faster malicious 2pc with online/offline dual execution

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collaborators:

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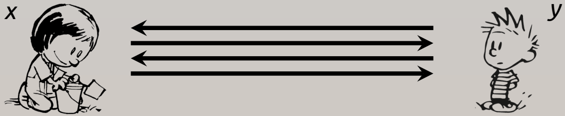
two-party secure computation

x

y

two-party secure computation



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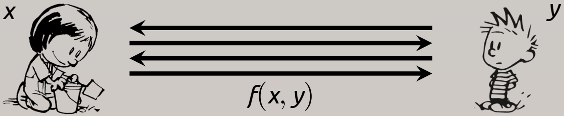

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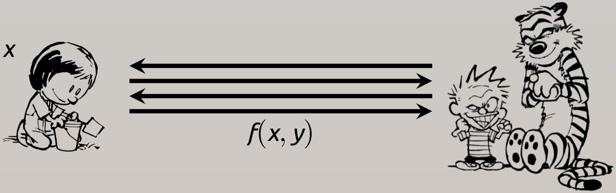


- Security against malicious adversaries

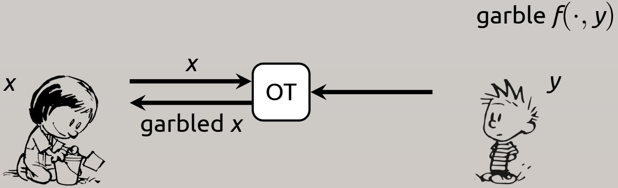
yao’s 2pc protocol

garble $f(\cdot, y)$

x

y

yao's 2pc protocol



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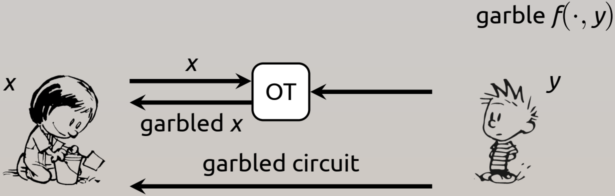

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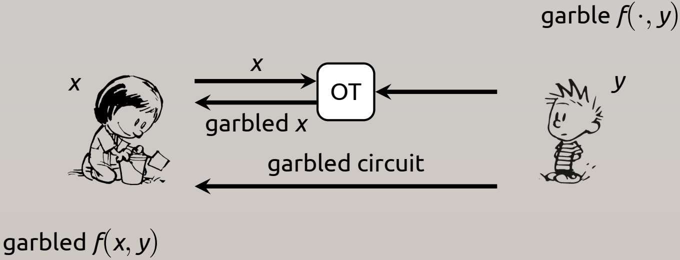

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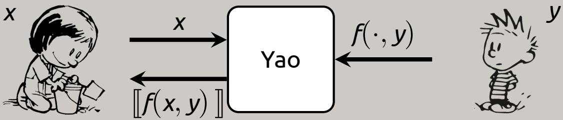

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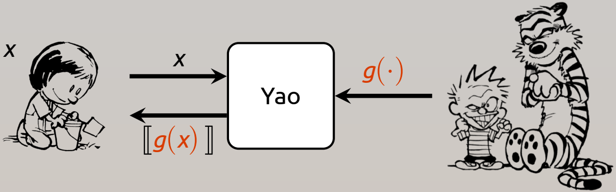
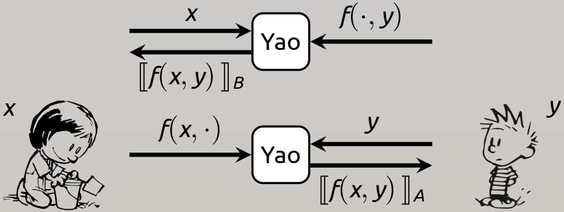


- Full security against malicious receiver
- Malicious sender can construct bad garbled circuit

dual execution protocol [MohasselFranklin06]



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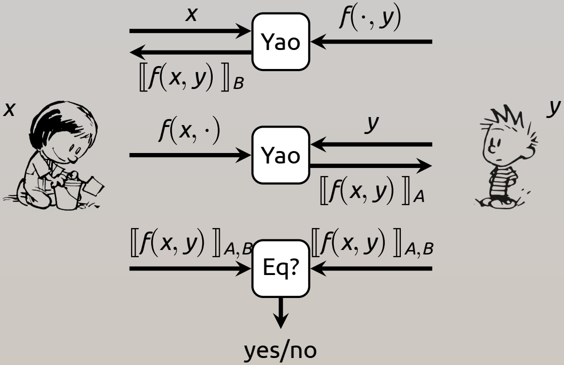
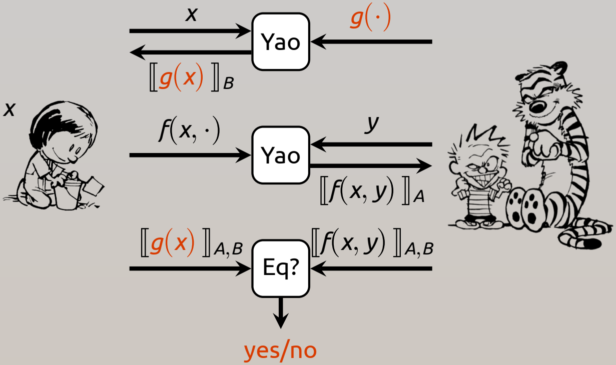


