Fast Zero-Knowledge Proofs and Post-Quantum Signatures

Claudio Orlandi – Aarhus University

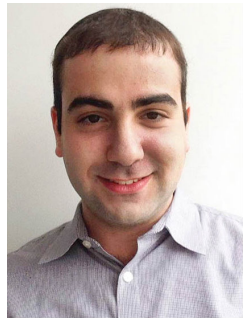
@claudiorlandi

Based on joint work with:

- Meliisa Chase (Microsoft)
- David Derler (TU Graz)
- Tore Frederiksen (BIU)
- Irene Giacomelli (UW-Madison)
- Steven Goldfeder (Princeton)
- Marek Jawurek (SAP)
- Florian Kerschbaum (SAP)
- Jesper Madsen (AU)
- Jesper Buus Nielsen (AU)
- Sebastian Ramacher (TU Graz)
- Christian Rechberger (TU Graz, DTU)
- Daniel Slamanig (TU Graz)
- Greg Zaverucha (Microsoft)



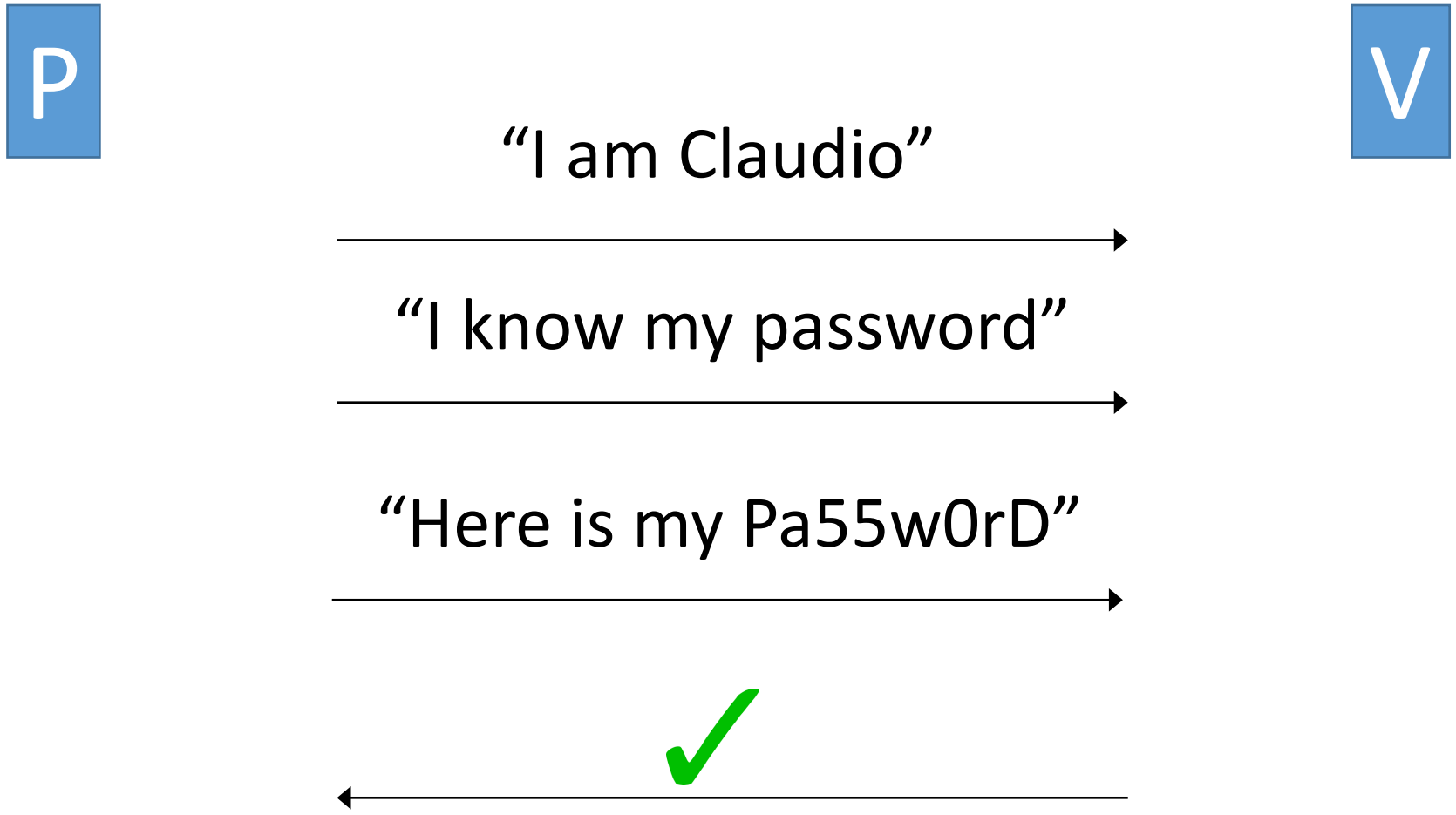









Motivation: Authentication



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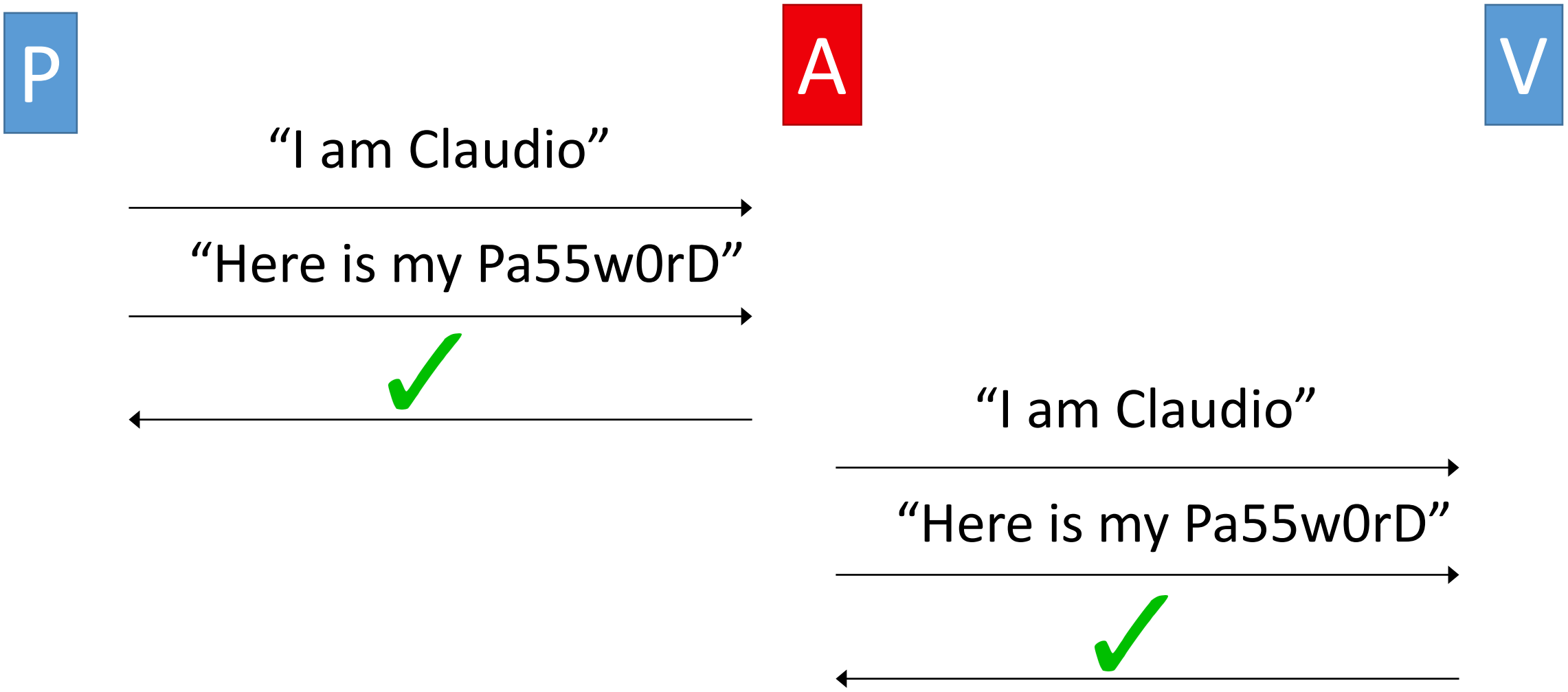
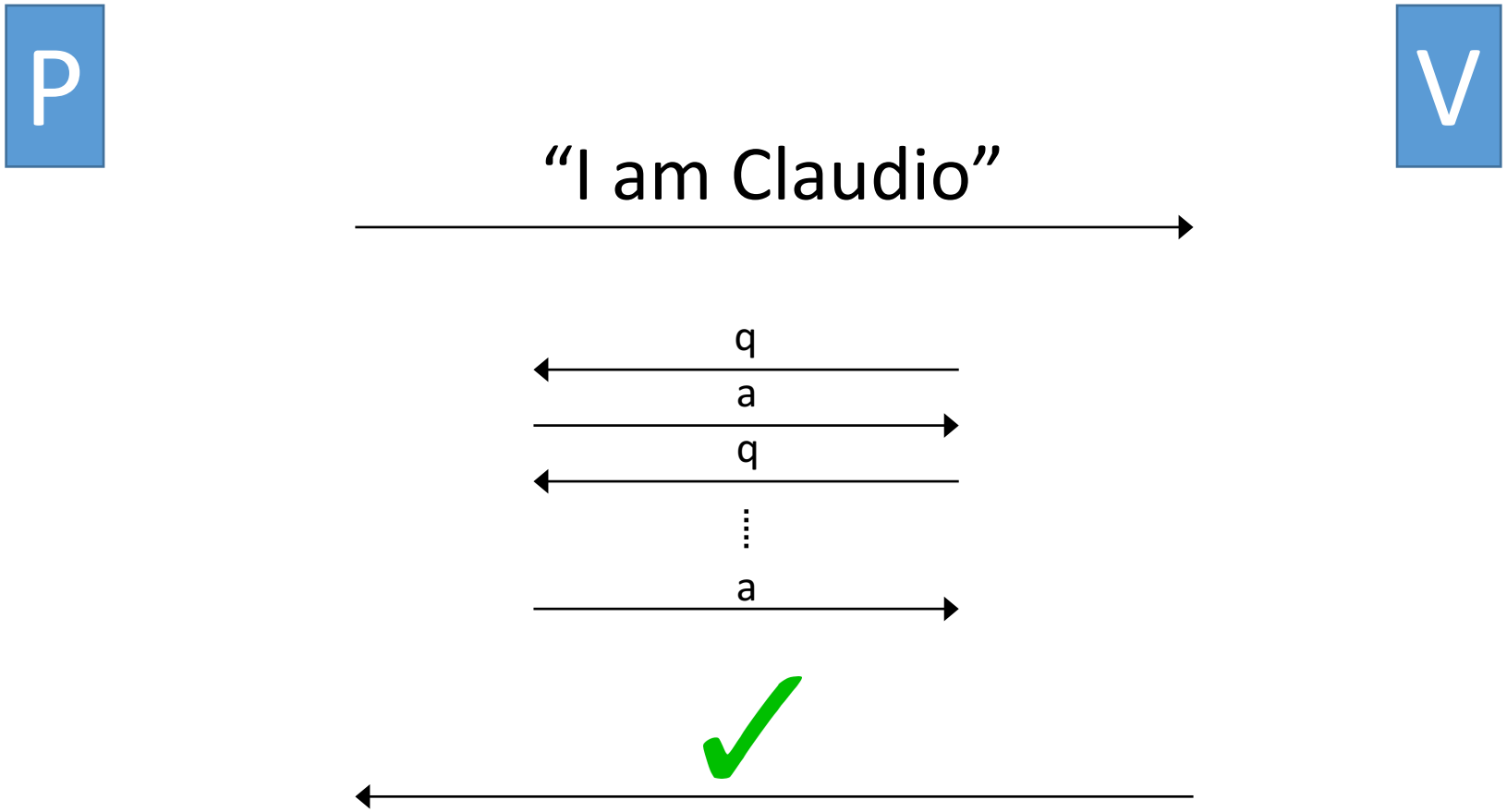
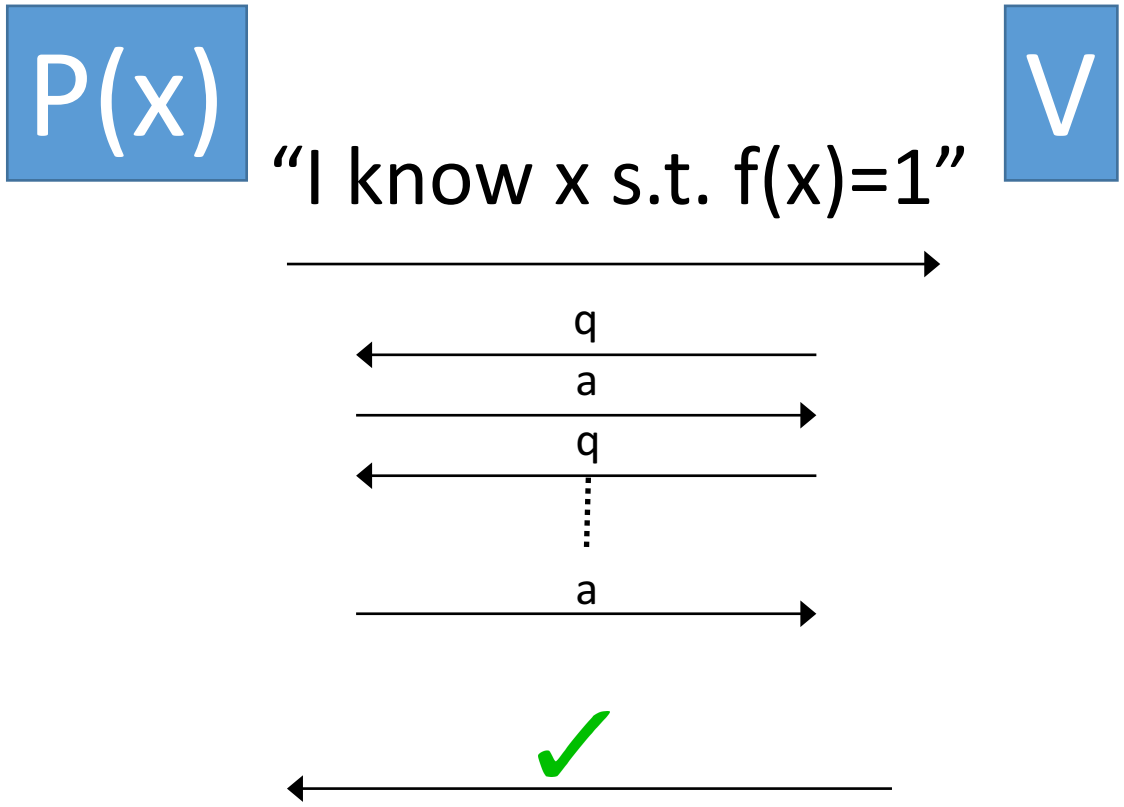


