Stacking Sigma

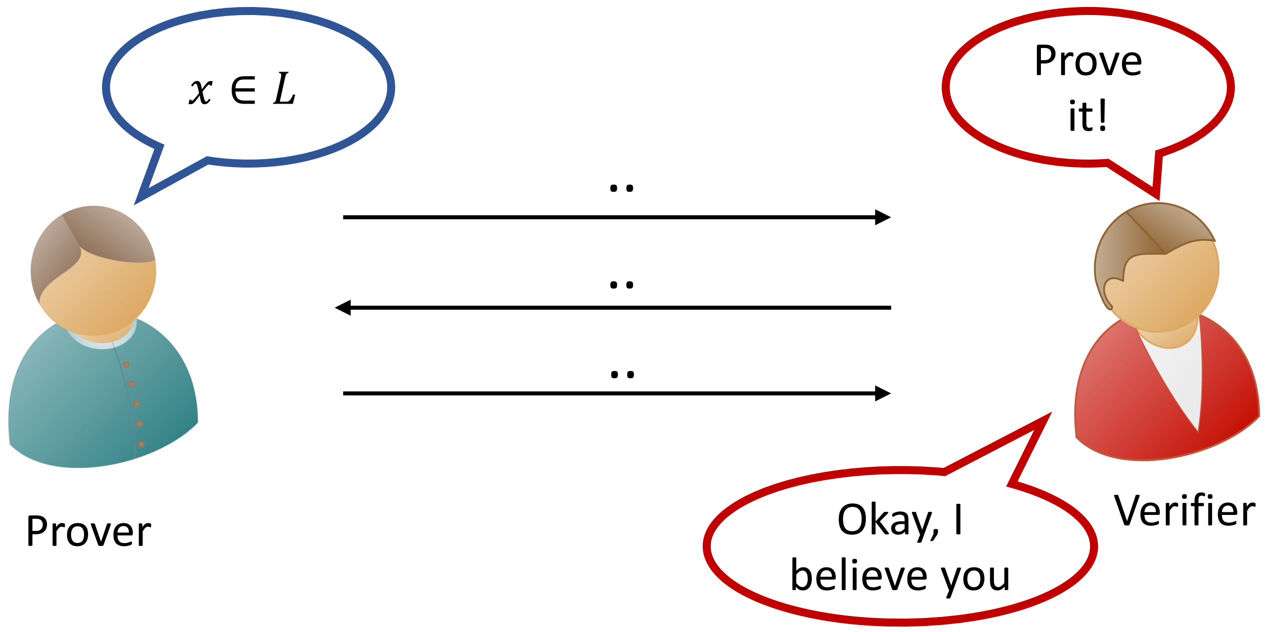
A Framework to Compose Σ–Protocols for Disjunctions

Aarushi Goel Matthew Green Mathias Hall-Andersen Gabriel Kaptchuk

JOHNS HOPKINS UNIVERSITY AARHUS UNIVERSITY BOSTON UNIVERSITY

Zero Knowledge Proofs

$\boxed{L \in NP}$



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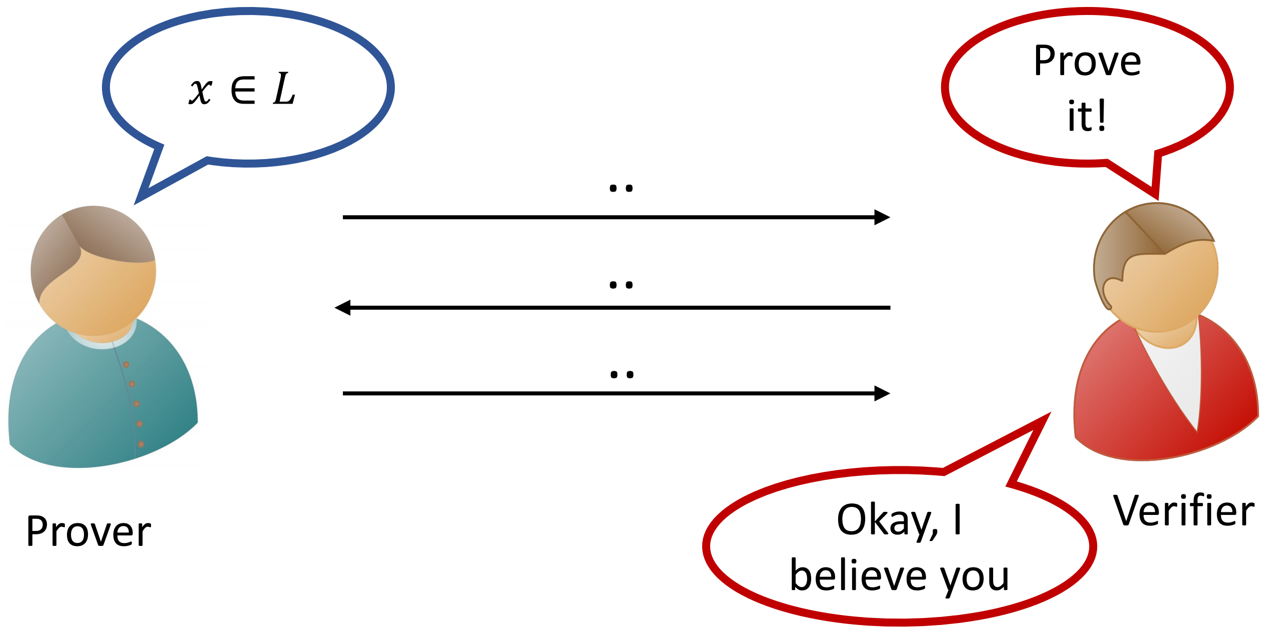

Soundness

Cheating prover should not be able to convince the verifier if $x \notin L$

Zero Knowledge Proofs

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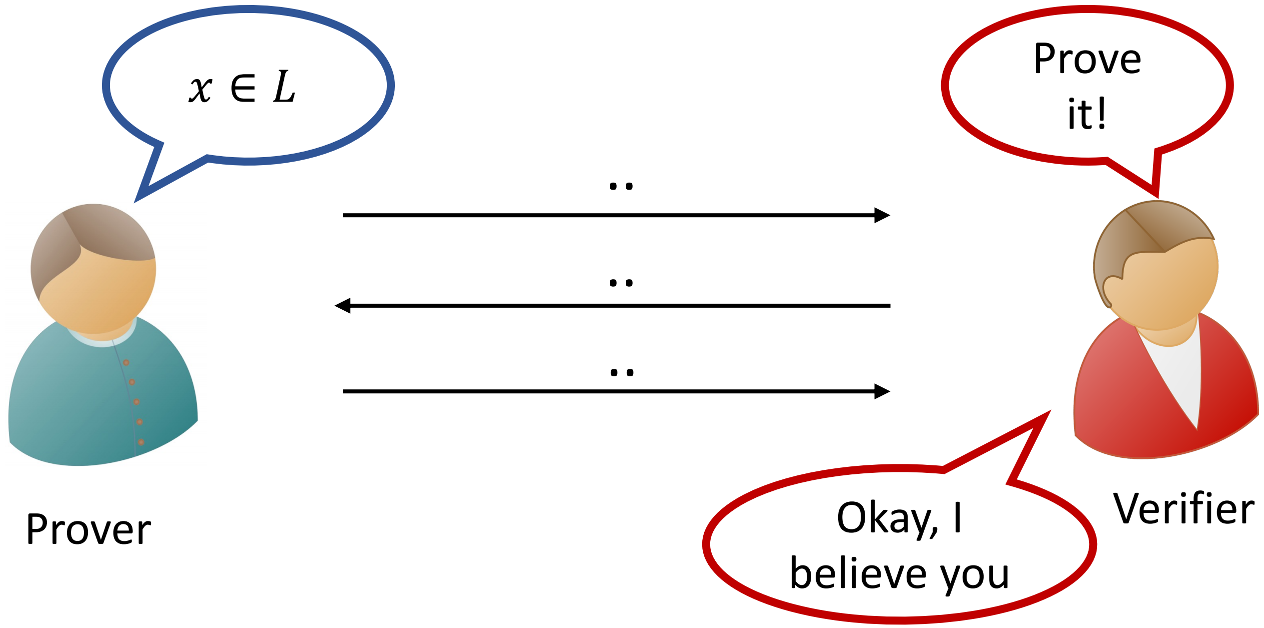

Soundness

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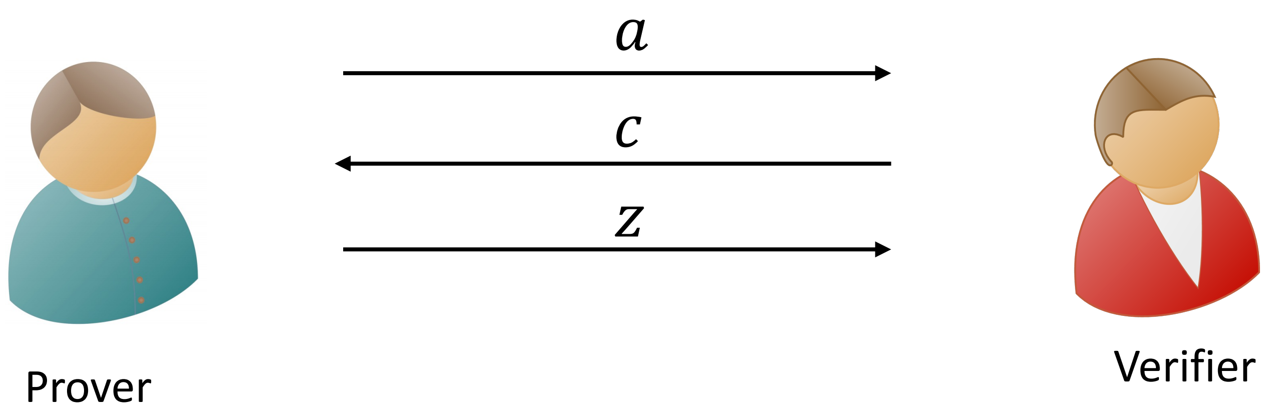
Zero knowledge

Verifier should not learn anything other than the validity of the statement

Sigma Protocols

$\boxed{L \in NP}$



Public coin proofs

Honest verifier zero-knowledge

Can be made non-interactive in the random oracle model

Disjunctive Statements: Interesting Class of Languages

$$x_1 \in L_1 \quad or \quad x_2 \in L_2 \quad or \quad \ldots\ldots \quad or \quad x_n \in L_n$$

Where each $L_i \in NP$

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Stacking Σ-Protocols for Disjunctions

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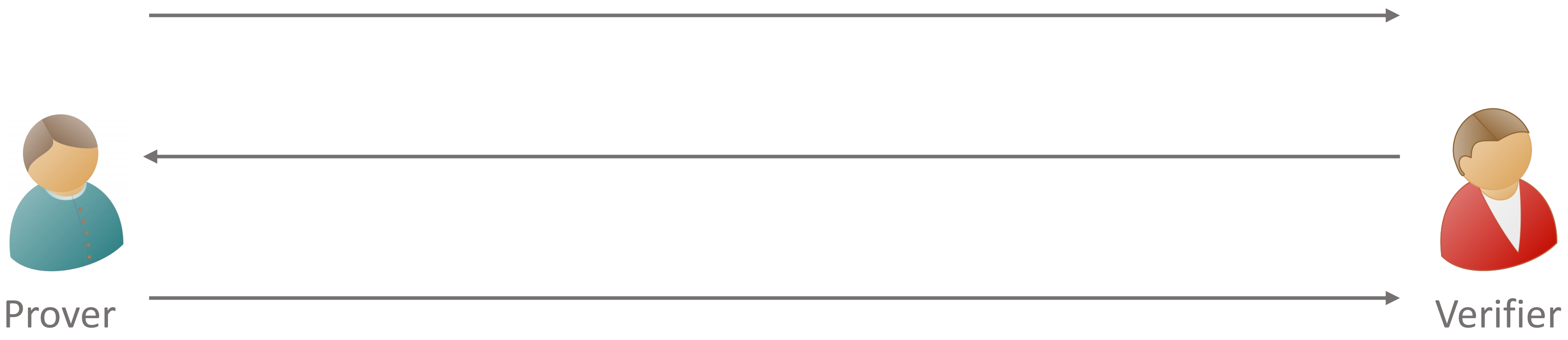

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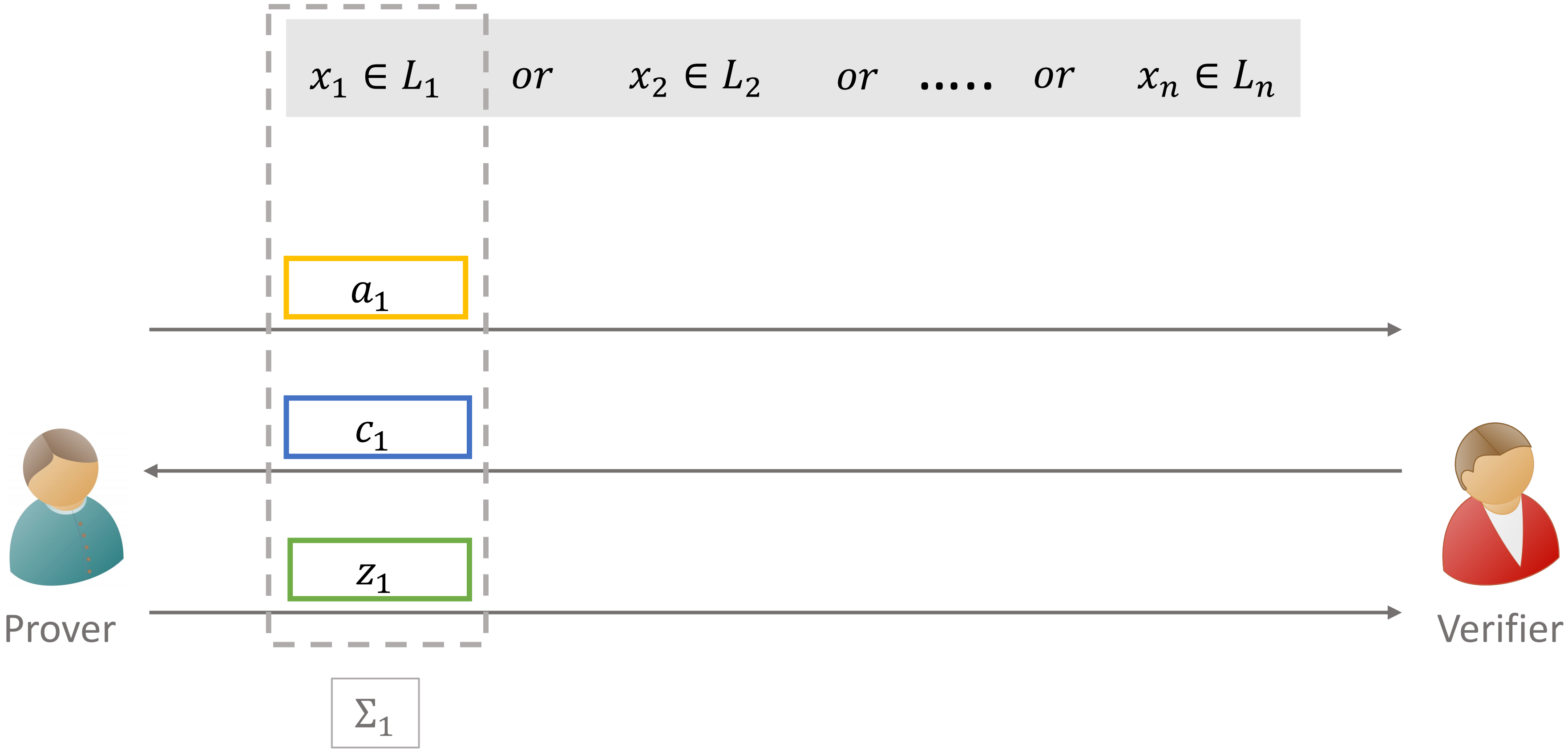