- Define a **common** garbled encoding: $[\![z]\!]_{A,B} \stackrel{\text{def}}{=} [\![z]\!]_A \oplus [\![z]\!]_B$

dual execution protocol [MohasselFranklin06]



- Define a **common** garbled encoding: $[\![z]\!]_{A,B} \stackrel{\text{def}}{=} [\![z]\!]_A \oplus [\![z]\!]_B$
- Malicious Bob learns whether $g(x) = f(x, y)$ (only 1 bit)

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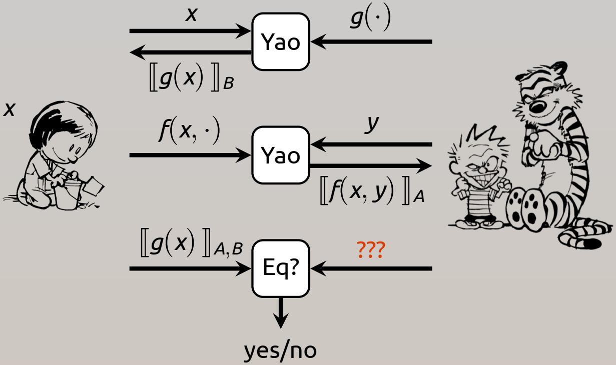

- Define a **common** garbled encoding: $[\![z]\!]_{A,B} \stackrel{\text{def}}{=} [\![z]\!]_A \oplus [\![z]\!]_B$
- Malicious Bob learns whether $g(x) = f(x, y)$ (only 1 bit)
- Malicious Bob can't predict $[\![z]\!]_{A,B}$ for for $z \neq f(x, y)$

  $\Rightarrow$ can't make Alice accept incorrect output!

reducing leakage [KolesnikovMohasselRivaR15]

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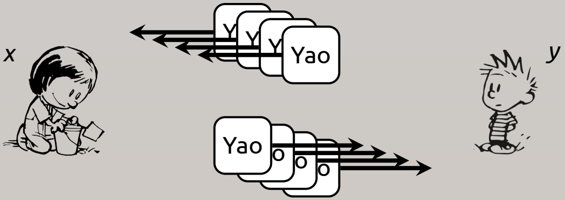
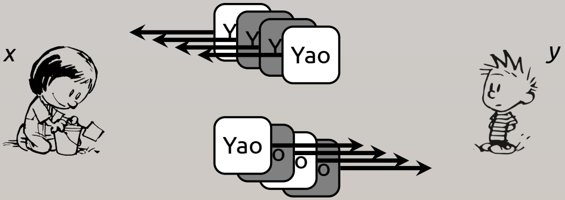


Main idea:

- Run κ copies of Yao's protocol in each direction

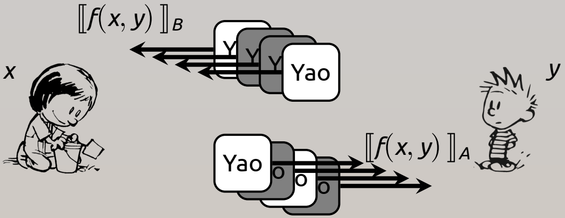
reducing leakage [KolesnikovMohasselRivaR15]



Main idea:

- Run κ copies of Yao's protocol in each direction
- Cut and choose: check each garbled circuit with probability 1/2.

reducing leakage [KolesnikovMohasselRivaR15]



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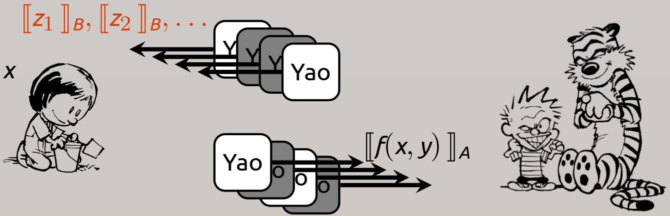


Main idea:

- Run κ copies of Yao's protocol in each direction
- Cut and choose: check each garbled circuit with probability 1/2.
- Garbled circuits in same direction have same output encoding
- What to do when Alice gets disagreeing outputs?

reconciliation technique

$[\![z^*]\!]_B$

$[\![z^*]\!]_A$

- Honest parties can compute common $[\![z^*]\!]_{A,B} \stackrel{\text{def}}{=} [\![z^*]\!]_B \oplus [\![z^*]\!]_A$

reconciliation technique

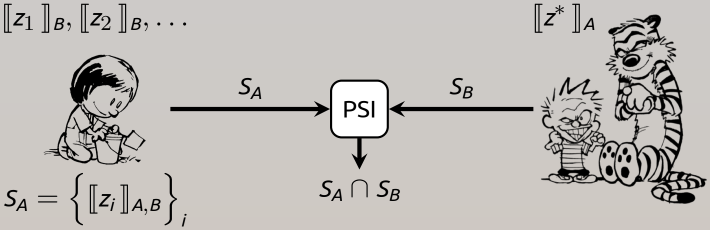
$\llbracket z_1 \rrbracket_B, \llbracket z_2 \rrbracket_B, \dots$

