Secure Multiparty Computation with Free Branching

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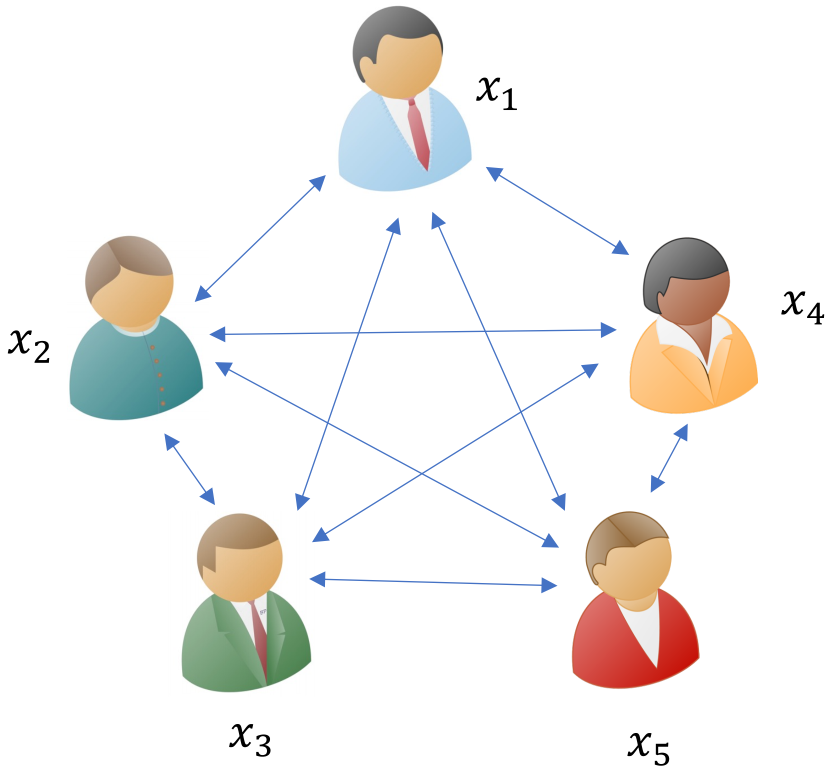
Secure Multiparty Computation (MPC)



MPC protocol for computing $y = f(x_1, x_2, x_3, x_4, x_5)$

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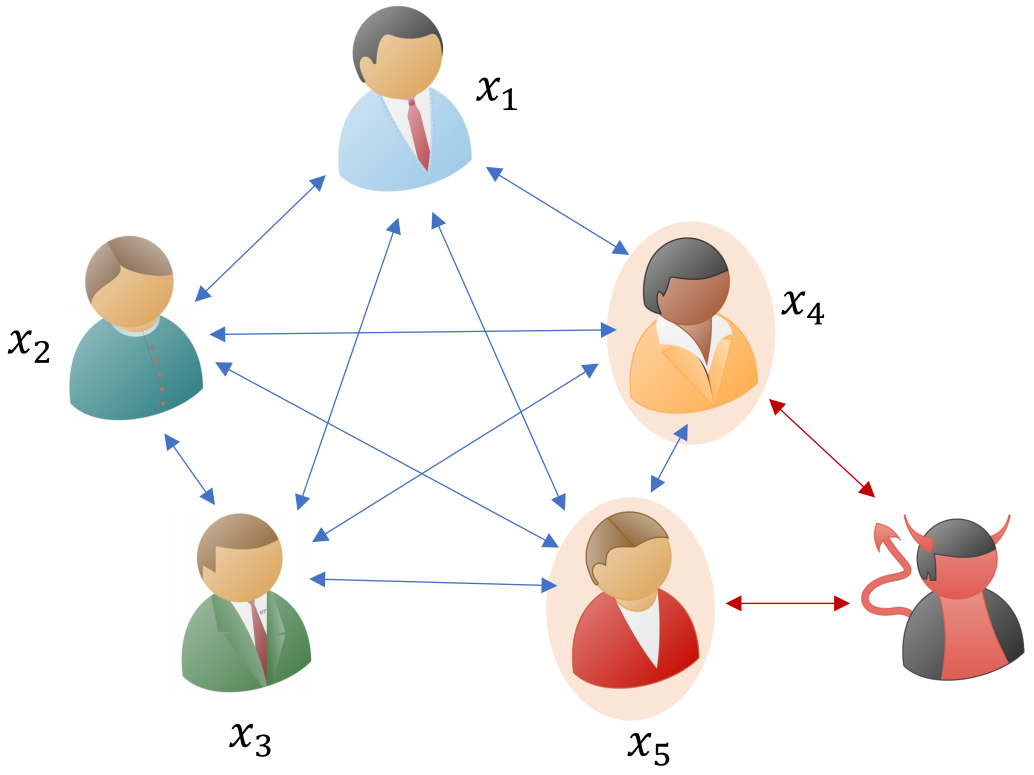
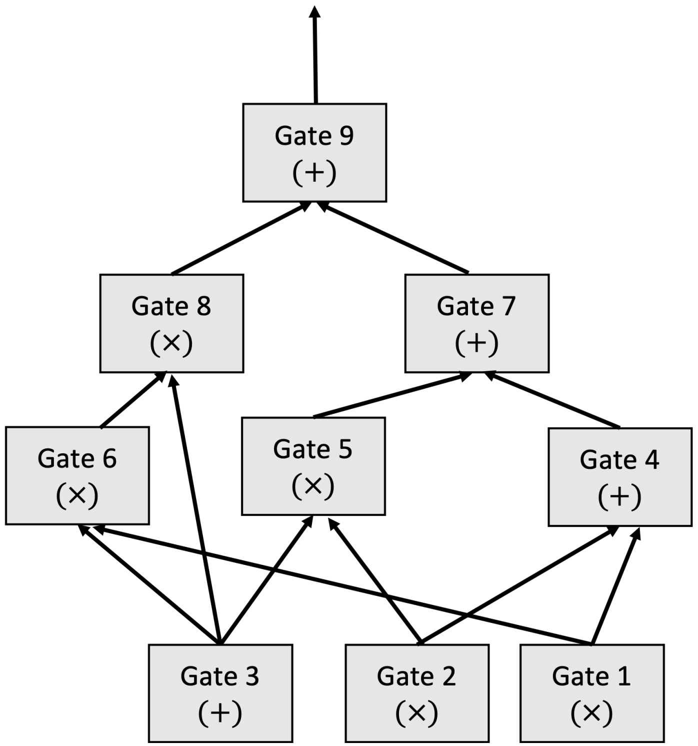


Adversary learns nothing beyond the output y

MPC protocol for computing $y = f(x_1, x_2, x_3, x_4, x_5)$

Limitation of Existing Efficient MPC Protocols



Existing protocols rely on circuit representation of functions

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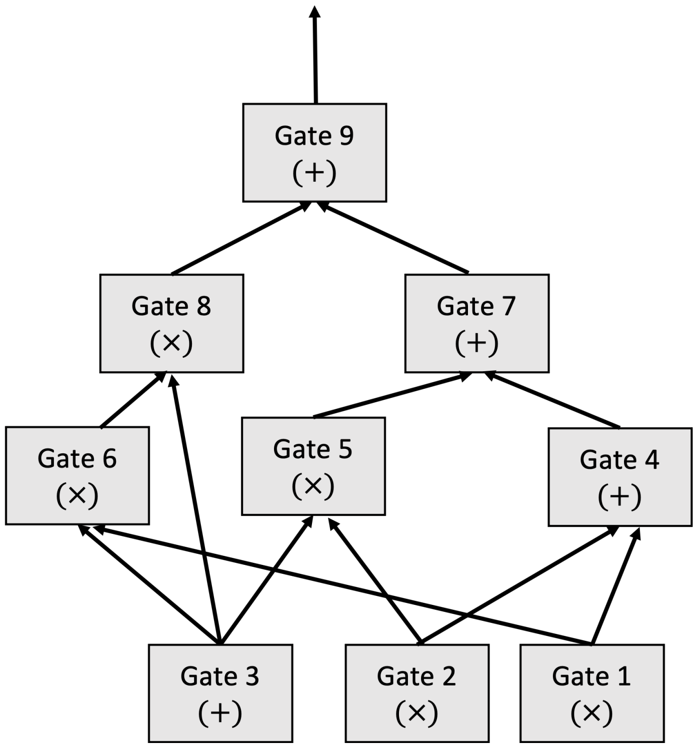

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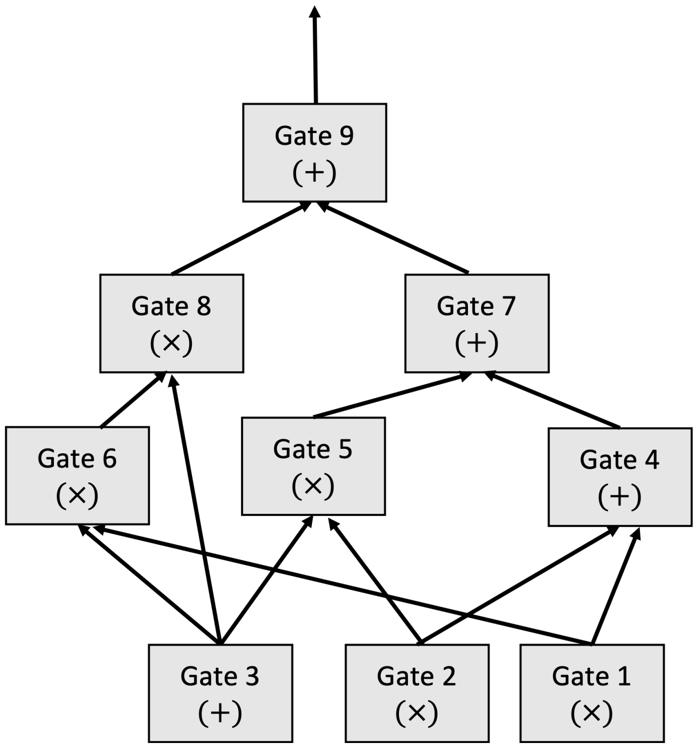
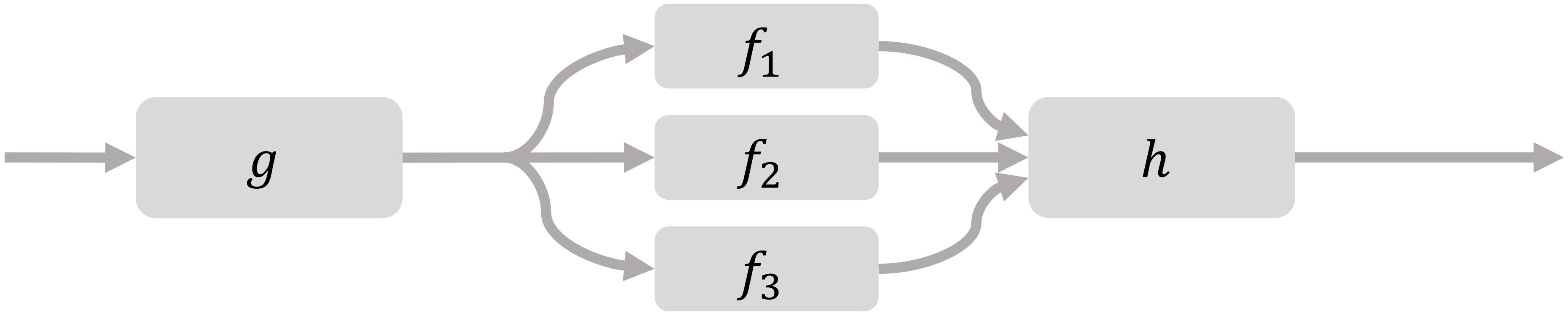


Existing protocols rely on circuit representation of functions

Communication complexity is linear in the size of circuit

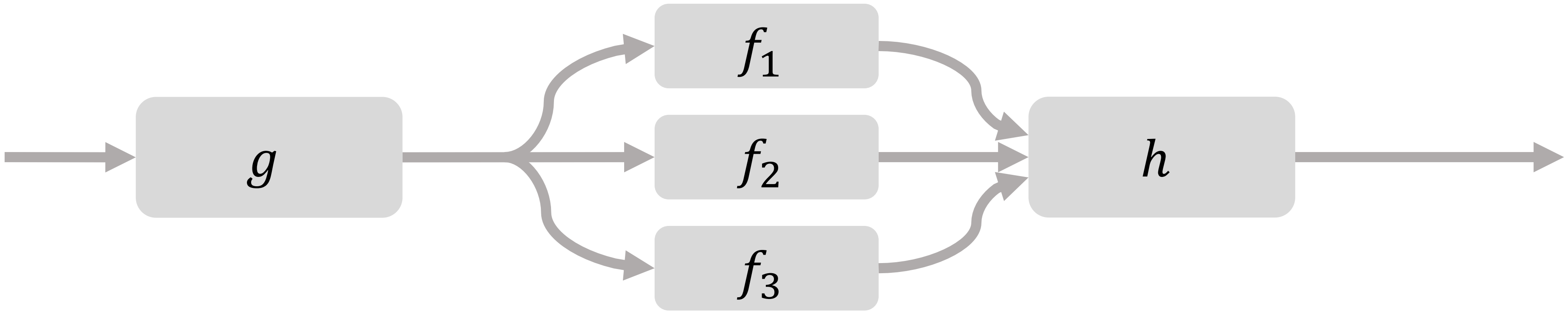
What about functions that don’t have an efficient circuit representation?