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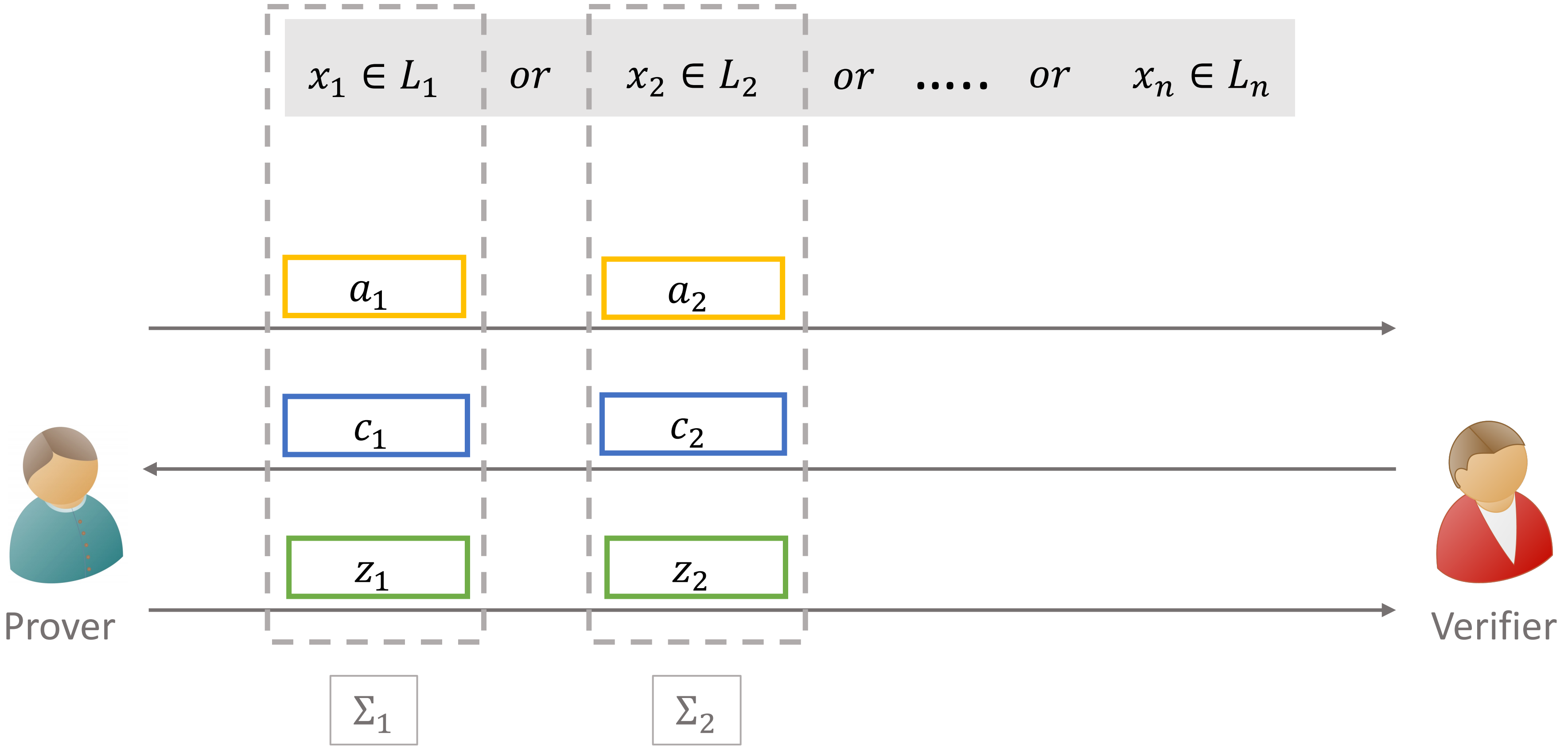

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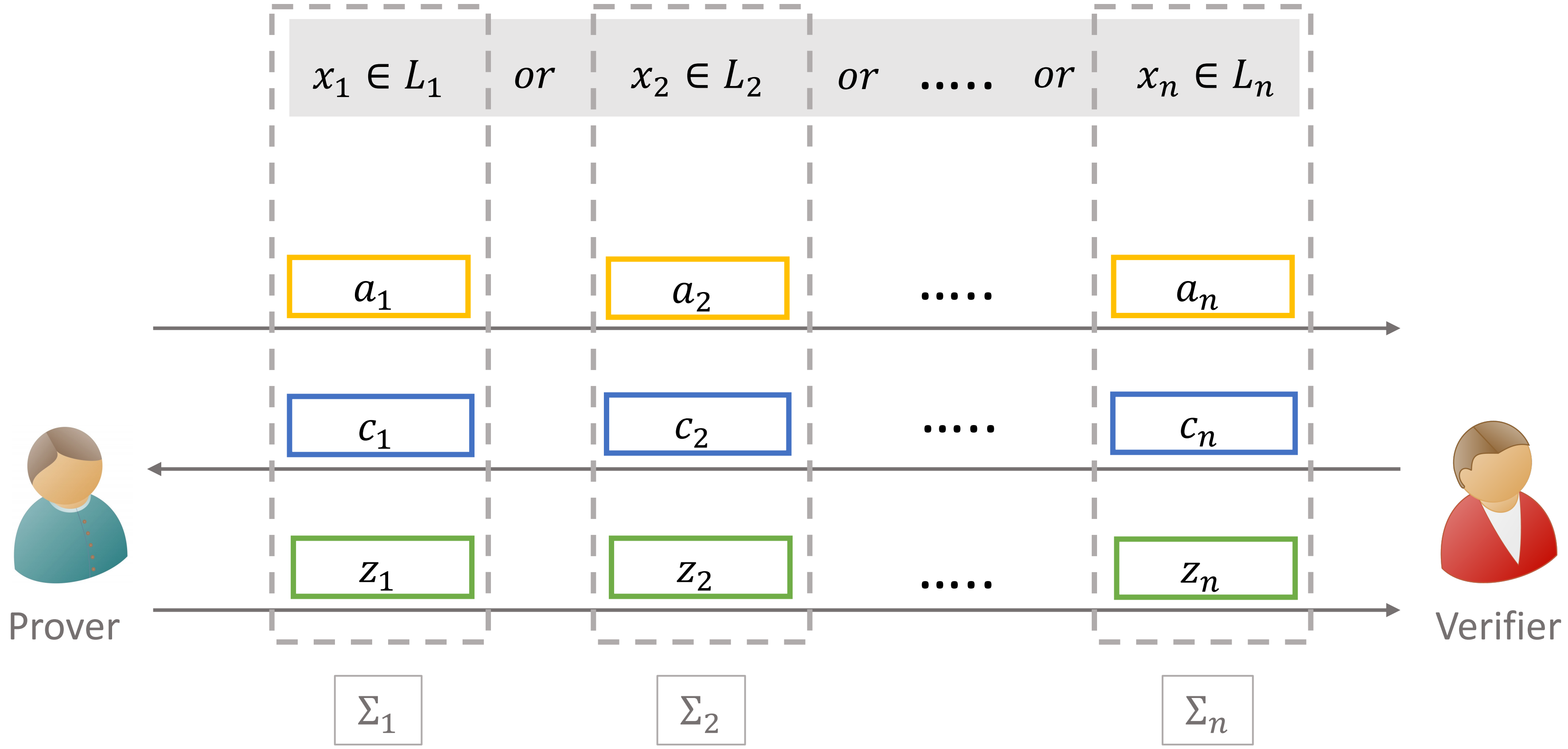

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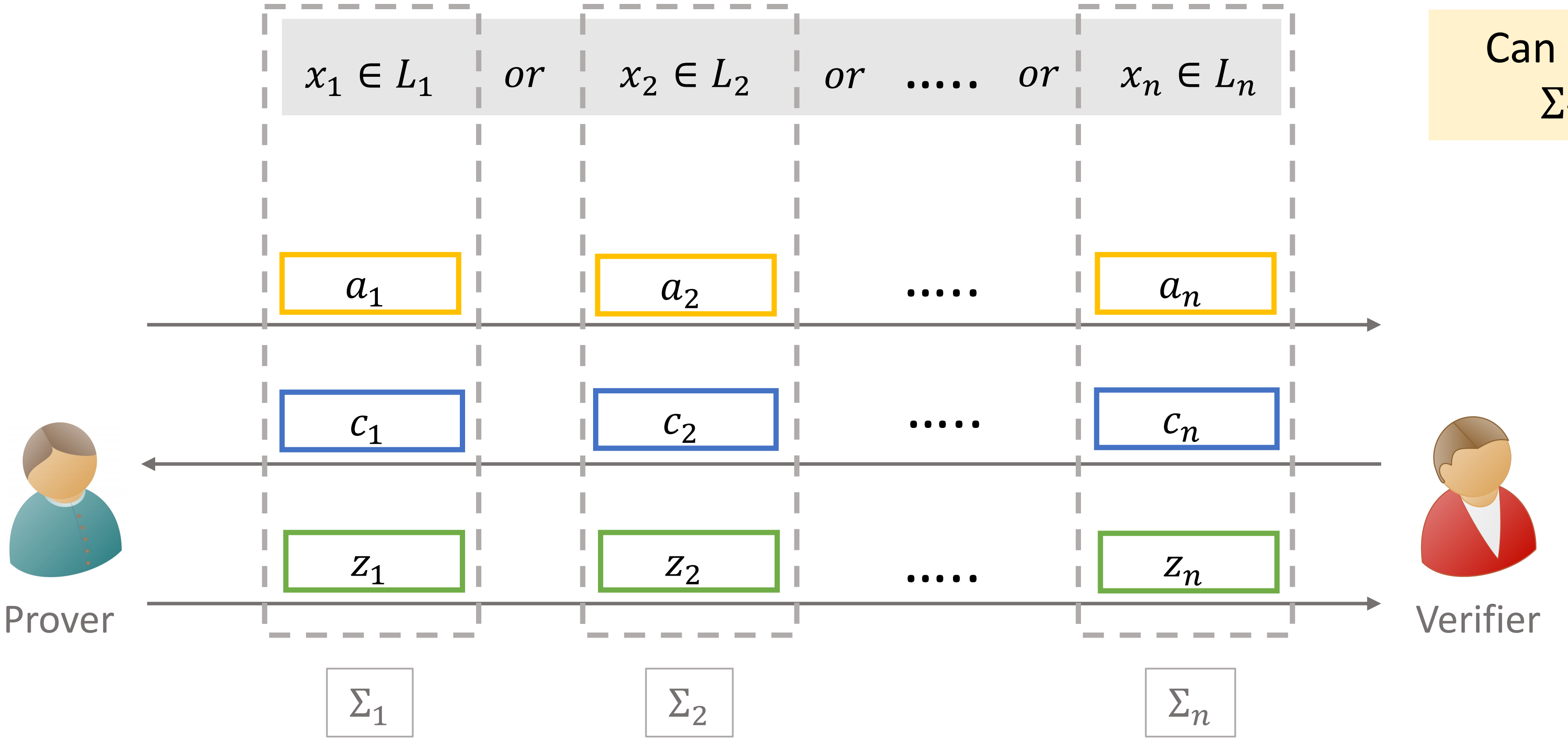
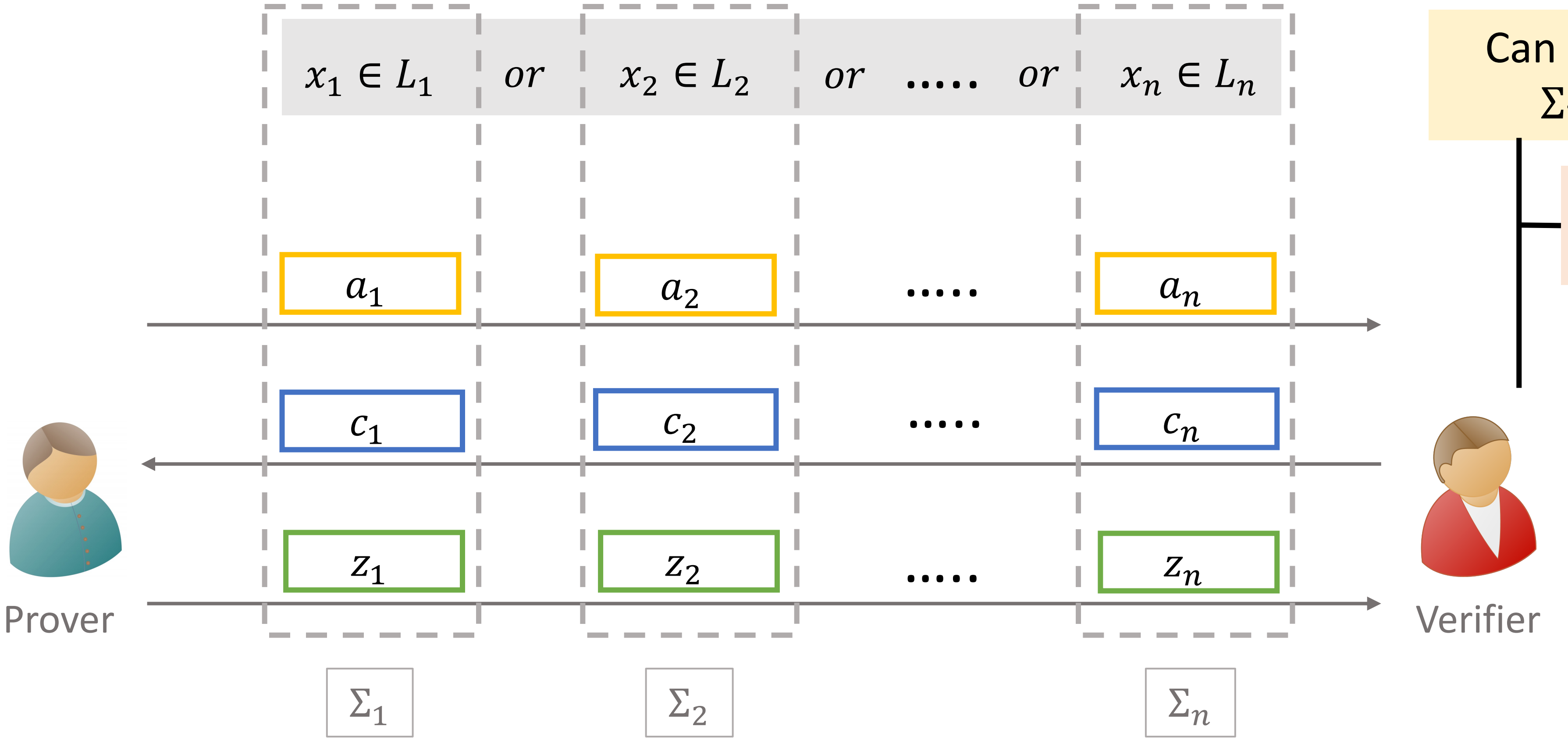


Can we generically compose these Σ-Protocols for disjunctions?