Motivation: Zero-Knoweldge Authentication



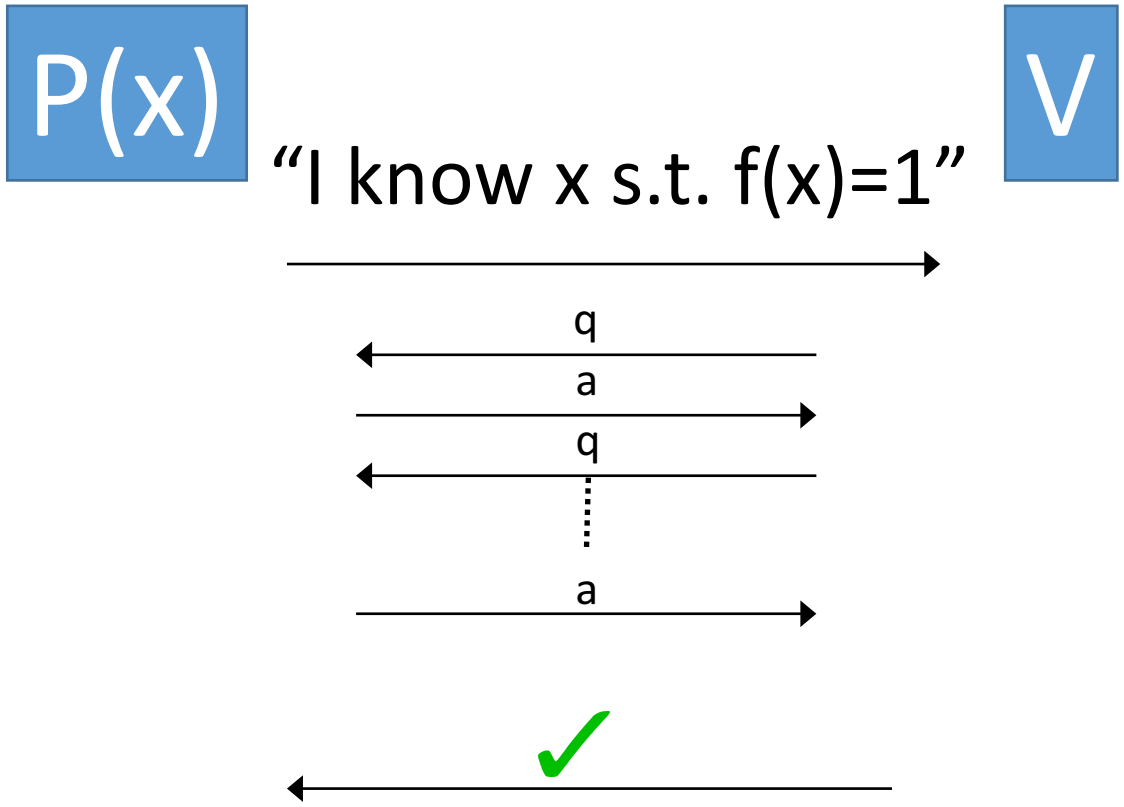
ZK: Definitions



Only P knows x

P,V know f

ZK: Definitions



- **Completeness**
  - P,V honest → V accepts

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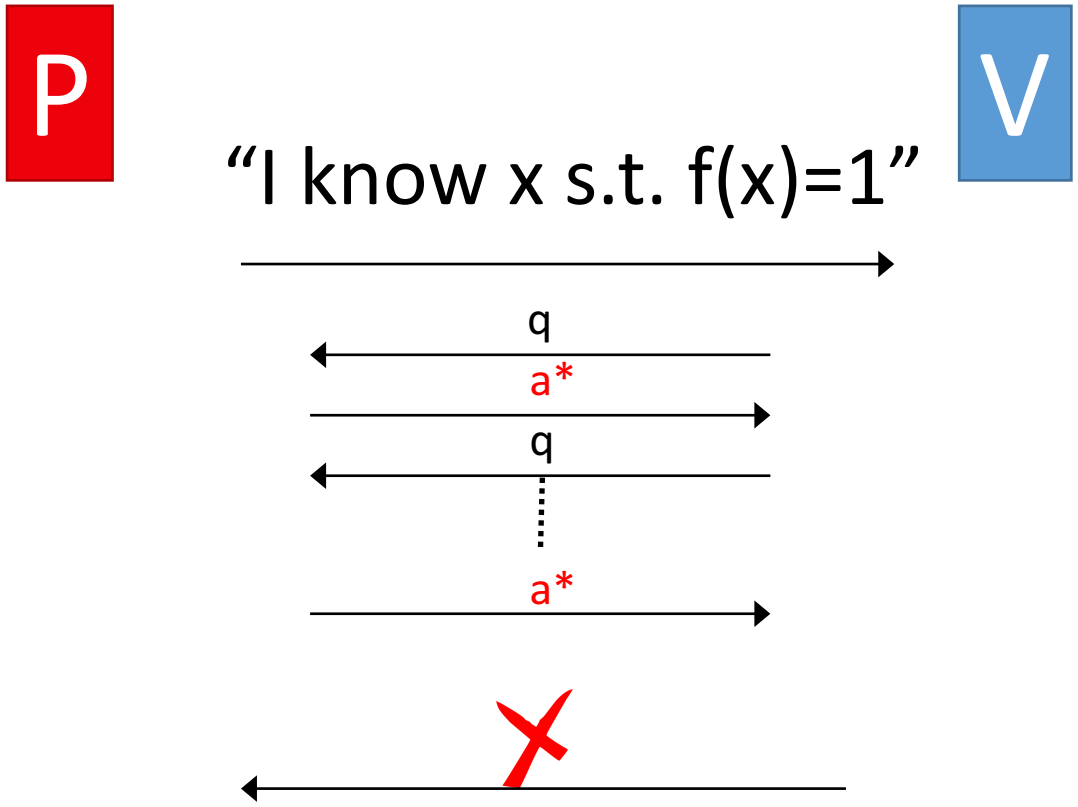
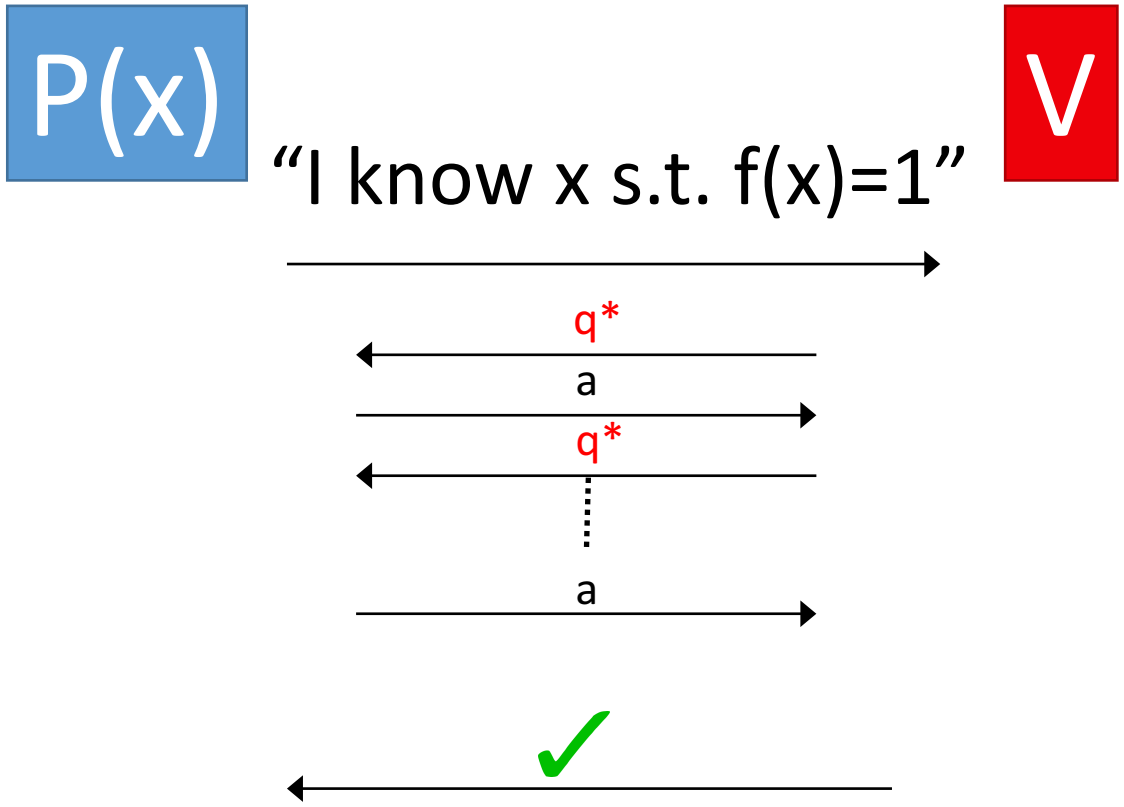


- **Completeness**
  - P,V honest → V accepts

- **Proof-of-Knowledge**
  - If P does not know x → V rejects

ZK: Definitions



- **Completeness**
  - P,V honest → V accepts
- **Proof-of-Knowledge**
  - If P does not know x → V rejects
- **Zero-Knowledge**
  - V learns nothing about x

What can be proven in ZK?

Feasability: NP, even PSPACE!

Efficiently: algebraic languages
(Schnorr, …, Groth-Sahai, …)

SNARKS (generic)

- **Short proofs, efficient verification ☺**
- **Slow prover ☹**
- Implementations: Pinocchio, libsnark,

This talk:

Can we construct efficient proofs for non-algebraic languages such as

"I know x such that SHA(x)=y"?

Two protocols:

- *ZKGC (from Garbled Circuits)*
- *ZKBoo (from MPC)*

One application:

- *Generic (post-quantum) signatures*

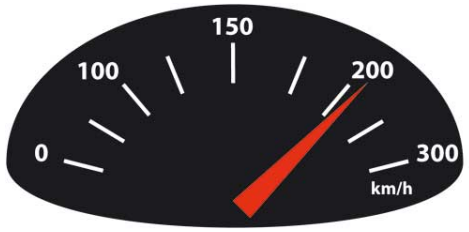
Example: Schnorr Protocol

Go to Example

The Crypto Toolbox

Weaker assumption ← Stronger assumption

OTP >> SKE >> PKE >> FHE >> Obfuscation



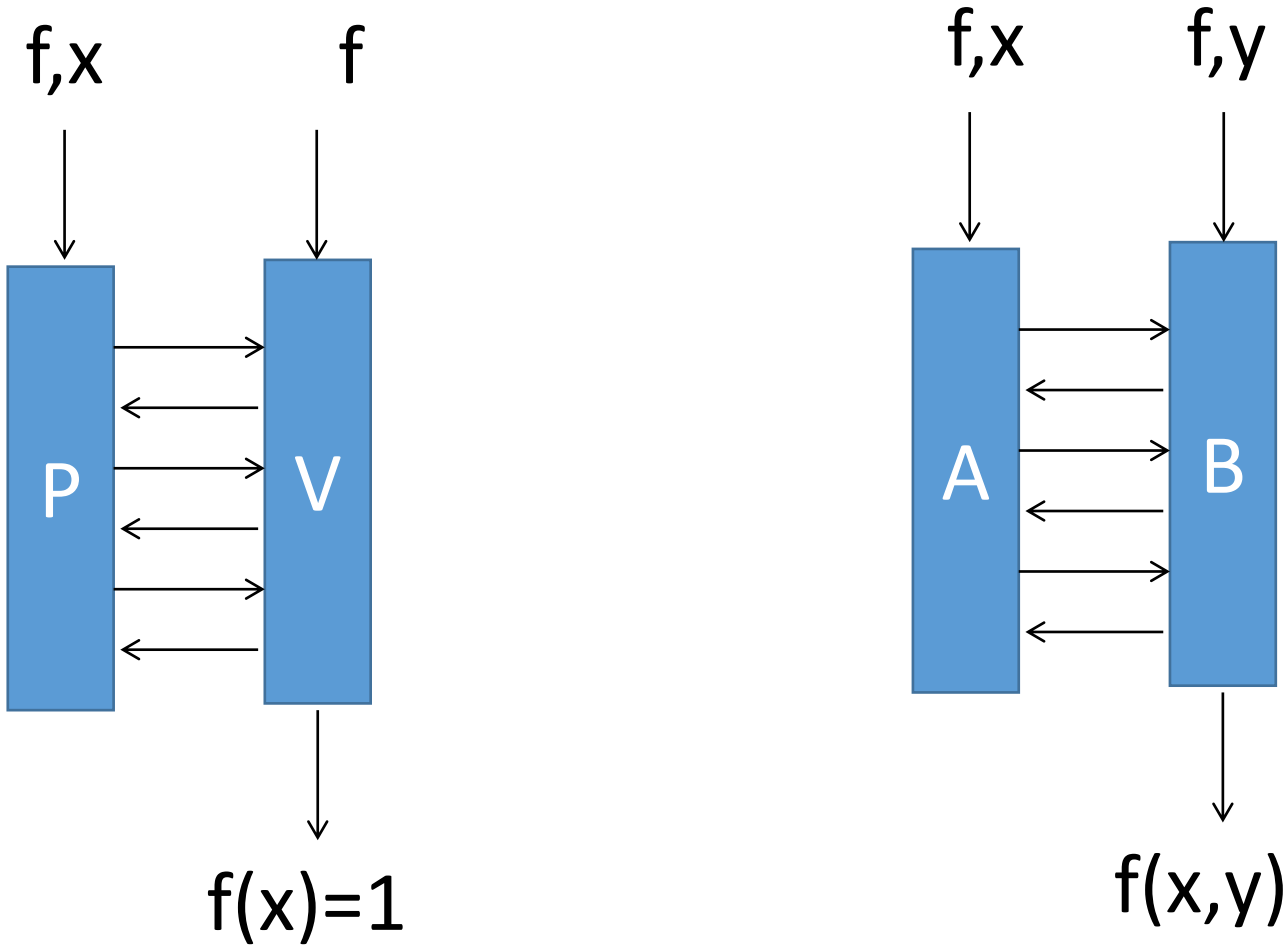
More efficient ← Less efficient

Zero-Knowledge from Garbled Circuits

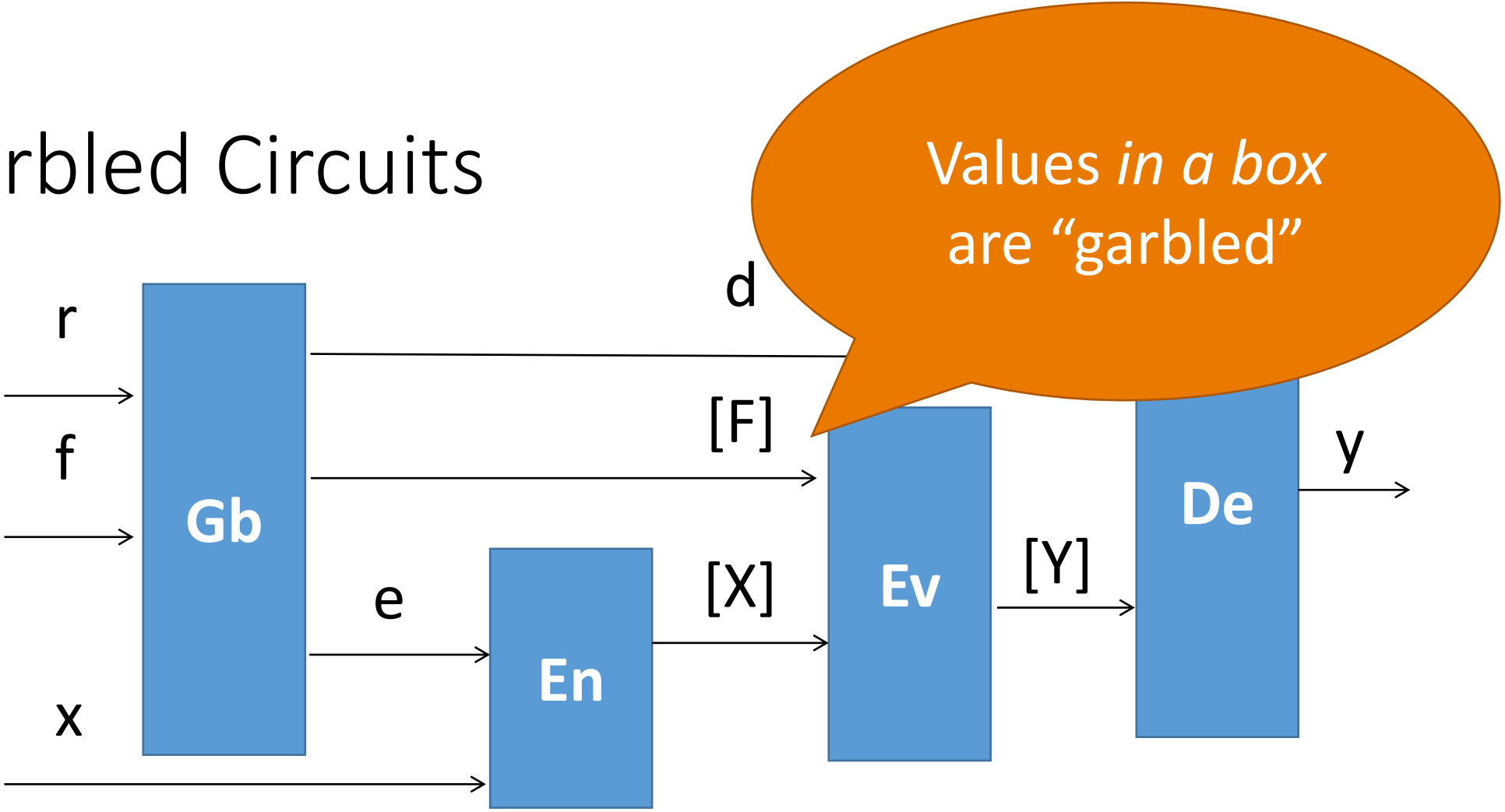
Jawurek, Ferschbaum, Orlandi

CCS 2013

Zero-Knowledge vs Secure 2PC

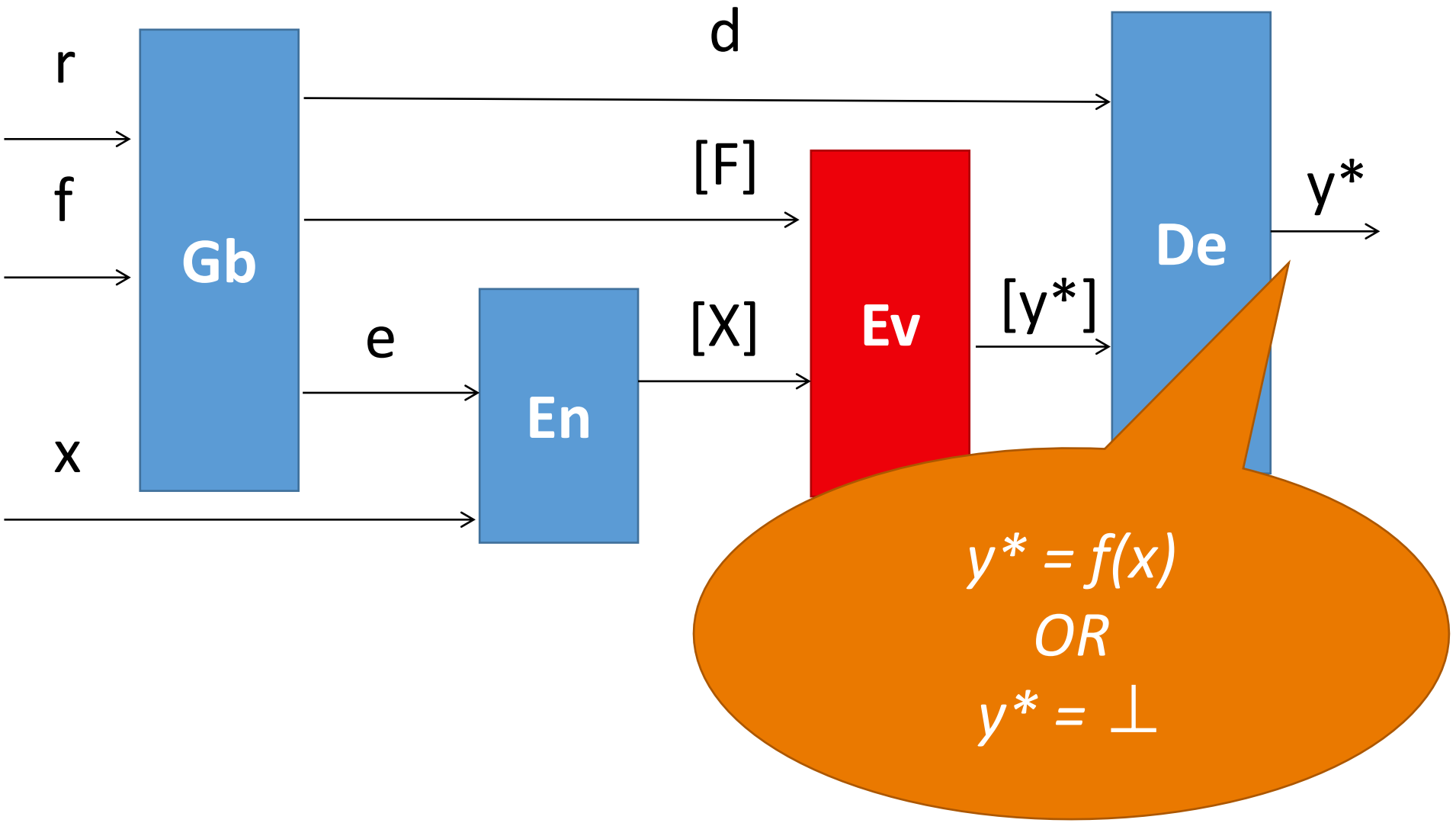


Garbled Circuits

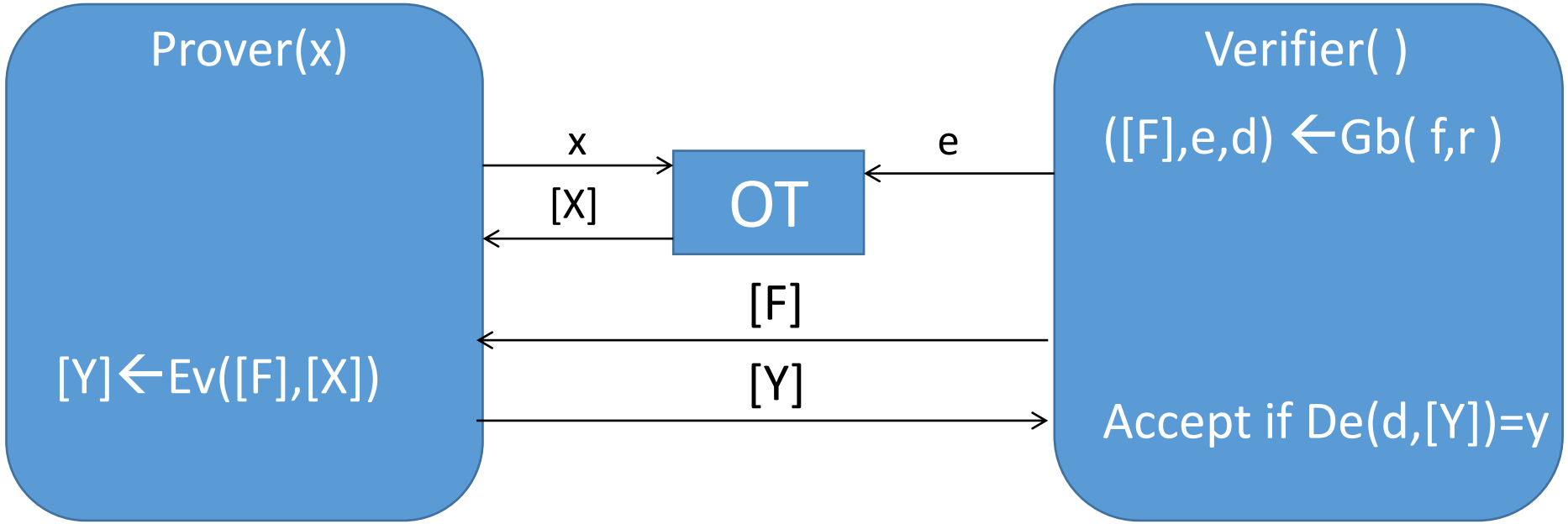


Correct if y=f(x)