Example: Conditional Branches



Example: Conditional Branches

Circuit Representation: depends on ALL 3 branches



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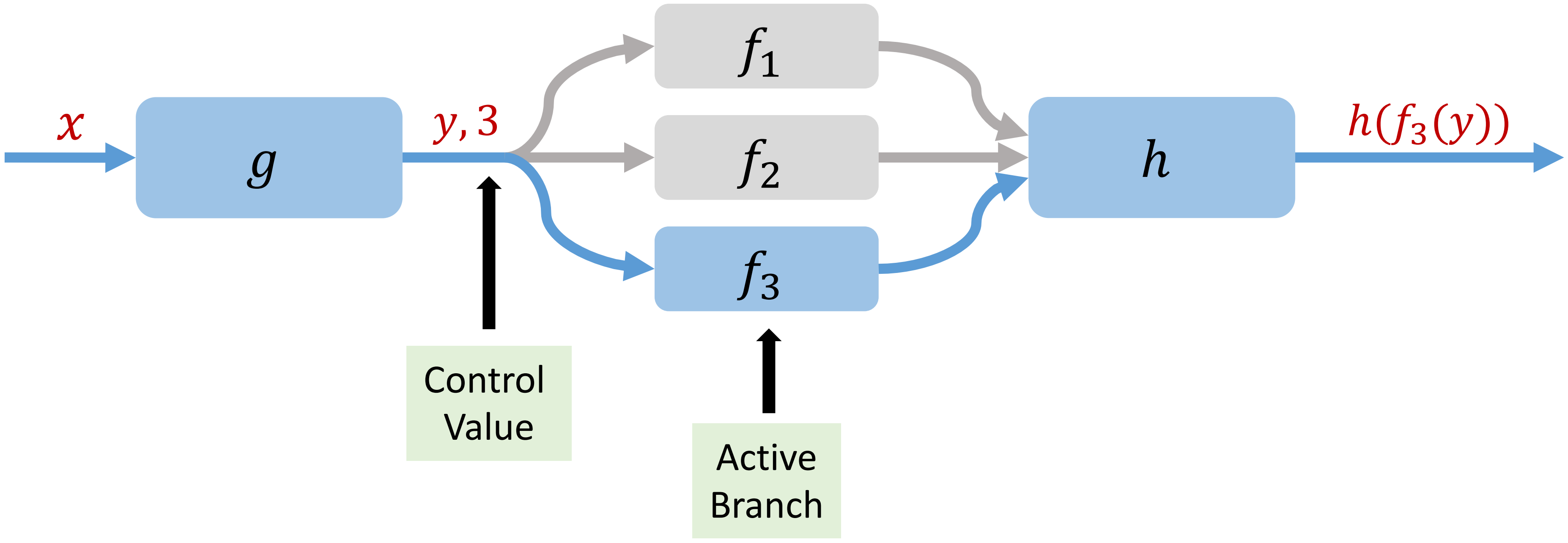

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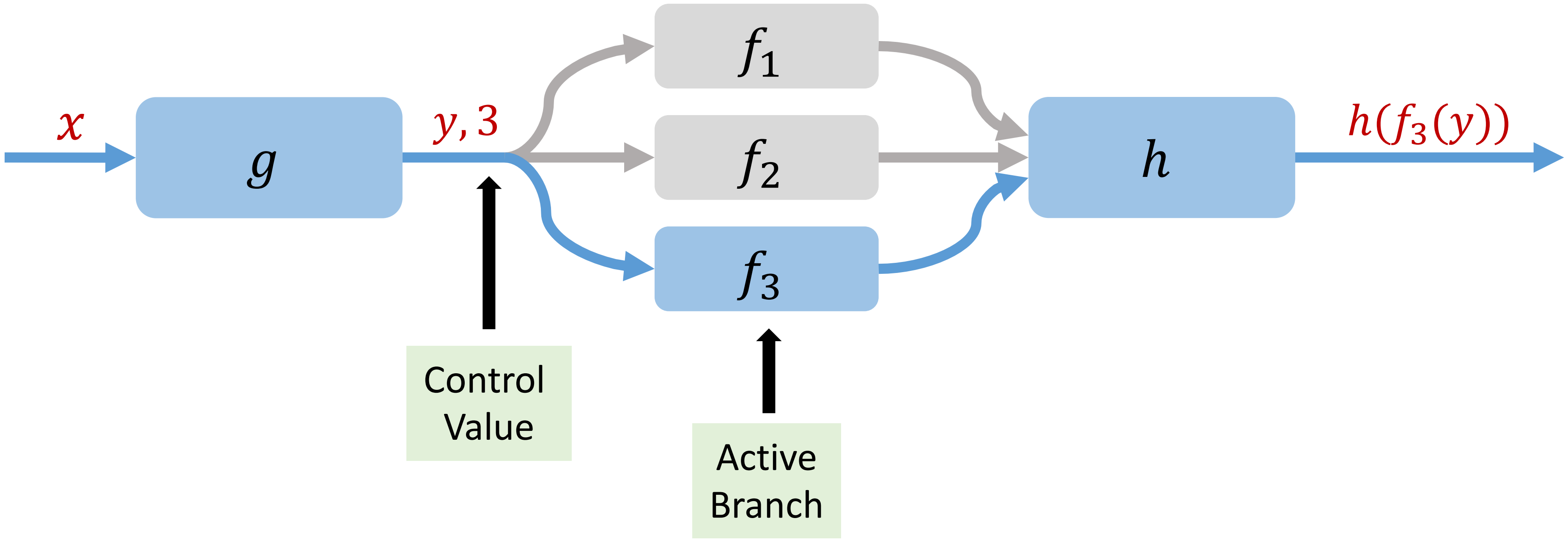
Circuit Representation: depends on ALL 3 branches

Circuit Evaluation: only depends on ONE branch



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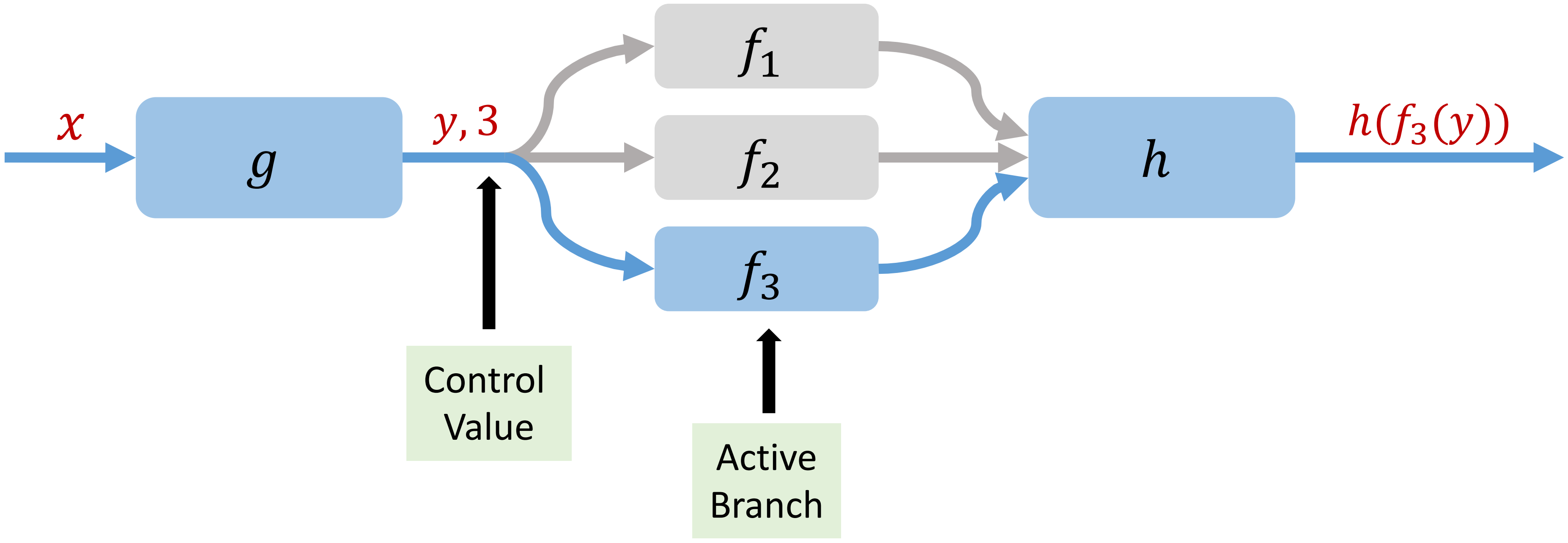

Naïve use of existing MPC protocols will result in communication proportional to all 3 branches

Main Question

Circuit Representation: depends on ALL 3 branches

Can we design efficient MPC protocols for computing conditional branches, where communication only depends on the size of a single branch?

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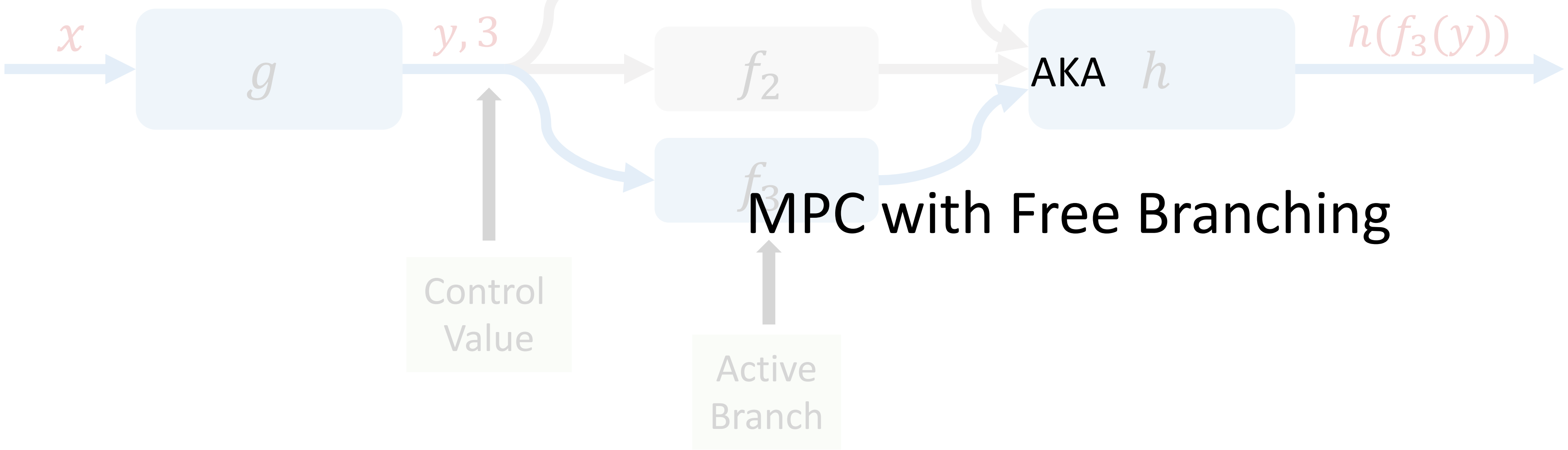

AKA MPC with Free Branching

Naïve use of existing MPC protocols will result in communication proportional to all 3 branches

MPC with Free Branching: Applications

Control flow instructions in computer programs

Collection of servers providing services that clients can pay and for and obliviously avail

Prior Work

k = # branches

$|C| =$ size of largest branch

Result	No. of Parties	Communication	Security	Rounds	Type of Circuits
[HK20]	2	$O(\|C\|)$	Semi-Honest	Non-interactive	Boolean
[HK21]	2	$O(\|C\|)$	Semi-Honest	Non-interactive	Boolean
[HKP20,HKP21]	n	$O(kn^2\|C\|)$	Semi-Honest	Linear in depth	Boolean

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No n-party protocol where communication only depends on the size of one branch

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No maliciously
secure protocol

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No protocol for arithmetic circuits

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Statistical security parameter

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Main Ideas

Prior Work: High-Level Approach

Evaluate all branches and then filter the correct output

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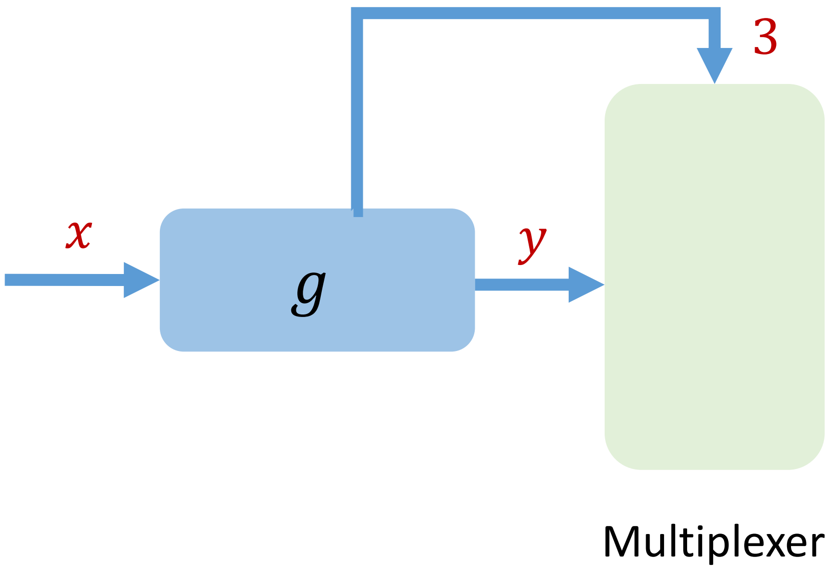

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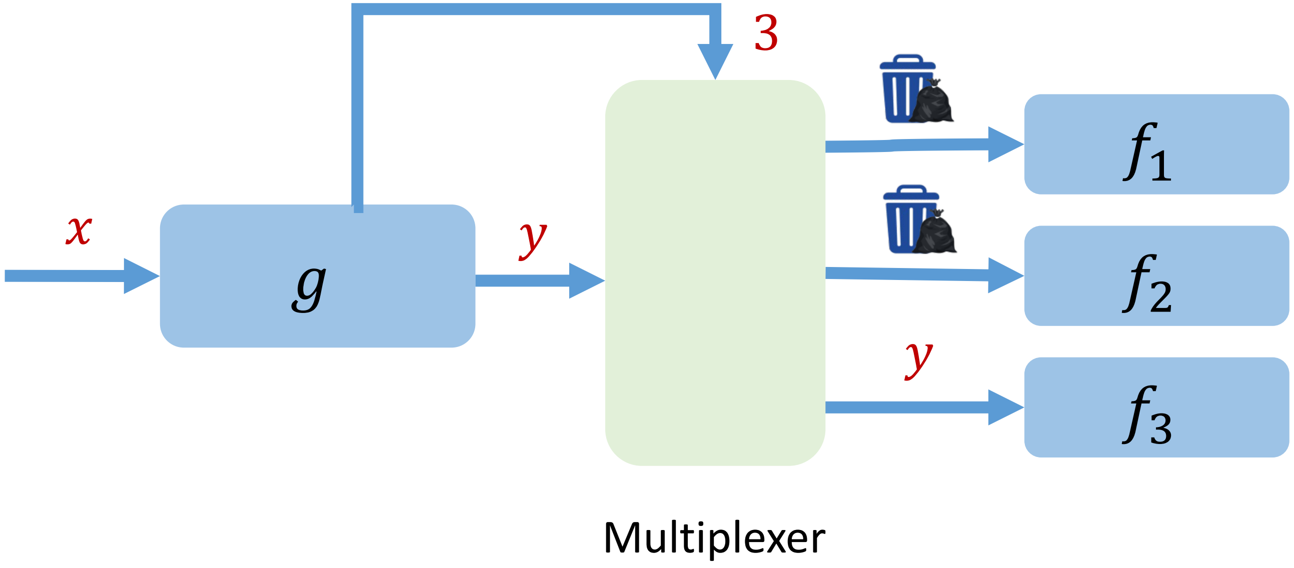