Stacking Σ-Protocols for Disjunctions



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Without modifying the underlying Σ-Protocols

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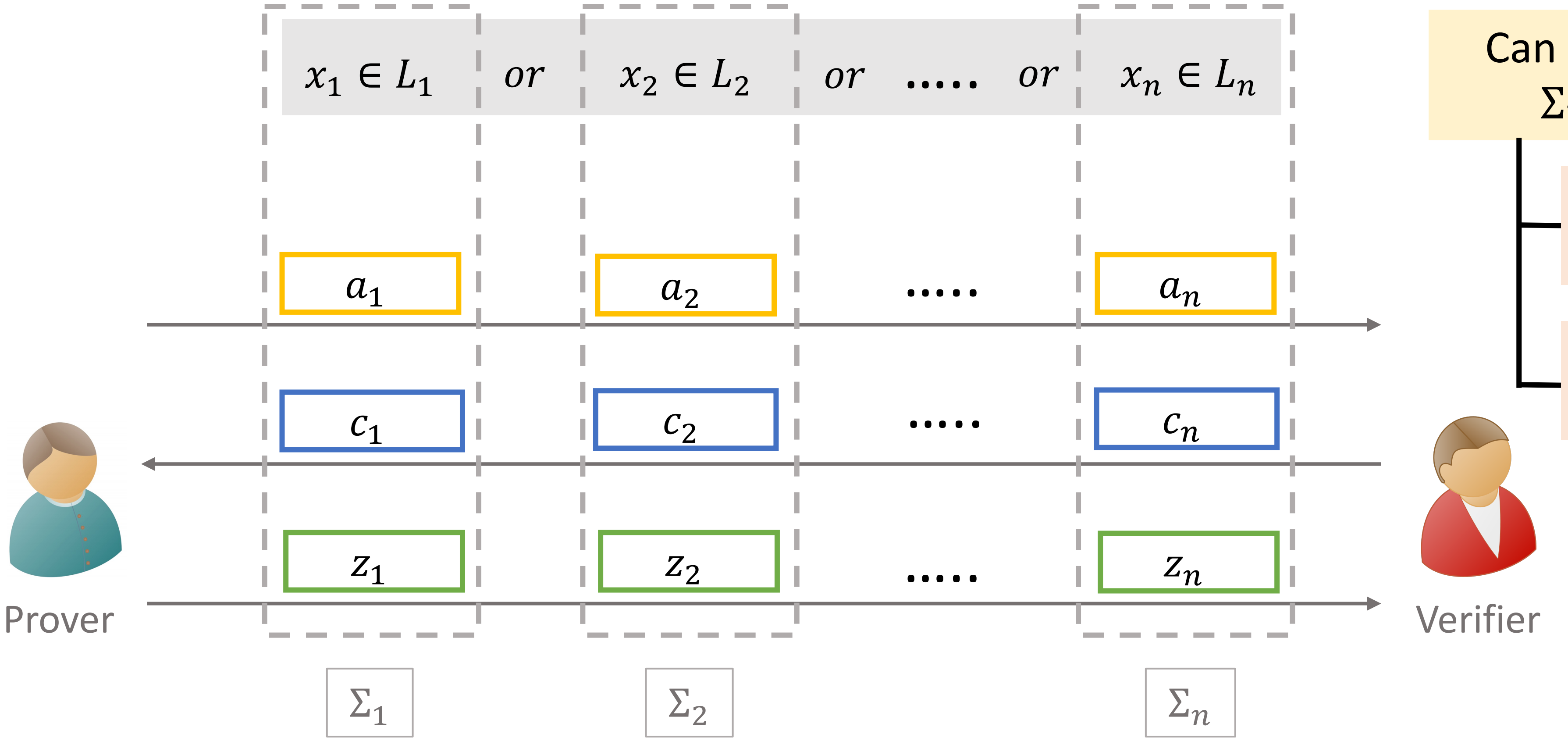

Can we generically compose these Σ-Protocols for disjunctions?

- Without modifying the underlying Σ-Protocols
- Communication is that same as that of proving a single branch

Applications of such Stacking Compilers

Reduces manual effort of modifying existing techniques

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Empowering protocol designers to choose appropriate Σ-protocols based on their application

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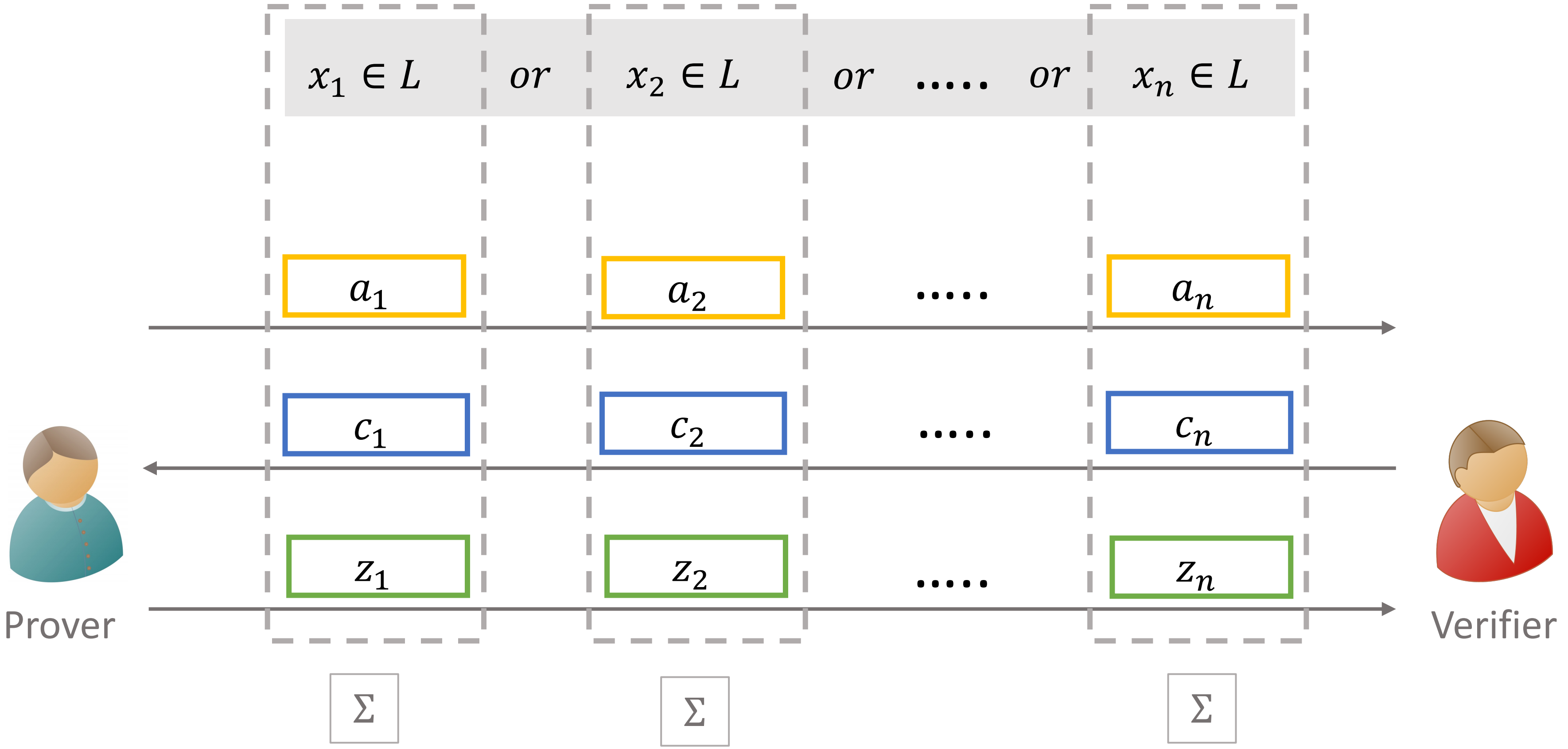

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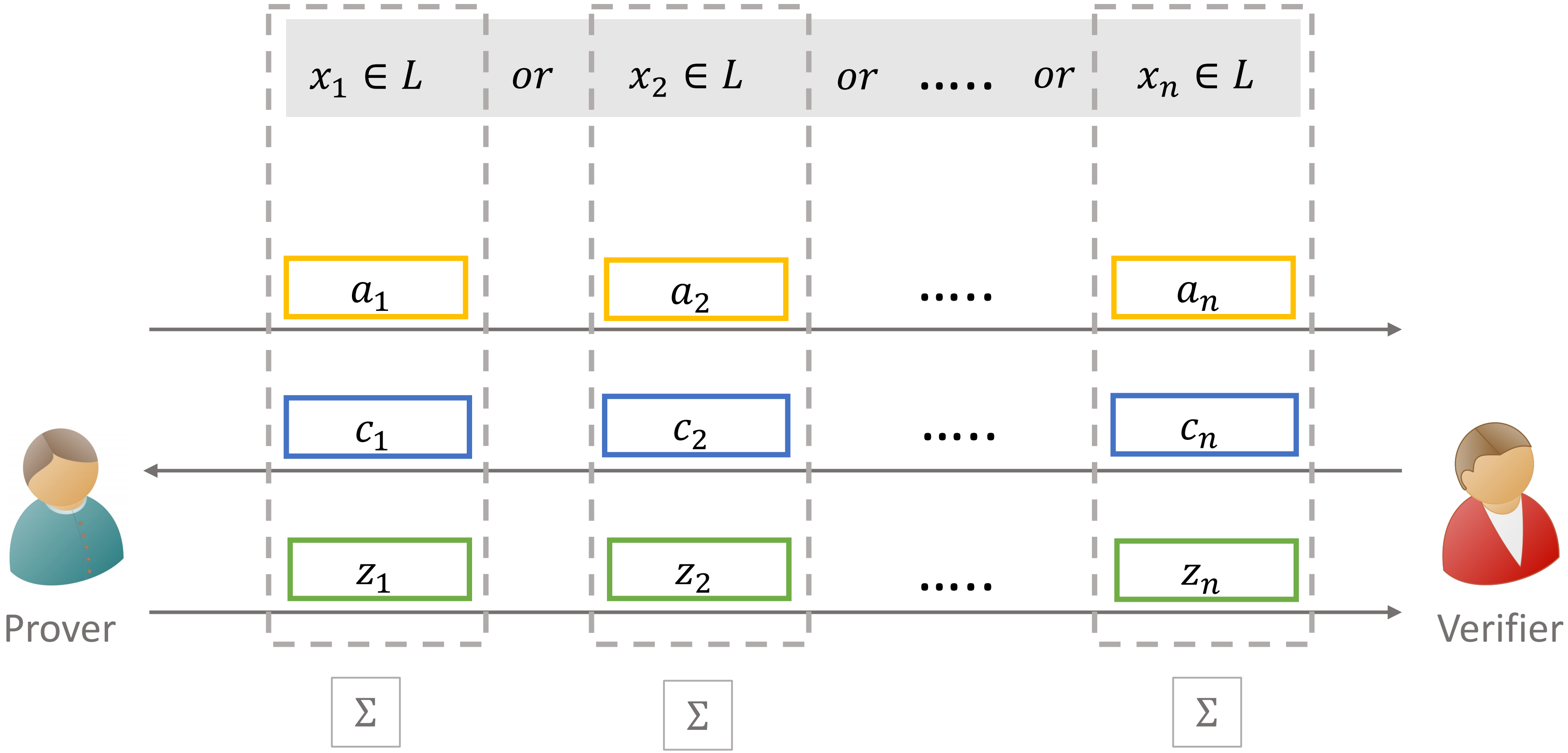
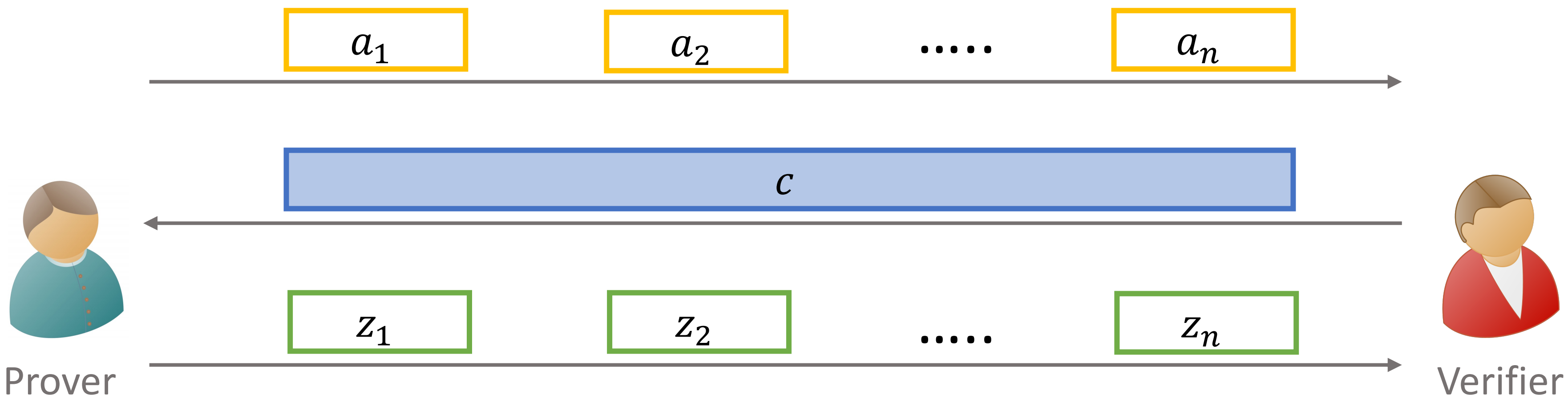


