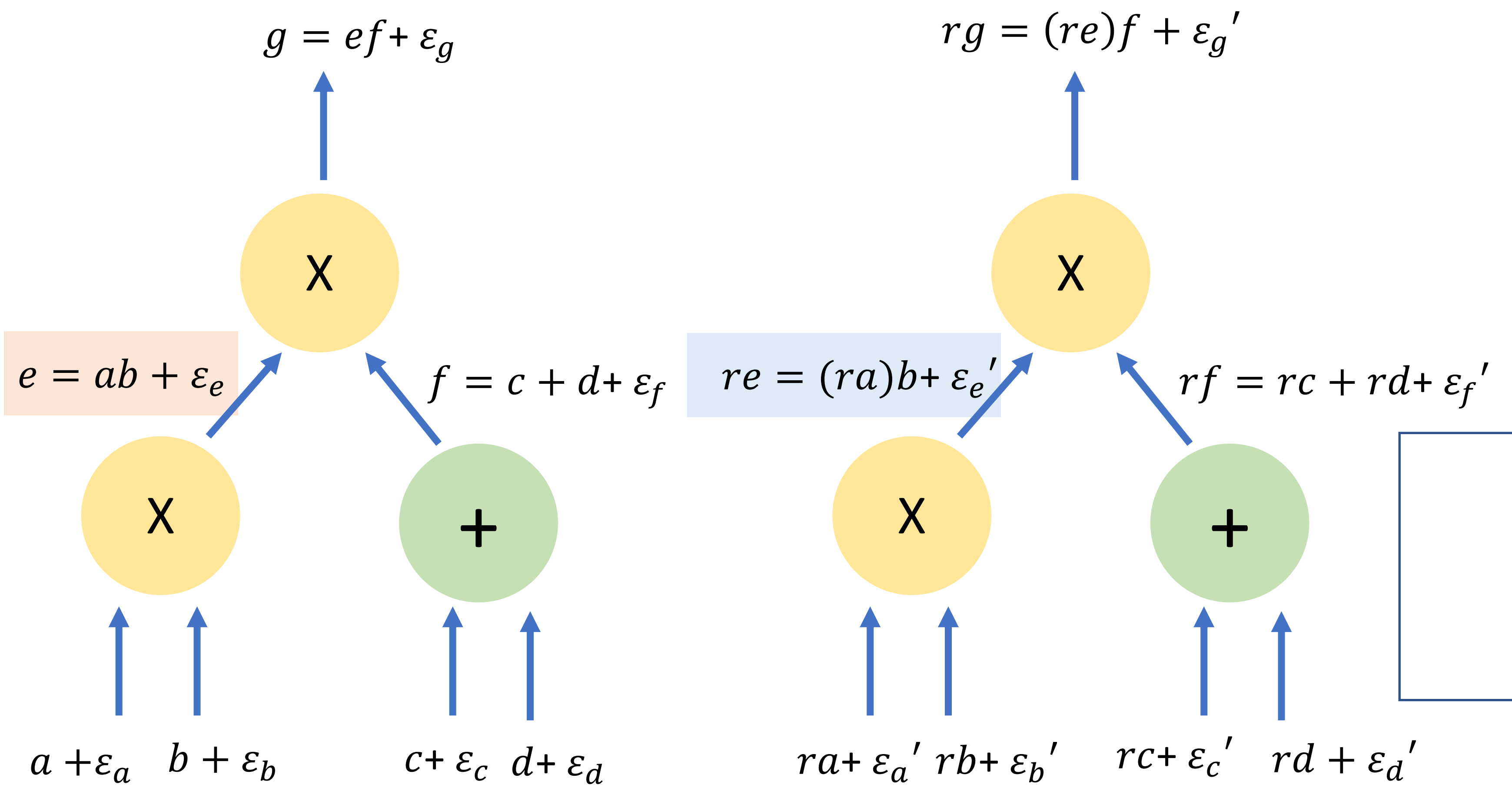
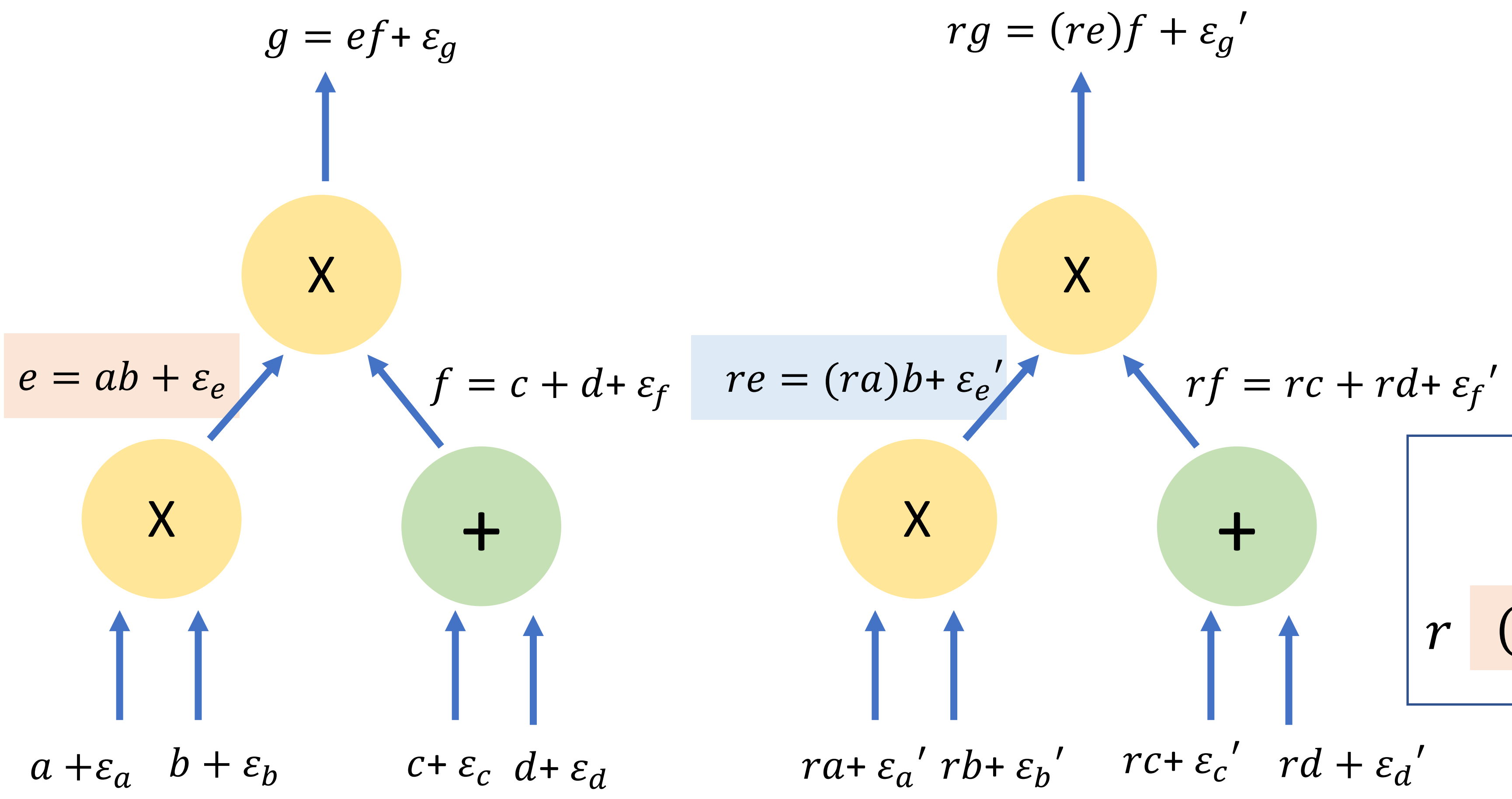