$S_A = \left\{ \llbracket z_i \rrbracket_{A,B} \right\}_i$

$\llbracket z^* \rrbracket_A$

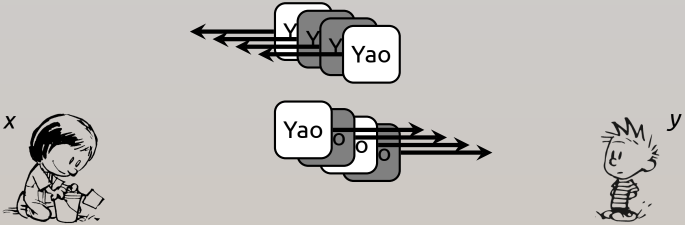
- Honest parties can compute common $\llbracket z^* \rrbracket_{A,B} \stackrel{\text{def}}{=} \llbracket z^* \rrbracket_B \oplus \llbracket z^* \rrbracket_A$
- If disagreeing outputs, compute **set of candidates**

reconciliation technique



- Honest parties can compute common $[\![z^*]\!]_{A,B} \stackrel{\text{def}}{=} [\![z^*]\!]_B \oplus [\![z^*]\!]_A$
- If disagreeing outputs, compute **set of candidates**
- Do **private set intersection** on the sets!
  - $\Rightarrow$ PSI output identifies the “correct” z_i

protocol summary



- κ instances of Yao in each direction, check random subset

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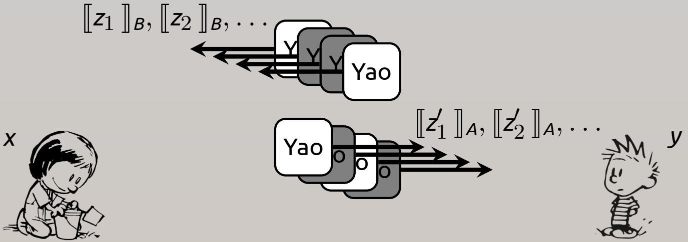
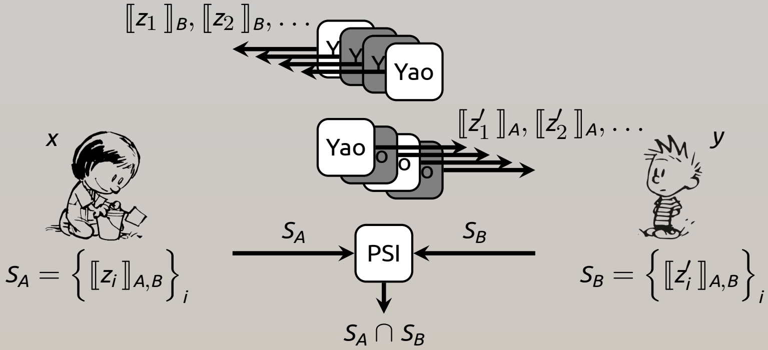


$$S_A = \left\{ [\![z_i]\!]_{A,B} \right\}_i \qquad S_B = \left\{ [\![z'_i]\!]_{A,B} \right\}_i$$

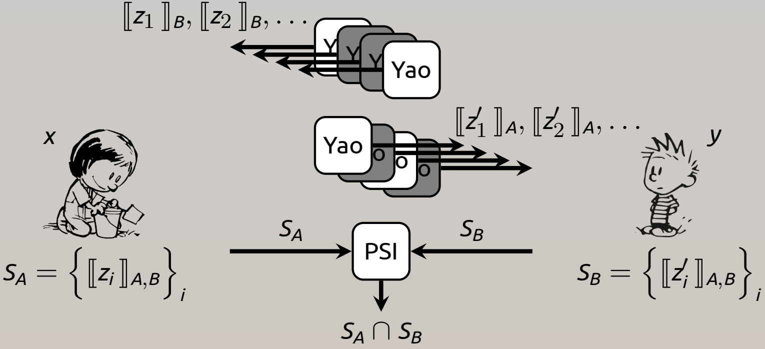
- κ instances of Yao in each direction, check random subset
- Compute set of reconciliation values

protocol summary

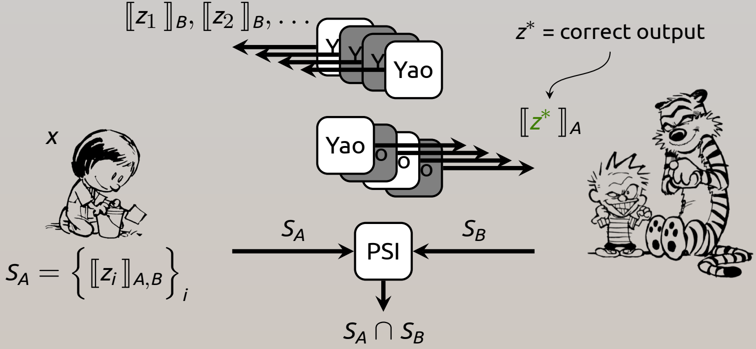


- κ instances of Yao in each direction, check random subset
- Compute set of reconciliation values
- Private set intersection to identify correct output