Stacking Σ-Protocols for Disjunctions

$x_1 \in L \quad or \quad x_2 \in L \quad or \quad ..... \quad or \quad x_n \in L$



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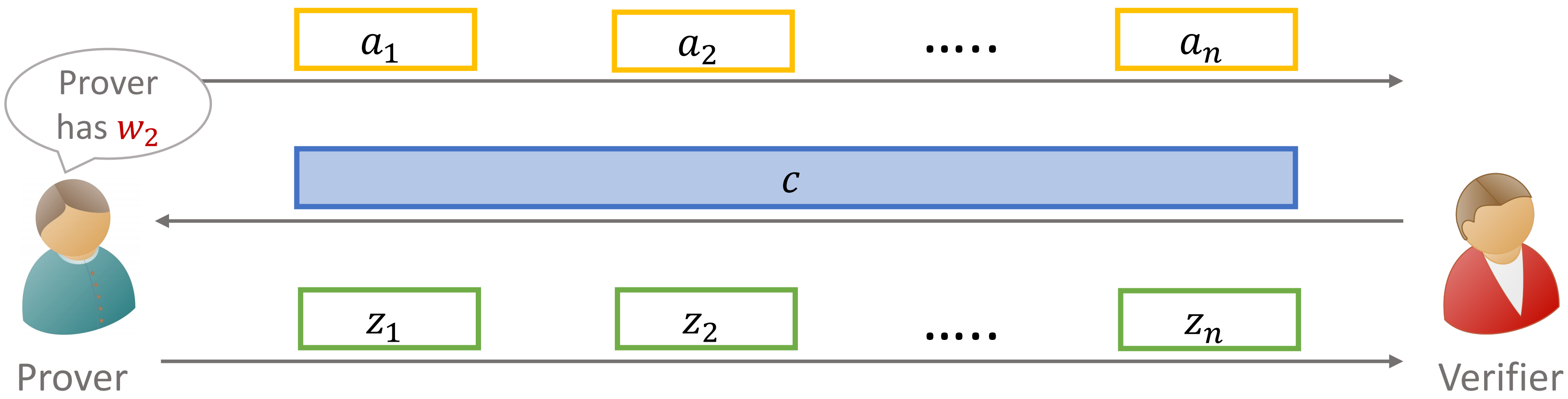

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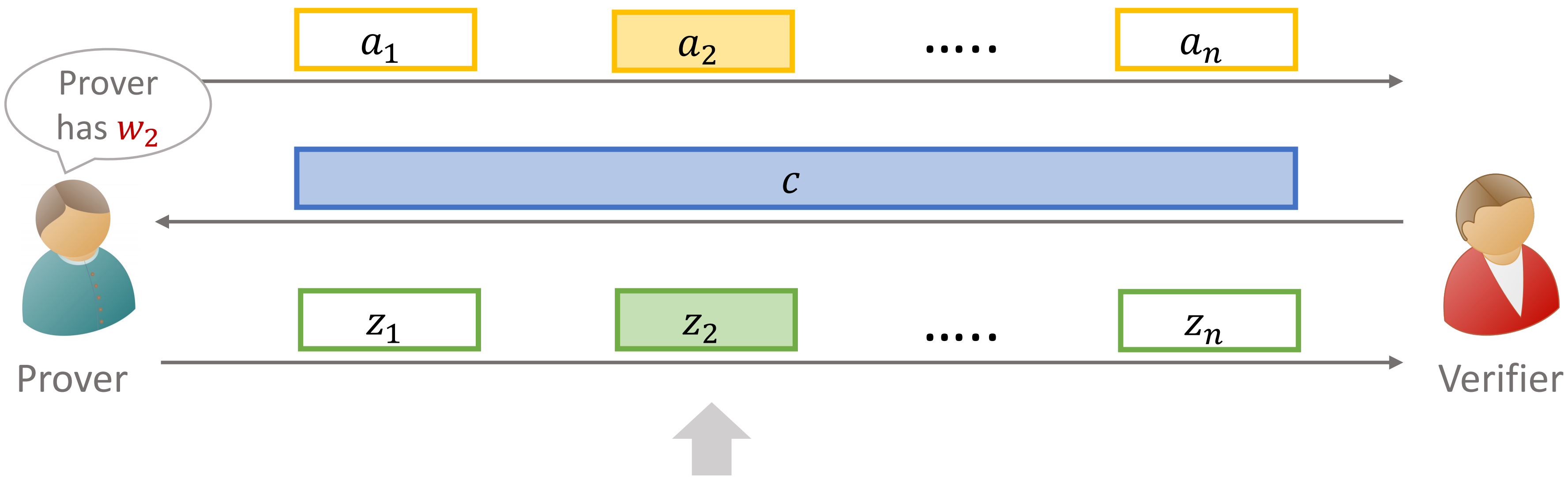

Prover can compute these messages

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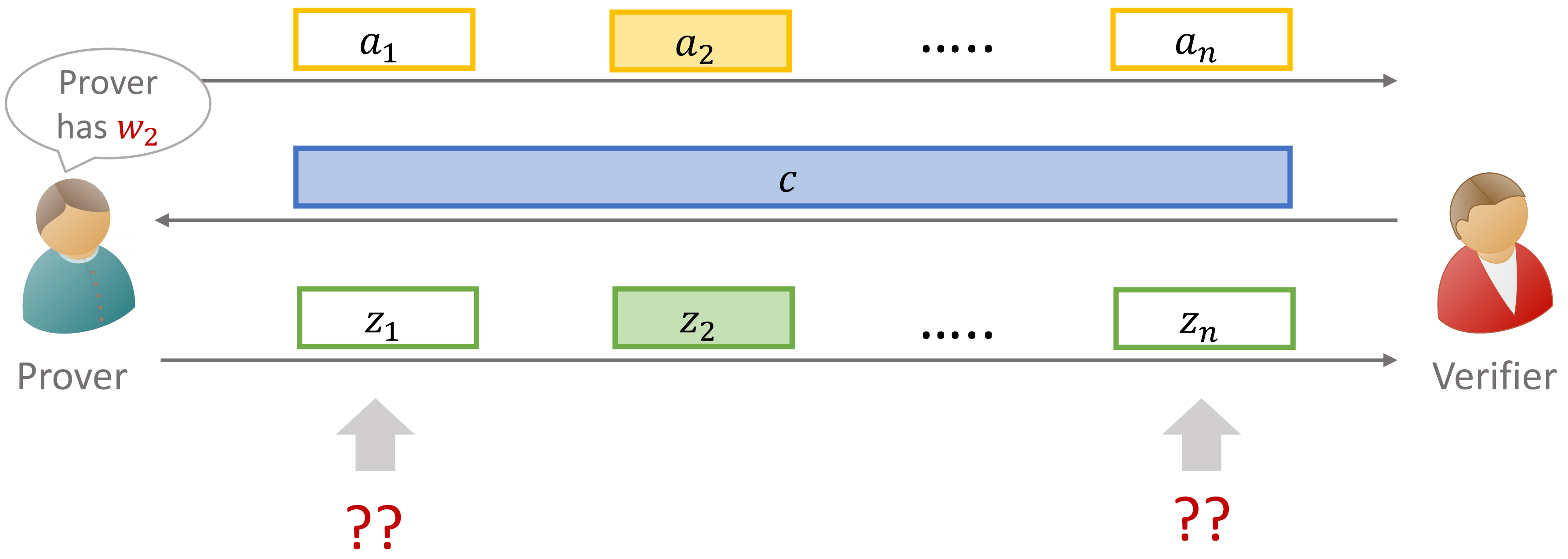

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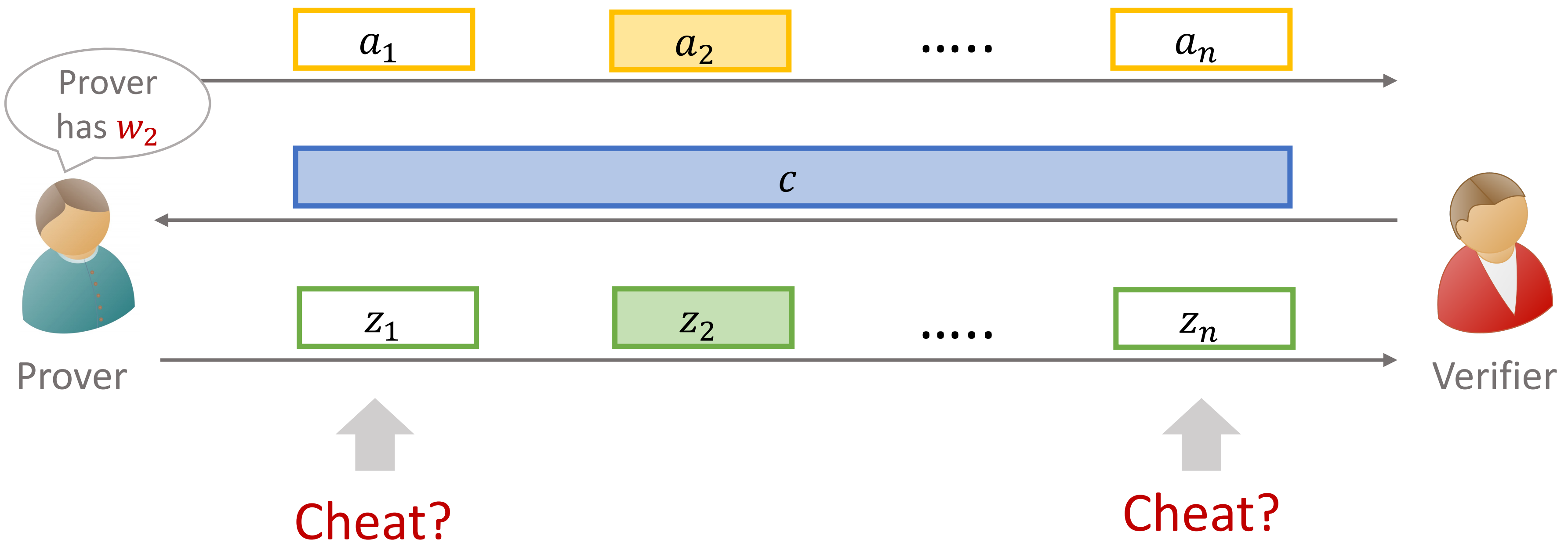

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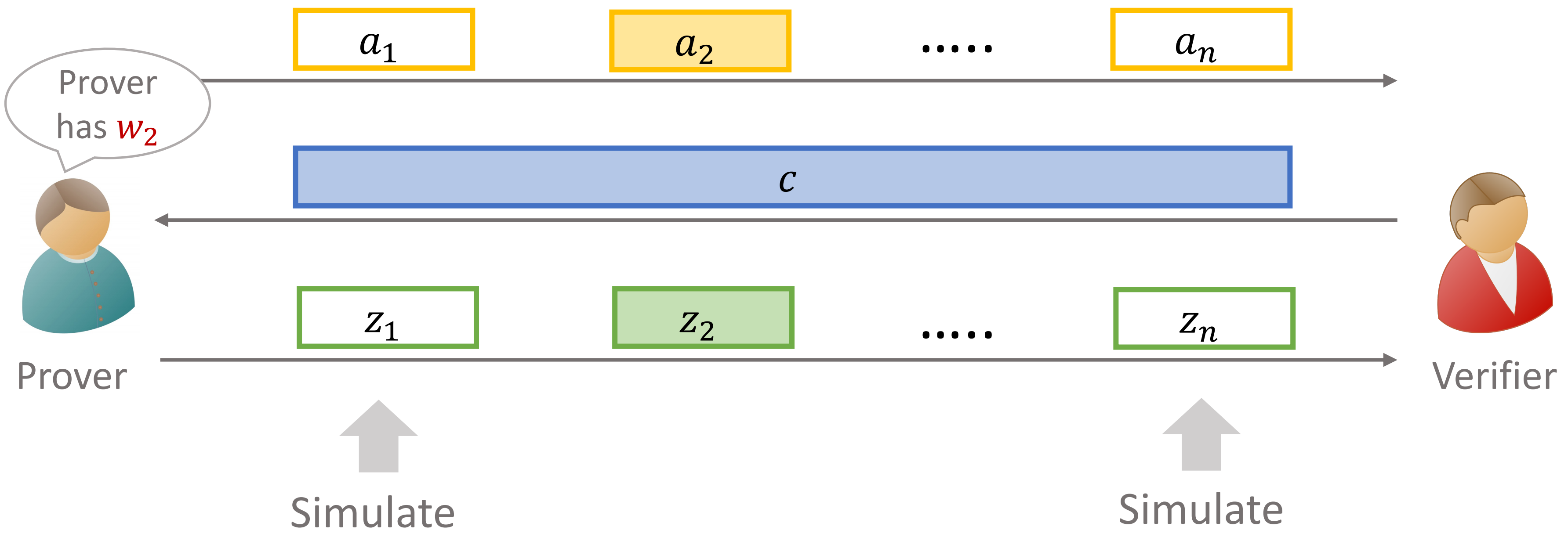