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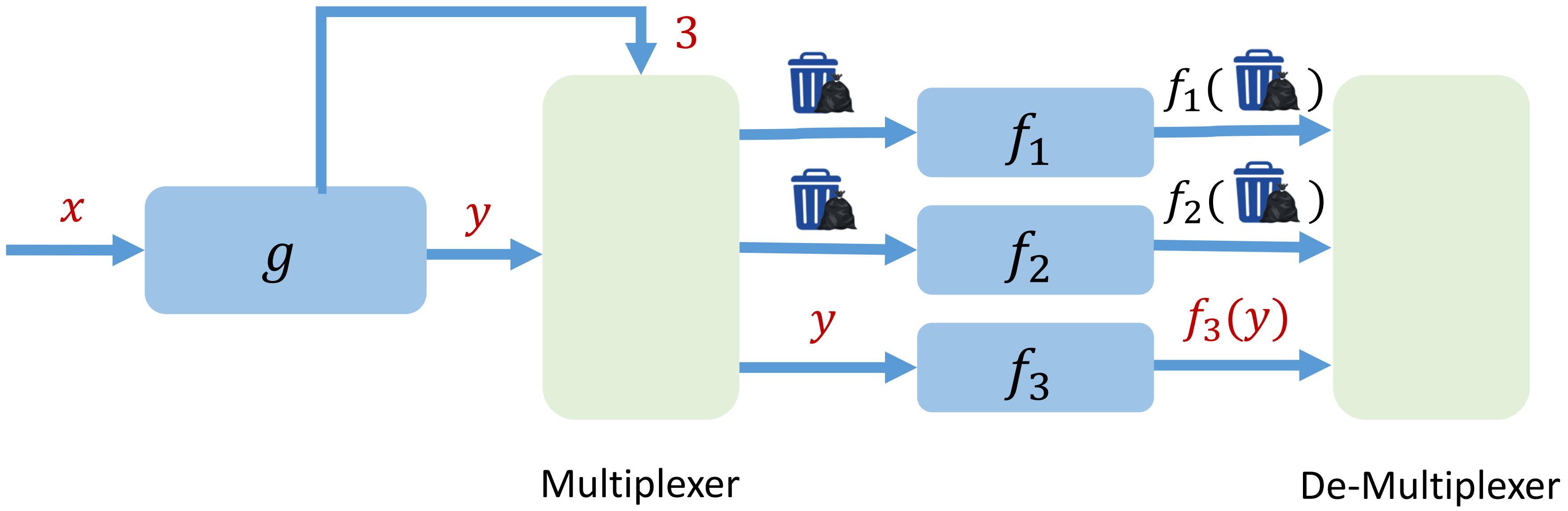

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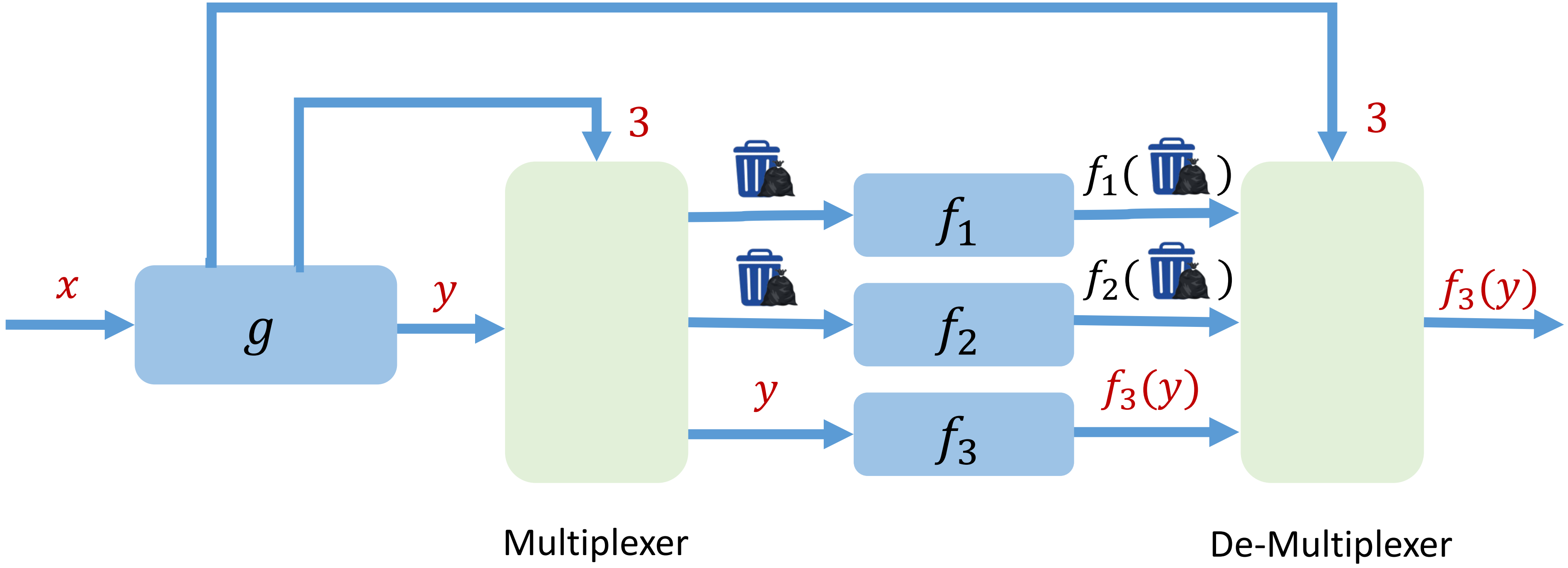

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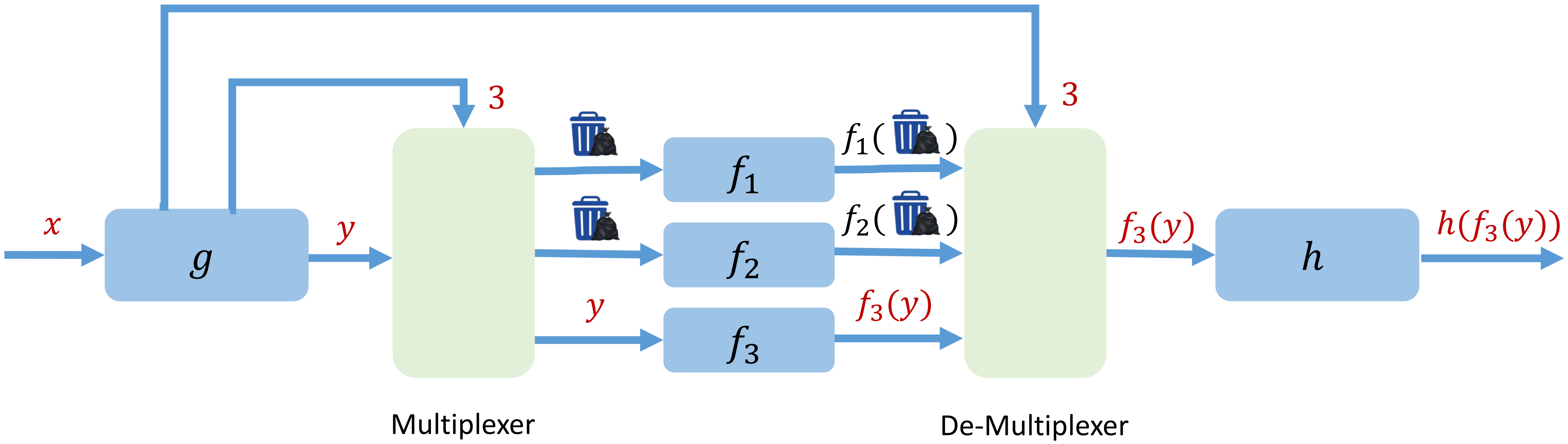

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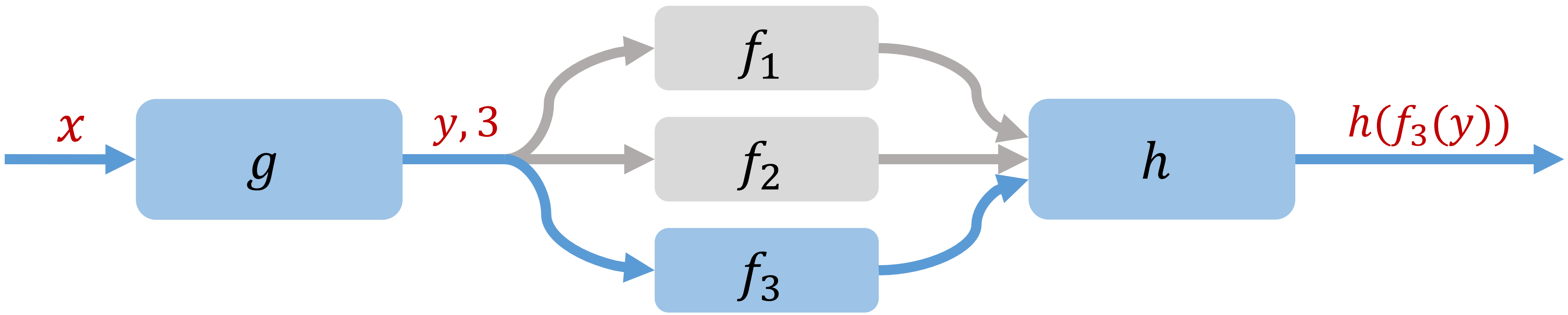

Obliviously select the active branch and only evaluate that on correct inputs

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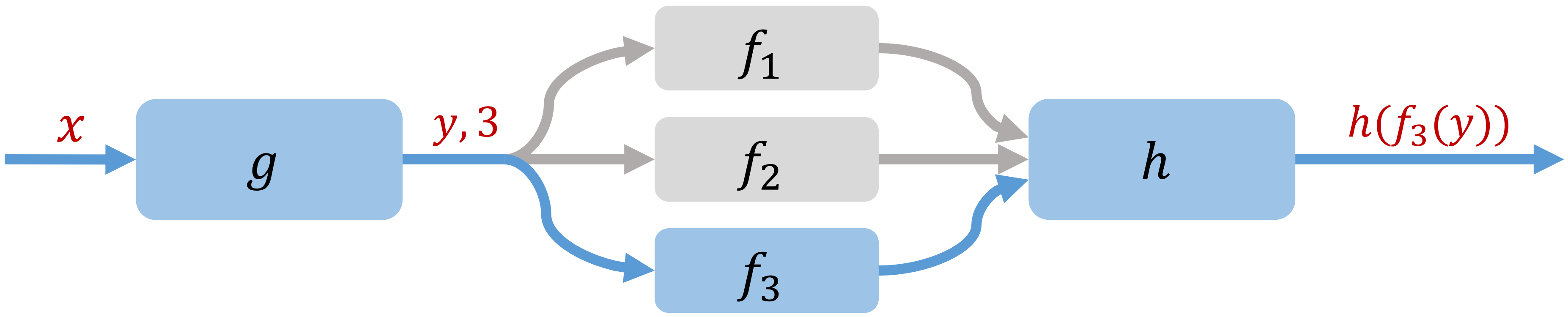
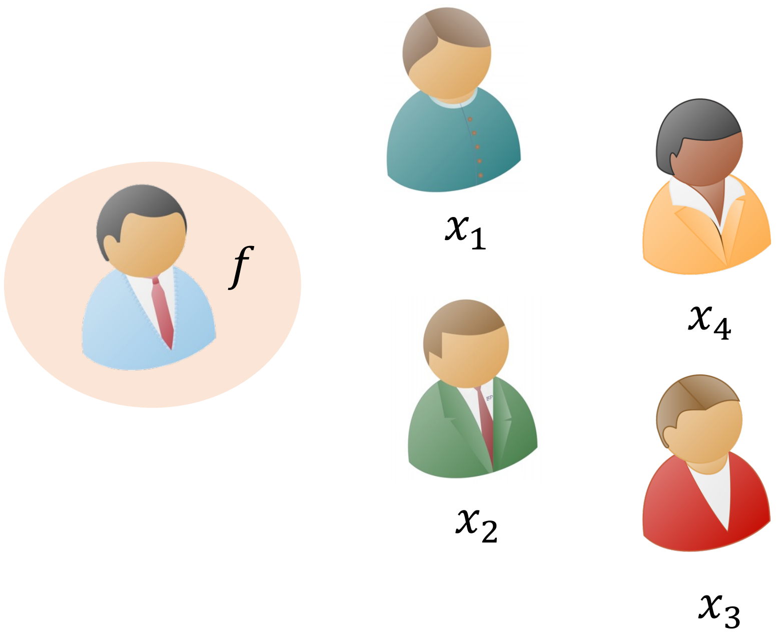


Obliviously select the active branch and only evaluate that on correct inputs

Since the active branch must remain hidden, how does one compute on a hidden function?

Our Initial Observation: Similarities with PFE



Private Function Evaluation

only 1 person knows the function!