protocol analysis



protocol analysis: corrupt Bob



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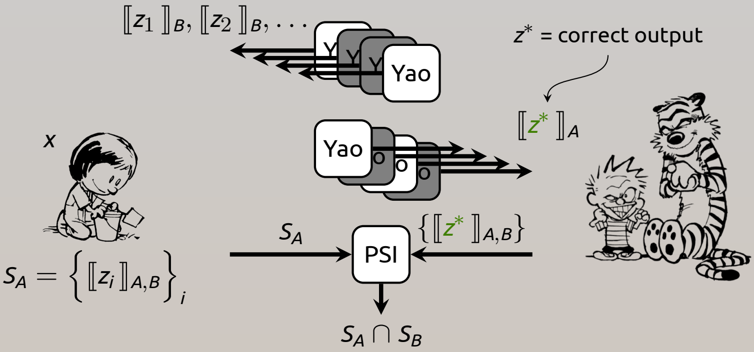
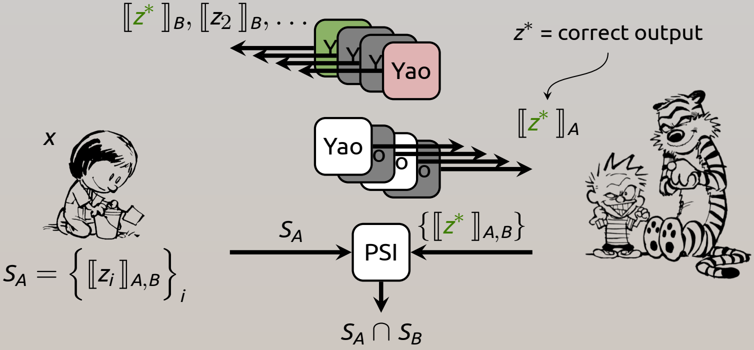


- Bob's only "useful" PSI input is $[\![z^*]\!]_{A,B}$

protocol analysis: corrupt Bob



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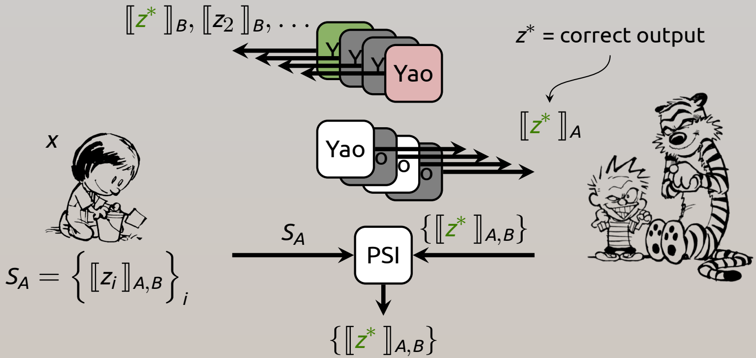
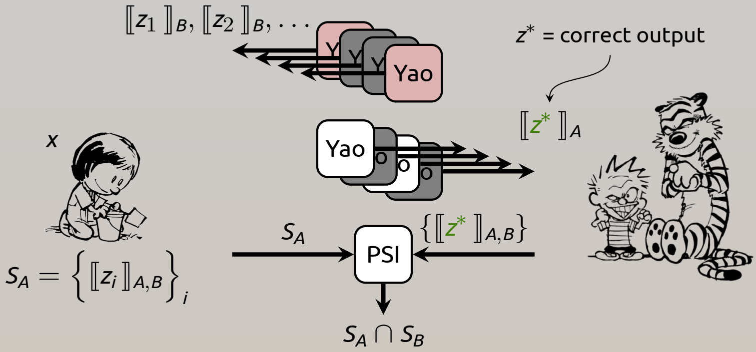
- One of Bob's garbled circuits **correct** $\Rightarrow$

protocol analysis: corrupt Bob



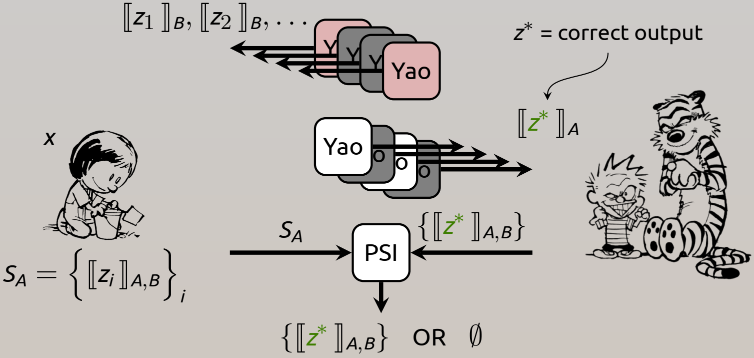
- Bob's only "useful" PSI input is $[\![z^*]\!]_{A,B}$
- One of Bob's garbled circuits **correct** $\Rightarrow$ PSI output leaks nothing!

protocol analysis: corrupt Bob



- Bob's only "useful" PSI input is $[\![z^*]\!]_{A,B}$
- One of Bob's garbled circuits **correct** $\Rightarrow$ PSI output leaks nothing!
- None of Bob's garbled circuits correct $\Rightarrow$

protocol analysis: corrupt Bob



- Bob's only "useful" PSI input is $[\![z^*]\!]_{A,B}$
- One of Bob's garbled circuits **correct** $\Rightarrow$ PSI output leaks nothing!
- None of Bob's garbled circuits correct $\Rightarrow$ PSI output leaks just 1 bit

“dual-ex+PSI” summary

κ garbled circuits in each direction (can be done simultaneously)

Adversary cannot violate output correctness

Adversary learns a single bit with probability $1/2^{\kappa}$; only when:

- All opened circuits are correct
- All evaluated circuits are incorrect

rest of the talk

Online/offline, multi-execution setting

- Reducing # of garbled circuits

Adapting “dual-execution+PSI” protocol to online/offline setting: [RindalR16]

- Ensuring input consistency
- Lightweight private set intersection

Implementation, performance

- Comparison to [LindellRiva15] and info-theoretic protocols

online/offline setting

Want to do 2PC of same circuit N times?