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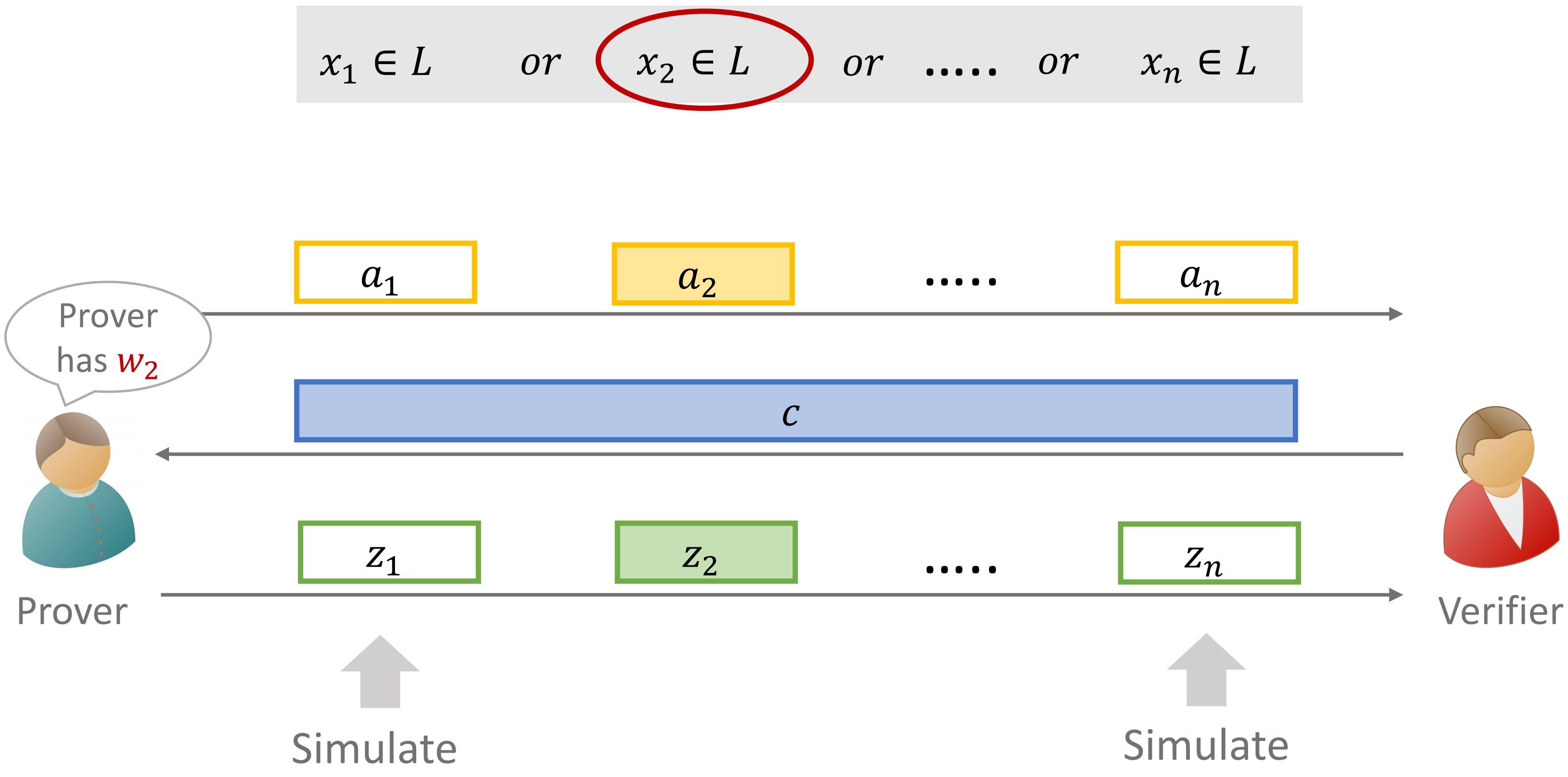
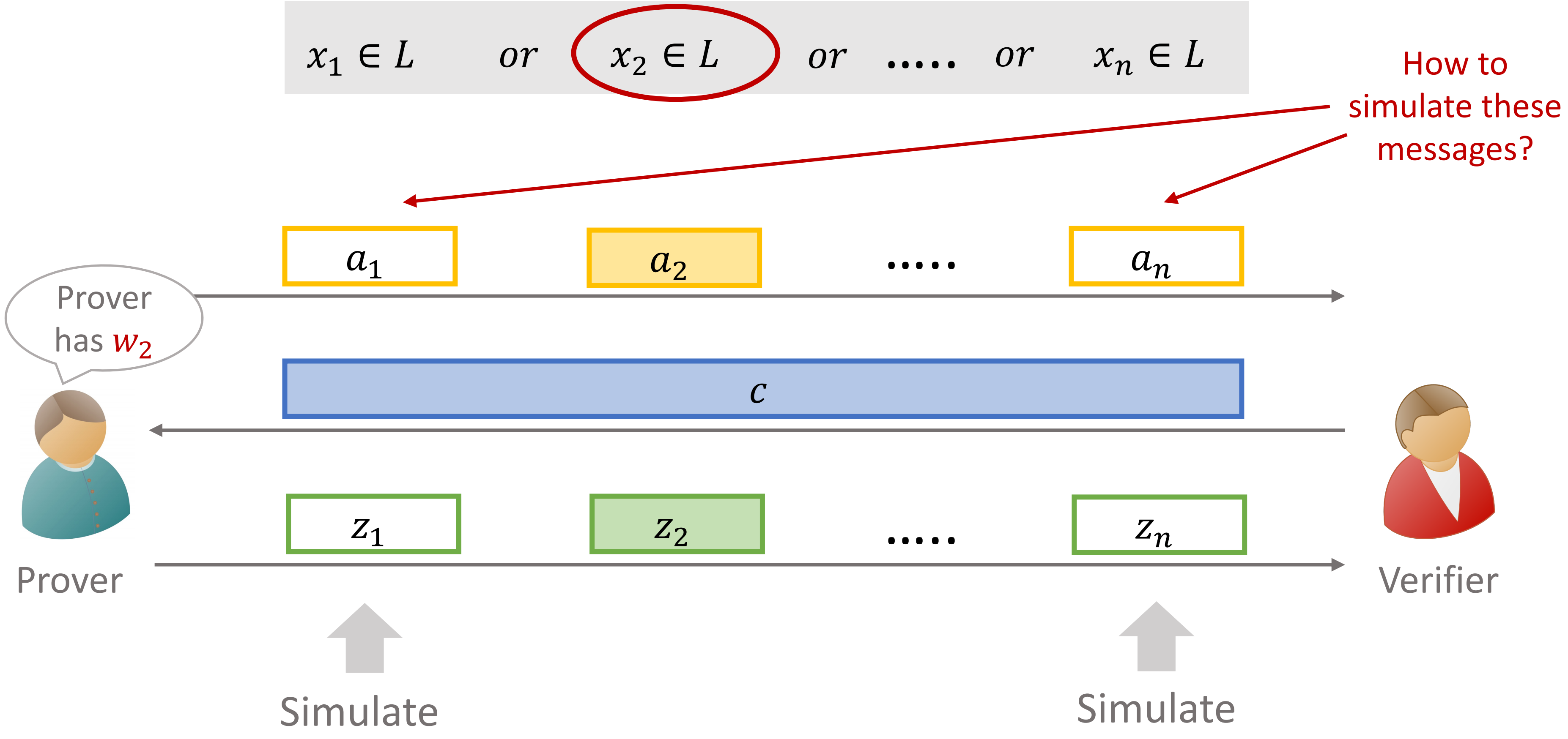


Common simulation strategy in Σ-protocols:

Step 1: Sample c

Step 2: Compute a, z

Stacking Σ-Protocols for Disjunctions



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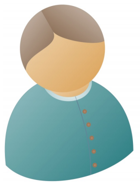
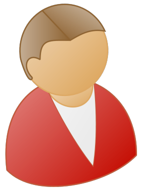
Prover has w_2



Prover



Verifier

<u>Common simulation strategy in Σ-protocols:</u>

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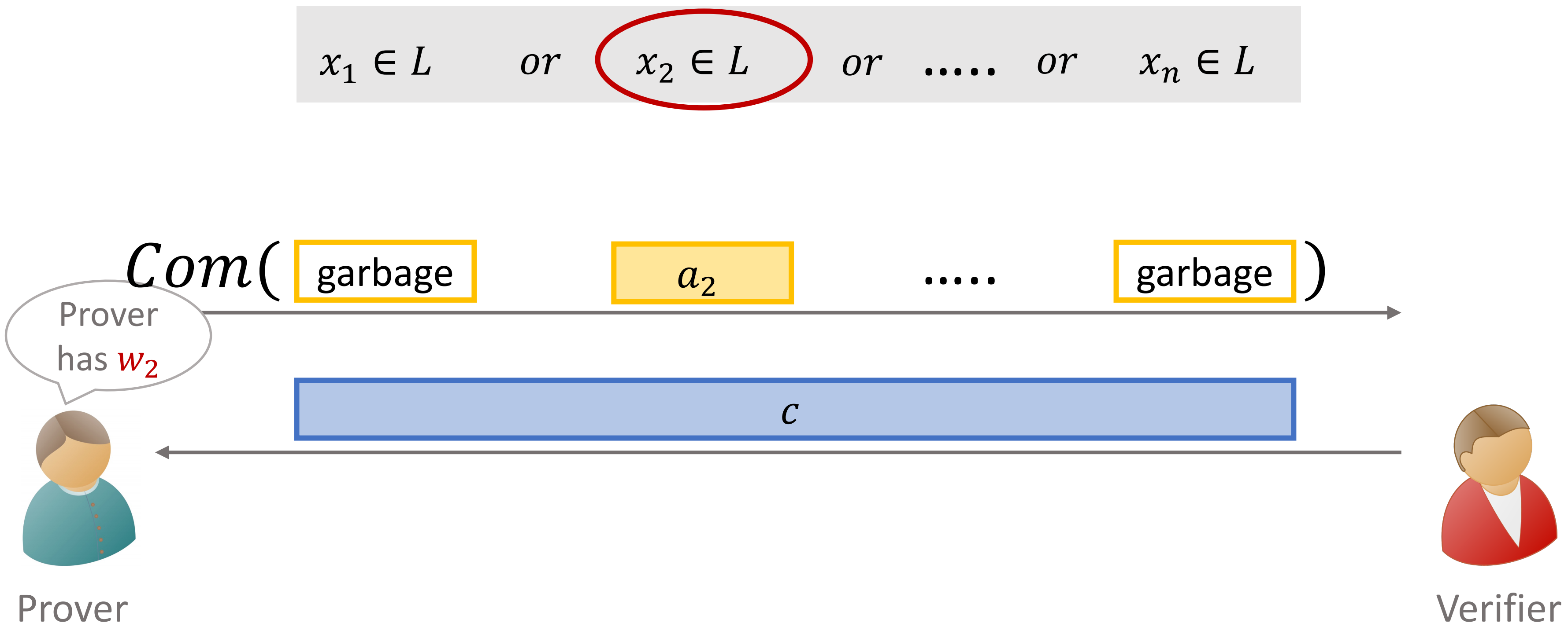
Stacking Σ-Protocols for Disjunctions



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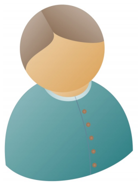

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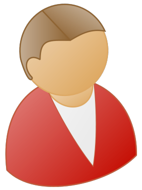

Verifier

Simulate $(a_1, z_1), (a_3, z_3) \ldots, (a_n, z_n)$

$op =$ Equivocate com to $[a_1, a_2, \ldots, a_n]$

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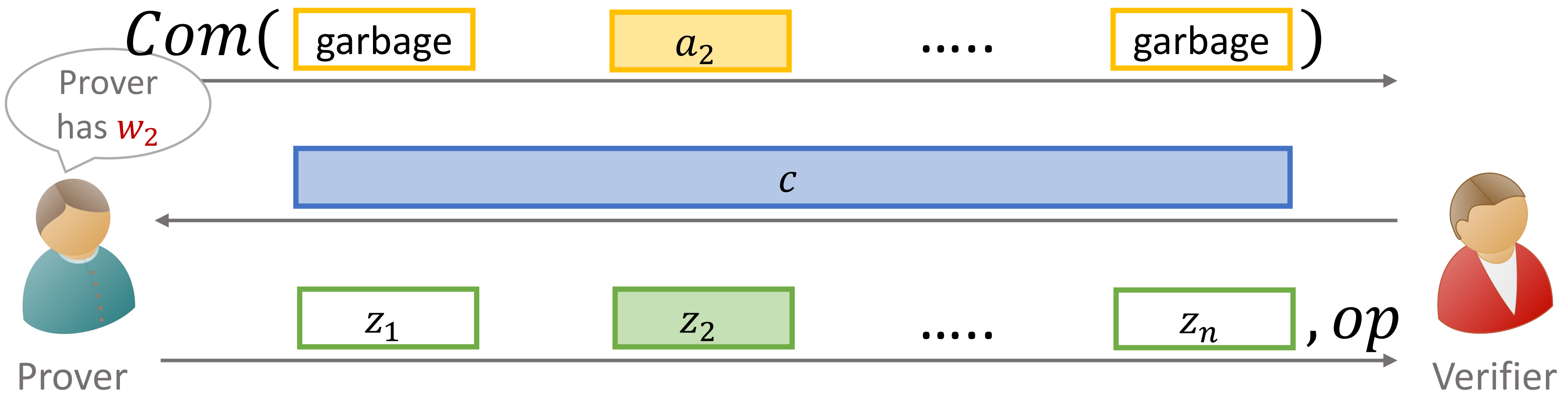

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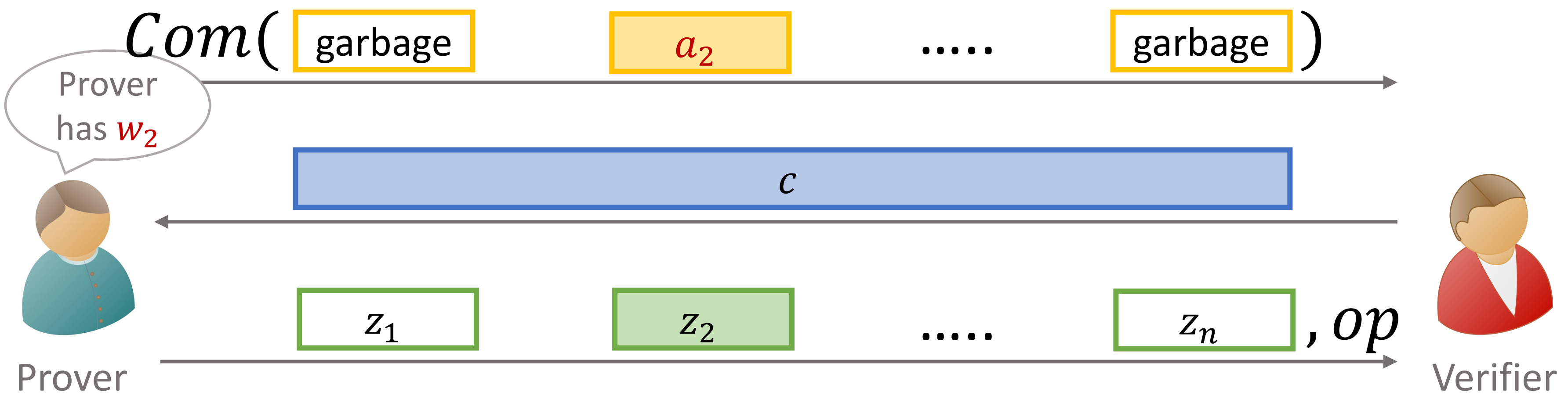

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Properties of these commitment schemes?

Partially Binding Vector Commitments

t-out-of-n positions are binding. Rest can be equivocated.

Binding positions are fixed at the time of commitment.

Binding positions remain hidden from the receiver.