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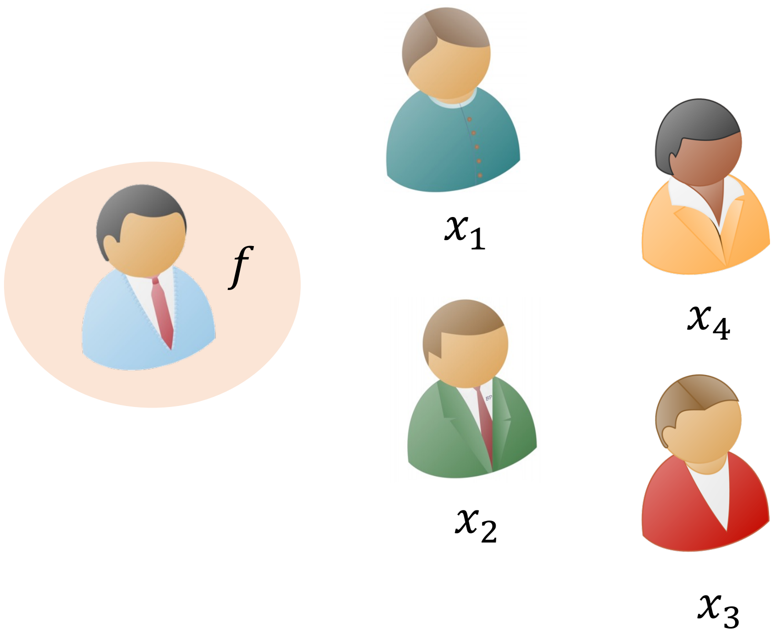

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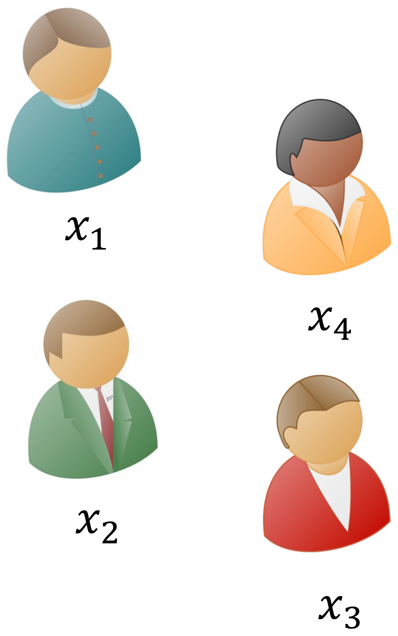
$$f \in \{f_1, f_2, f_3\}$$



MPC for Conditional Branches
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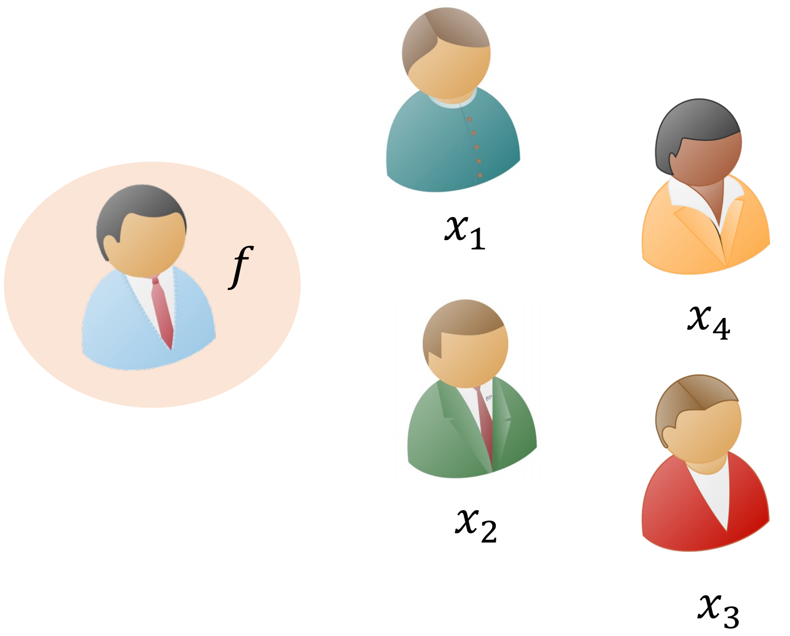

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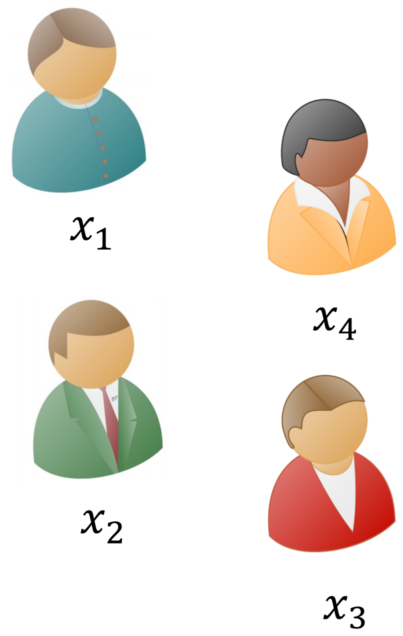

MPC for Conditional Branches
No one knows the function!

Parties collectively hold information about the active branch

Talk Outline

- Overview of the [MS13] PFE protocol
- Our semi-honest non-constant round protocol for conditional branches
- Performance Evaluation
- Remarks on additional results

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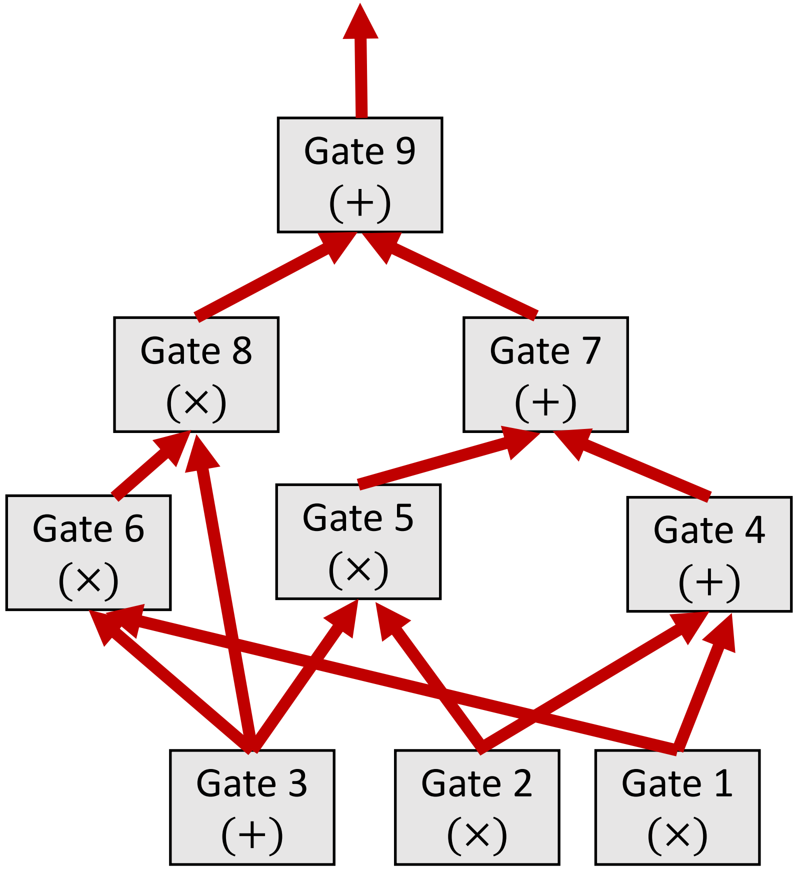
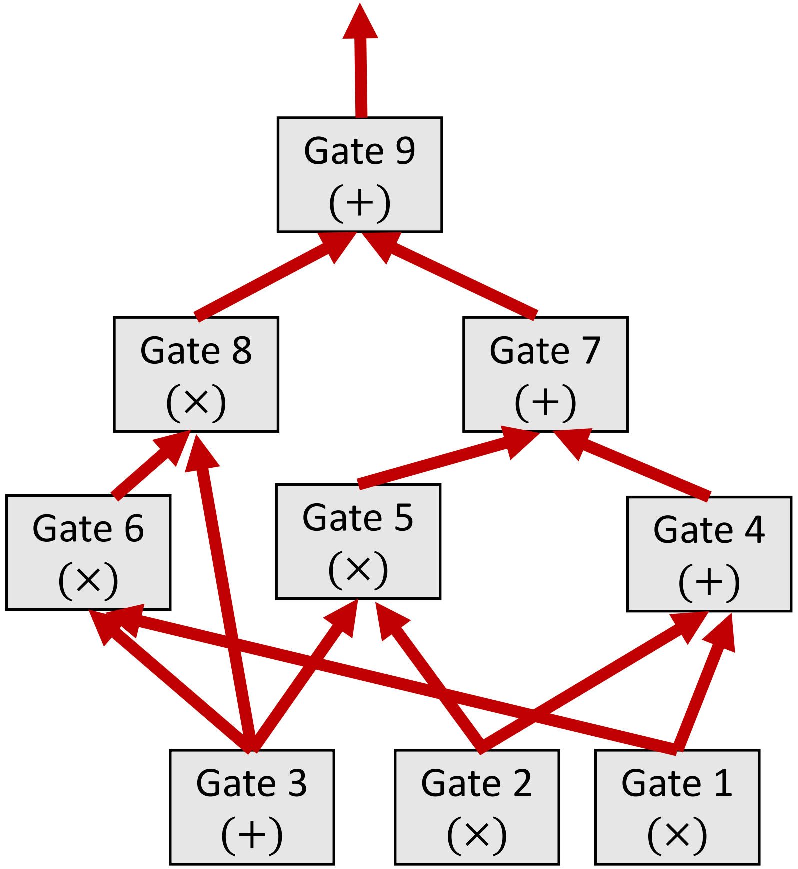


Hide wire configurations

PFE: How to Hide Circuit Topology? [MS13]



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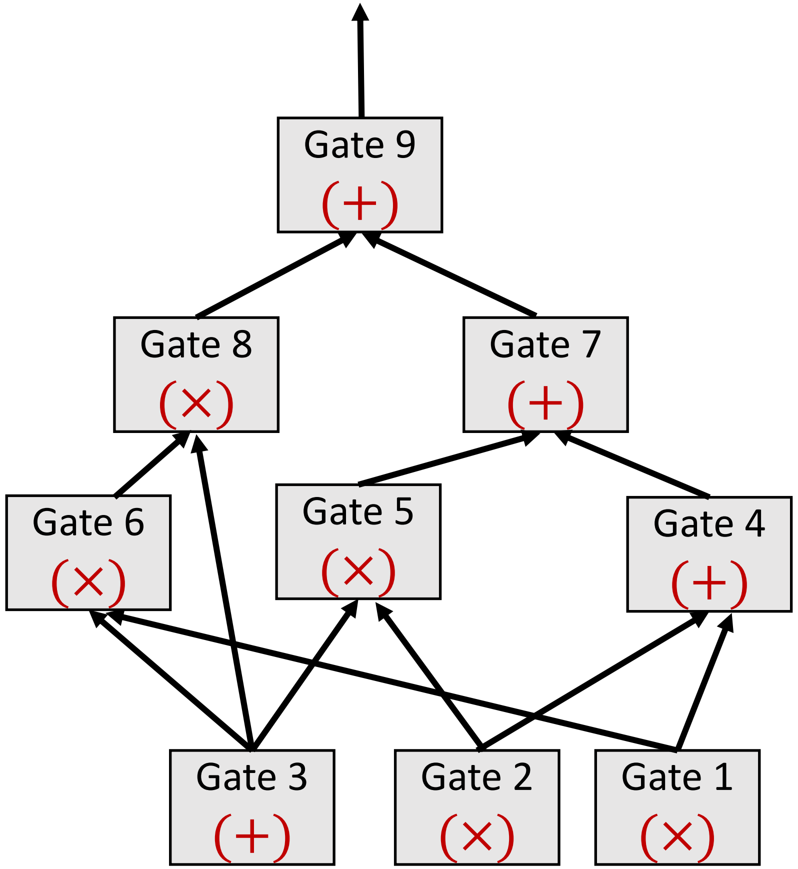

Hide gate functions

PFE: Hiding Gate Functions [MS13]

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f

For every gate g:

x_1 x_2 x_3 x_4

- Let $type_g = 0$: if g is a multiplication gate
- Let $type_g = 1$: if g is an addition gate

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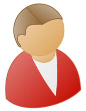
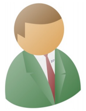
x_2



x_3



x_4

- Let $type_g = 0$: if g is a multiplication gate
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Secret share $type_g$

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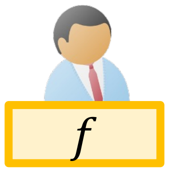

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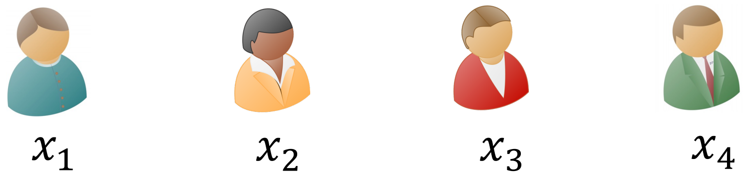

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Given shares $[L_g], [R_g]$ of left and right input wires, compute

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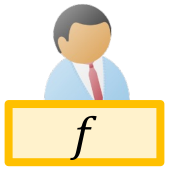

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Compute using an MPC that can operate over shares!

Given shares $[L_g], [R_g]$ of left and right input wires, compute

$$[type_g].([L_g].[R_g]) + (1 - [type_g]).([L_g] + [R_g])$$

PFE: Hiding Gate Functions [MS13]

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How to compute this without knowing wire configurations?