[HuangKatzKolesnikovKumaresanMalozemoff14,LindellRiva14]

online/offline setting

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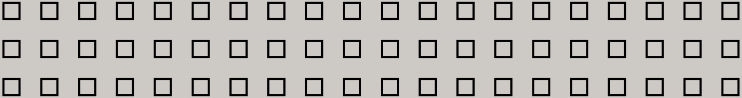

generate a lot of garbled circuits

online/offline setting

Want to do 2PC of same circuit N times?

[HuangKatzKolesnikovKumaresanMalozemoff14,LindellRiva14]

open and check some fraction of them

online/offline setting

Want to do 2PC of same circuit *N* times?

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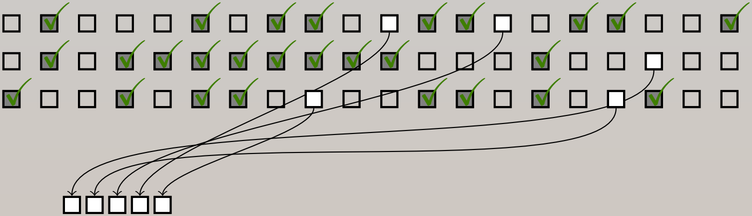

pick a random "bucket" of available circuits and evaluate them

online/offline setting

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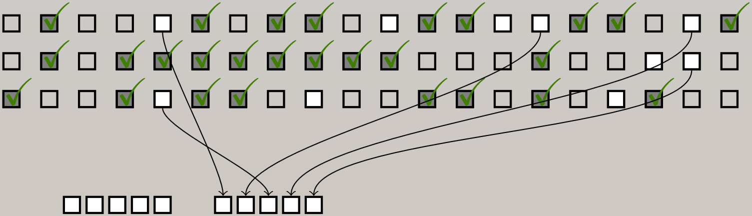

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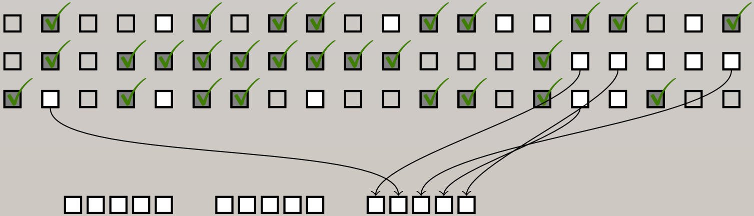

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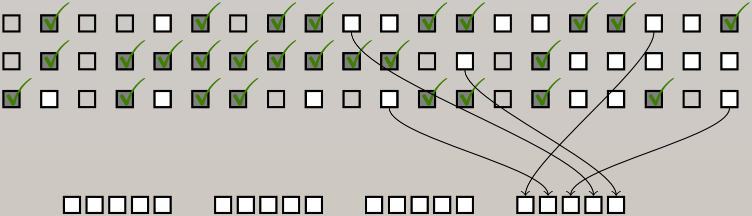

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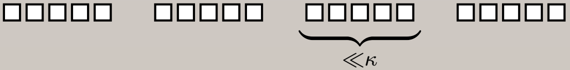


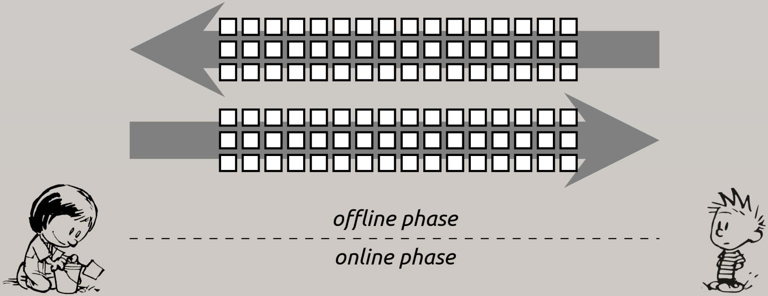
- for security $1/2^{\kappa}$, need $O(\kappa/\log N)$ circuits per execution
- example: $N = 1024$, $\kappa = 40 \implies$ 4 circuits per execution

online/offline dual-ex [RindalR16]

offline phase

online phase

online/offline dual-ex [RindalR16]



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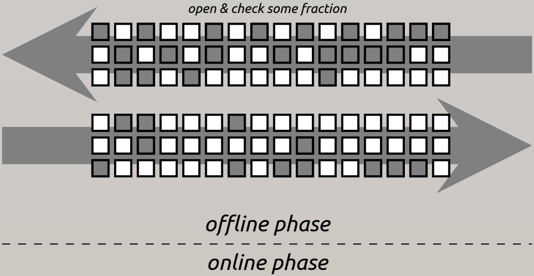