We propose a construction using Discrete Log

Stacking Σ-Protocol for Disjunctions

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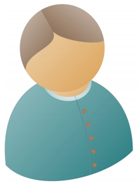

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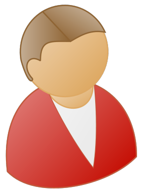

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Compute z_2 honestly

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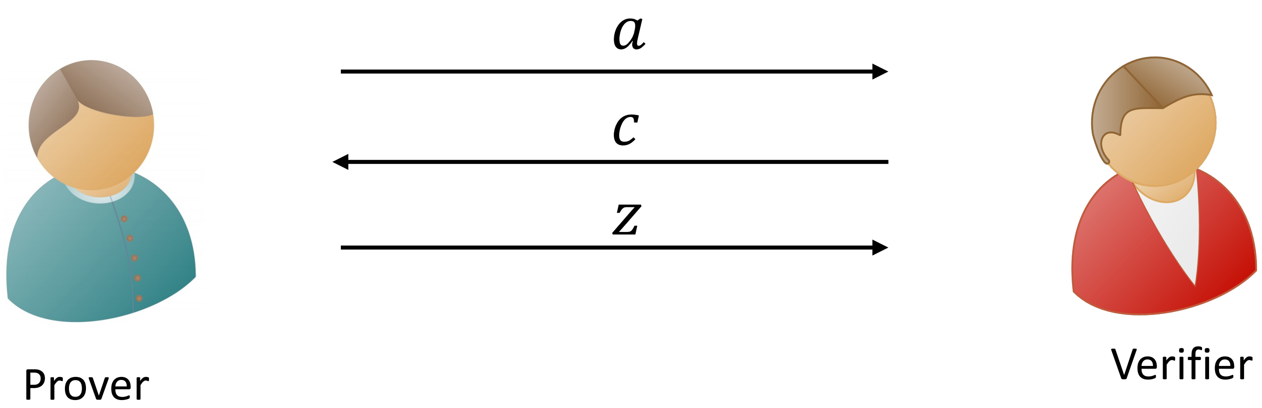
z_1 z_2 ..... z_n $, op$

This is a valid Σ-protocol for disjunctions. But we haven't really saved any communication?

Bulkiest Part of a Σ-Protocol



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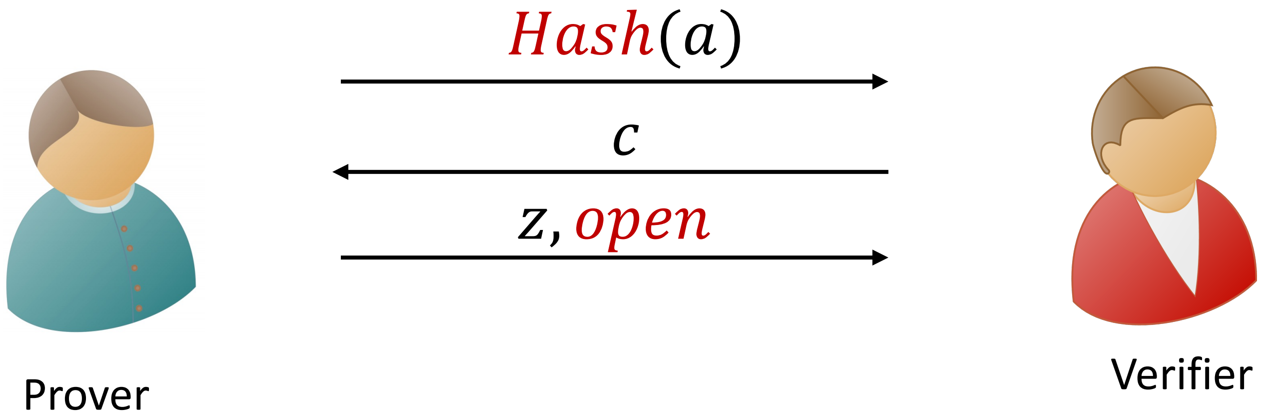
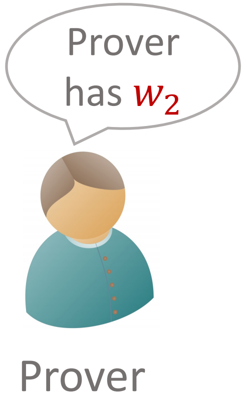


W.l.o.g., Third round messages are the longest!

Stacking Σ-Protocol for Disjunctions



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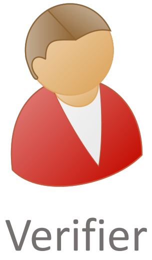
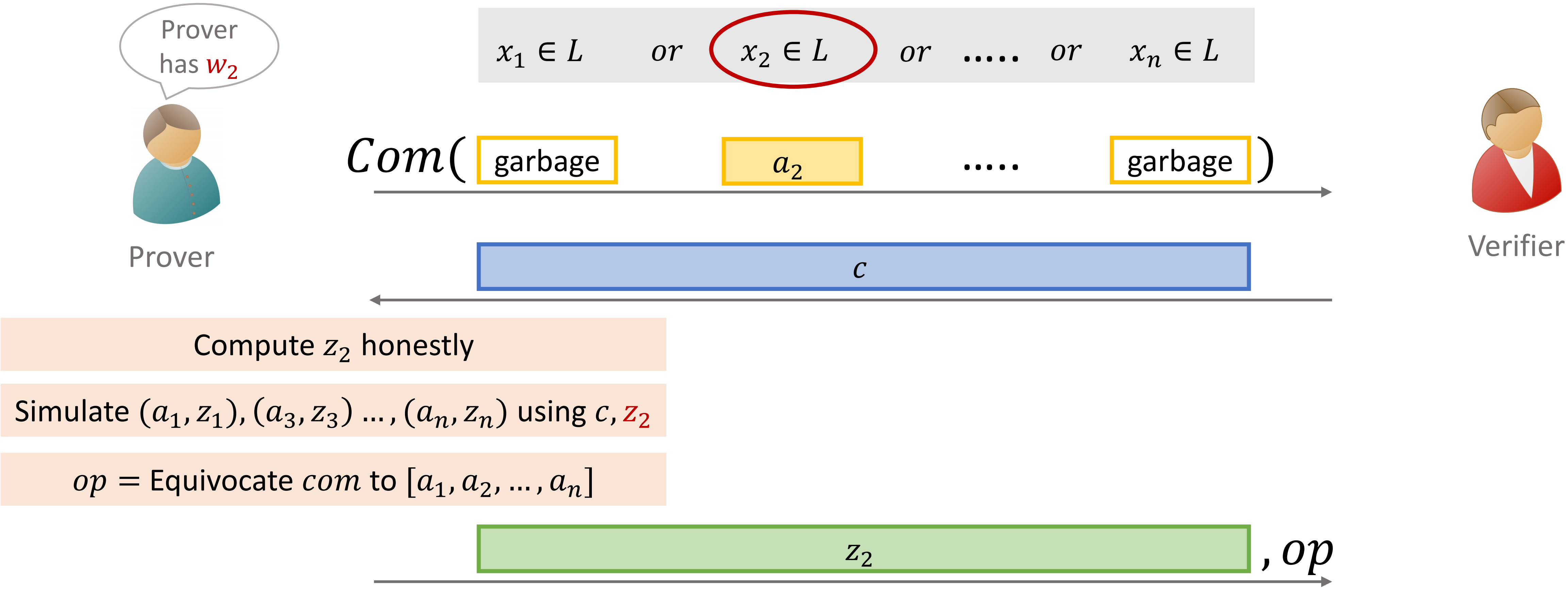


Can we re-use the third-round message of the active branch?

Stacking Σ-Protocol for Disjunctions



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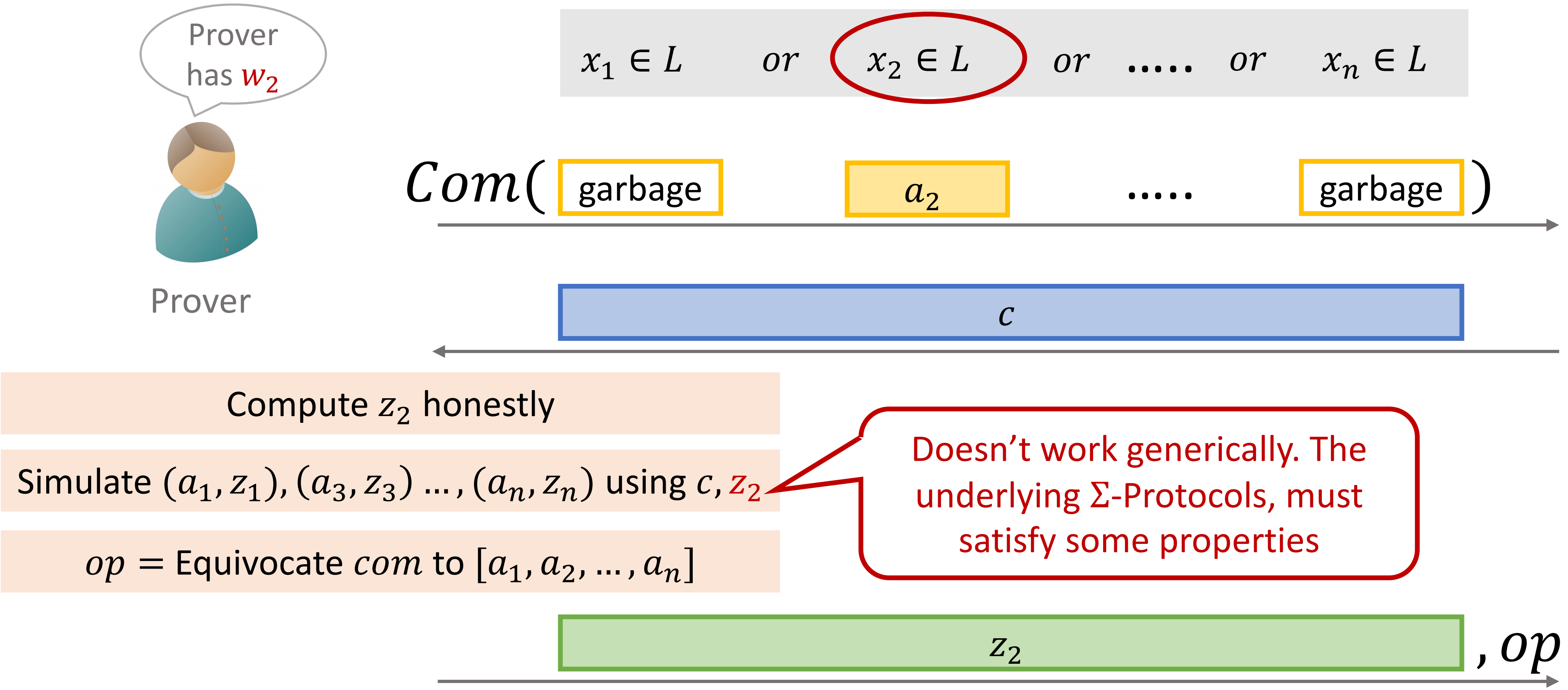

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$$\mathcal{D}_c^{(z)} \approx \left\{z \mid r^p \xleftarrow{\$} \{0,1\}^\lambda; a \leftarrow A(x,w;r^p); z \leftarrow Z(x,w,c;r^p)\right\}$$

Stackable Properties

Property 1: Extended Honest Verifier Zero-knowledge

$$\left\{(a,c,z) \mid r^p \xleftarrow{\$} \{0,1\}^\lambda; a \leftarrow A(x,w;r^p); z \leftarrow Z(x,w,c;r^p)\right\} \approx \left\{(a,c,z) \mid z \xleftarrow{\$} \mathcal{D}_{x,c}^{(z)}; a \leftarrow \mathcal{S}^{\text{EHVZK}}(1^\lambda,x,c,z)\right\}$$

+

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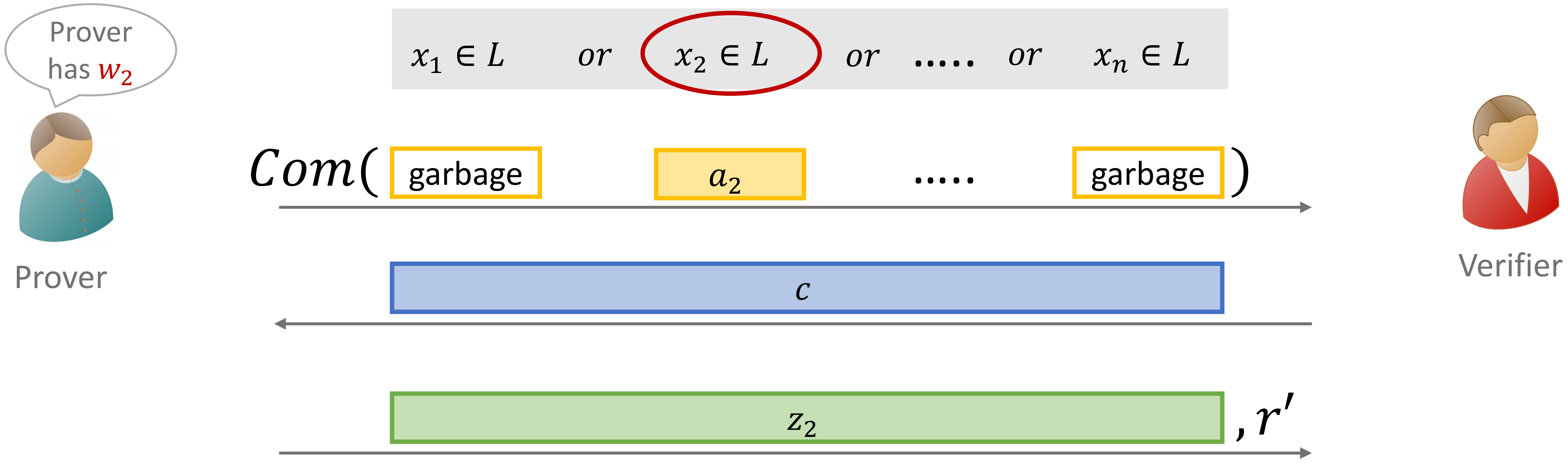
Stacked Σ-Protocol for Disjunctions



Communication = proof size for proving a single branch + size of commitment + size of opening

Can be short

At least linear in the length of the vector

Recursive Stacking

$x_1 \in L \quad or \quad x_2 \in L \quad or \quad \ldots.. \quad or \quad x_n \in L$

1 out of 2 disjunction

$\Sigma_2 =$ Stack Σ and Σ

Communication = | Σ | + Commitment + 1

Recursive Stacking

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1 out of 2 disjunction	Σ_2 = Stack Σ and Σ	Communication = | Σ | + Commitment + 1
1 out of 4 disjunction	Σ_4 = Stack Σ_2 and Σ_2	Communication = | Σ | + 2 $\times$ Commitment + 1 + 1

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1 out of 2 disjunction	Σ_2 = Stack Σ and Σ	Communication = | Σ | + Commitment + 1
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1 out of 8 disjunction	Σ_8 = Stack Σ_4 and Σ_4	Communication = | Σ | + 3 $\times$ Commitment + 1 +1 + 1

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.....