Garbled Circuits: Authenticity



(HV)ZKGC to prove f(x)=y



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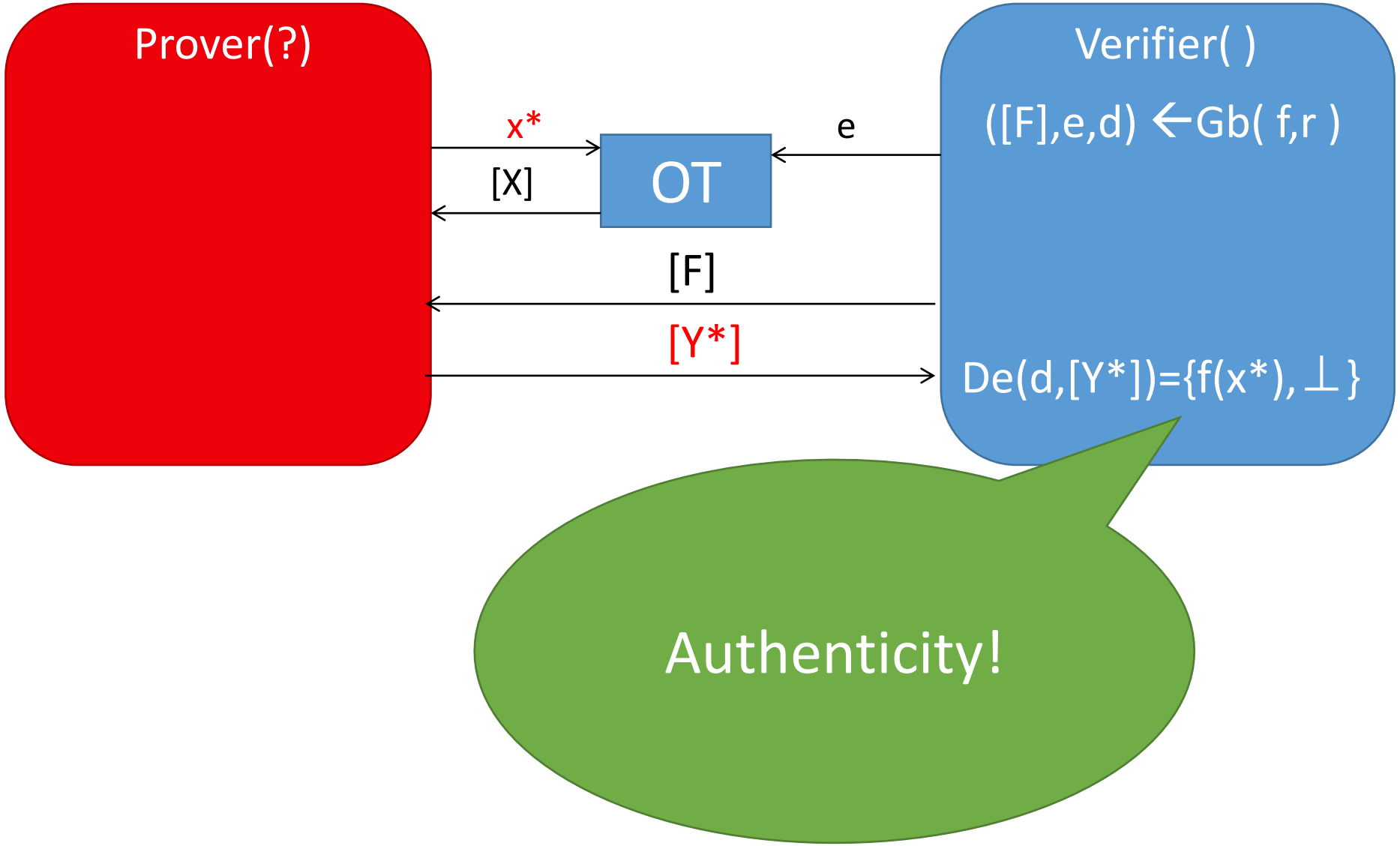

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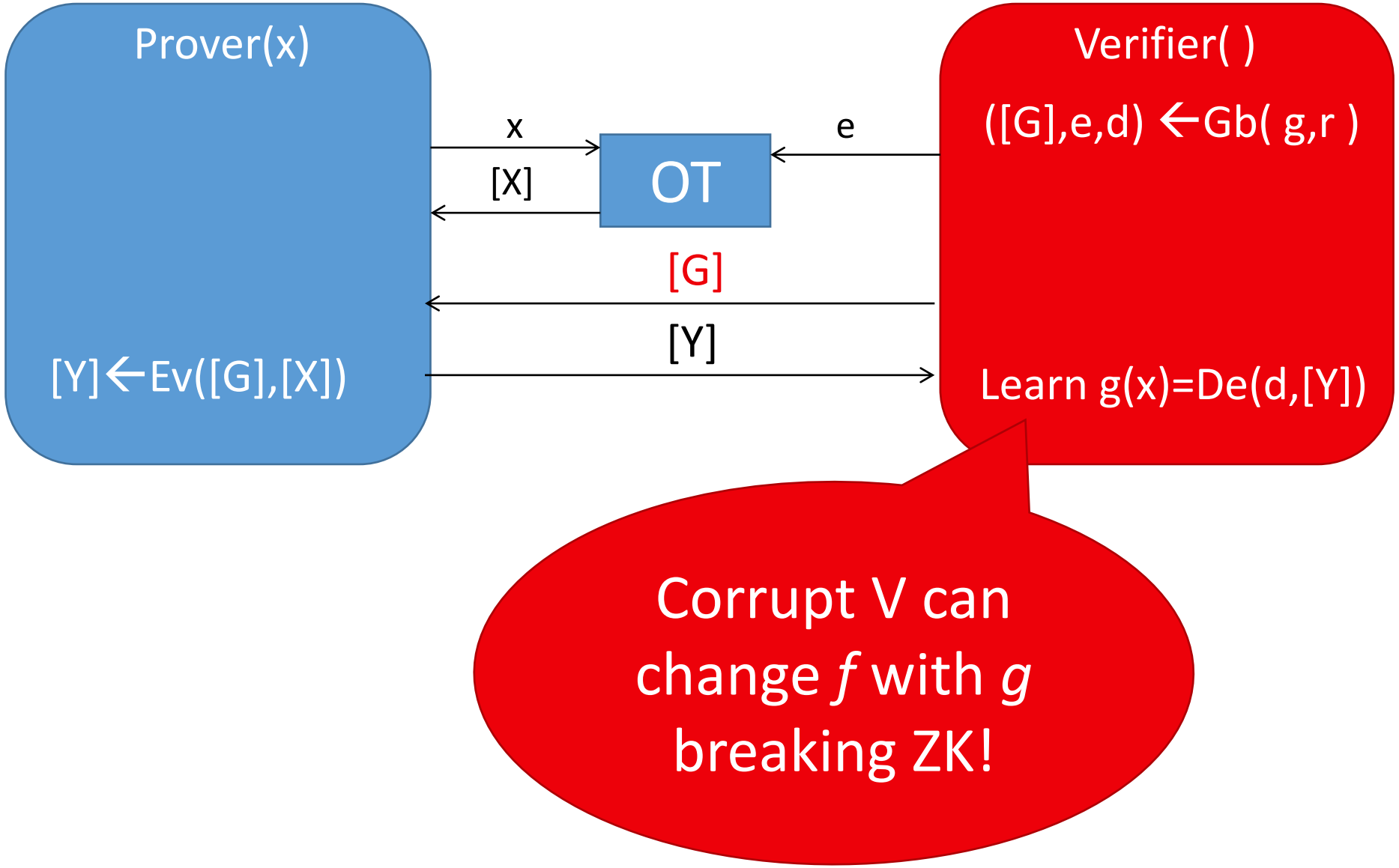


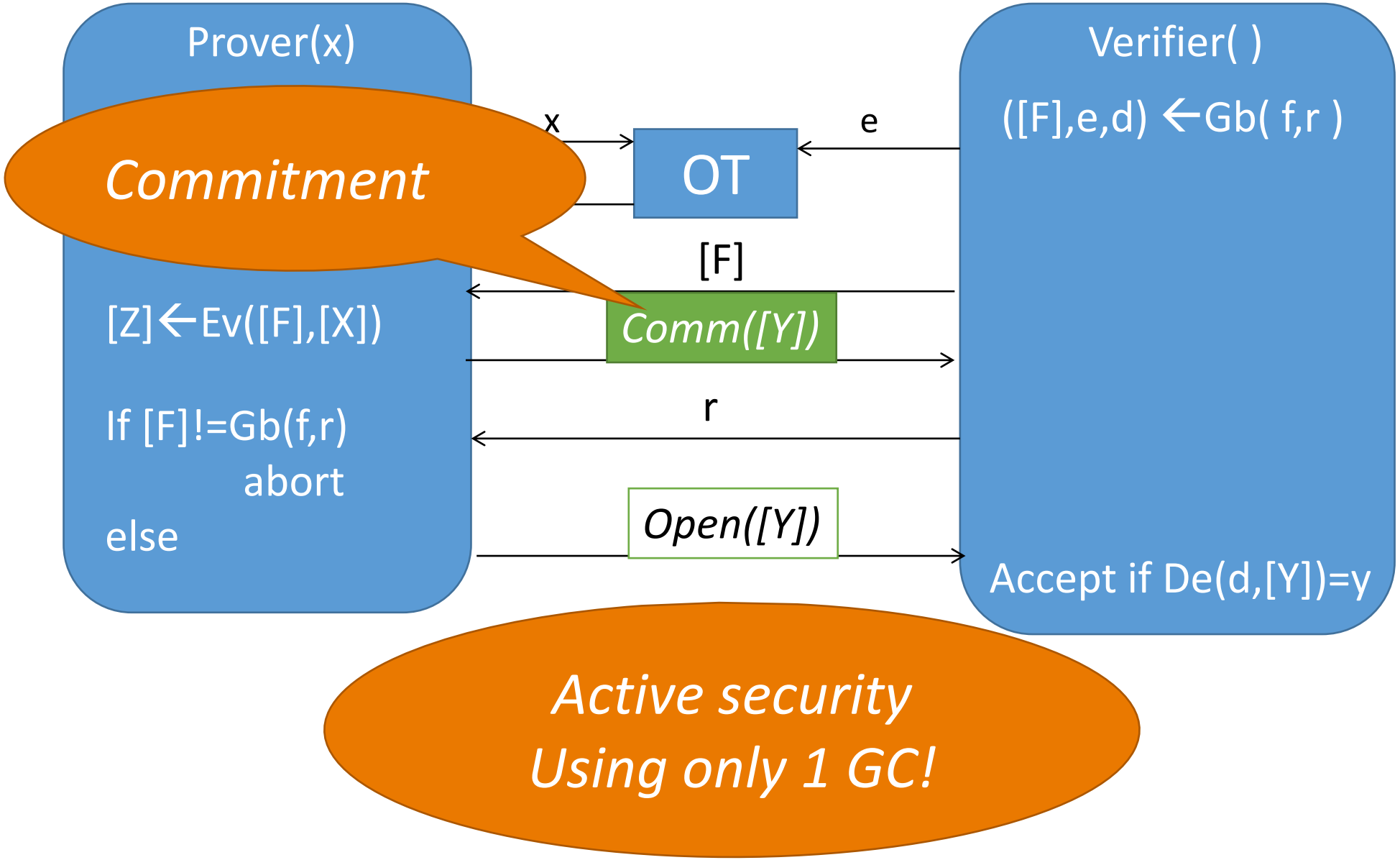
Garbled circuits with active security?

How can the verifier prove that f was garbled correctly

(without breaking soundness)?

- Plenty of (costly) solutions are known for 2PC
  - Zero-Knowledge
  - Cut-and-choose
  - Etc.
- **Can we do better for ZK?**

ZKGC to prove f(x)=y



Recap: ZK based on GC

- **The main idea:**
  - In ZK the verifier (Bob) has no secrets!
  - After the protocol, Bob can reveal all his randomness.
  - Alice can simply check that Bob behaved honestly

    by *redoing his entire computation*.

Privacy-Free Garbled Circuits

Frederiksen, Nielsen, Orlandi

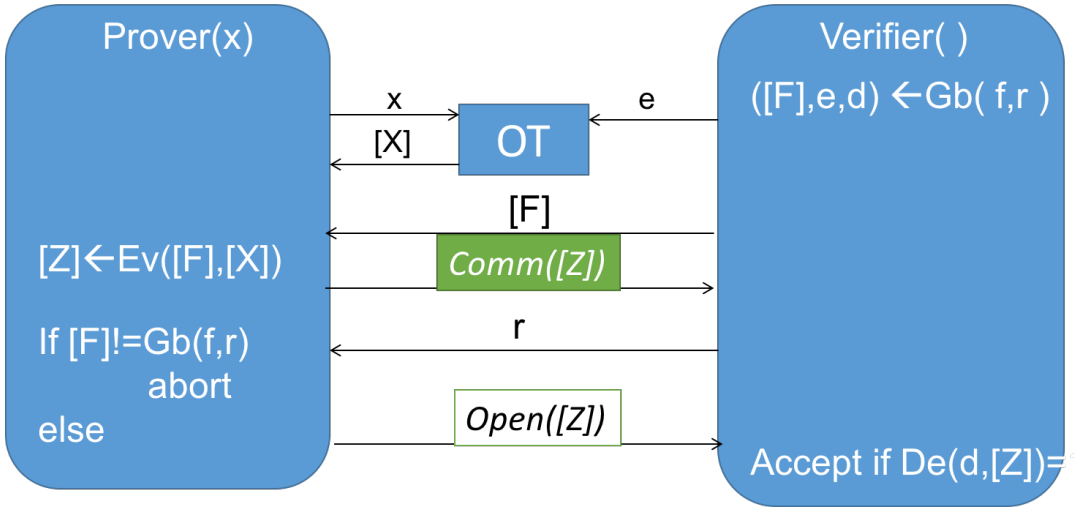
EUROCRYPT 2015

Main idea

- In 2PC the garbler has **secret input**
- GC privacy → privacy of input

- In ZK V has **no input to protect**
- Can we get more efficient GC without privacy?