Given shares $[L_g], [R_g]$ of left and right input wires, compute

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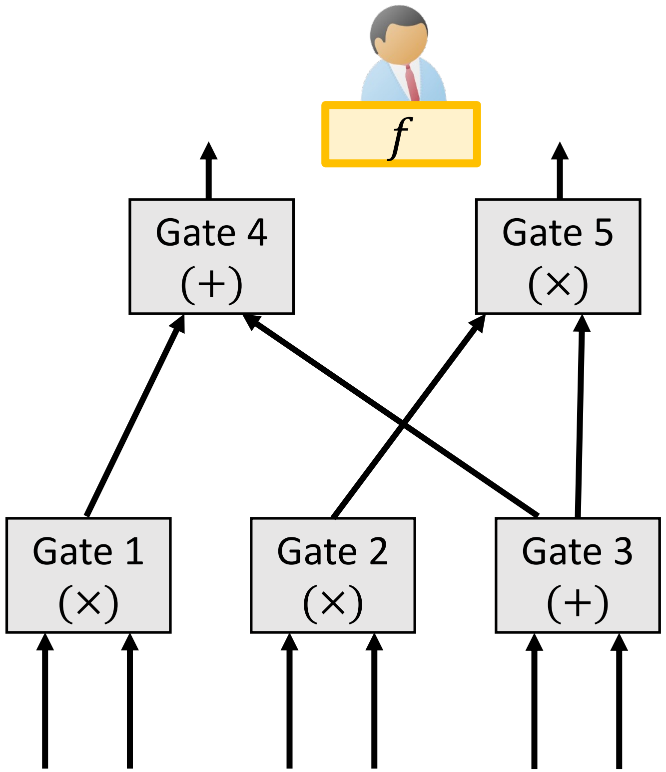
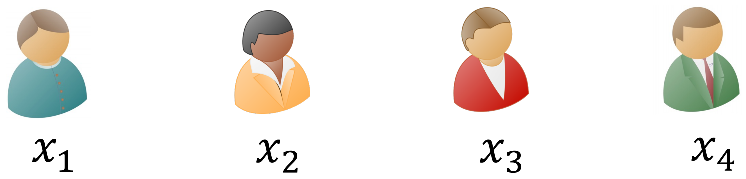


Pre-Processing Phase



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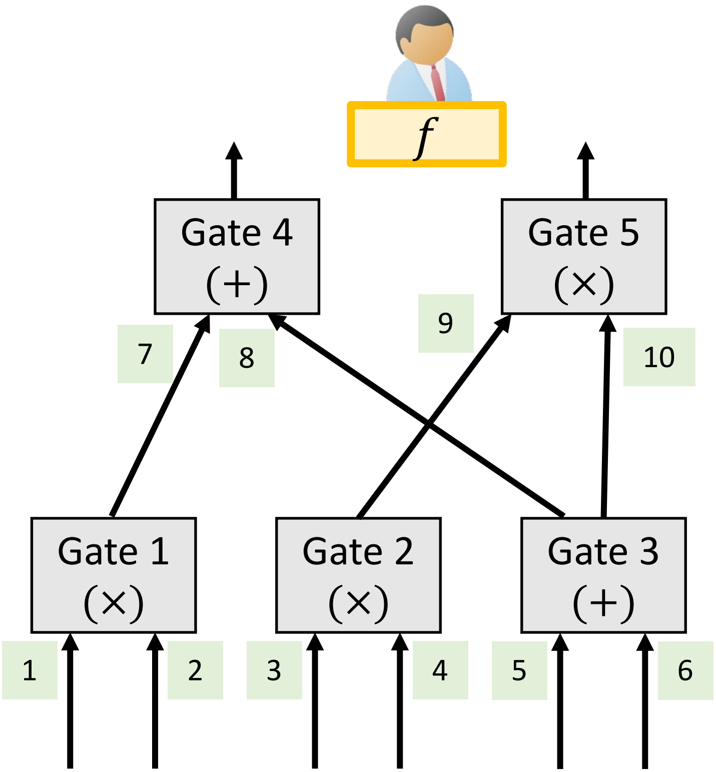

Pre-Processing Phase

For every wire w:

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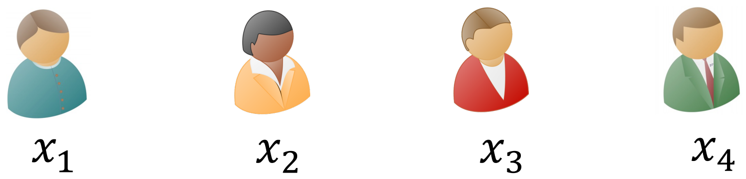

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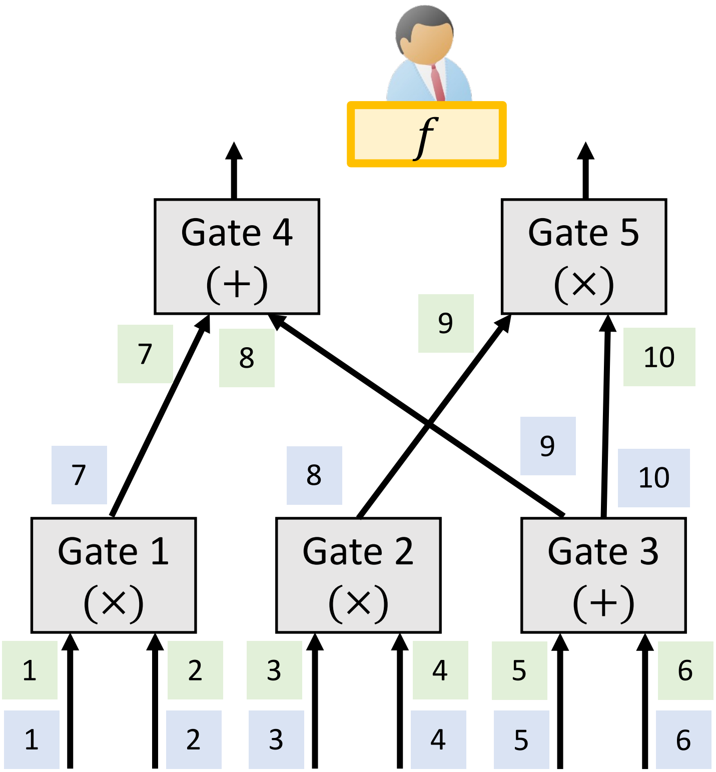

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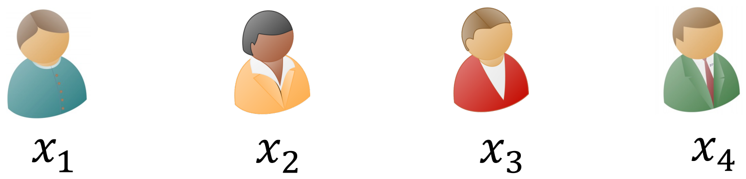

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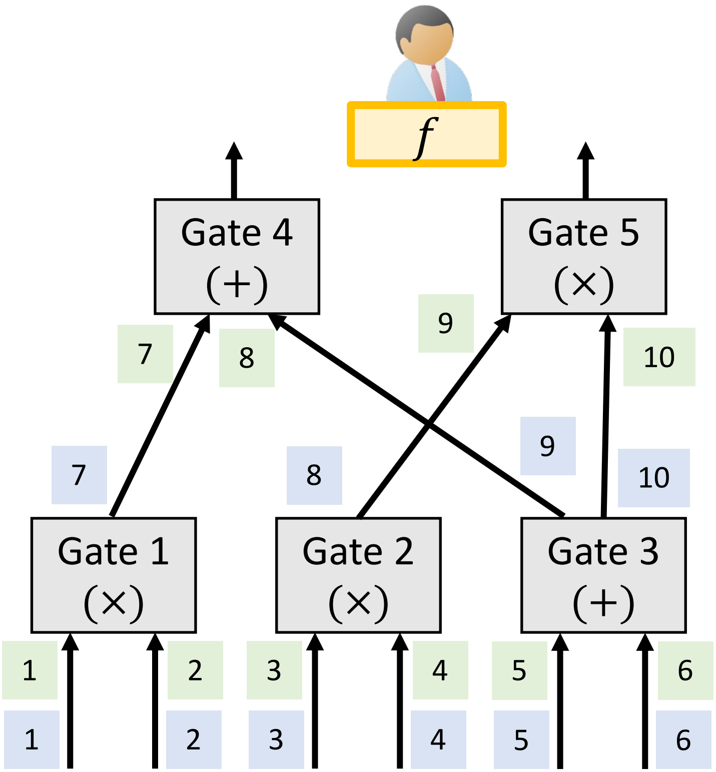

Pre-Processing Phase

For every wire w:

1. Assign an incoming label and an outgoing label

2. Compute a mapping: $\pi: in \rightarrow out$

x_1 x_2 x_3 x_4

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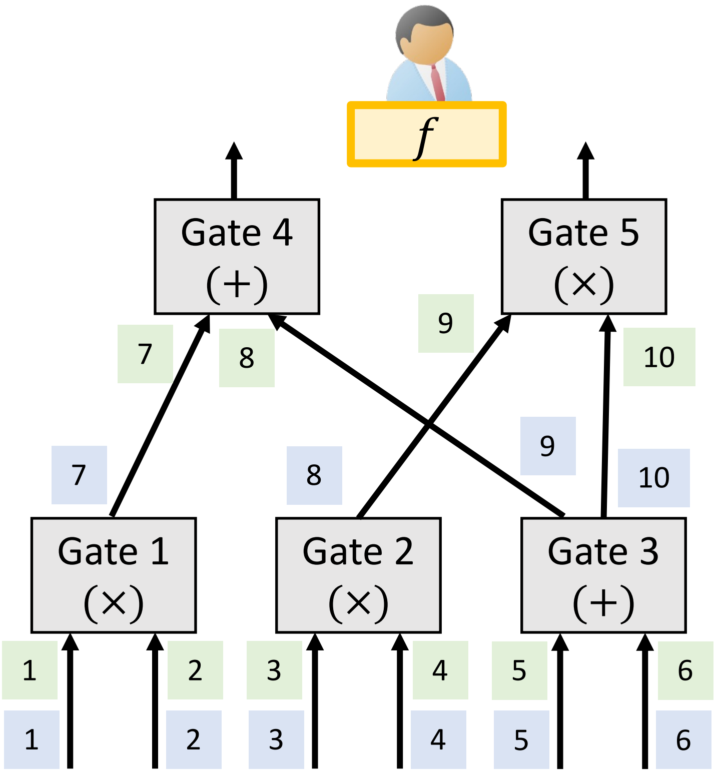

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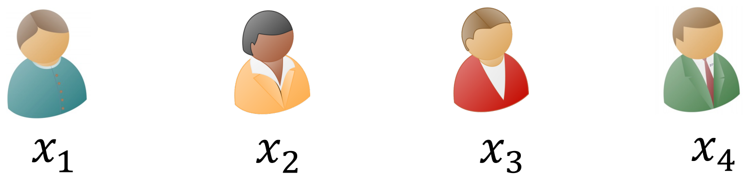

3 Share random masks: $[imask_w], [omask_w]$

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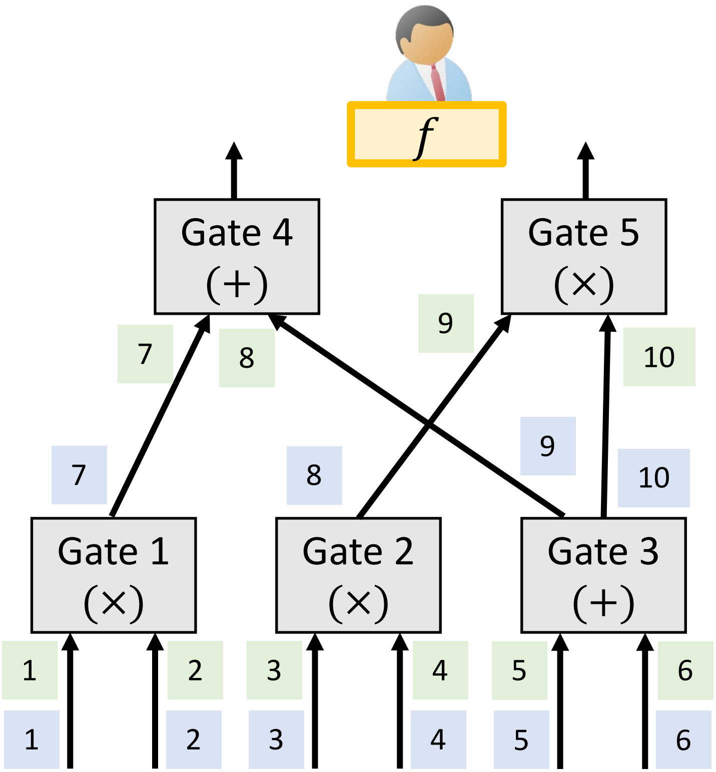

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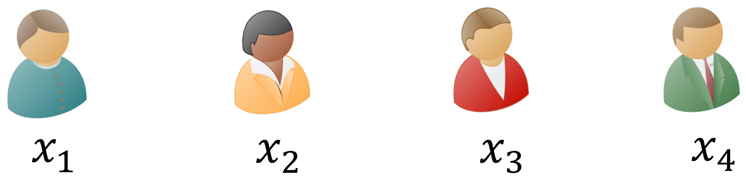

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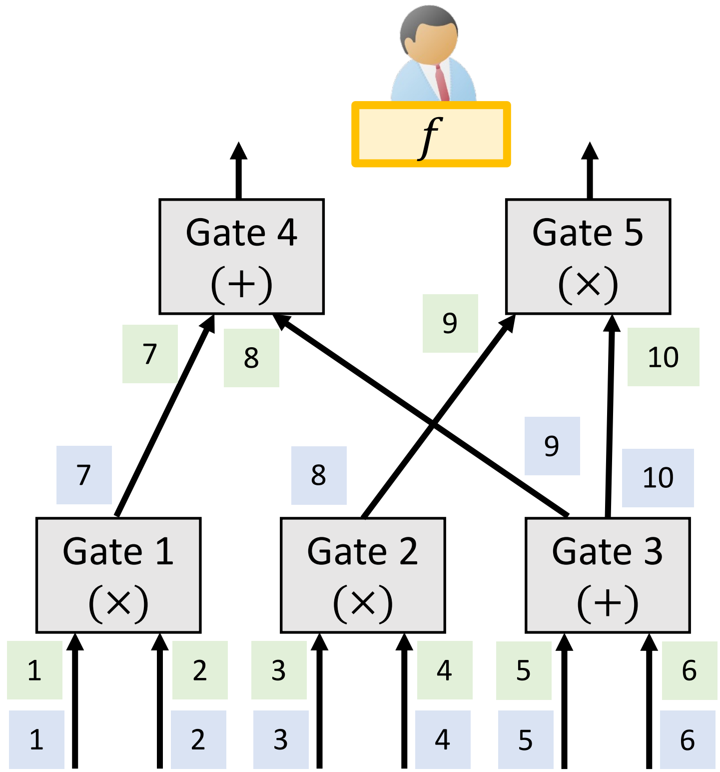