For each gate, check if:

$$r\ (e) \ =?= \ re$$

Efficient Maliciously Secure Protocols [DPSZ12,CGHIKLN18]

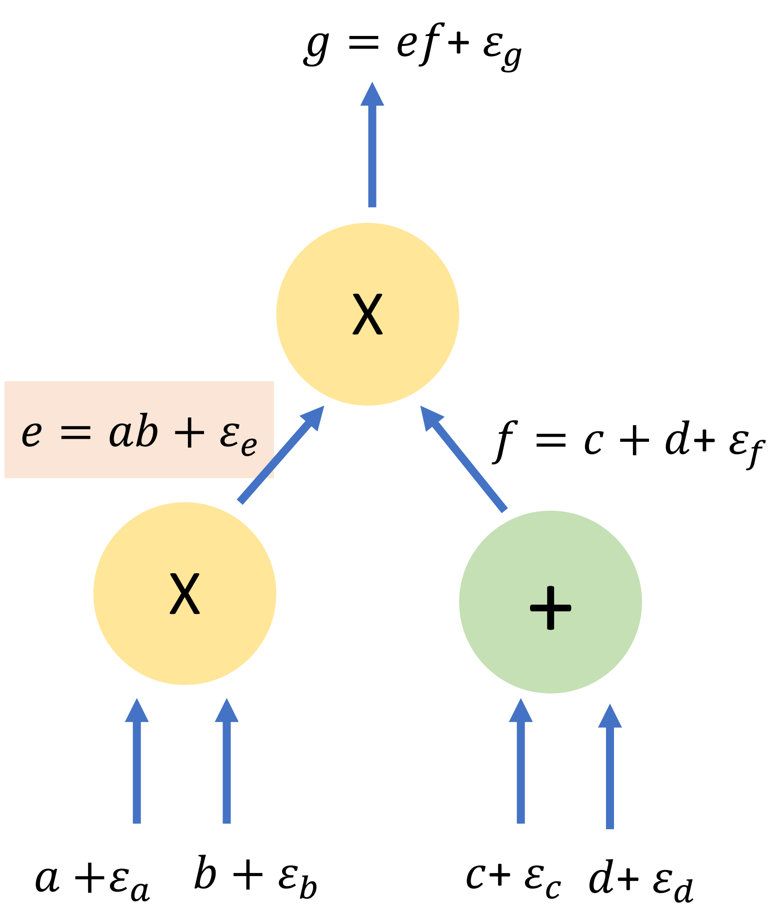


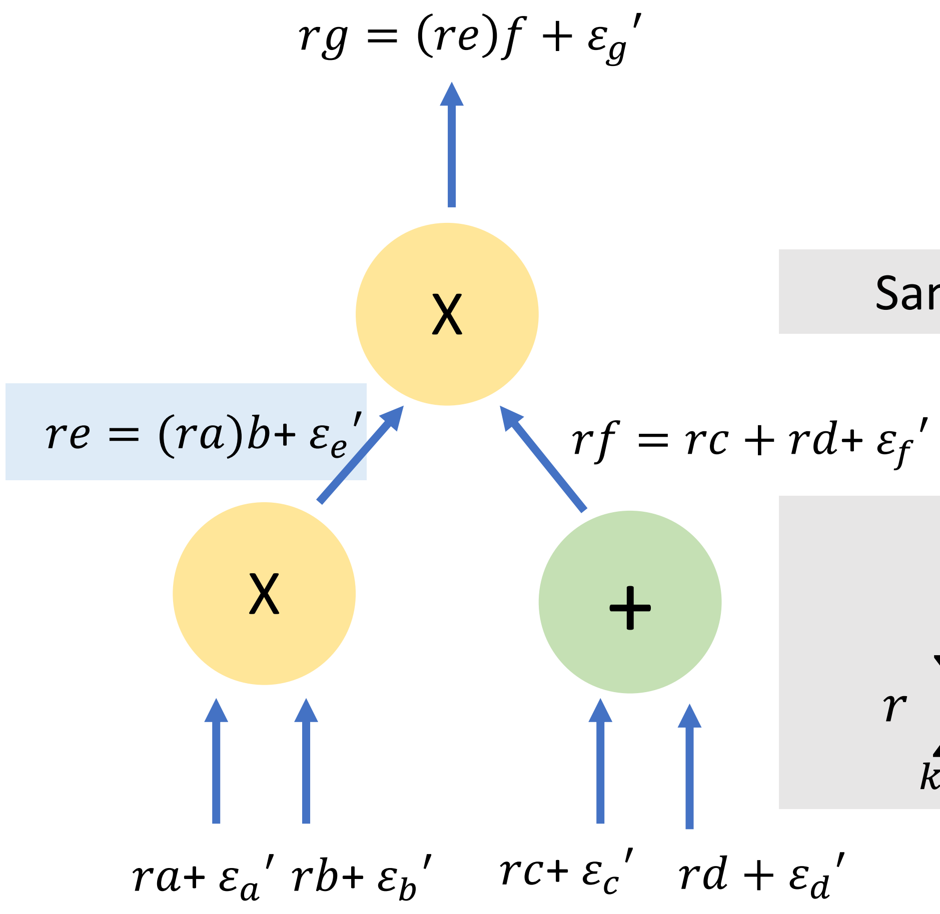
For each gate, check if:

$$r\,(e) \;=?=\; re$$

$$r\,(ab + \varepsilon_e) \;=?=\; (ra)b + \varepsilon'_e$$

Efficient Maliciously Secure Protocols [DPSZ12,CGHIKLN18]





Sample a random α_k for each gate

Consolidated check:

$$r \sum_{k \in |C|} \alpha_k(z_k) =?= \sum_{k \in |C|} \alpha_k(rz_k)$$

Maliciously secure Fluid MPC

Additive Attack Paradigm?