Yes!



Example: Privacy Free Garbling

Go to PFGC

Runtime (rough estimates)

- Proof of “c=AES(k,m)” for secret k and public (c,m)
- AES: 35k gates (7k ANDs/28k XORs)
- **Communication**: **204kB** (98% GC)
- **Runtime**:
  - **OT**: 29.4ms (Using Chou-Orlandi OT) (|w|=128)
  - **Garbling**: 721µs (Using JustGarble GaXR)
  - **Eval**: 273 µs
  - **Total** (Garble+OT+Eval+Garble) **~ 31.2ms** (+network)

Applications

Hu, Mohassel, Rosulek

- ***Sublinear ZK (via ORAM)***, Crypto 2015

Chase, Ganesh, Mohassel,

- **Privacy-Preserving Credentials**, Crypto 2016

Kolesnikov, Krawczyk, Lindell, Malozemoff, Rabin,

- **Attribute-Based KE with General Policies**, CCS 2016

Baum; Katz, Malozemoff, Wang; Afshar, Mohassel, Rosulek,

- **Input validity in 2PC**, SCN 2016; ePrint; ePrint

…

ZKBoo: Faster Zero-Knowledge for Boolean Circuits

Giacomelli, Madsen, Orlandi

USENIX Security 2016

From ZKGC to ZKBoo

- ZKGC is inherently **interactive** (**private coin,** cannot use Fiat-Shamir)

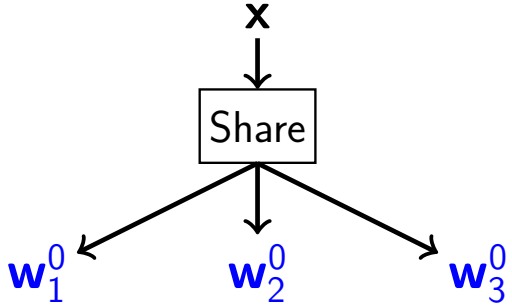
- **IKOS** (*Ishai, Kushilevitz, Ostrovsky, Sahai*) proposed in 2007 a method to get ZK from MPC. Plugging the right MPC protocol one can get ZK with very good ***asymptotic complexity.***

- ***ZKBoo*** can be seen as a generalization, simplification and implementation of IKOS with the sole goal of ***practical efficiency.***

To build ZKBoo, we need to find a suitable

$(2,3)$-**decomposition** for C:

$$\{\mathsf{Share}, \mathsf{Output}_1, \mathsf{Output}_2, \mathsf{Output}_3, \mathsf{Rec}\}$$
$$\cup$$
$$\{f_1^{(j)}, f_2^{(j)}, f_3^{(j)}\}_{j=1,\ldots,N}$$



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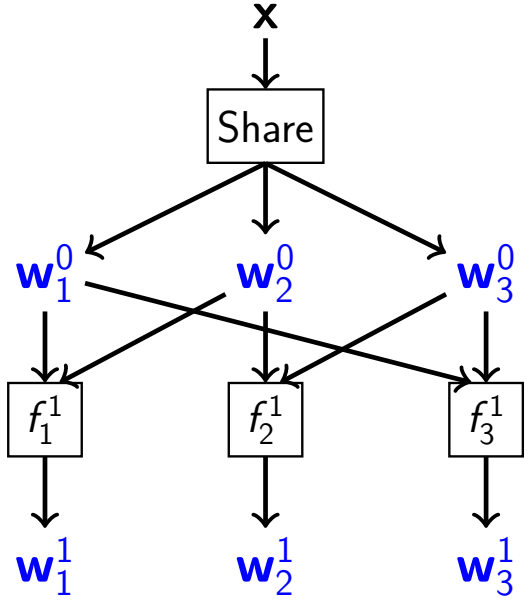

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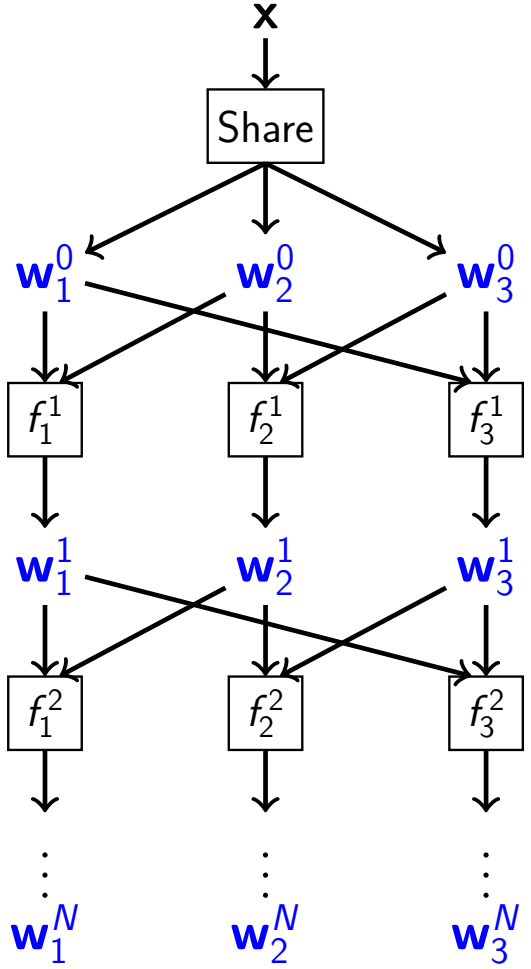

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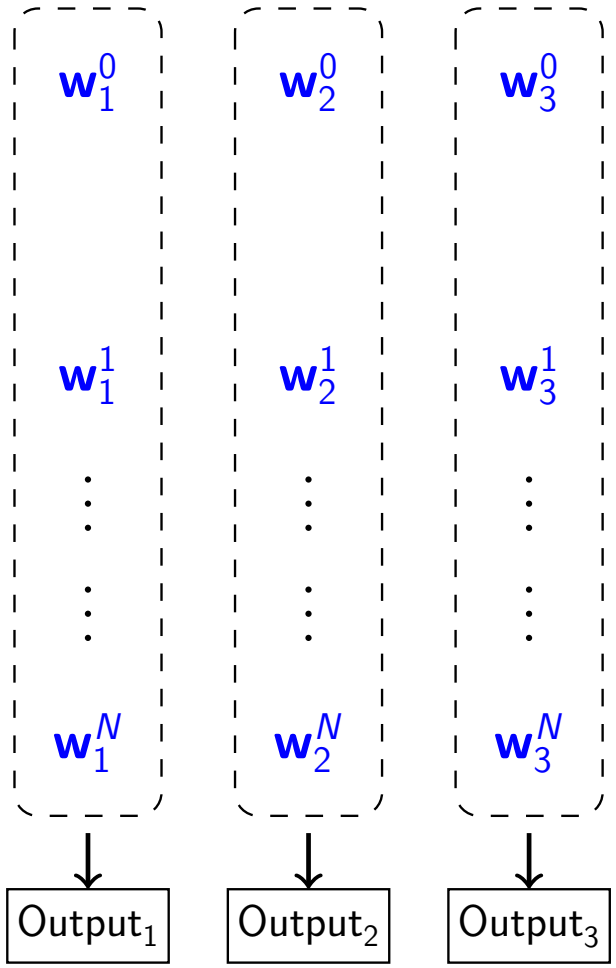

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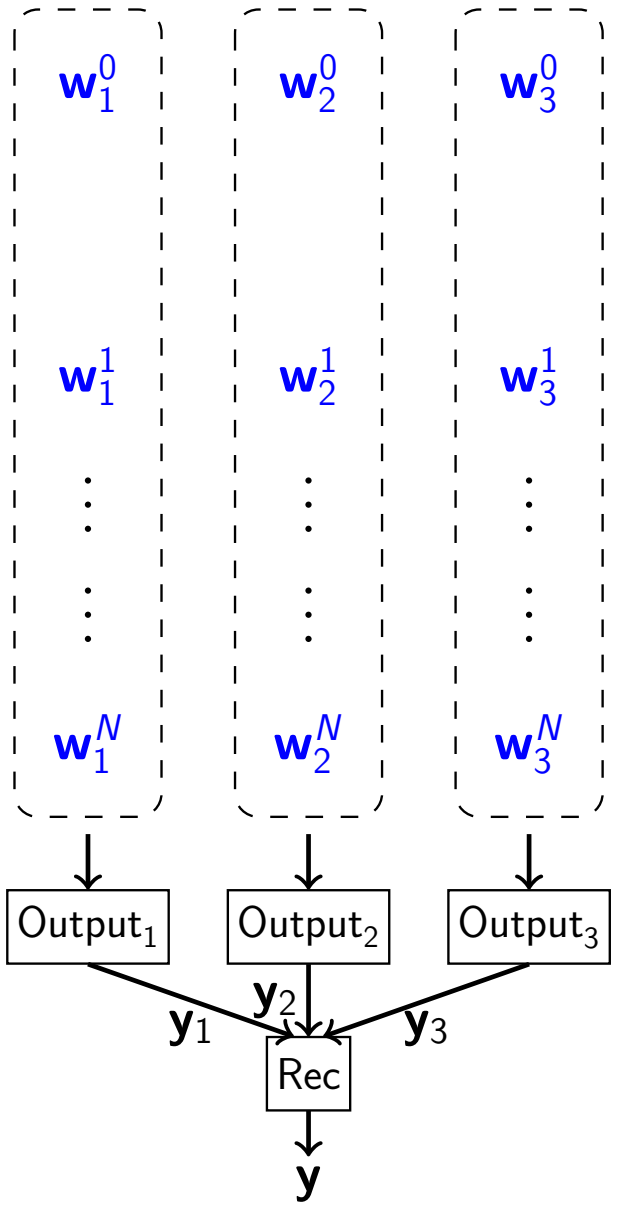

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- correct: $\mathbf{y} = C(\mathbf{x})$
- 2-private: $\forall\, e \in [3]$ $\exists$ a PPT simulator S_e that perfectly simulate the distribution of $(\{\mathbf{w}_i\}_{i\in\{e,e+1\}}, \mathbf{y}_{e+2})$

Example: the linear decomposition

- *Computation in a ring $(R,+,\cdot)$*
- *Share(x)*
  - *Get random $x_1, x_2 \leftarrow R$*
  - *Let $x_3 = x - x_1 - x_2$*
- *Rec(y_1,y_2,y_3)*
  - $y = y_1 + y_2 + y_3$
- *Add(x_1,x_2,x_3,y_1,y_2,y_3)*
  - $z_1 = x_1 + y_1$
  - $z_2 = x_2 + y_2$
  - $z_3 = z_3 + y_3$
- *Mul(x_1,x_2,x_3,y_1,y_2,y_3)*
  - $z_1 = x_1y_1 + x_1y_2 + x_2y_1 + r_1 - r_2$
  - $z_2 = x_2y_2 + x_2y_3 + x_3y_2 + r_2 - r_3$
  - $z_3 = x_3y_3 + x_3y_1 + x_1y_3 + r_3 - r_1$

...composition

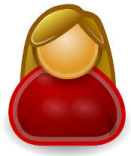
Correctness:
$z_1+z_2+z_3 =$
$(x_1+x_2+x_3)\ (y_1+y_2+y_3)$

- *Sha...*

2-privacy:
Any pair (z_i,z_{i+1}) is uniform random (thanks to r_1,r_2,r_3)

- *Add*$(x_1,x_2,x_3,y_1,y_2,y_3)$
  - $z_1 = x_1 + y_1$
  - $z_2 = x_2 + y_2$
  - $z_3 = z_3 + y_3$
- *Mul*$(x_1,x_2,x_3,y_1,y_2,y_3)$
  - $z_1 = x_1y_1 + x_1y_2 + x_2y_1 + r_1 - r_2$
  - $z_2 = x_2y_2 + x_2y_3 + x_3y_2 + r_2 - r_3$
  - $z_3 = x_3y_3 + x_3y_1 + x_1y_3 + r_3 - r_1$

Public data: $C : \{0,1\}^n \to \{0,1\}^m$ (boolean circuit) and $\mathbf{y} \in \{0,1\}^m$



Input: $\mathbf{x}$ s.t. $C(\mathbf{x}) = \mathbf{y}$

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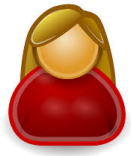

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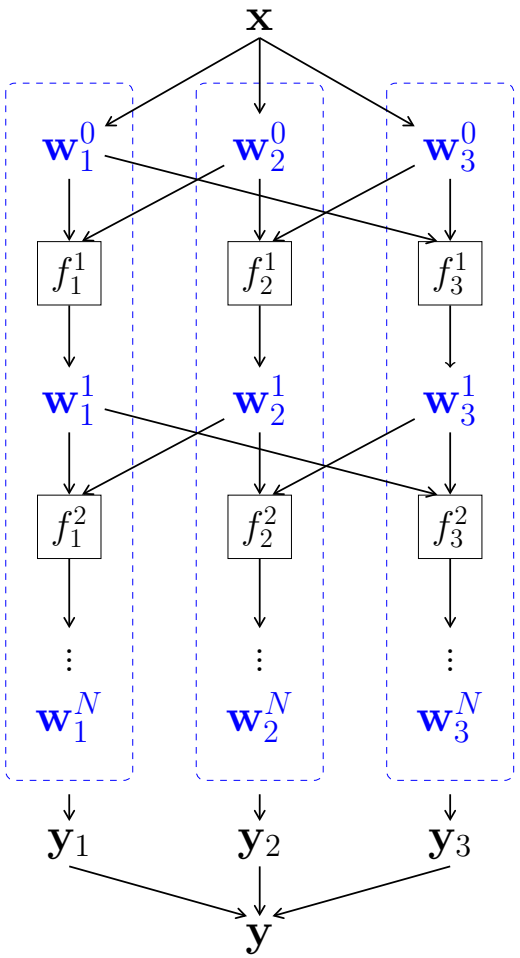