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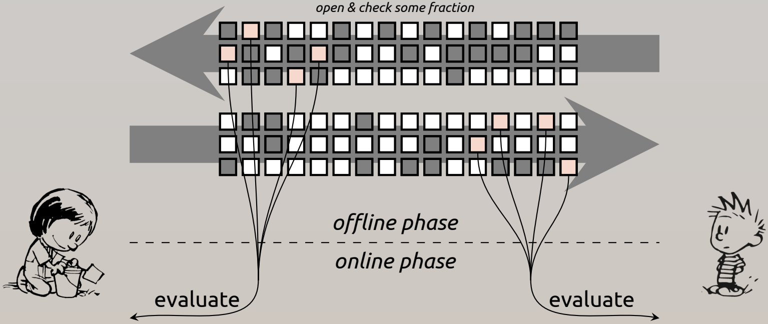

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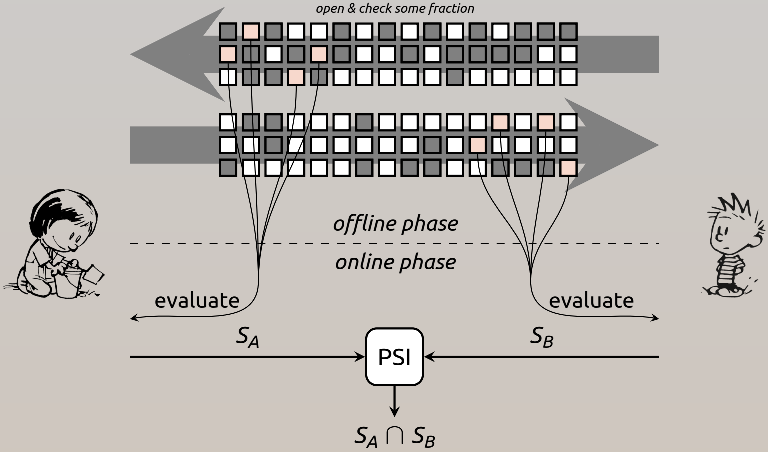


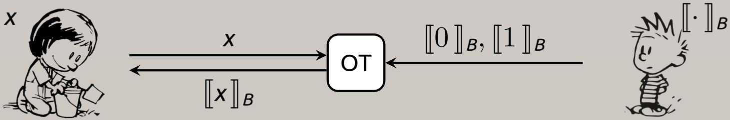
challenge #1: input consistency

How to ensure same inputs in Alice/Bob circuits?

[KolesnikovMohasselRivaR15,shelatShen13] technique incompatible with offline circuit garbling

pre-computing OTs [Beaver95]

[for simplicity: 1 input bit from Alice]



pre-computing OTs [Beaver95]

$r, k_r \xleftarrow{\quad} \boxed{\text{R-OT}} \xrightarrow{\quad} k_0, k_1$

x

offline phase

- -

online phase

$[\![\cdot]\!]_B$

pre-computing OTs [Beaver95]

$r, k_r \xleftarrow{\quad} \boxed{\text{R-OT}} \xrightarrow{\quad} k_0, k_1$

x

offline phase

- -

online phase

$\llbracket \cdot \rrbracket_B$

$$\xrightarrow{d = r \oplus x}$$

$$\llbracket x \rrbracket_B \xleftarrow{k_0 \oplus \llbracket d \rrbracket_B;\ \ k_1 \oplus \llbracket \bar{d} \rrbracket_B}$$

consistency b/w A & B circuits

r, k_r R-OT k_0, k_1

x

offline phase

online phase

$[\![\cdot]\!]_B$

$d = r \oplus x$

$k_0 \oplus [\![d]\!]_B;\;\; k_1 \oplus [\![\bar{d}]\!]_B$

$[\![x]\!]_B$

consistency b/w A & B circuits

$r, k_r \xleftarrow{\quad} \boxed{\text{R-OT}} \xrightarrow{\quad} k_0, k_1$

$[\![\cdot]\!]_A, x$

offline phase

online phase

$[\![\cdot]\!]_B$

$$\xrightarrow{d = r \oplus x}$$

$$[\![x]\!]_B \xleftarrow{k_0 \oplus [\![d]\!]_B;\ \ k_1 \oplus [\![\bar{d}]\!]_B} \ ?\ [\![x]\!]_A\ ?$$

consistency b/w A & B circuits

$\xleftarrow{r,\ k_r}$ R-OT $\xrightarrow{k_0,\ k_1}$

$$\xrightarrow{c_0 = \mathsf{Com}(\llbracket r \rrbracket_A);\ \ c_1 = \mathsf{Com}(\llbracket \bar{r} \rrbracket_A)}$$

$\llbracket \cdot \rrbracket_A, x$

$\llbracket \cdot \rrbracket_B$

offline phase

online phase

$$\xrightarrow{d = r \oplus x}$$

$\llbracket x \rrbracket_B \xleftarrow{k_0 \oplus \llbracket d \rrbracket_B;\ \ k_1 \oplus \llbracket \bar{d} \rrbracket_B}$? $\llbracket x \rrbracket_A$?

consistency b/w A & B circuits

R-OT

r, k_r ← R-OT → k_0, k_1

$C_0 = \mathsf{Com}(\llbracket r \rrbracket_A);\;\; C_1 = \mathsf{Com}(\llbracket \bar{r} \rrbracket_A)$ →

$\llbracket \cdot \rrbracket_A, x$

offline phase

online phase

$\llbracket \cdot \rrbracket_B$

$d = r \oplus x;\;\; \mathsf{Open}(C_d)$ →

$k_0 \oplus \llbracket d \rrbracket_B;\;\; k_1 \oplus \llbracket \bar{d} \rrbracket_B$ ←