Semi-honest Fluid BGW $\longrightarrow$ Maliciously secure Fluid MPC

Maliciously secure Fluid MPC

Additive Attack Paradigm?

Semi-honest Fluid BGW → Maliciously secure Fluid MPC

We want this transformation to preserve the communication complexity and fluidity of fluid BGW

Maliciously secure Fluid MPC

Additive Attack Paradigm?

Semi-honest Fluid BGW → Maliciously secure Fluid MPC

We want this transformation to preserve the communication complexity and fluidity of fluid BGW

Observation: Additive Attack Paradigm extends to the Fluid MPC setting in a natural way

Maliciously secure Fluid MPC

Can we use known techniques in the additive attack paradigm?

Maliciously secure Fluid MPC

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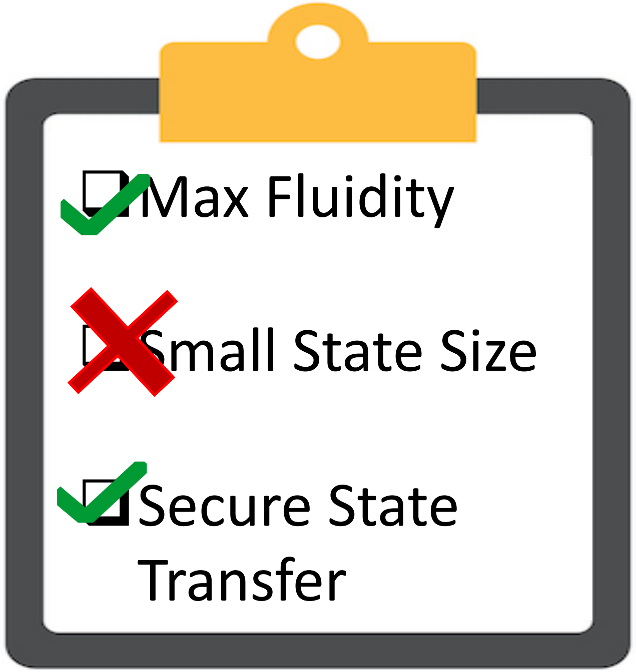
If the linear combination is computed at the end

the values of rz and z must have been passed along as part of the state till the end of the protocol.



Maliciously secure Fluid MPC

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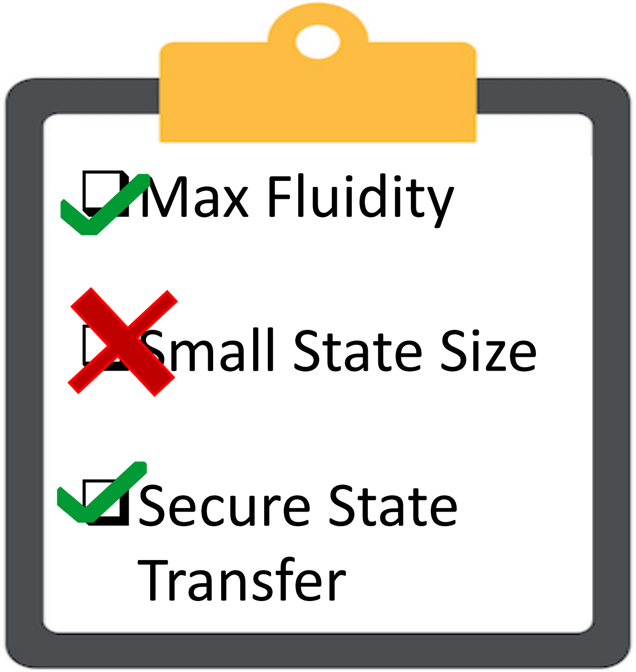
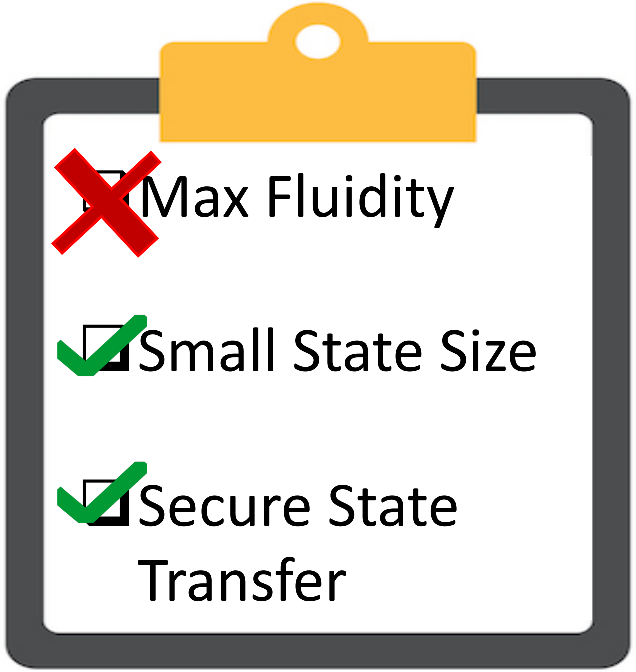
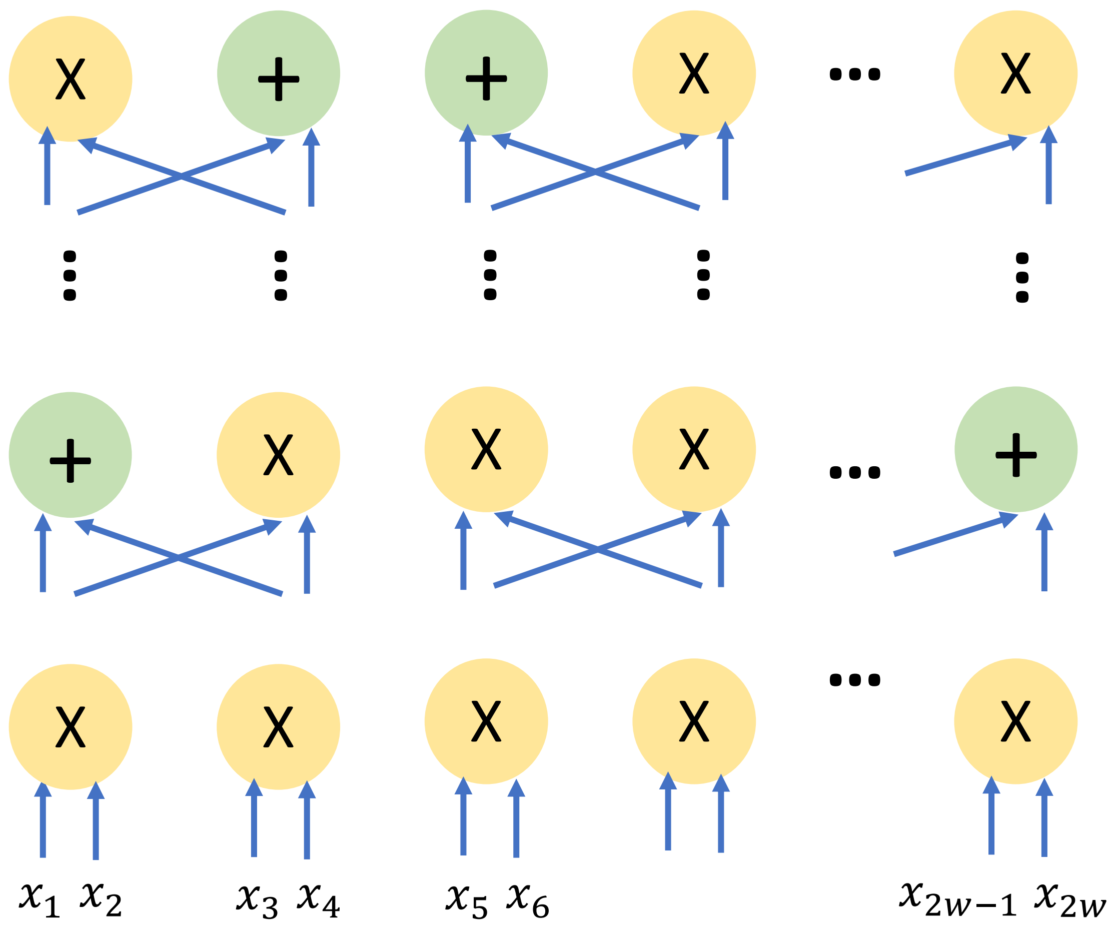