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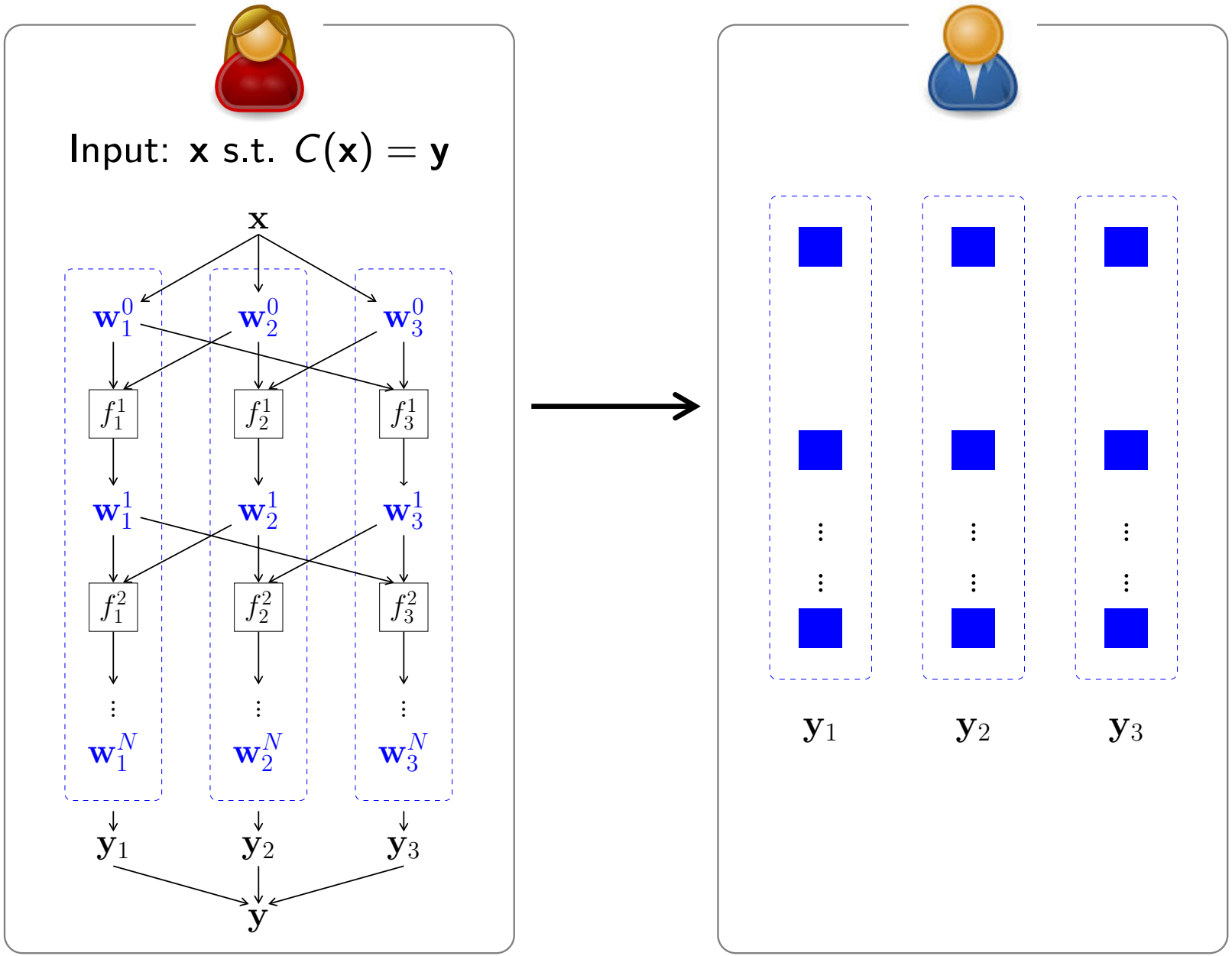

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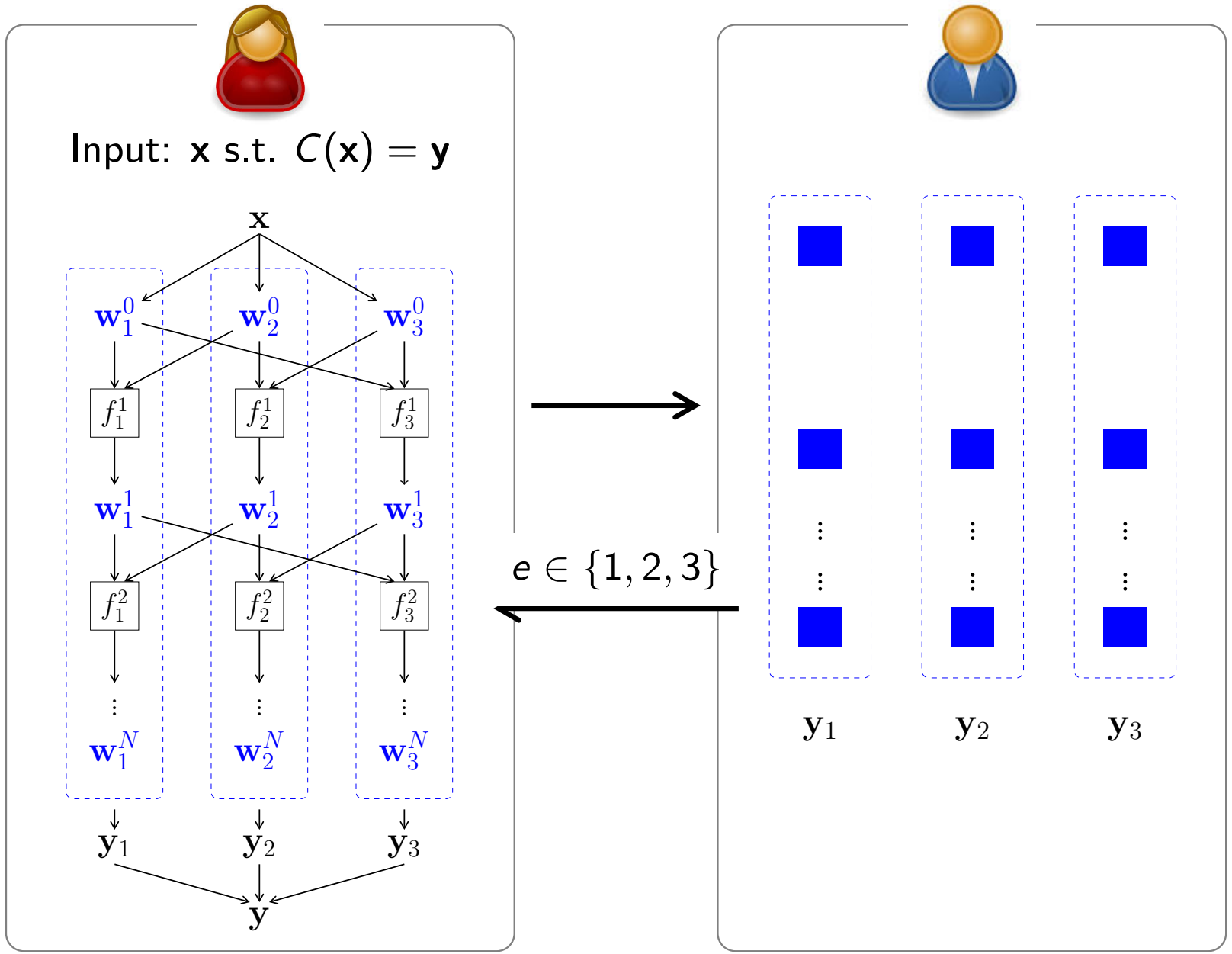

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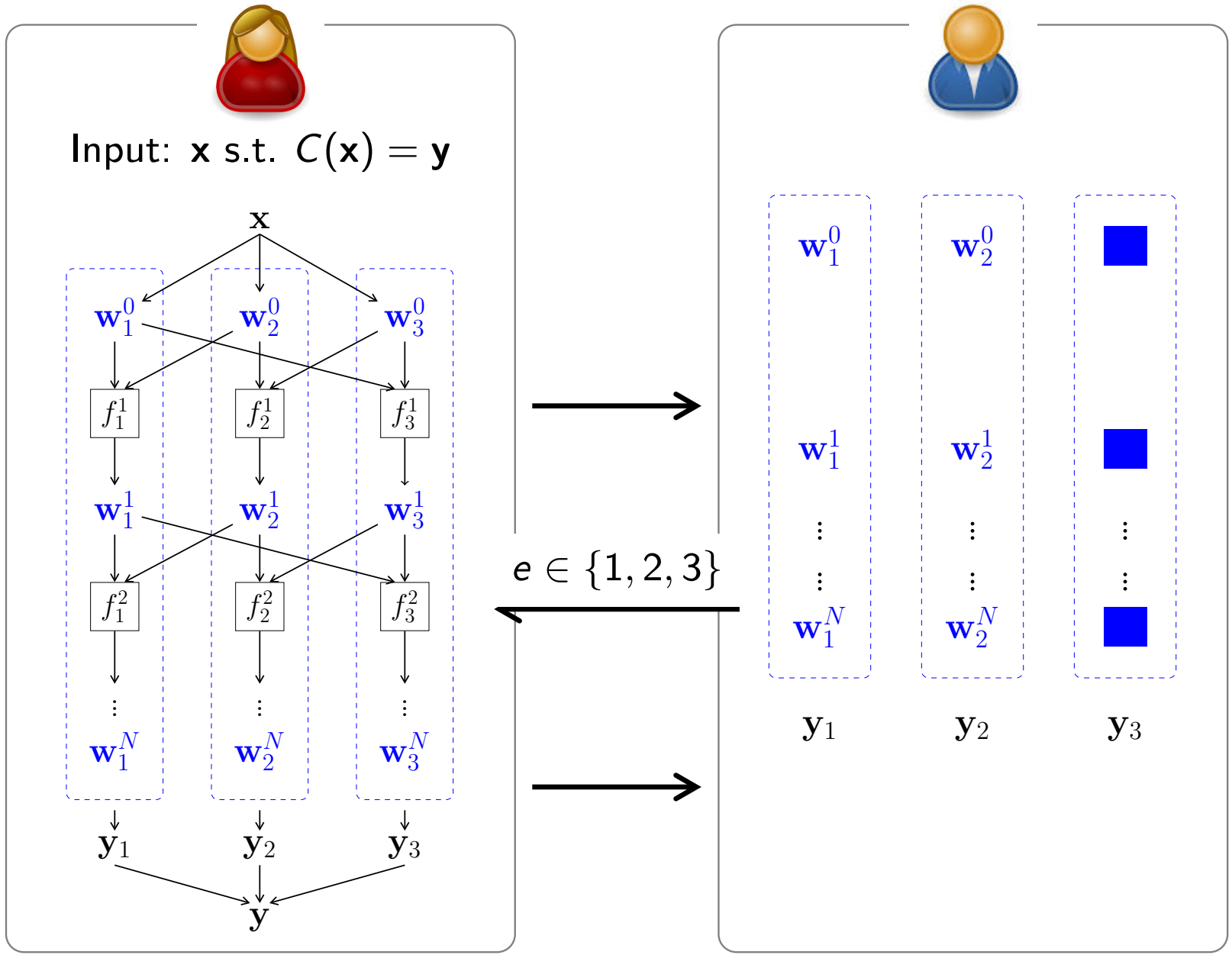