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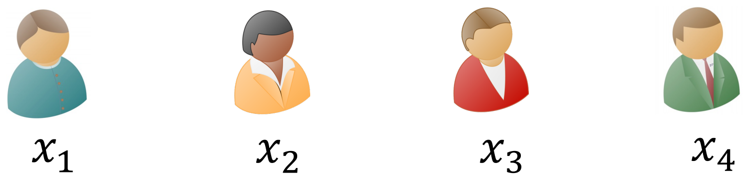

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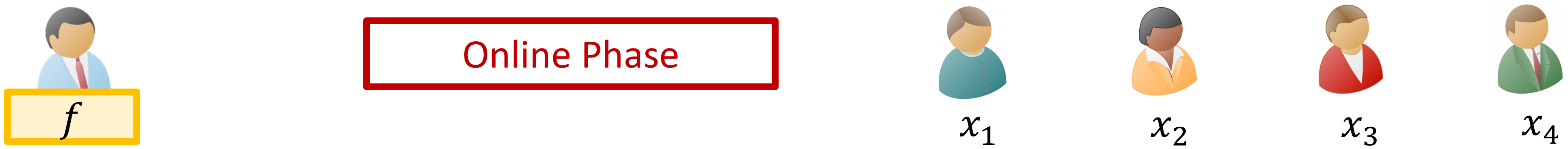
4. function holder learns: $\Delta_w = imask_w - omask_{\pi(w)}$

PFE: Hiding Wire Configuration [MS13]



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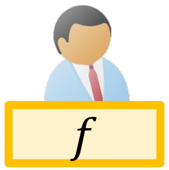

Online Phase

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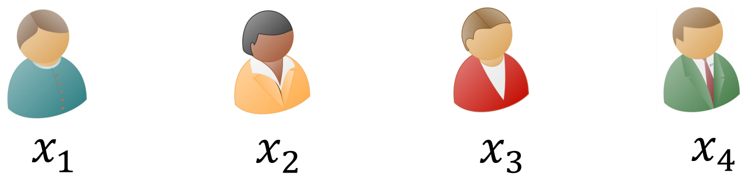

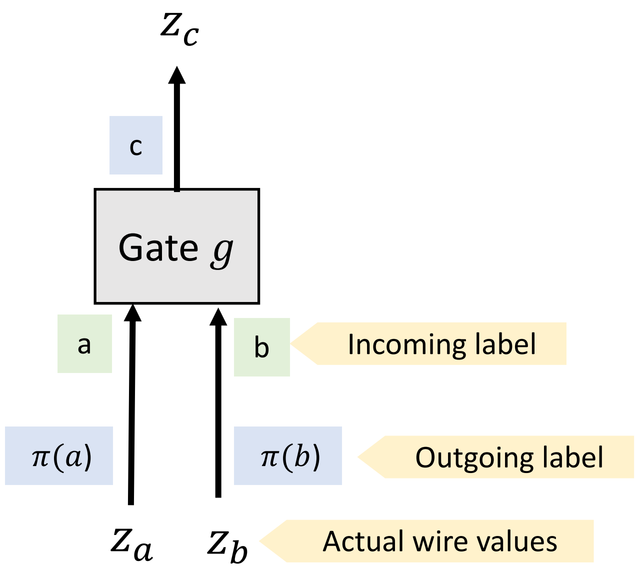

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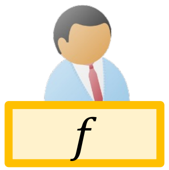

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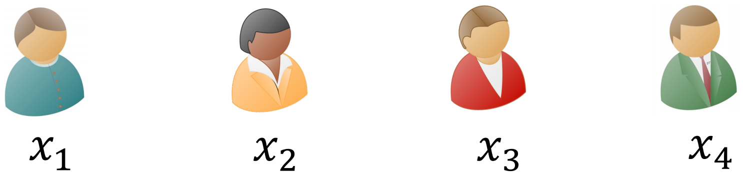
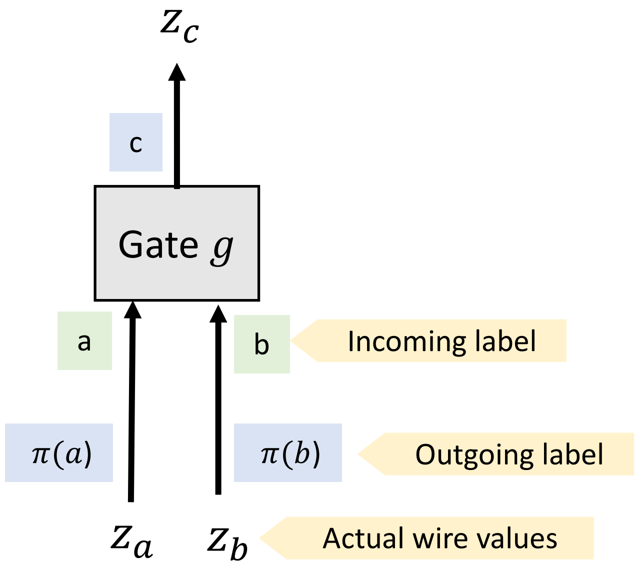


After computing g



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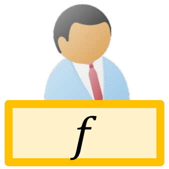

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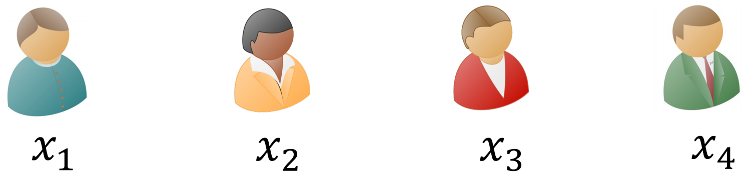

After computing g

Compute $[u_c] = [z_c] + [omask_c]$
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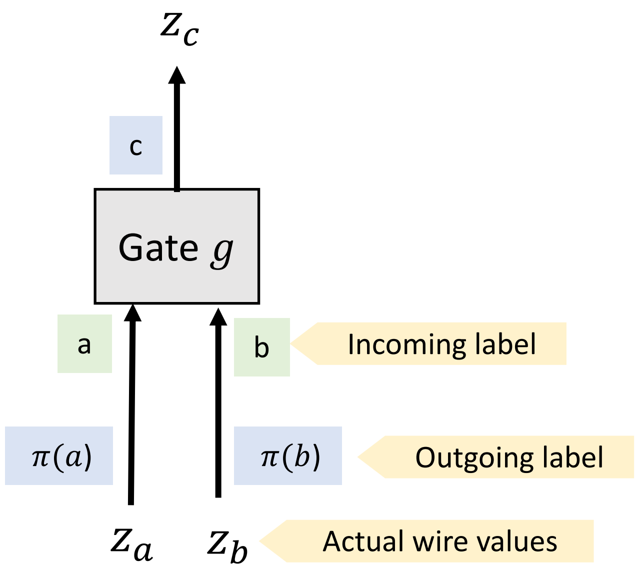

PFE: Hiding Wire Configuration [MS13]

f

Online Phase

For every gate g:

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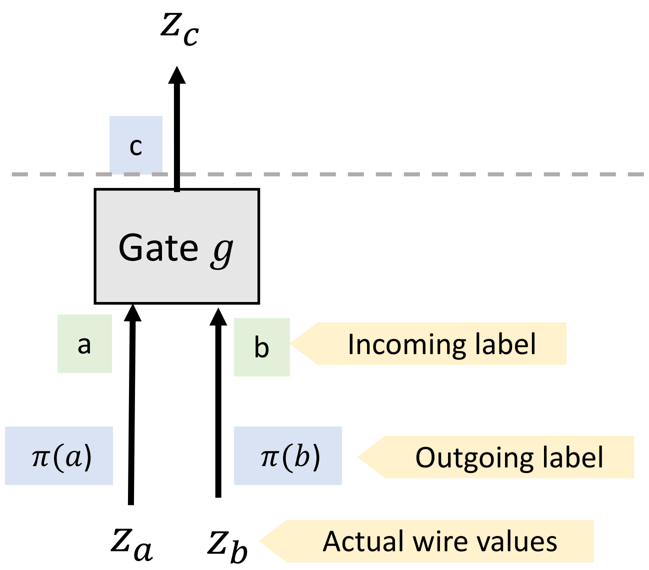
For computing g



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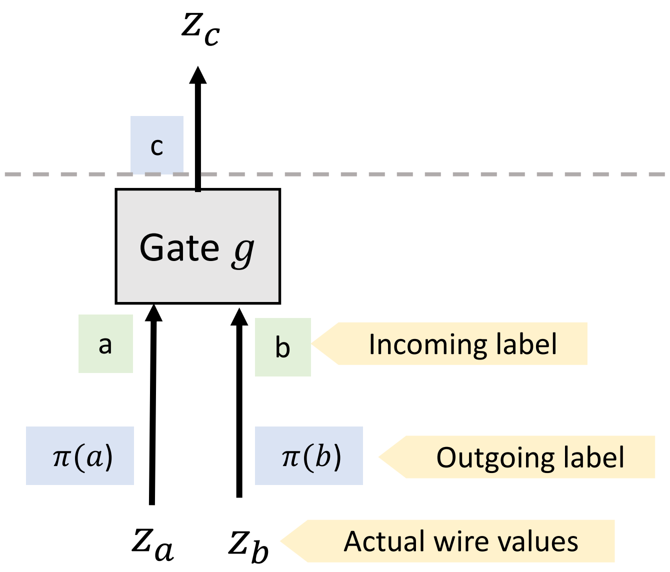

For computing g

Compute and send
$A = u_{\pi(a)} + \Delta_a$
$B = u_{\pi(b)} + \Delta_b$

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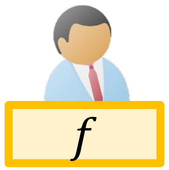

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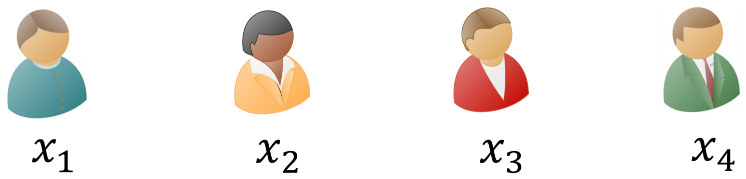

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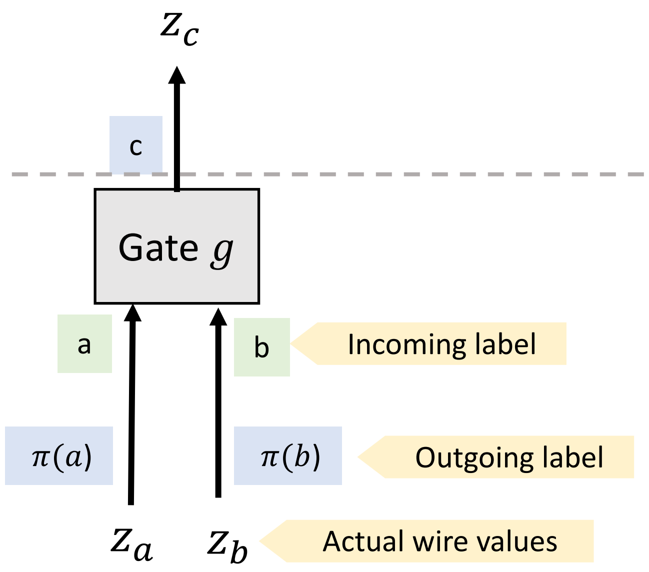

Compute
$[z_a] = A - [imask_a]$
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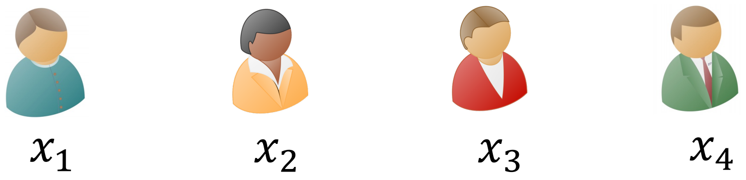
Conditional Branches: Hiding Gate Functions



Let's assume parties have secret sharing of unary representation of α, i.e., $[b_1], \ldots, [b_k]$

Index of the active branch

Conditional Branches: Hiding Gate Functions

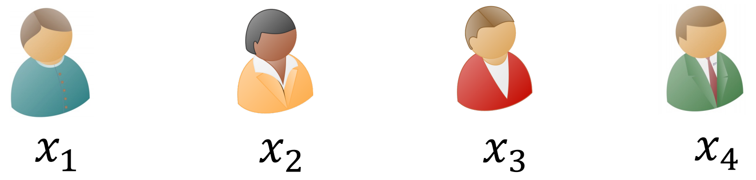
x_1 x_2 x_3 x_4

Let's assume parties have secret sharing of unary representation of α, i.e., $[b_1], \ldots, [b_k]$

Type of gate g in Branch 1

For every gate g: $[type_g] = [b_1].\, type_{1,g} + \cdots + [b_k].\, type_{k,g}$

Conditional Branches: Hiding Gate Functions



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For every gate g:

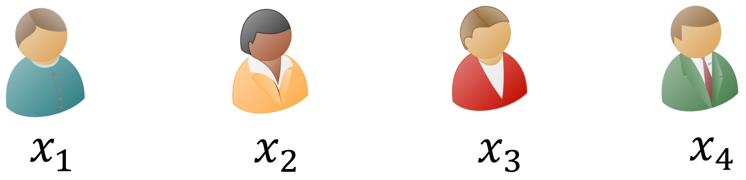
$$[type_g] = [b_1].\, type_{1,g} + \cdots + [b_k].\, type_{k,g}$$

Given shares $[L_g], [R_g]$ of left and right input wires, compute

$$[type_g].\,([L_g].\,[R_g]) + (1 - [type_g]).\,([L_g] + [R_g])$$

Conditional Branches: Hiding Wire Configuration

Pre-Processing Phase



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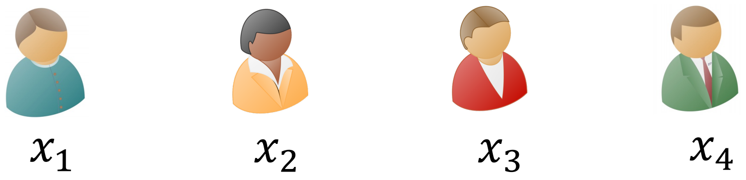