If the linear combination is computed incrementally layer-by-layer

the α values will have to be generated on the fly, which may take many rounds.



Maliciously secure Fluid MPC: Our Idea



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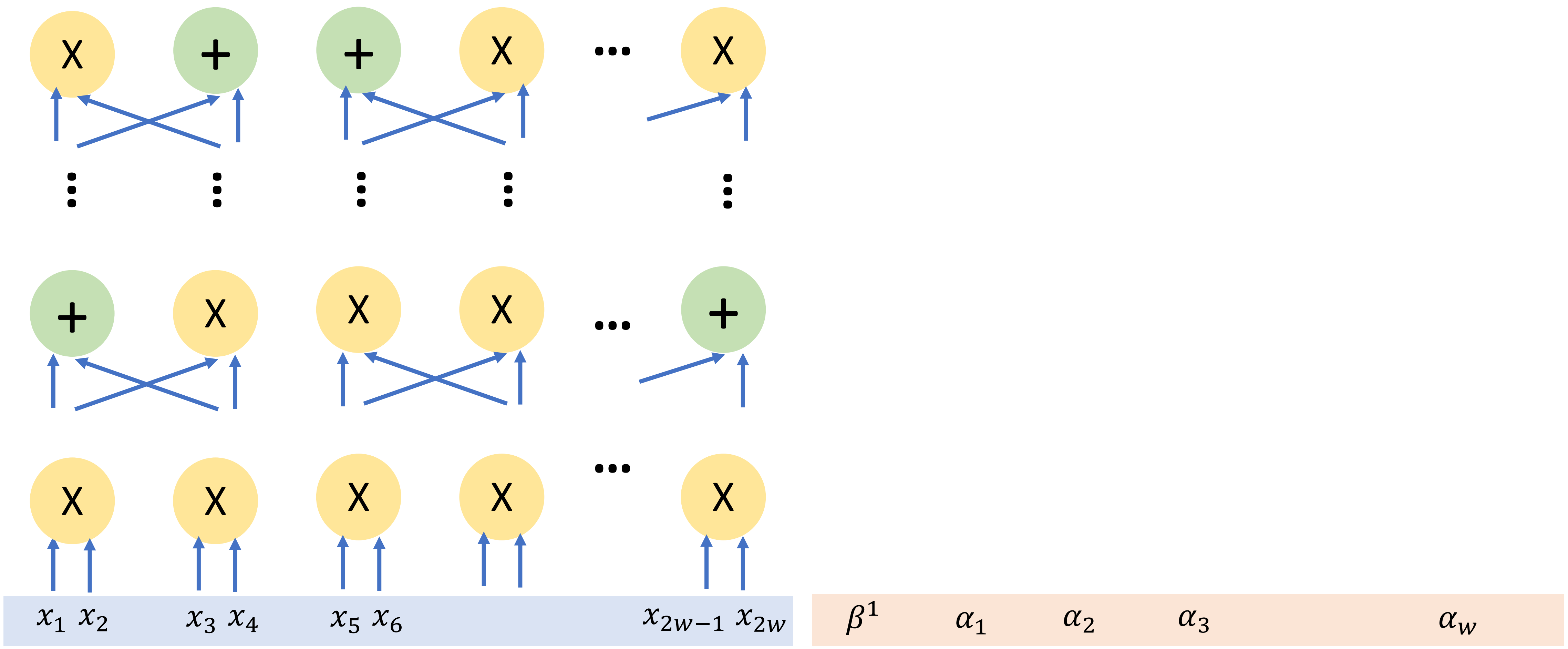