$\llbracket x \rrbracket_B$

$\llbracket x \rrbracket_A$ ✓

consistency b/w A & B circuits

r, k_r ← R-OT → k_0, k_1

$$C_0 = \mathsf{Com}(\llbracket r \rrbracket_A);\;\; C_1 = \mathsf{Com}(\llbracket \bar{r} \rrbracket_A) \longrightarrow$$

$\llbracket \cdot \rrbracket_A, x$

offline phase

- -

online phase

$\llbracket \cdot \rrbracket_B$

Can check consistency of commitments in cut-and-choose:

- Alice can show k_r to prove what r she got from OT

$\Rightarrow$ at least one pair of A/B circuits with consistency

input consistency

Within each bucket,

- Alice uses same input *x* on all Bob-circuits (easy)
- At least one Alice-circuit where Alice uses *x* (except prob $1/2^{\kappa}$)

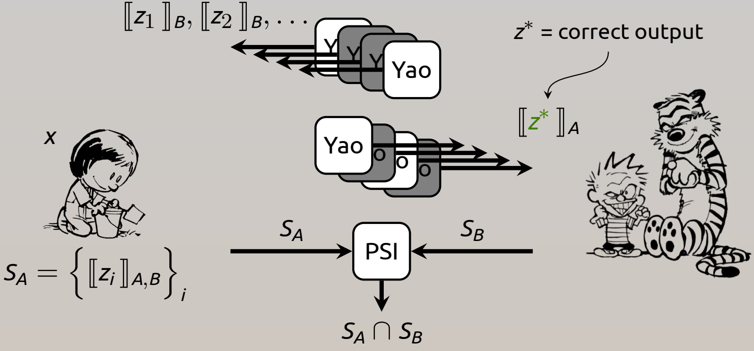
Suffices for security!

Zero online cost for input consistency!

challenge #2: psi

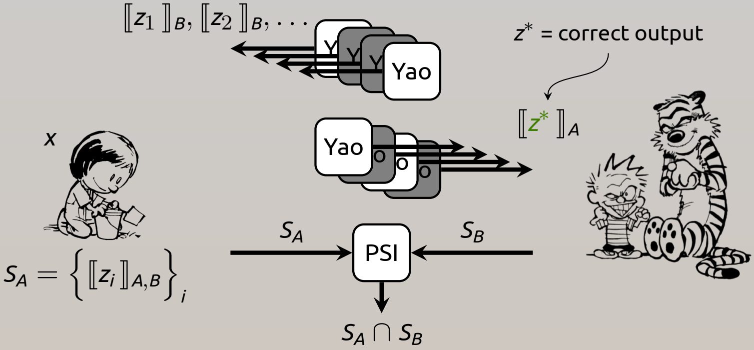
How to efficiently instantiate PSI?

closer look at PSI



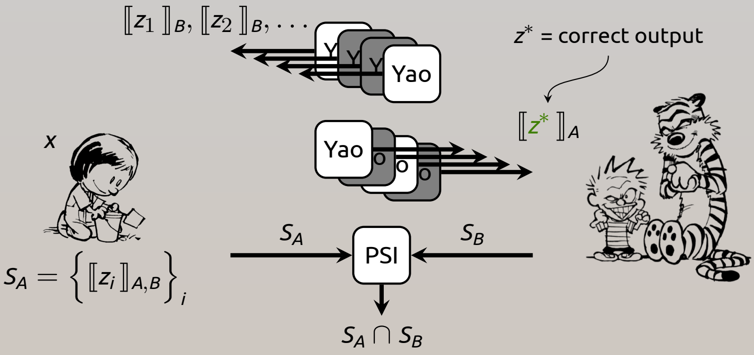
Bob's only "useful" PSI input is $[\![z^*]\!]_{A,B}$

closer look at PSI



- Simulator knows $[\![z^*]\!]_{A,B}$; rest of S_A independent of Adv's view

closer look at PSI



- Simulator knows $[\![z^*]\!]_{A,B}$; rest of S_A independent of Adv's view
- ⋆ Simulator **does not need to extract** Adv's input S_B!

  . . . it suffices to check whether $[\![z^*]\!]_{A,B} \in S_B$

instantiating psi

[KolesnikovMohasselRivaR15]:

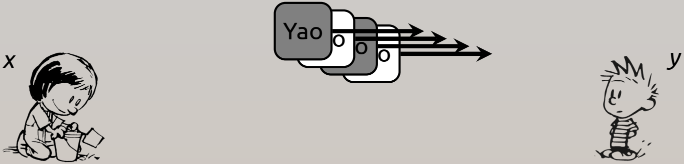
- Suggest using fully malicious PSI subprotocol

[RindalR16]:

- PSI protocol with "non-extracting security" suffices
- Implementation uses semi-honest PSI protocol of [PinkasSchneiderZohner14]
- Very cheap, based on pre-processed OTs (no public-key operations)

comparison to [LindellRiva15]

[LindellRiva14/15]: online/offline, malicious security, based on “traditional cut and choose” [Lindell13]:

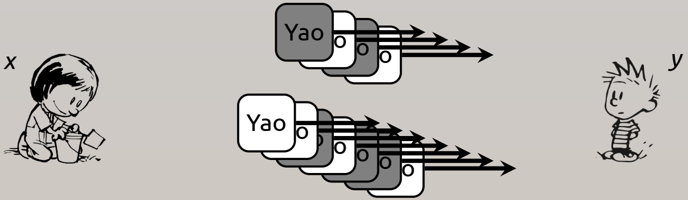


Two phases:

1. B circuits computing $f(x, y)$

comparison to [LindellRiva15]

[LindellRiva14/15]: online/offline, malicious security, based on “traditional cut and choose” [Lindell13]:

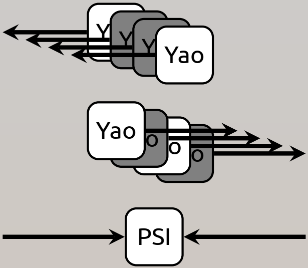


Two phases:

1. B circuits computing $f(x, y)$
2. $\sim 3B$ circuits computing:
   “if Bob can prove Alice cheated in phase 1, then reveal x to Bob”

protocol comparison

[KolesnikovMohasselRivaR15,RindalR16]:



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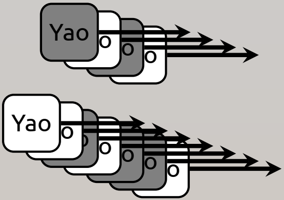

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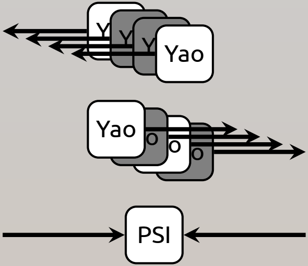

- *B* primary circuits in each direction (evaluated **simultaneously!**)

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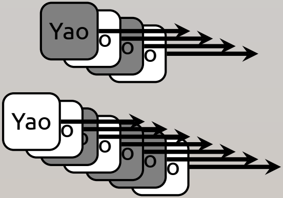

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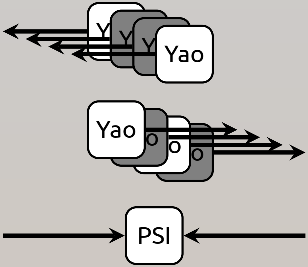
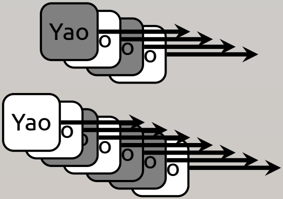


- B primary circuits in each direction (evaluated **simultaneously!**)
- PSI computation scales only with B

[LindellRiva14/15]:



- B primary circuits
- Aux computation scales as $3B \cdot \ell_{\text{input}}$

a closer look at κ

κ_c: Computational security parameter (e.g., 128)

κ_s: Statistical security parameter: security properties violated with probability $1/2^{\kappa_s}$ (e.g., 40)

"Traditional cut-and-choose" [LindellRiva14/15]:

- When cut-and-choose fails, adversary can completely break privacy & correctness

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Dual-execution approach [KolesnikovMohasselRivaR15,RindalR16]:

- When cut-and-choose fails, adversary learns only a bit

$\Rightarrow$ # of garbled circuits scales with $\kappa_b \leq \kappa_s$

some parameter possibilities

[RindalR16] with $\kappa_s = \kappa_b = 40$:

- same security as [LindellRiva] with $\kappa_s = 40$
- same # of garbled circuits

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- fewer garbled circuits (25% savings for $N = 1024$, 40% for $N = 512$)

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[RindalR16] with $\kappa_s = 80$, $\kappa_b = 40$:

- **strictly stronger** security than [LindellRiva] with $\kappa_s = 40$
- same # of garbled circuits (only PSI cost increases)

implementation

	[RindalR16]		[LindellRiva]		[DamgårdZakarias15]	
	offline	online	offline	online	offline	online
AES circuit	**5.1ms**	**1.3ms**	74ms	7ms	high?	6ms
SHA256 circuit	**48ms**	**8.4ms**	206ms	33ms	-	-

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Amortized cost over $N = 1024$ executions:

- same hardware, LAN connection
  (Amazon `c4.8xlarge` = 36 core, 64GB RAM)
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Maximum **throughput:** 0.26ms / AES block (3800+ Hz)

- [DamgårdZakarias15] reports 0.4ms

summary

Online-offline dual execution:

- Fastest 2PC with malicious security to date: 1.3ms AES
- Some protocol advantages over “classic” cut-and-choose

Future work:

summary

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Future work:

	garbled circ	info-theoretic
online latency	low ✓ ✓	low ✓
online throughput	high ✓	high ✓ ✓
constant rounds?	yes ✓	no ✗
offline time	low ✓	(very) high ✗
function-indep pre-processing?	no ✗	yes ✓

summary

Online-offline dual execution:

- Fastest 2PC with malicious security to date: 1.3ms AES
- Some protocol advantages over “classic” cut-and-choose

Future work: Combine GC with info-theoretic? (at least for 2-party)

	garbled circ	info-theoretic	hybrid
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online throughput	high ✓	high ✓ ✓	high ✓ ✓
constant rounds?	yes ✓	no ✗	no ✗
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function-indep pre-processing?	no ✗	yes ✓	yes ✓

the end; thanks.

Richer Efficiency/Security Tradeoffs in 2PC

Vladimir Kolesnikov, Payman Mohassel, Ben Riva & Mike Rosulek

`ia.cr/2015/055`

Faster Malicious 2-party Secure Computation with Online/Offline Dual Execution

Peter Rindal & Mike Rosulek

in submission