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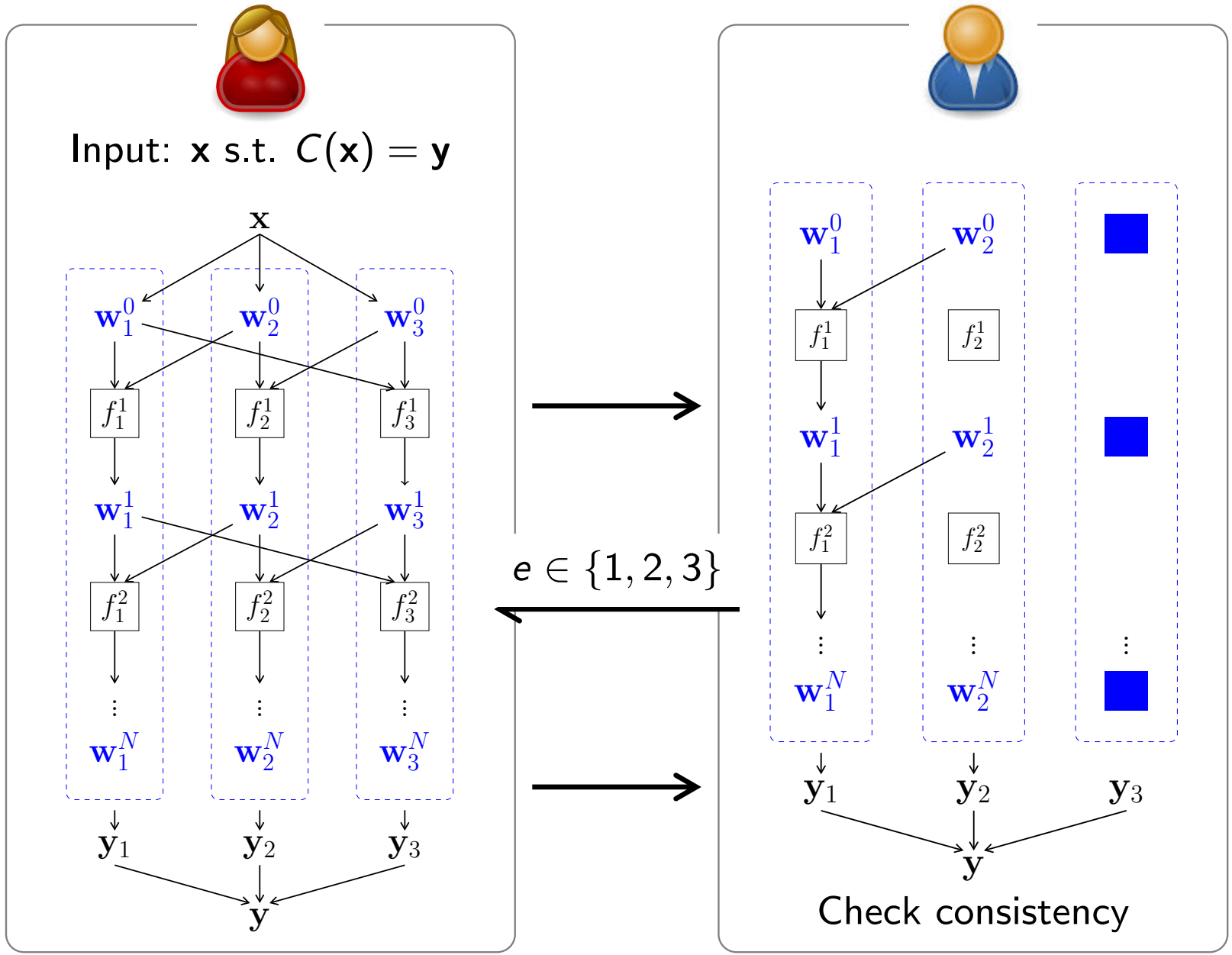


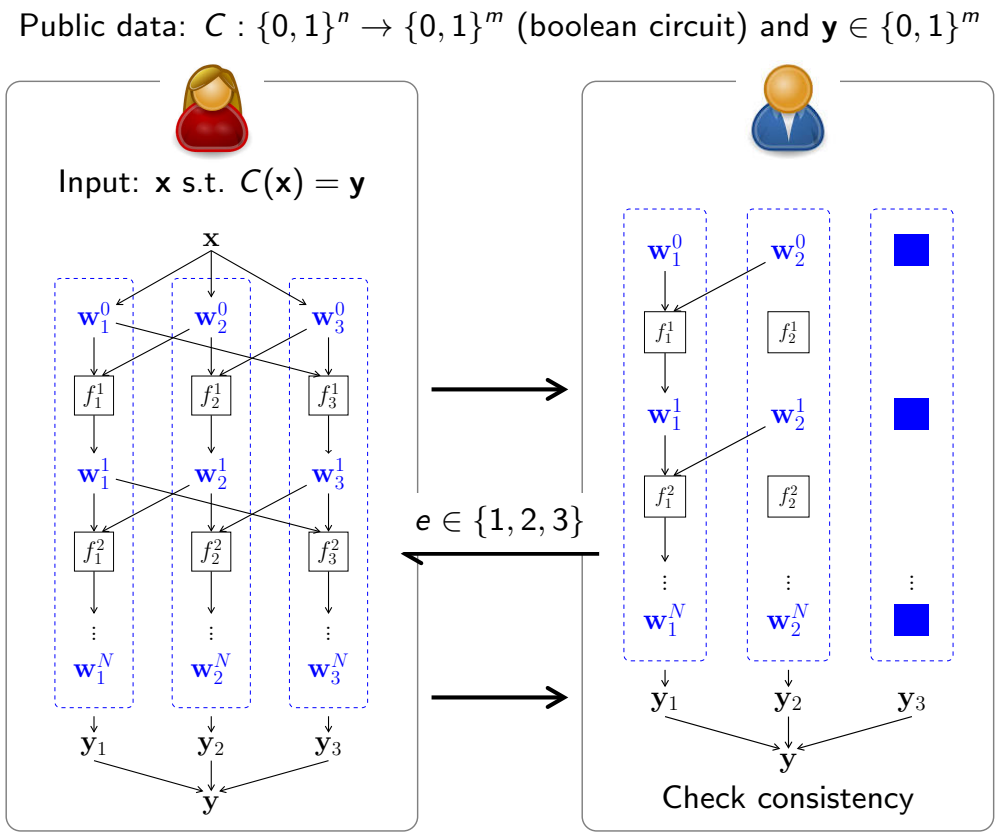
Linear Decomposition: Consistency Check

- Mul(x_1,x_2,x_3,y_1,y_2,y_3,r_1,r_2,r_3)
  - $z_1 = x_1y_1 + x_1y_2 + x_2y_1 + r_1 - r_2$
  - $z_2 = x_2y_2 + x_2y_3 + x_3y_2 + r_2 - r_3$
  - $z_3 = x_3y_3 + x_3y_1 + x_1y_3 + r_3 - r_1$

- Verify(. ,x_2,x_3,. ,y_2,y_3,. ,r_2,r_3)
  - ?
  - $z_2 = x_2y_2 + x_2y_3 + x_3y_2 + r_2 - r_3$
  - ?

ZKBoo

- **Soundness/PoK**
  - Correctness of decomposition
  - Commitments are binding
- **Zero-Knowledge**
  - 2-privacy of decomposition
  - Commitments are hiding
- **Efficiency**
  - Comm. and comp. complexity ~ # mul
  - Only very efficient crypto involved (secret sharing, commitments)



	SHA-1		SHA-256	
	Serial	Paral.	Serial	Paral.
Prover (ms)	31.73	12.73	54.63	15.95
Verifier (ms)	22.85	4.39	67.74	13.20
Proof size (KB)	444.18		835.91	

Soundness error: 2^{-80}

	SHA-1		SHA-256	
	Serial	Paral.	Serial	Paral.
Prover (ms)	18.98	8.12	30.81	12.45
Verifier (ms)	11.68	2.35	34.16	6.77
Proof size (KB)	223.71		421.01	

Soundness error: 2^{-40}

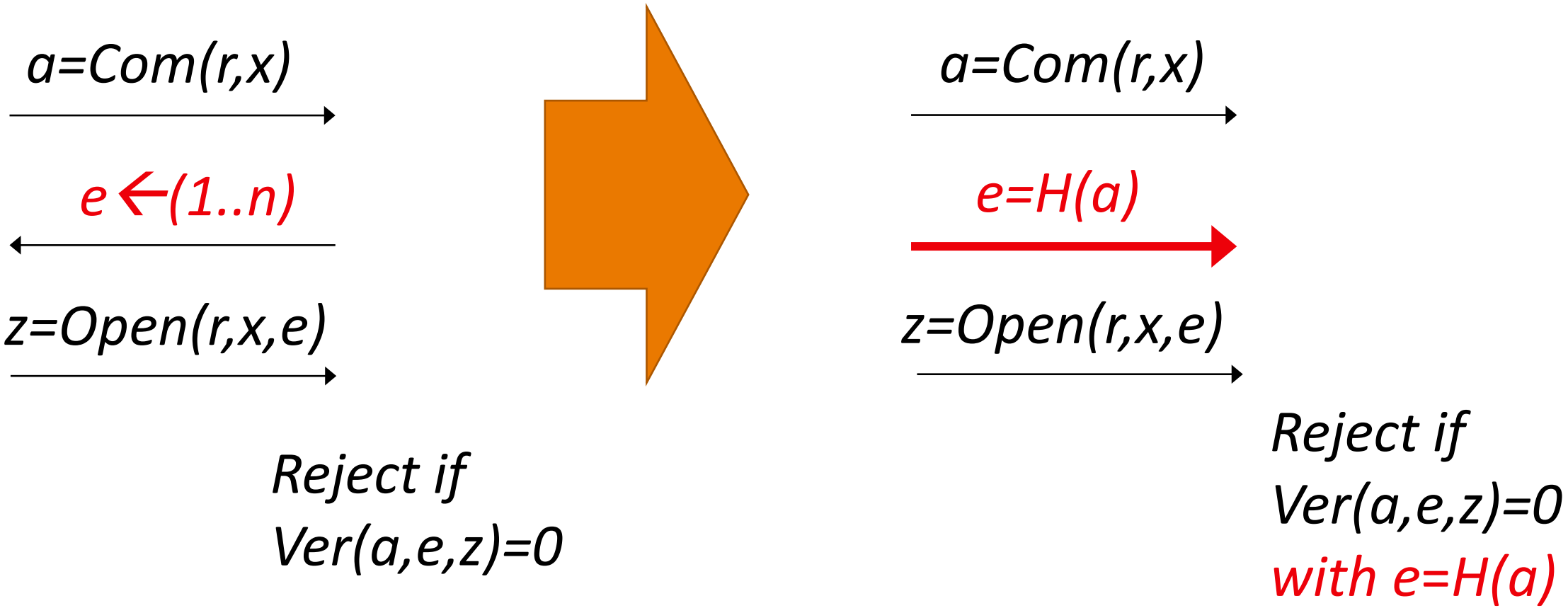
Post-Quantum Zero-Knowledge and Signatures from Symmetric-Key Primitives

Chase, Derler, Goldfeder, Orlandi, Ramacher, Rechberger, Slamanig, Zaverucha

ACM CCS 2017

Fiat-Shamir Heuristic

P(x) "I know x s.t. f(x)=y" V(y)



Signatures from Fiat-Shamir

Gen

- *sk* : x
- *vk* : y = OWF(x)

Sig(sk,m)

- a = *Com*(r,x)
- z = *Open*(r,x,H(m,a))
- output (a,z)

Ver(vk,m,(a,z))

- reject if:
  Ver(a,H(m,a),z)=0

Signatures from ZKB++ + LowMC

LowMC

Block cipher with low AND Complexity (<1000)

Different instances give different tradeoffs between comp./comm. overhead

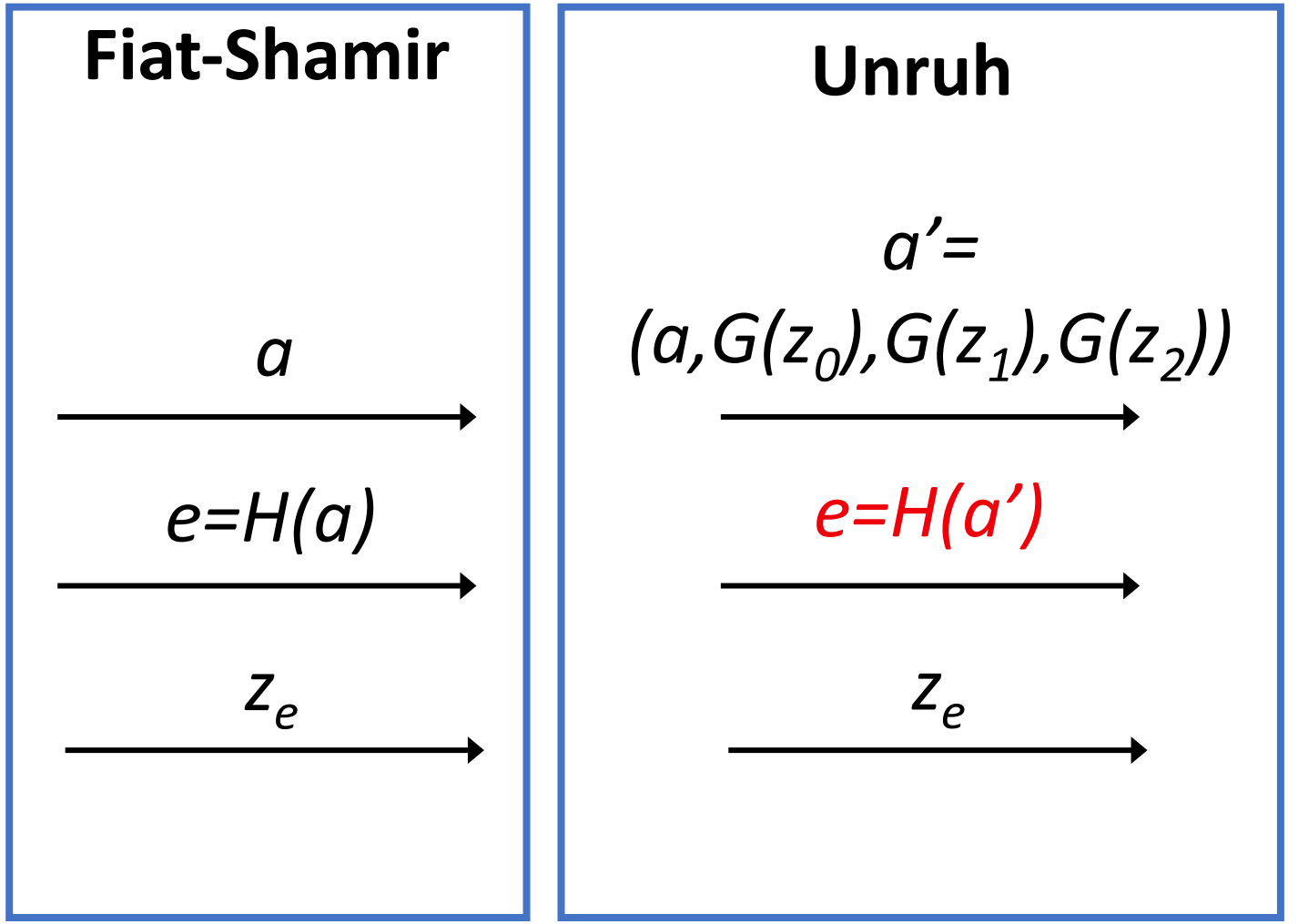
Candidate for PQ signature from symmetric primitive only!