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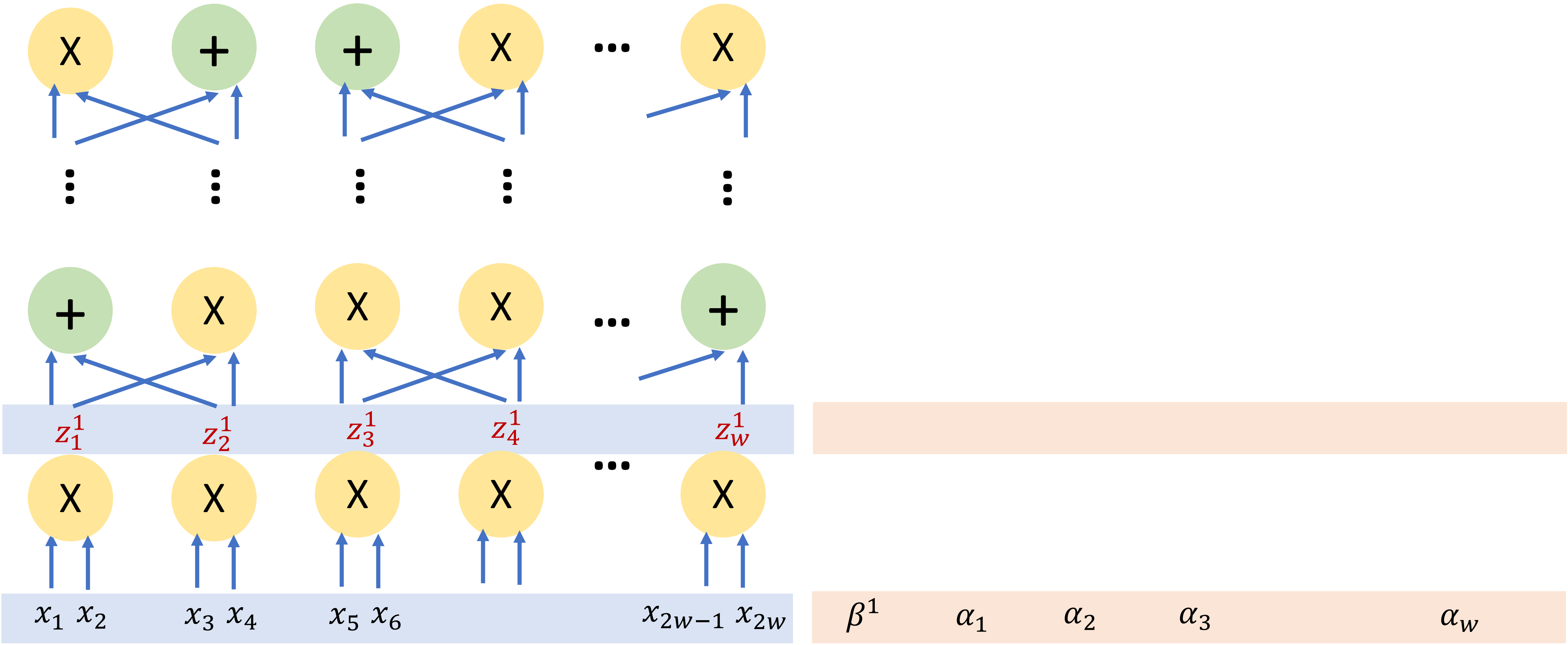

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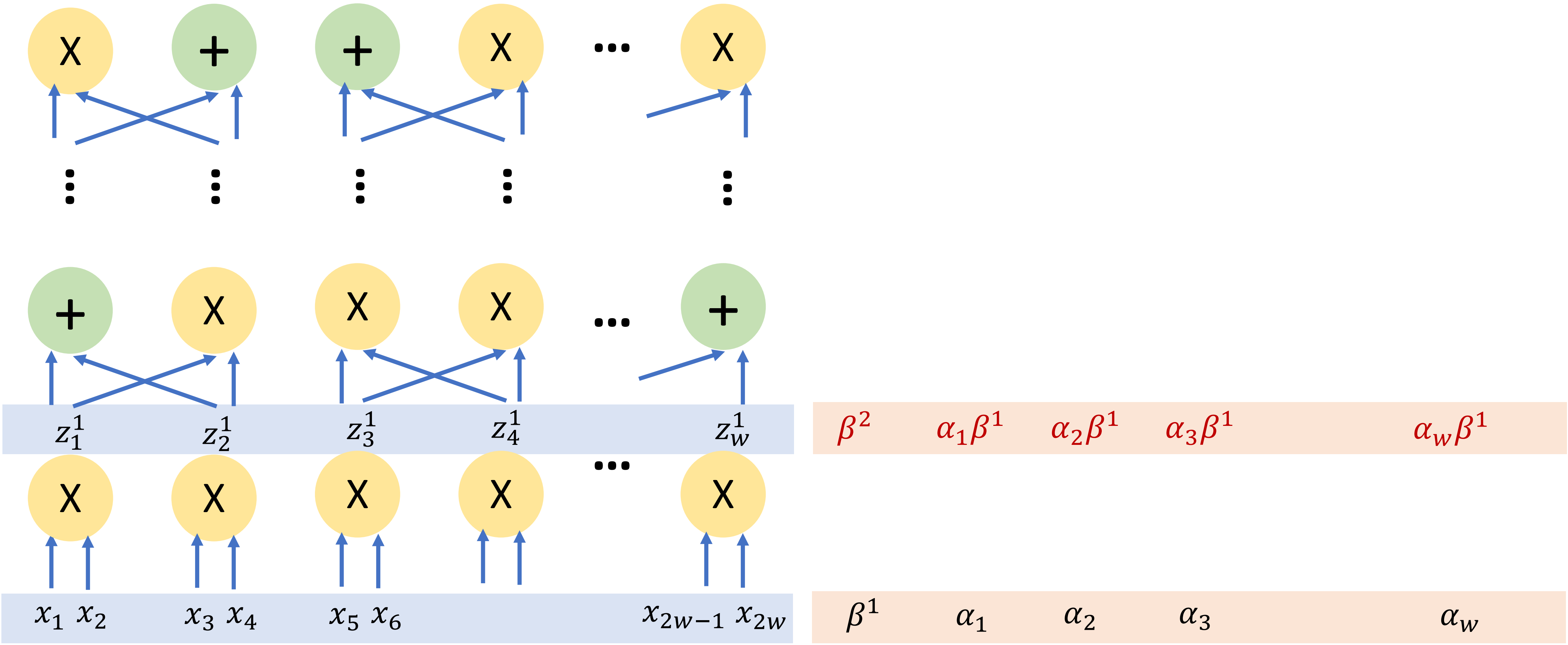