1 out of n disjunction	$\Sigma_n =$ Stack $\Sigma_{n/2}$ and $\Sigma_{n/2}$	Communication = | Σ | + log(n) $\times$ Commitment + log(n)

Examples of Stackable Σ-Protocols

Many natural sigma protocols are stackable

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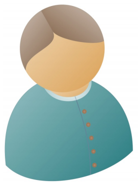
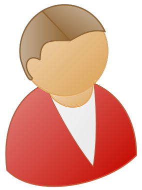


Prover

$$\xrightarrow{a = g^r}$$

$$\xleftarrow{c}$$

$$\xrightarrow{z = cw + r}$$



Verifier

Examples of Stackable Σ-Protocols

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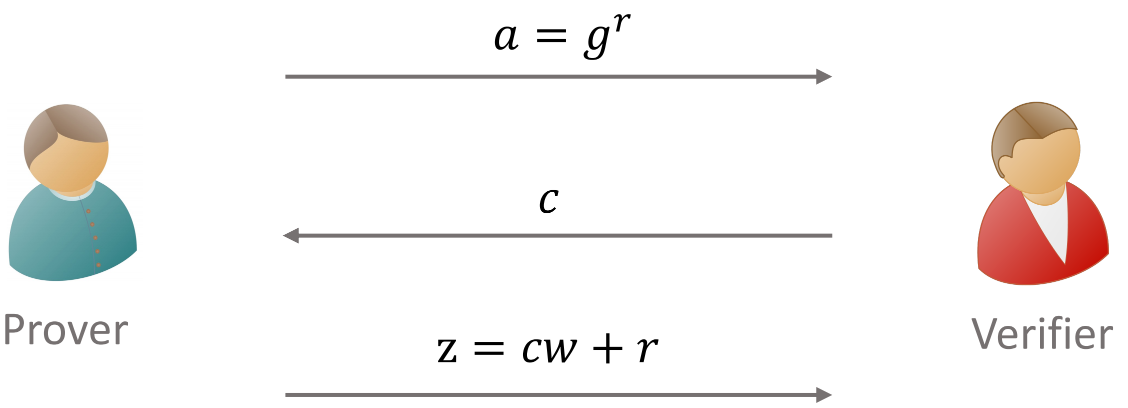

Simulation Strategy: Sample random z. Compute $a = g^z x^{-c}$

Independent of instance

Examples of Stackable Σ-Protocols

Many natural sigma protocols are stackable

Example 1:	Schnorr's Σ-Protocol
Example 2:	Graph 3-coloring

Is a graph $G = (V, E)$, 3-colorable?

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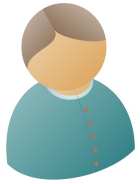
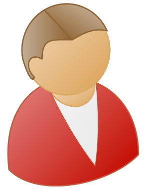


Prover

$a =$ commitment of permuted 3-coloring

c = random edge in graph

z =open colors of the edge



Verifier

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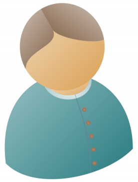

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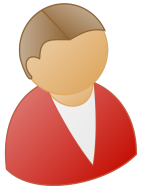

Verifier

Examples of Stackable Σ-Protocols

Many natural sigma protocols are stackable

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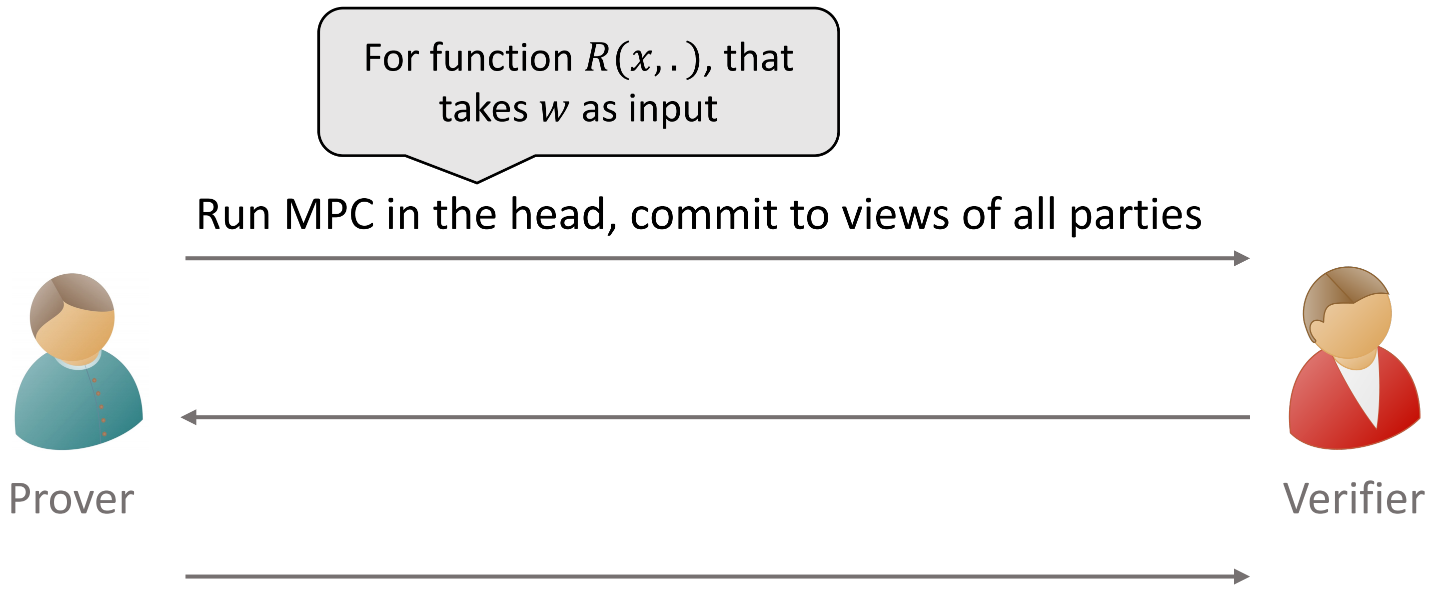
Example 2:	Graph 3-coloring
Example 2:	MPC-in-the-head [IKOS]

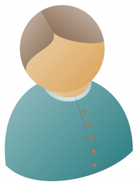
[IKOS07] is Stackable?



[IKOS07] is Stackable?

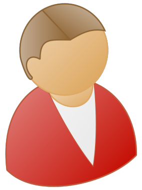
For function $R(x,.)$, that takes w as input

Run MPC in the head, commit to views of all parties



Prover

Choose a random subset of parties



Verifier

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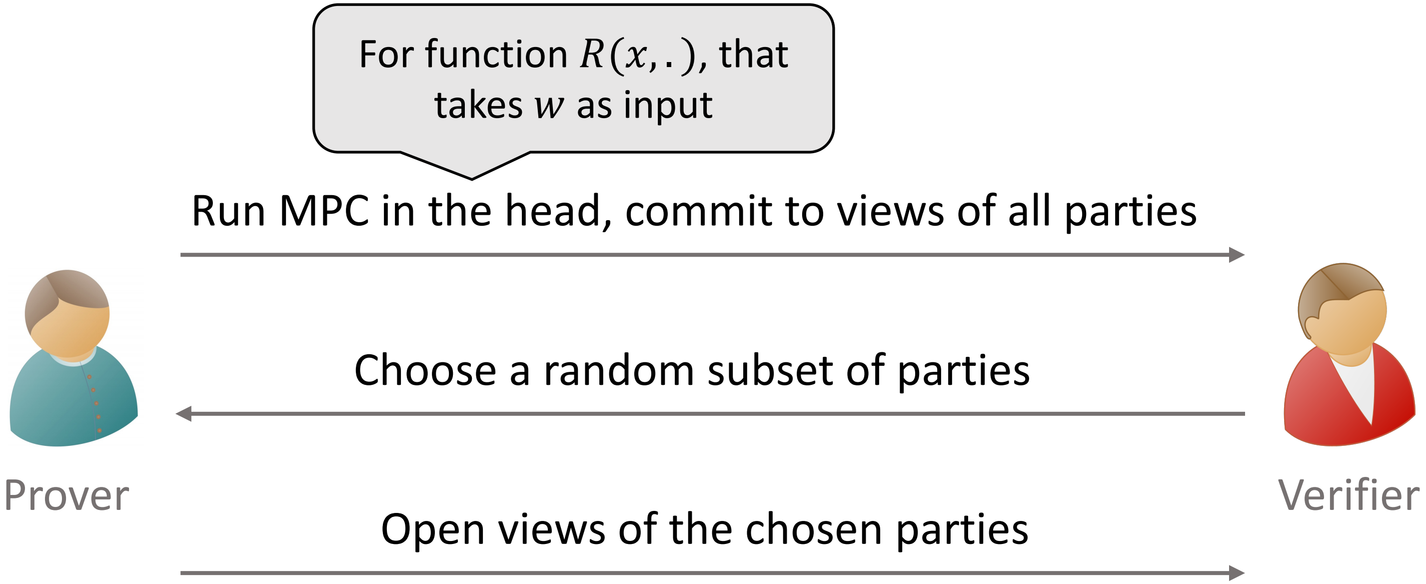

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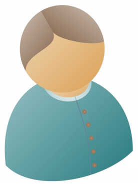

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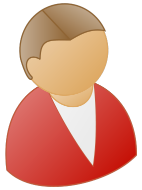


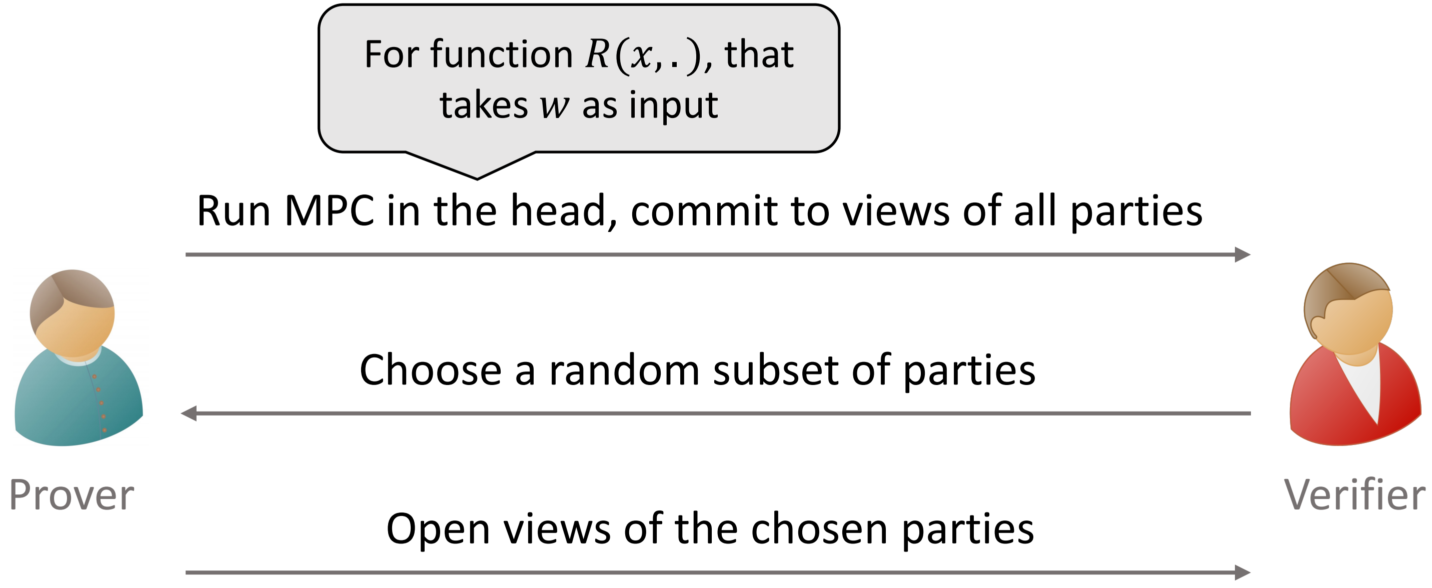
Verifier

Open views of the chosen parties →

Simulator

Choose a random subset of parties

[IKOS07] is Stackable?



Simulator

Choose a random subset of parties

Simulate the views of these parties' using simulator of the underlying MPC protocol

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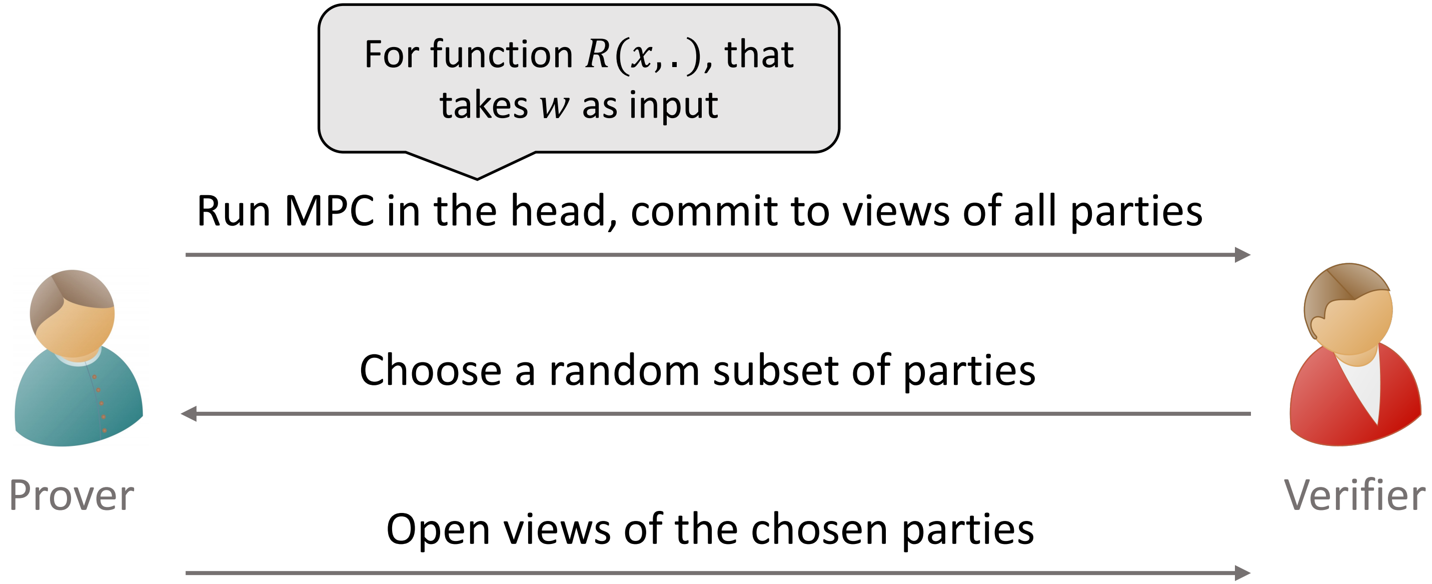