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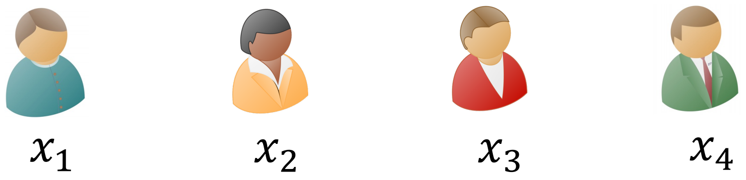

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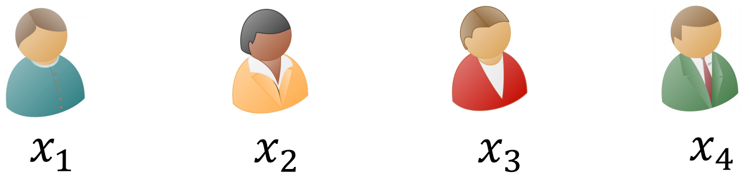

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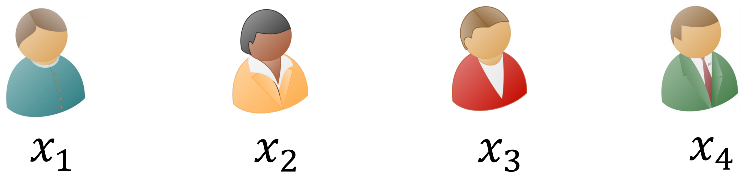

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$$[omask_{\pi_\alpha(w)}] = [b_1][omask_{\pi_1(w)}] + \cdots + [b_1][omask_{\pi_1(w)}]$$

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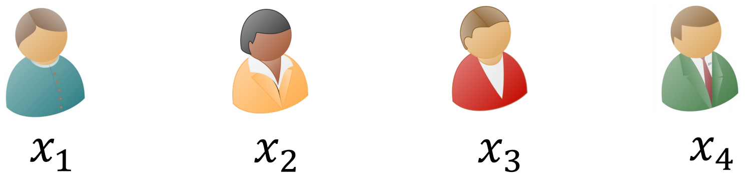

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$$[\Delta_w] = [imask_w] - [omask_{\pi_\alpha(w)}]$$

(Δ values for the active branch)

Conditional Branches: Hiding Wire Configuration

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This computation depends on the size of all branches

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Conditional Branches: Hiding Wire Configuration

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x_1 x_2 x_3 x_4

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This computation depends on the size of all branches	$[omask_{\pi_\alpha(w)}] = [b_1][omask_{\pi_1(w)}] + \cdots + [b_1][omask_{\pi_1(w)}]$
How can we compute this efficiently?	$[\Delta_w] = [imask_w] - [omask_{\pi_\alpha(w)}]$

Oblivious Inner Product

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$$< b_1 > \xleftarrow{Enc} [b_1], \dots, < b_k > \xleftarrow{Enc} [b_k]$$

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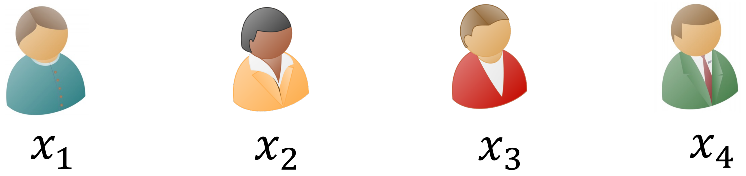
Decrypt mask to shares

$$[omask_{\pi_\alpha(w)}] \overset{Dec}{\longleftarrow} < omask_{\pi_\alpha(w)} >$$

Communication only depends on the size of one branch

Conditional Branches: Hiding Wire Configuration

Online Phase



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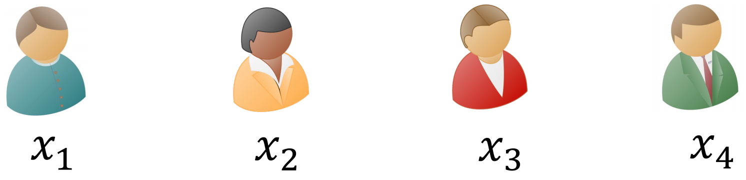

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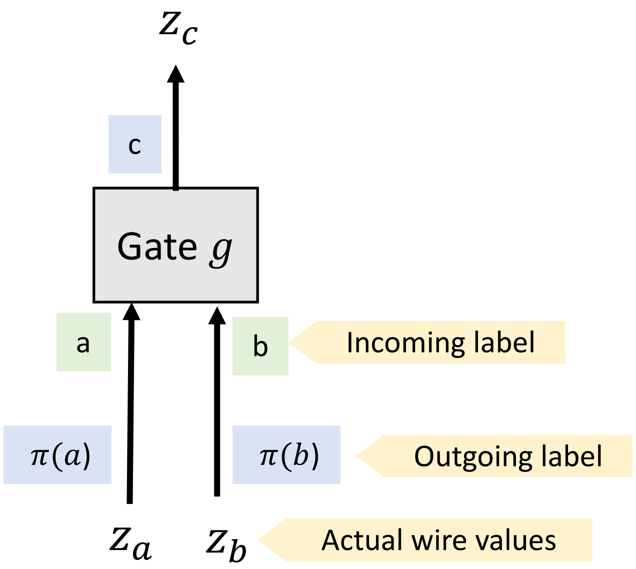

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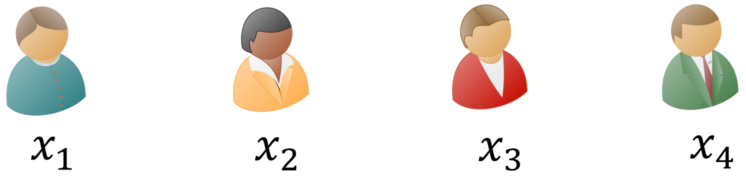

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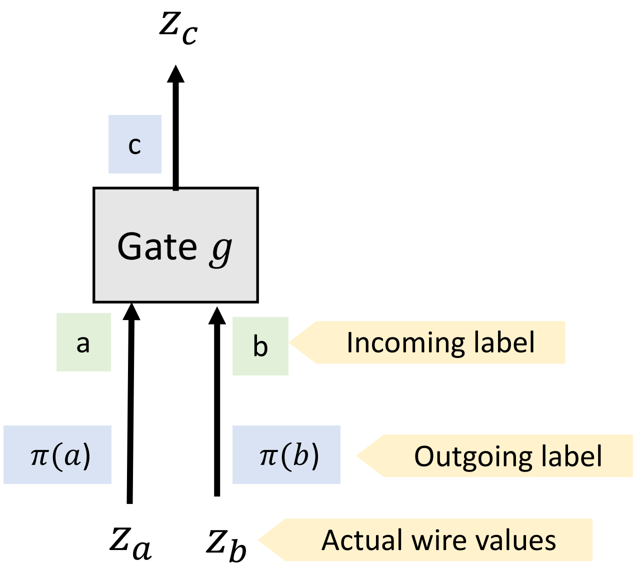

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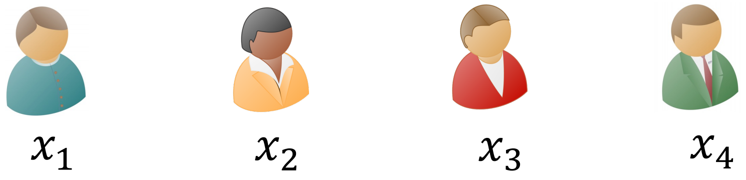

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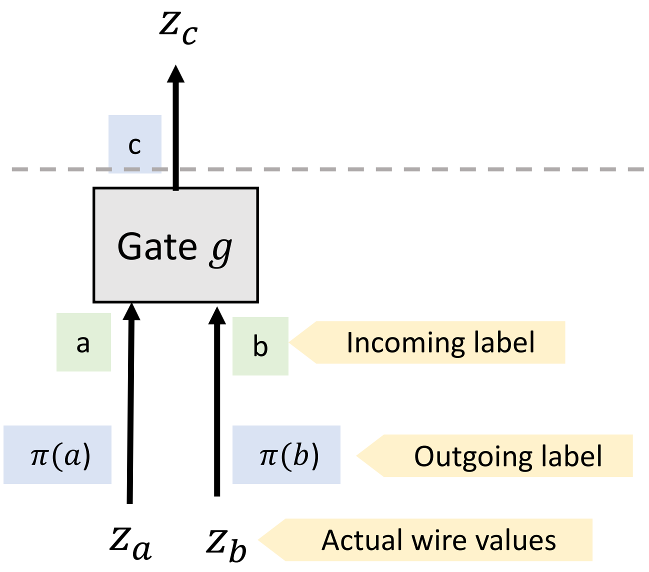

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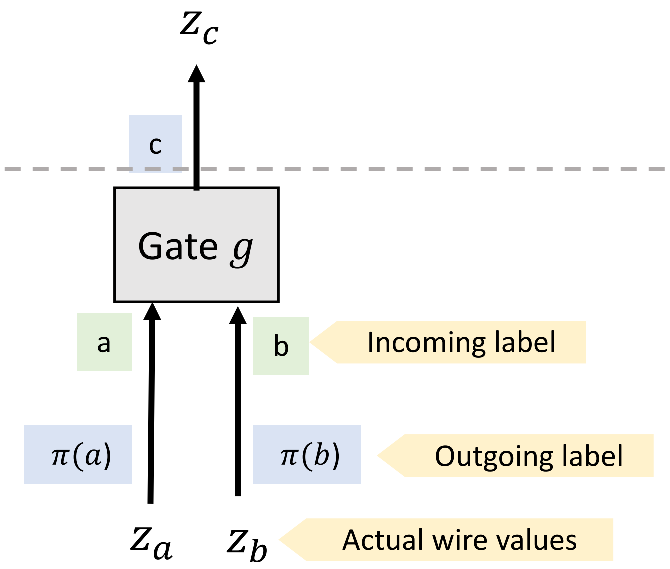

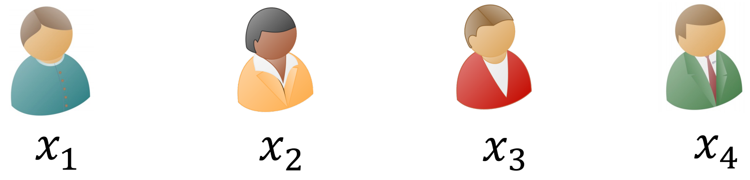

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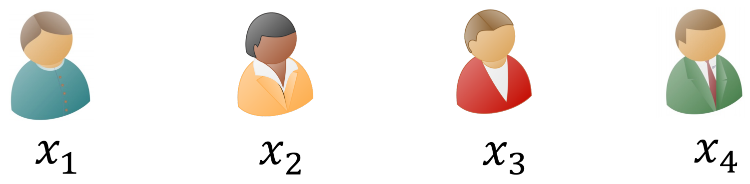

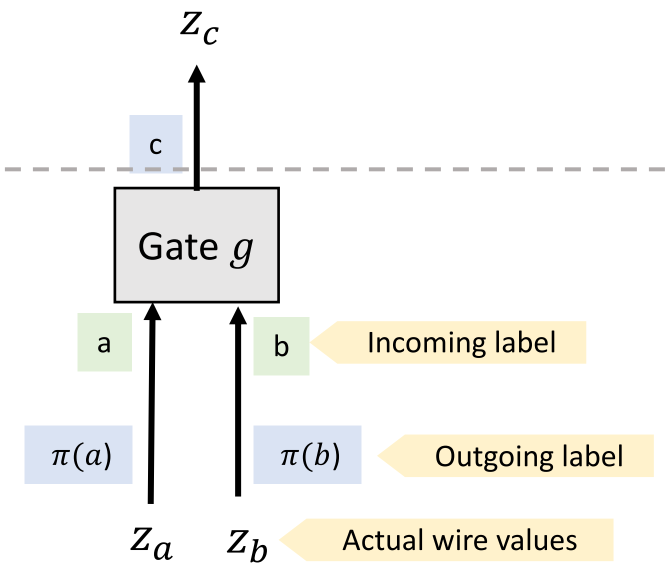

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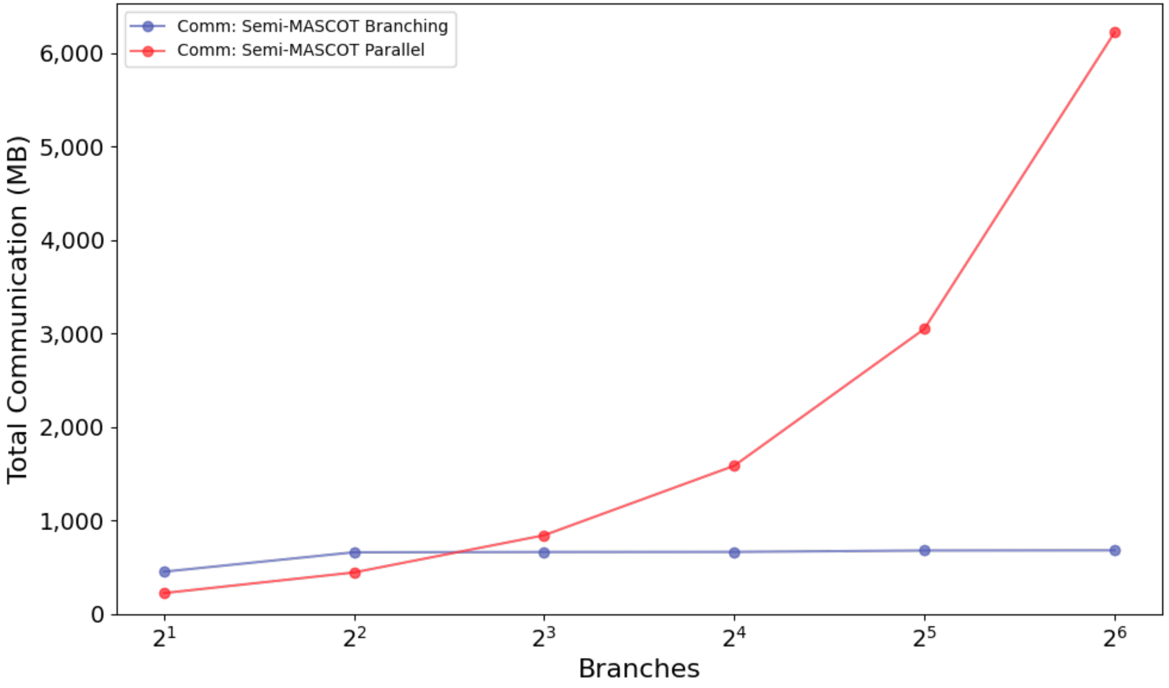