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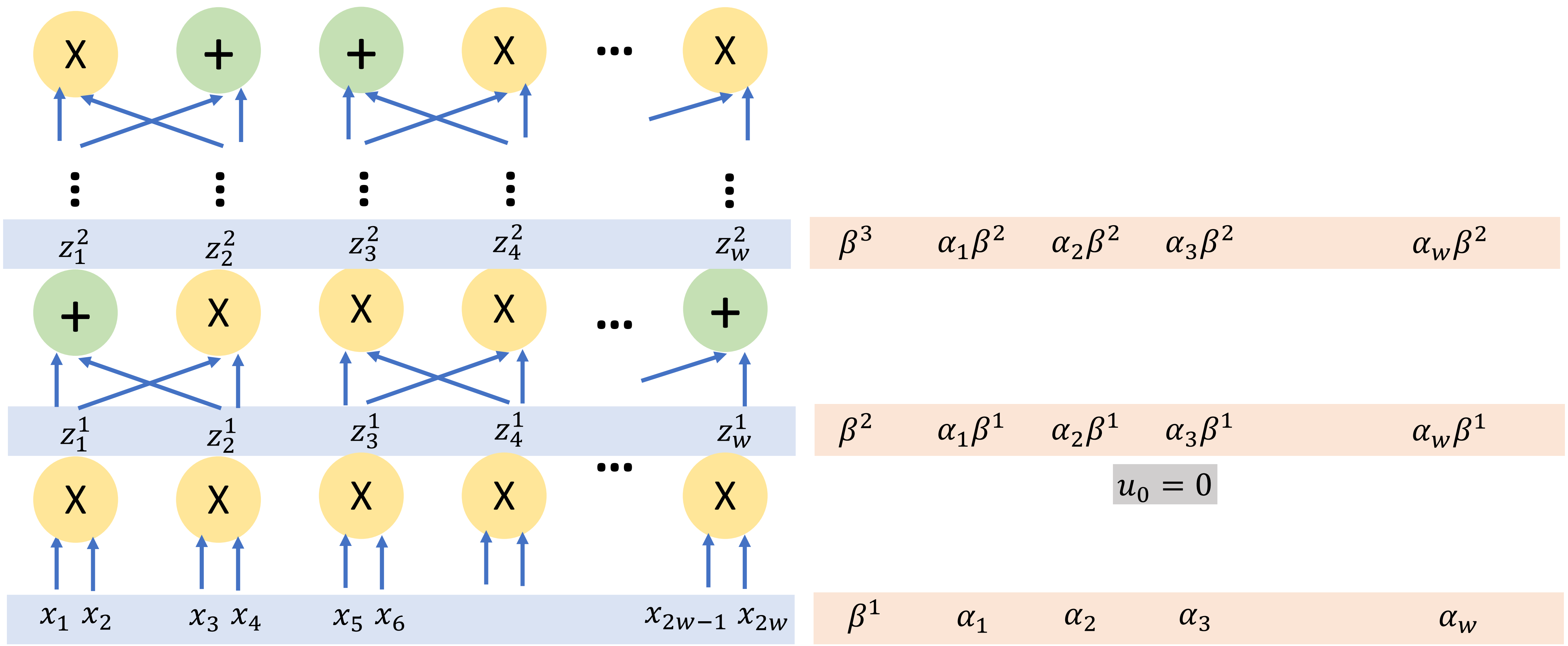

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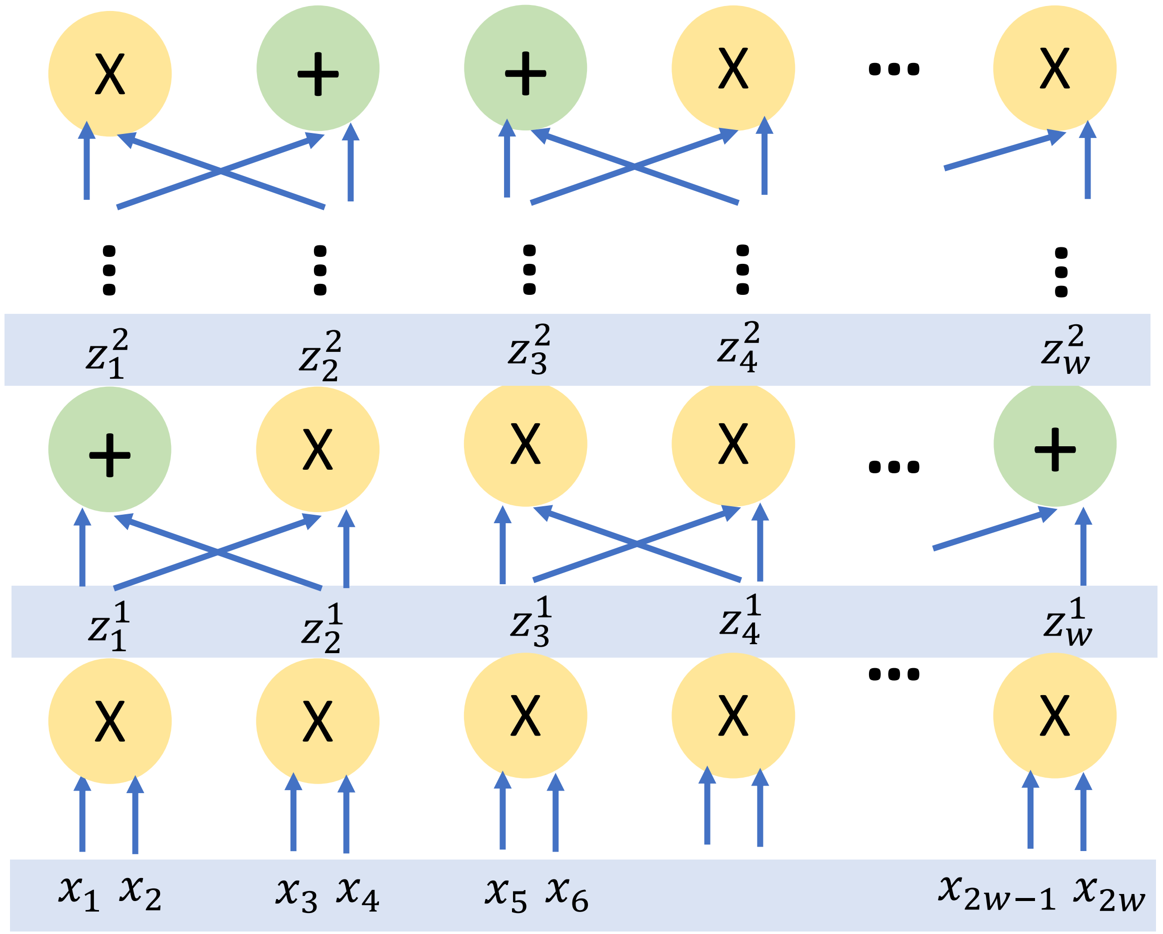