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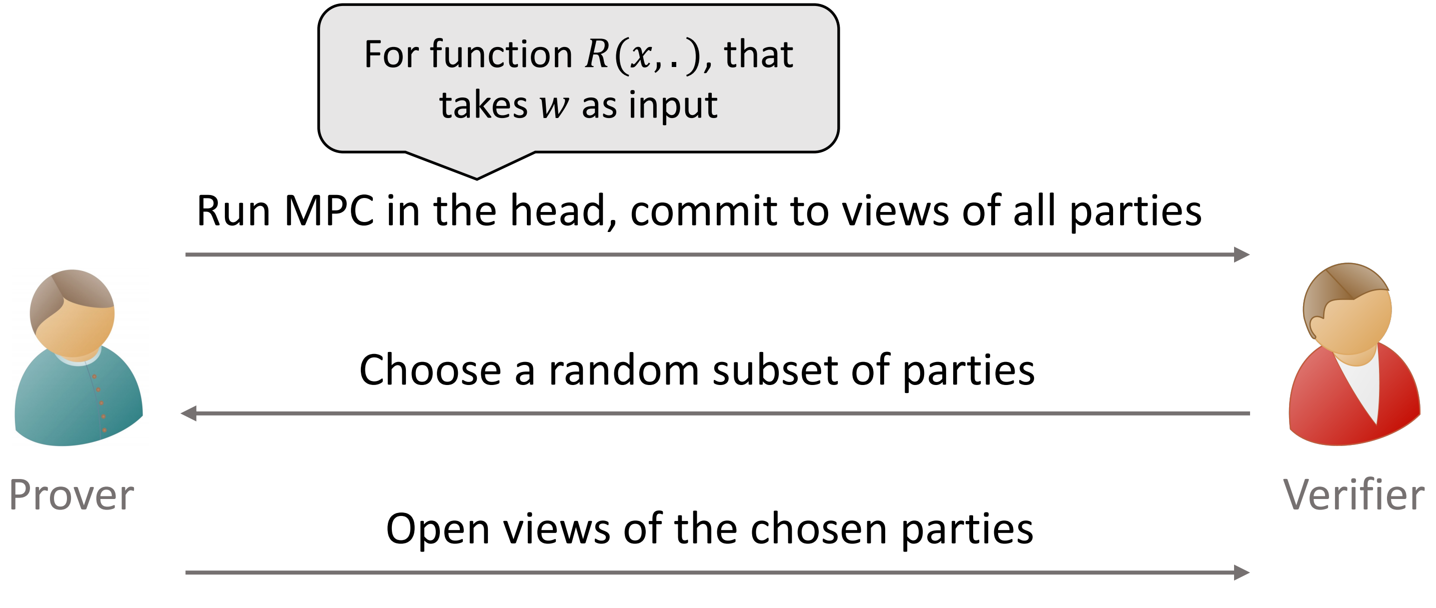

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It is naturally EHVZK. What about recyclable third round messages?

F-Universally Simulatable MPC

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Adversary's view in many MPC protocols can be condensed and decoupled from the structure of the functionality being evaluated

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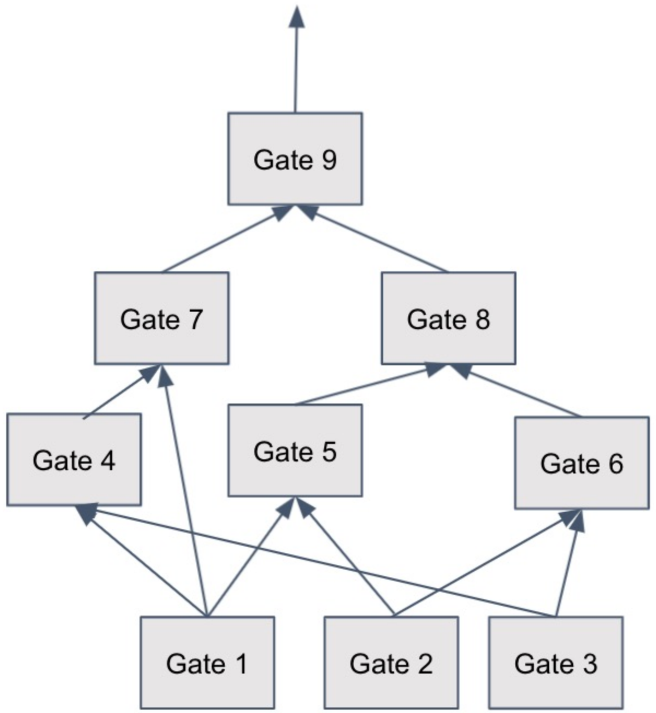
Example: Many secret sharing-based MPC (e.g. [BGW88])



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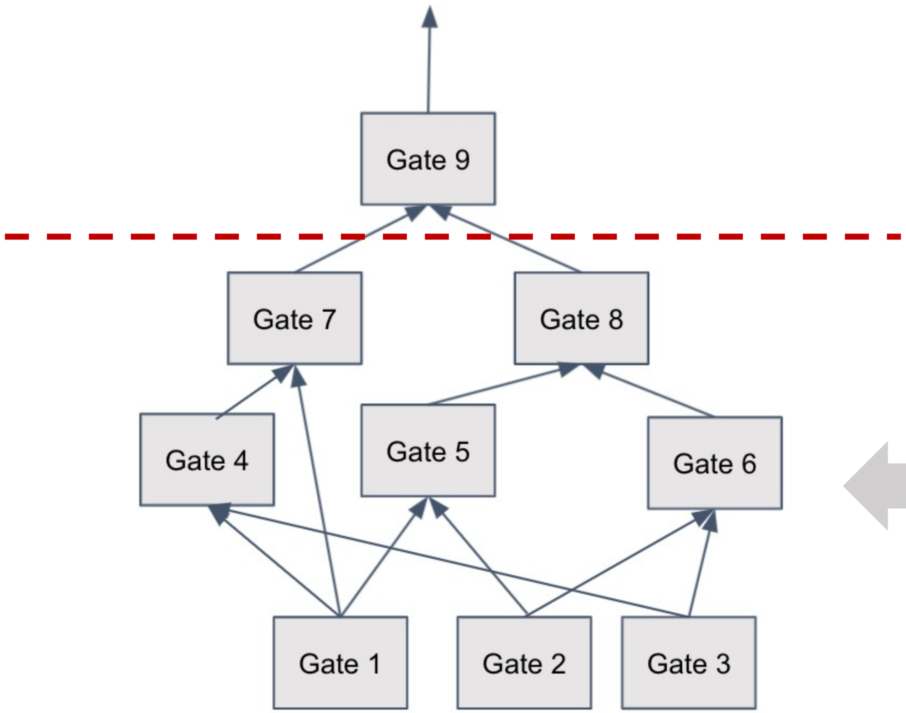

Simulator simulates random shares for the adversary for each of these gates

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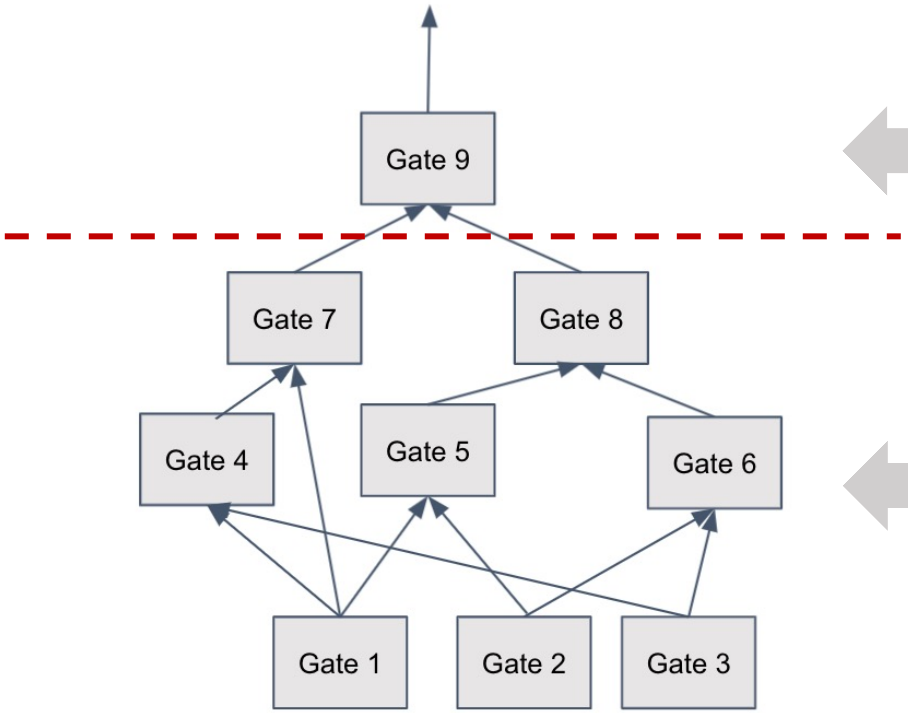

Given previously simulated shares and the output, simulate the final message

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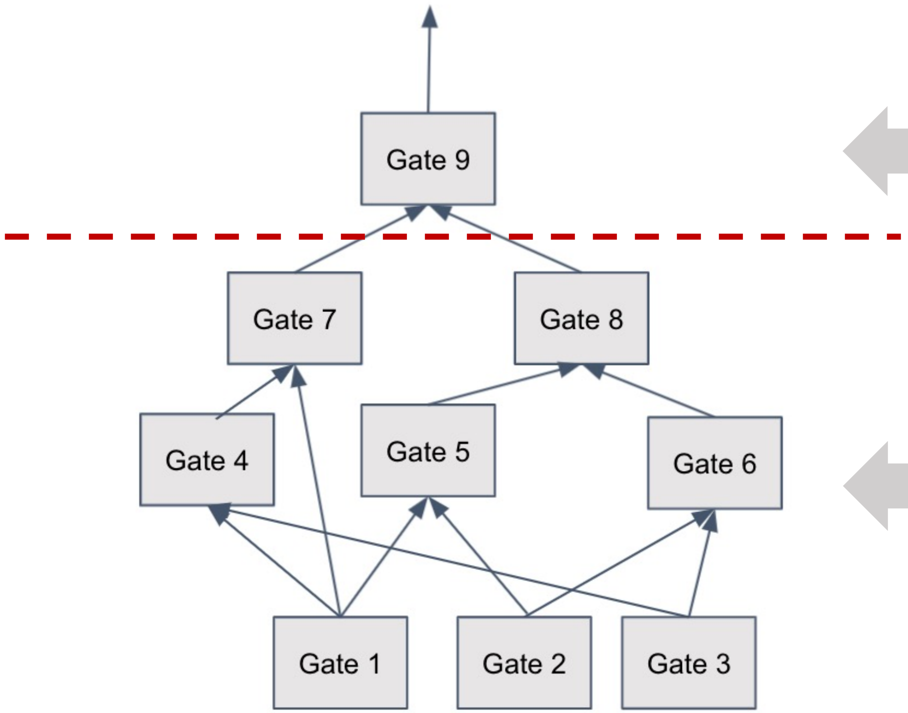

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Deterministic computation

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Independent of the function/circuit!

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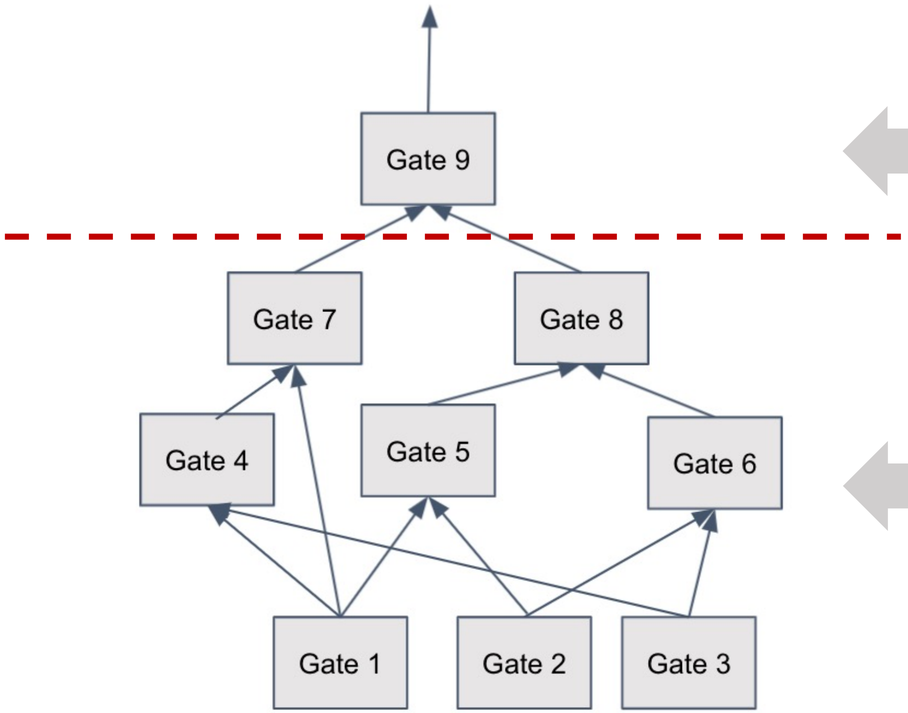

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Expanded Views

Deterministic computation

Simulator simulates random shares for the adversary for each of these gates

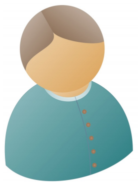
Condensed Views

Independent of the function/circuit!

Modified [IKOS07] for F-Universally Simulatable MPC

For function $R(x,.)$, that takes w as input

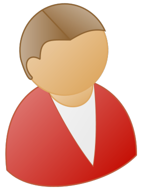
Run MPC in the head, commit to views of all parties



Prover

Choose a random subset of parties

Condensed views of the chosen parties and randomness used in corresponding commitments



Verifier

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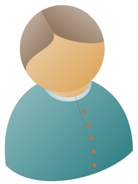

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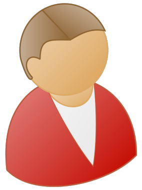

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Condensed views of the chosen parties and randomness used in corresponding commitments

Verifier can expand condensed views assuming output is 1, check if commitments are valid and perform all other consistency checks

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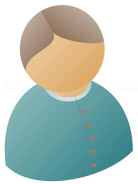

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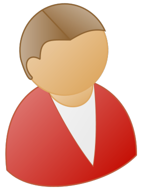

Verifier

Since condensed views are independent of the functionality, this protocol now has recyclable third-round message

Verifier can expand condensed views assuming output is 1, check if commitments are valid and perform all other consistency checks

Disjunctions with Different Languages

$$x_1 \in L_1 \quad or \quad x_2 \in L_2 \quad or \quad \textbf{.....} \quad or \quad x_n \in L_n$$

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Sometimes same protocol works for different languages

If third round messages are over different fields/rings – represent as bits and see what parts can be re-used

Thank You!