Communication

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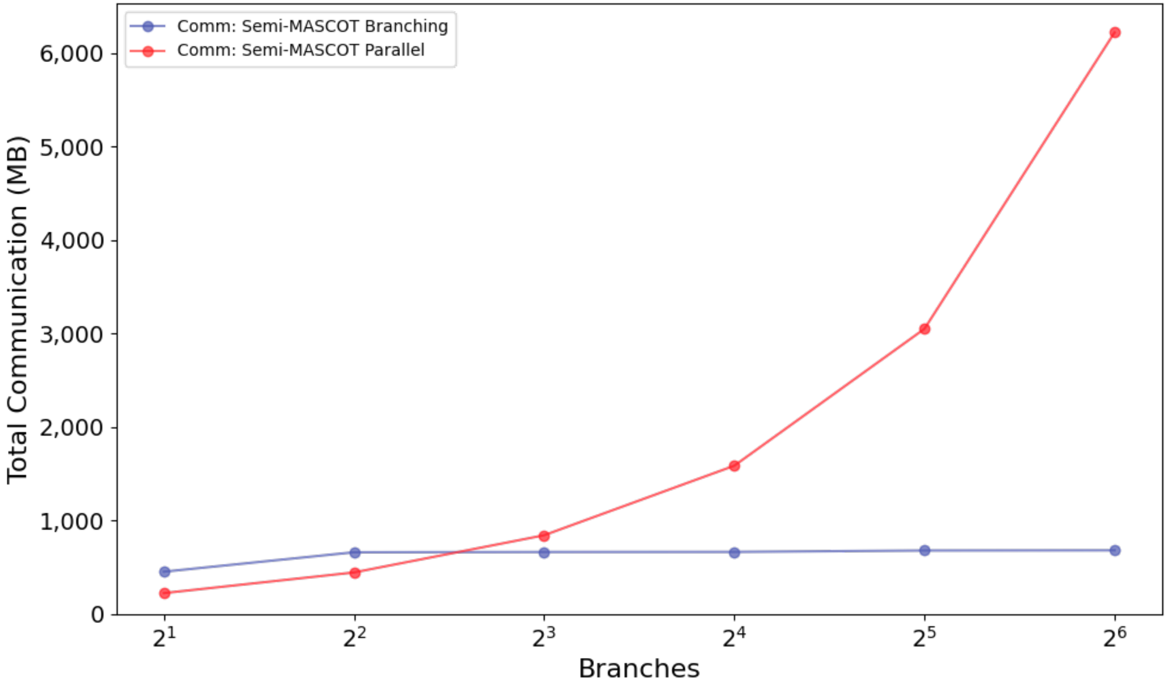

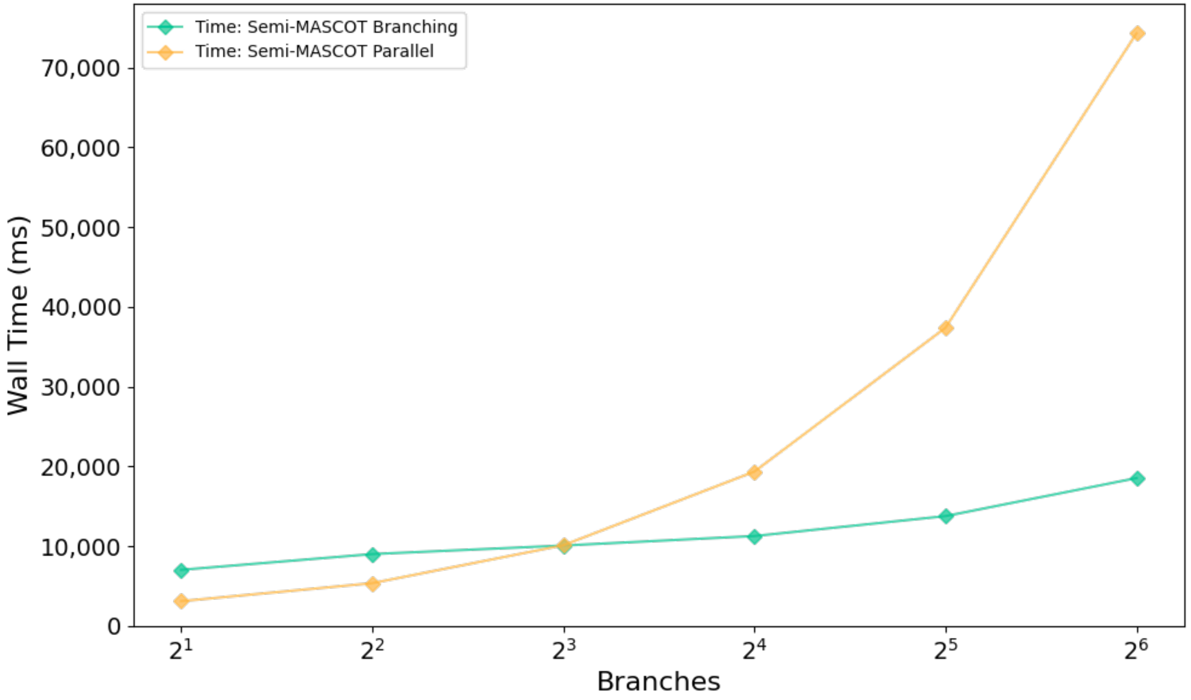

Communication

Run-Time

3 parties, 2^{16} gates in each branch

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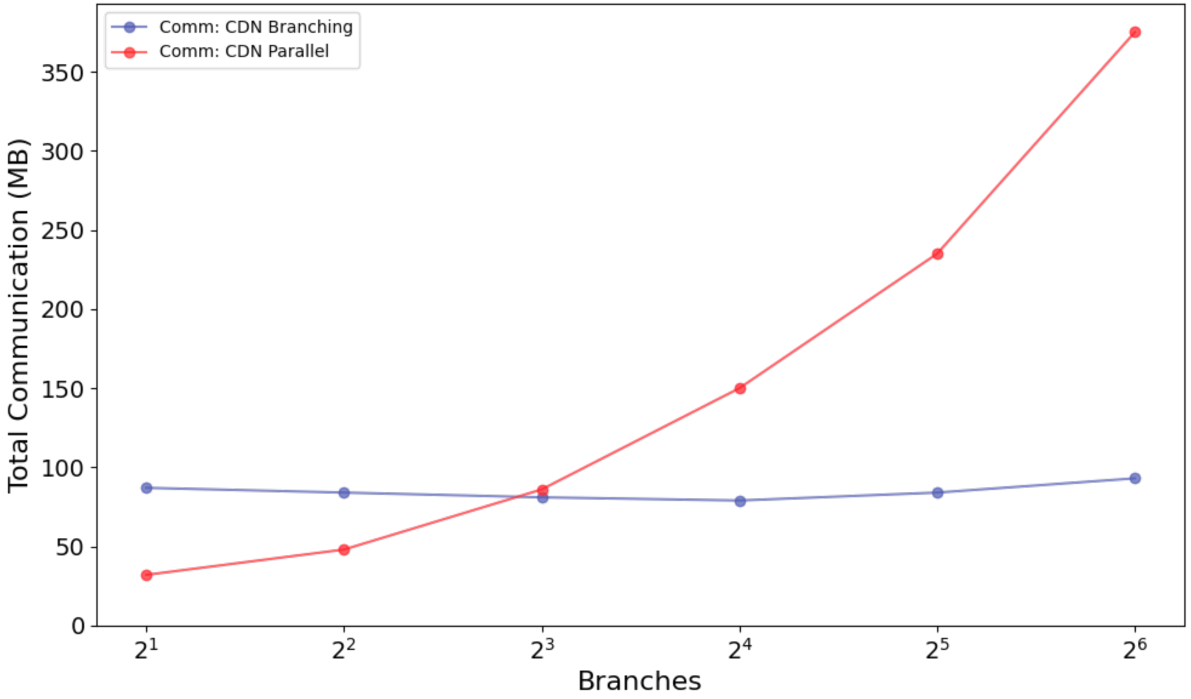

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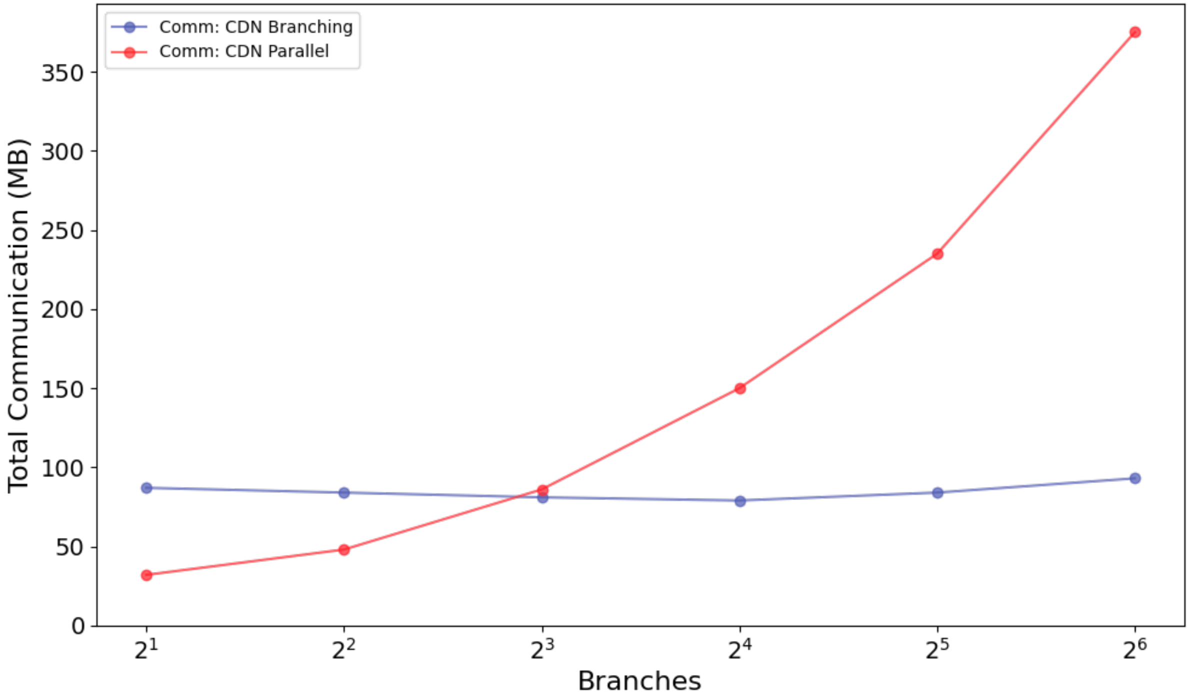

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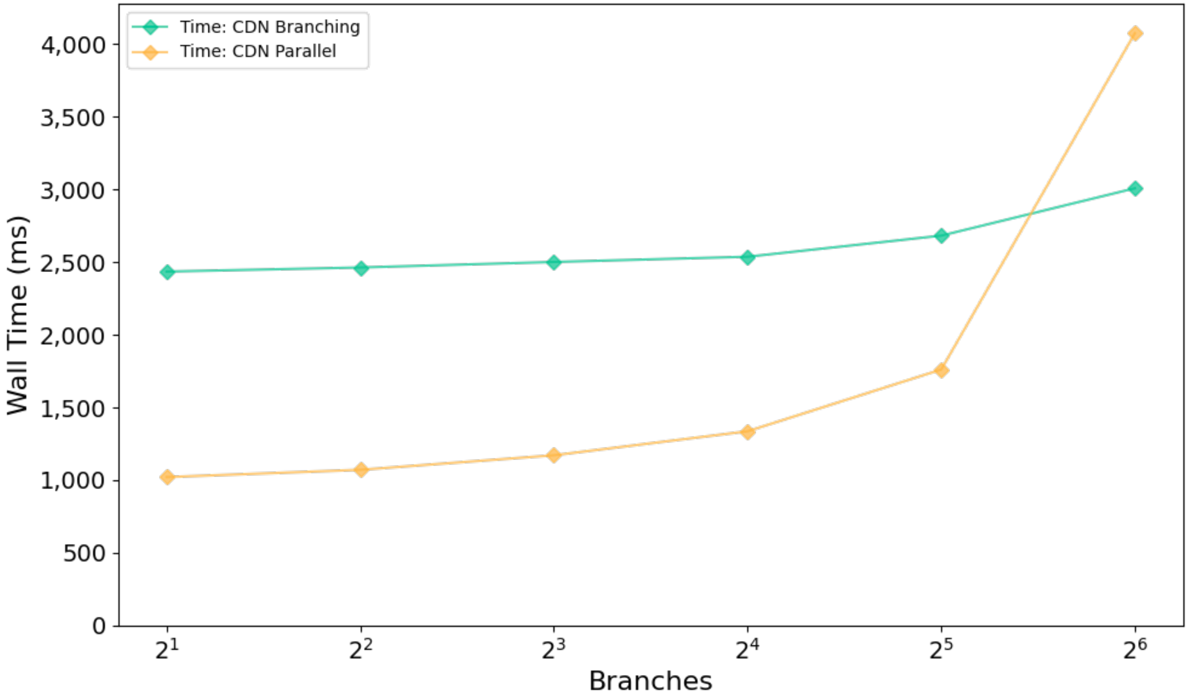

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This protocol can be extended to malicious security

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We present an alternate solution using the linearly key-homomorphic PRFs based garbling approach from [BLO17]

Conclusion

A multi-party protocol for securely computing conditional branches, where the total communication only depends on the size of the largest branch

Extensions to malicious security and a semi-honest constant round protocol

Thank You!