β^3 $\alpha_1\beta^2$ $\alpha_2\beta^2$ $\alpha_3\beta^2$ $\alpha_w\beta^2$

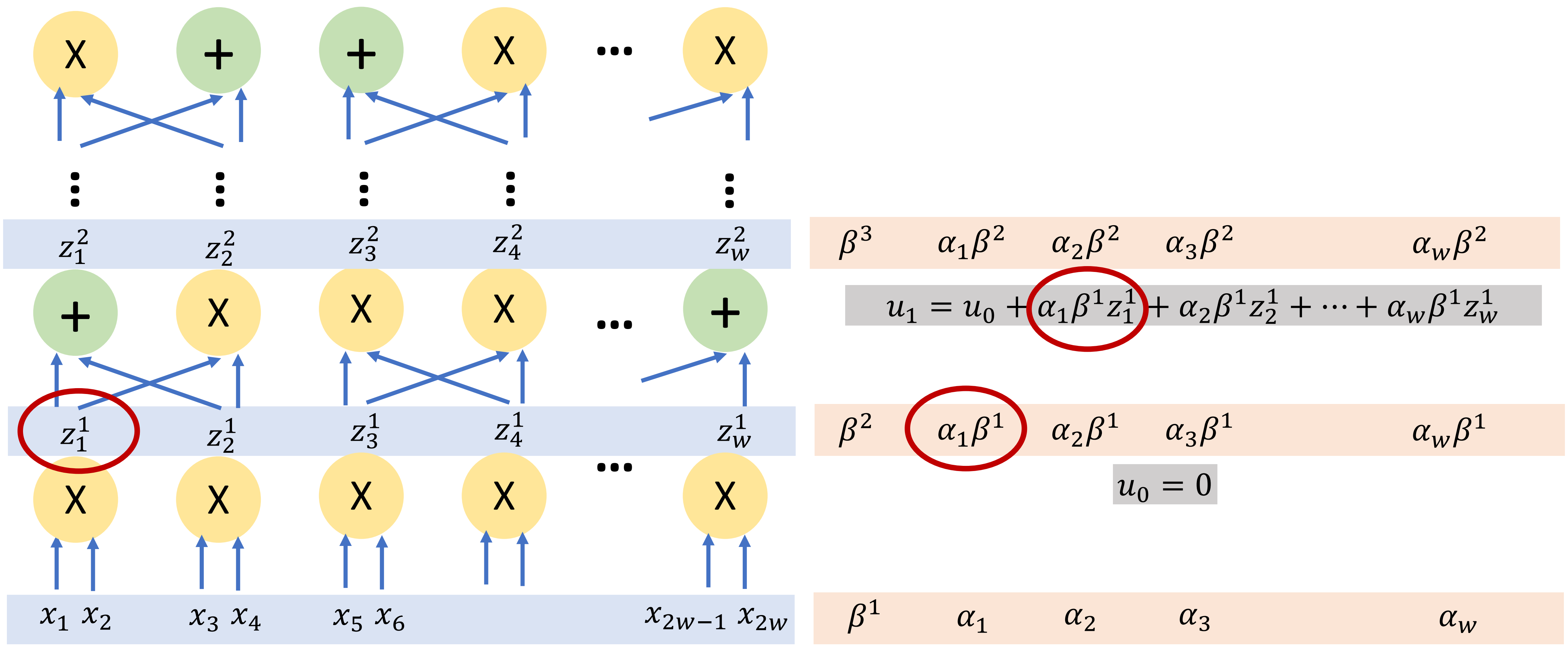
$u_1 = u_0 + \alpha_1\beta^1 z_1^1 + \alpha_2\beta^1 z_2^1 + \cdots + \alpha_w\beta^1 z_w^1$

β^2 $\alpha_1\beta^1$ $\alpha_2\beta^1$ $\alpha_3\beta^1$ $\alpha_w\beta^1$

$u_0 = 0$

β^1 α_1 α_2 α_3 α_w

Maliciously secure Fluid MPC: Our Idea



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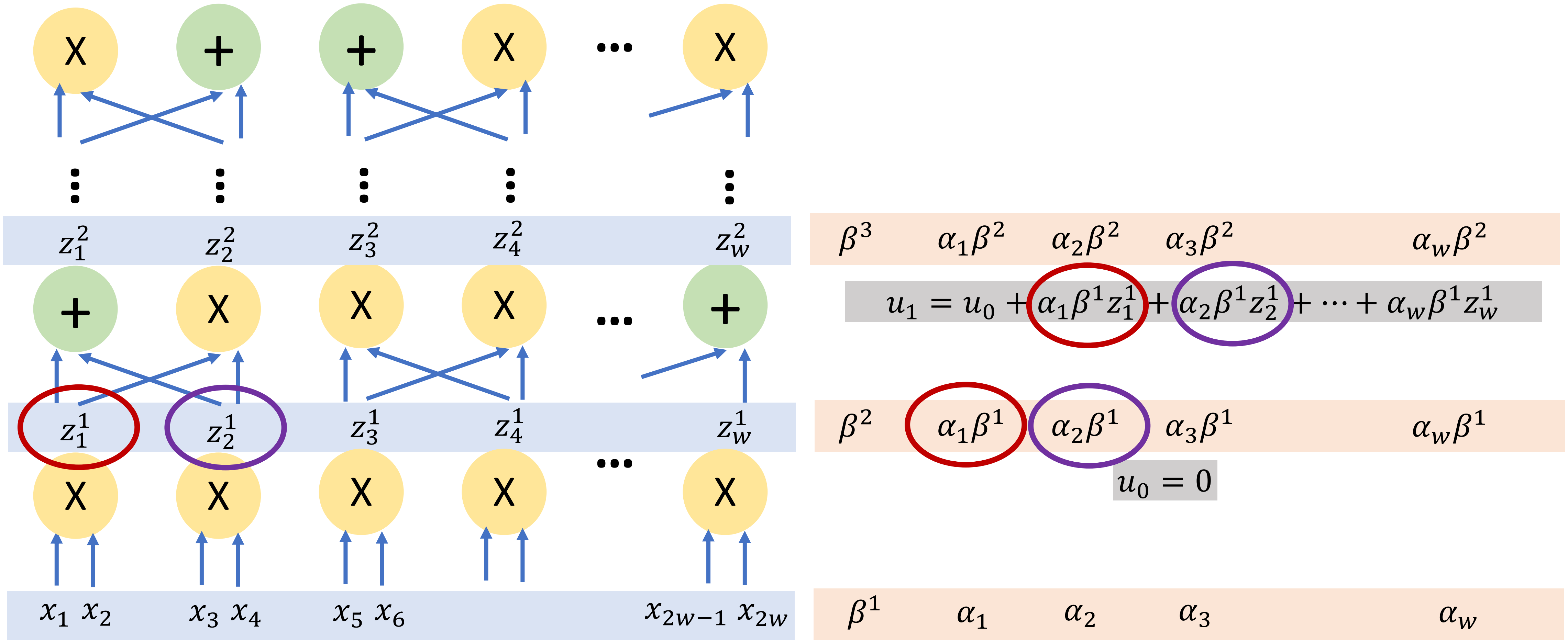

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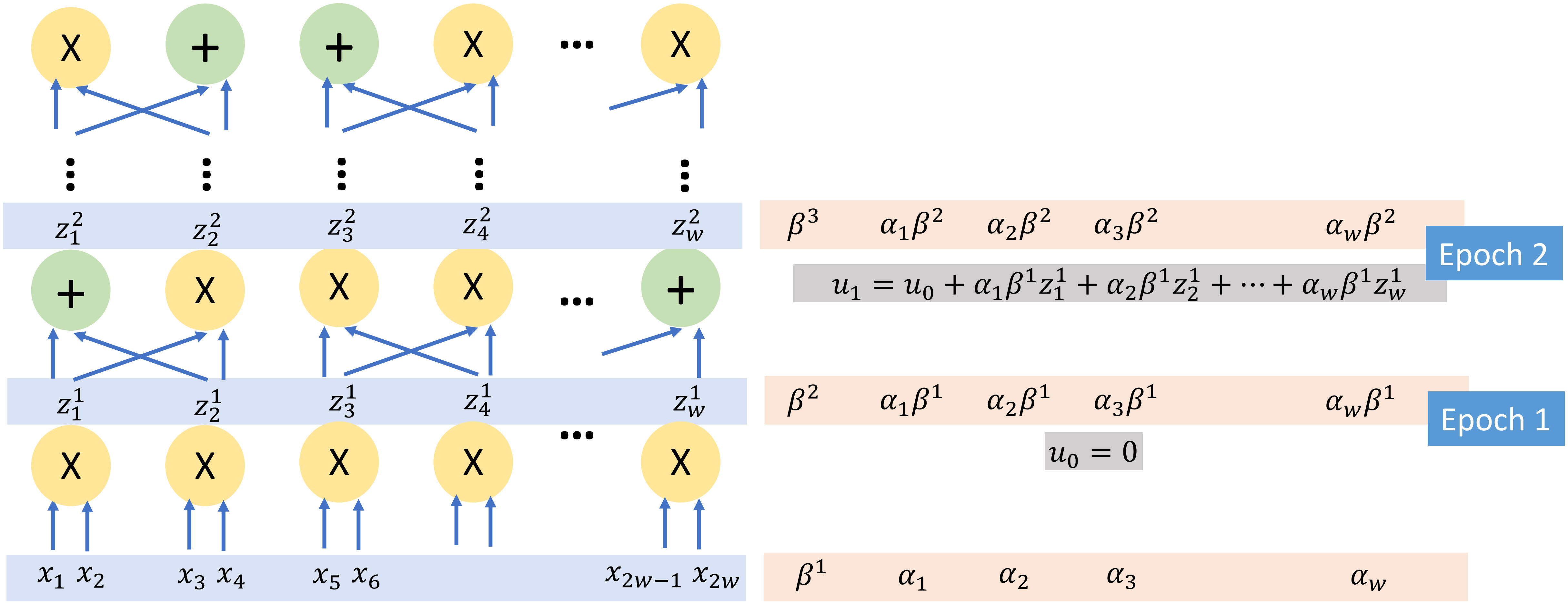
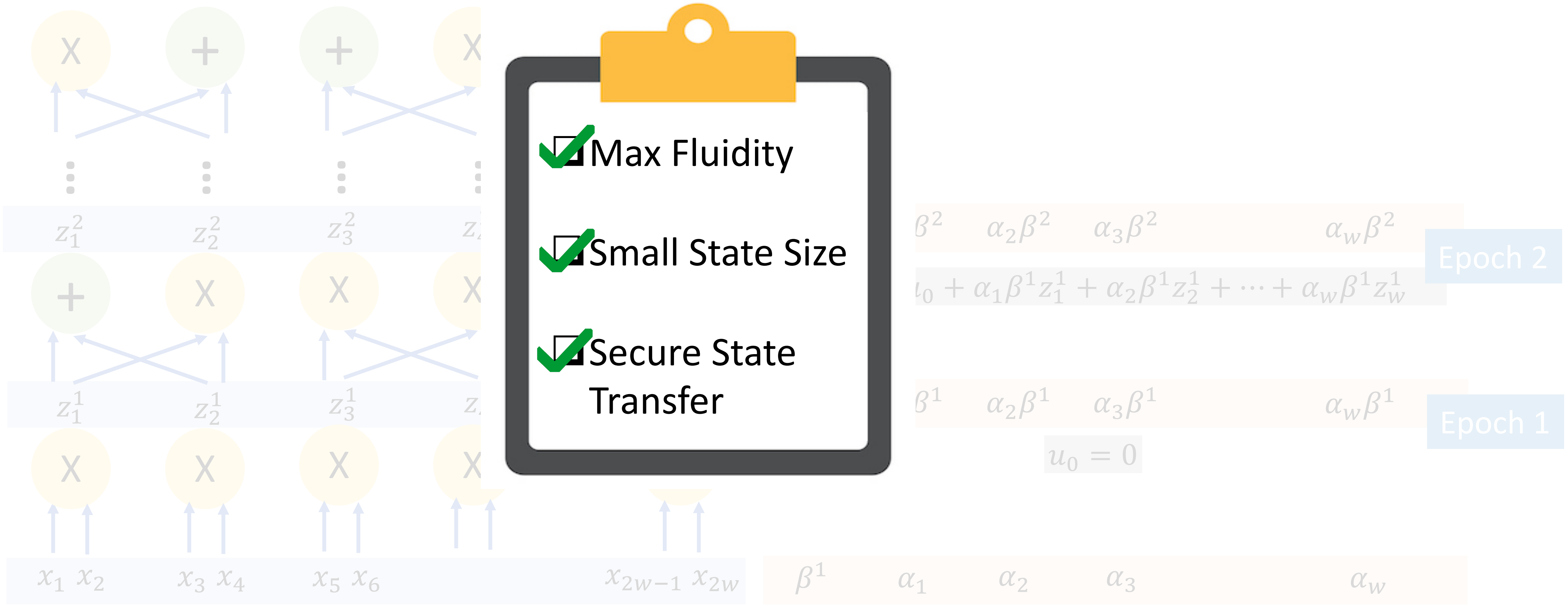


Malicious Security Compiler for Fluid MPC



Conclusion and Open Questions

- Exciting new direction.
- Communication Complexity semi-honest Fluid BGW is $O(n^2|C|)$.
- Our compiler preserves the fluidity and communication complexity of the underlying semi-honest protocol, but only achieves security with abort.
- Open Questions:
  - Improved efficiency
  - Guaranteed output delivery
  - Exploring other modeling choices

https://eprint.iacr.org/2020/754

Thank You

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