Scheme	Gen [ms]	Sign [ms]	Verify [ms]	|sk| [bytes]	|pk| [bytes]	|σ| [bytes]	Model
Fish-1-316	0.01	364.11	201.17	32	64	108013	ROM
Fish-10-38	0.01	29.73	17.46	32	64	118525	ROM
Fish-42-14	0.01	13.27	7.45	32	64	152689	ROM
Picnic-10-38	0.01	31.31	16.30	32	64	195458	QROM
MQ 5pass	0.96	7.21	5.17	32	74	40952	ROM
SPHINCS-256	0.82	13.44	0.58	1088	1056	41000	SM
BLISS-I	44.16	0.12	0.02	2048	7168	5732	ROM
Ring-TESLA*	16*k*	0.06	0.03	12288	8192	1568	ROM
TESLA-768	48*k*	0.65	0.36	3216*k*	4128*k*	2336	(Q)ROM
FS-Véron	n/a	n/a	n/a	32	160	129024	ROM
SIDHp751	16.41	7.3*k*	5.0*k*	48	768	141312	QROM

Table 1: Timings and sizes of private keys (sk), public keys (pk) and signatures (σ). *An errata to [3] says that this parameter set is not supported by the security analysis (due to a flaw in the analysis).

Picnic
Security in QROM using Unruh's Transform

- Fiat-Shamir is not provably secure vs. quantum adversary
  - Cannot program RO
  - Cannot rewind adversary
- Unruh transform (EUROCRYPT'15) is secure in QROM
- ZKBoo/ZKB++ can be optimized for Unruh, only ~1.5x larger!
  - Instead of 4x



Flexible design! Ring/Group Signatures

- Sign(pk_0,pk_1,sk_b, m)→ s
- Ver(pk_0,pk_1,m,s)→ accept

- **Indistinguishability**:
  Sign(pk_0,pk_1,sk_0, m) ≈
  Sign(pk_0,pk_1,sk_1, m)

- Prove in ZK that
  "I know sk : pk_0=f(sk) or pk_1=f(sk)"

- See
- **PQ ZK Proofs for Accumulators with Applications to Ring Signatures from Symmetric-Key Primitives**
  Derler, Ramacher, Slamanig
- **PQ EPID Group Signatures from Symmetric Primitives**
  Boneh, Eskandarian, Fisch
- **Improved NIZK with Applications to PQ Signatures**
  Katz, Kolesnikov, Wang

Young design! ZK proofs are improving! ZKBoo, ZKB++, Ligero, KKW, …

- Any improvements in the ZK proof leads to better signatures!
- **Ligero: Lightweight Sublinear Arguments Without a Trusted Setup**
  Ames, Hazay, Ishai, Venkitasubramaniam:
- **Improved NIZK with Applications to PQ Signatures**
  Katz, Kolesnikov, Wang

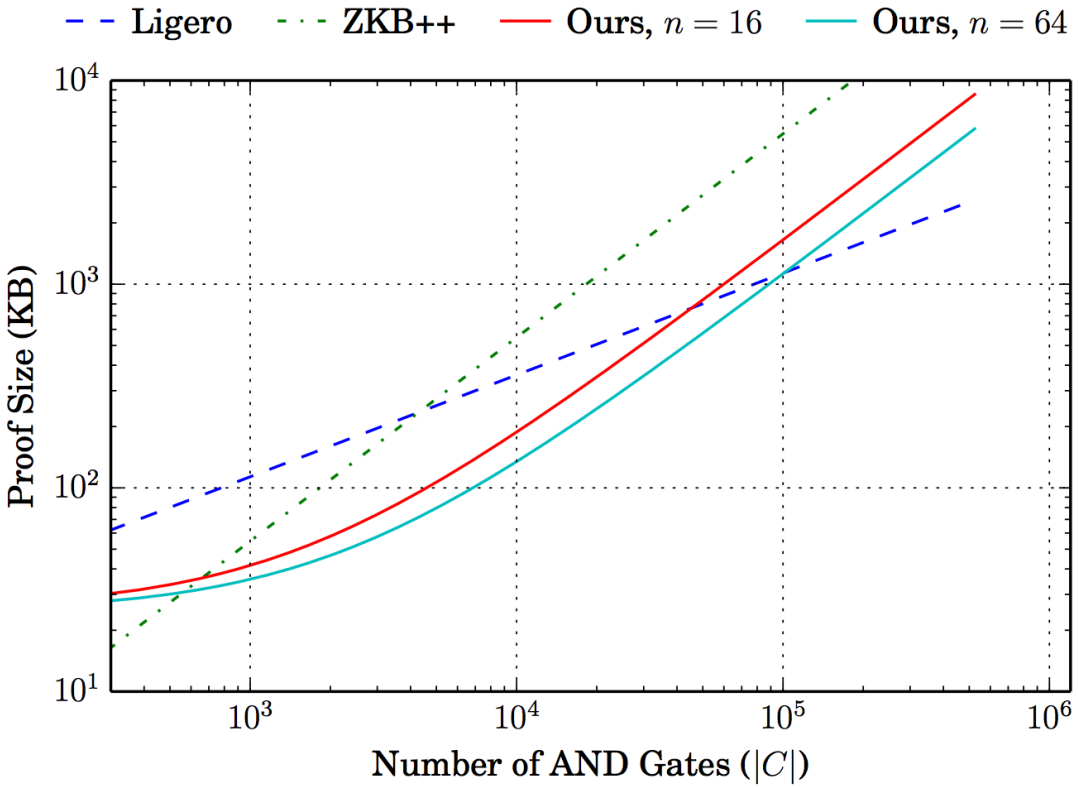


Figure from KKW

NIST Submission:

Picnic
A Family of Post-Quantum Secure Digital Signature Algorithms

Chase, Derler, Goldfeder, Orlandi, Ramacher, Rechberger, Slamanig, Zaverucha

Project page: https://microsoft.github.io/Picnic/

(Next few slides from Greg’s talk at NIST Workshop)

Performance: Key and Signature Size

Signature and key sizes (bytes)

Parameter Set	Public Key	Private Key	Signature
Picnic-L1-FS	32	16	34,000
Picnic-L1-UR	32	16	53,929
Picnic-L3-FS	48	24	76,740
Picnic-L3-UR	48	24	121,813
Picnic-L5-FS	64	32	132,824
Picnic-L5-UR	64	32	209,474

Performance: Timings

Optimized Implementation (ms), Intel(R) Core(TM) i7-4790 CPU @ 3.60GHz

Parameter Set	Keygen	Sign	Verify
Picnic-L1-FS	0.00	1.95	1.36
Picnic-L1-UR	0.00	2.64	1.91
Picnic-L3-FS	0.01	6.61	4.63
Picnic-L3-UR	0.01	8.84	6.29
Picnic-L5-FS	0.02	14.71	10.64
Picnic-L5-UR	0.02	18.67	13.60

TLS Experiments

Are there challenges to using Picnic in TLS?

- We added Picnic to the *Open Quantum Safe library* (OQS), the OQS fork of OpenSSL and Apache web server

Experiment:

- Use Picnic-signed X.509 certificates certifying Picnic keys
- L1-FS parameter set
- Use Picnic certificates to authenticate TLS 1.2 connections
- Fetch HTML files

Performance, client-side latency:

- For 45B files: increase of 1.4x to 1.7x
- For 100KB files: increase of 1.1x to 1.3x

Challenges:

- TLS 1.2 has limit of $2^{16} - 1$ bytes/signature: too short for our higher security parameter sets

Ciphersuite KEX, SIG	Page Size	Mean fetch time (seconds) Slow network	Mean fetch time (seconds) Fast network
ECDHE-ECDSA	45B	0.470	0.299
(not PQ)	100K	1.226	0.452
LWEFRODO-RSA	45B	0.578	0.366
	100K	1.335	0.518
LWEFRODO-PICNIC	45B	0.984	0.513
	100K	1.733	0.594
SIDH-RSA	45B	0.655	0.385
	100K	1.370	0.541
SIDH-PICNIC	45B	1.084	0.523
	100K	1.738	0.600

Also, experiments with HSM and inclusion in OpenVPN Post-Quantum fork

Conclusions and directions

Thanks!

After >30 years of ZK ***we have the first truly efficient protocols*** for generic statements.

Many applications ***are enabled*** by efficient ZK for arbitrary circuits.

And I expect many more to come!

ZKGC vs ZKBoo?

- ZKBoo allows Fiat-Shamir ☺
- ZKBoo does not need OT ☺

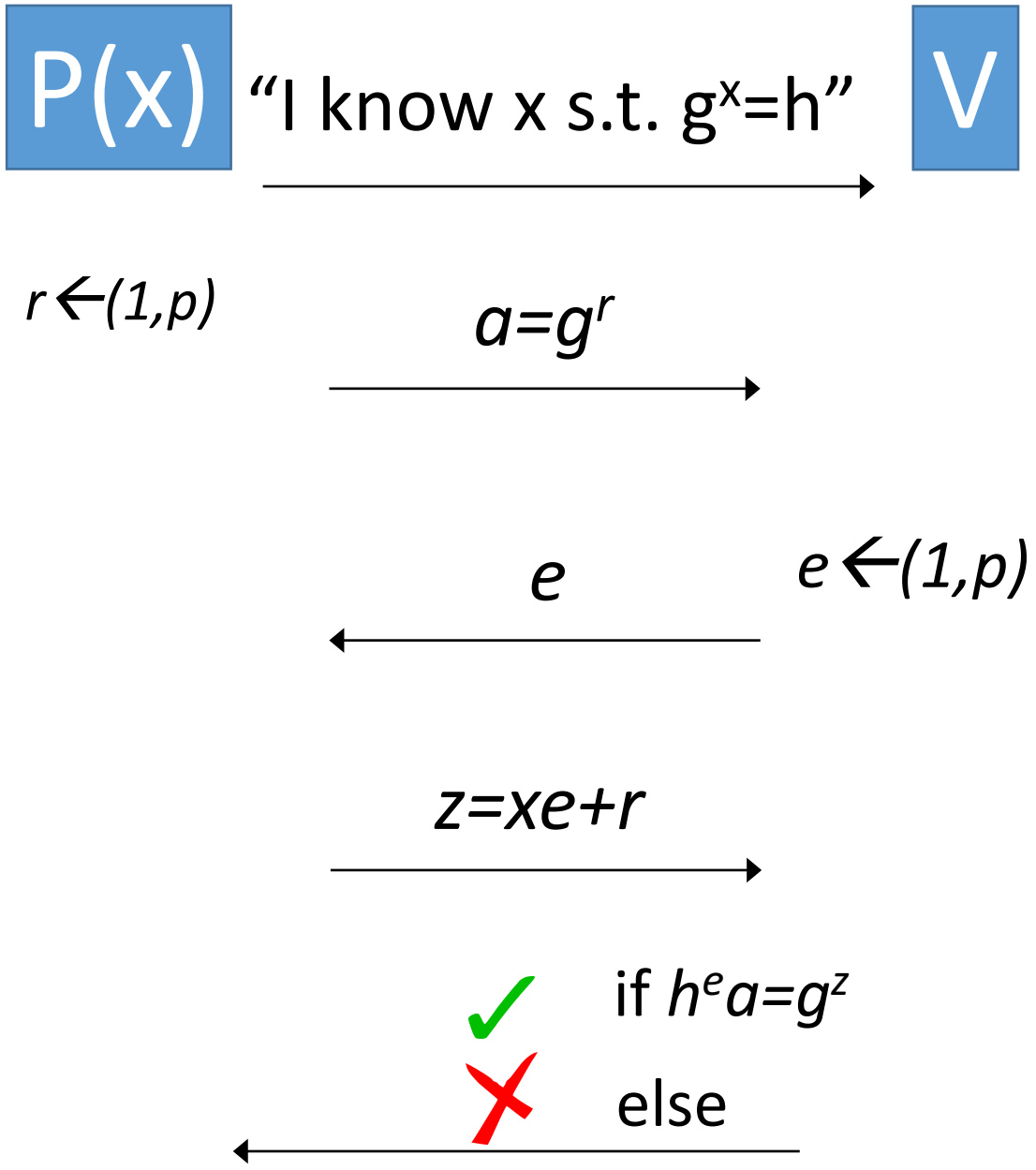
The end of ZKGC?

- Are there better privacy-free GCs?

Improving MPC based ZK proofs?

- ZKBoo, ZKB++, Ligero, KKW, *[your name here?]*

Example: Schnorr Protocol



Example: Schnorr Protocol

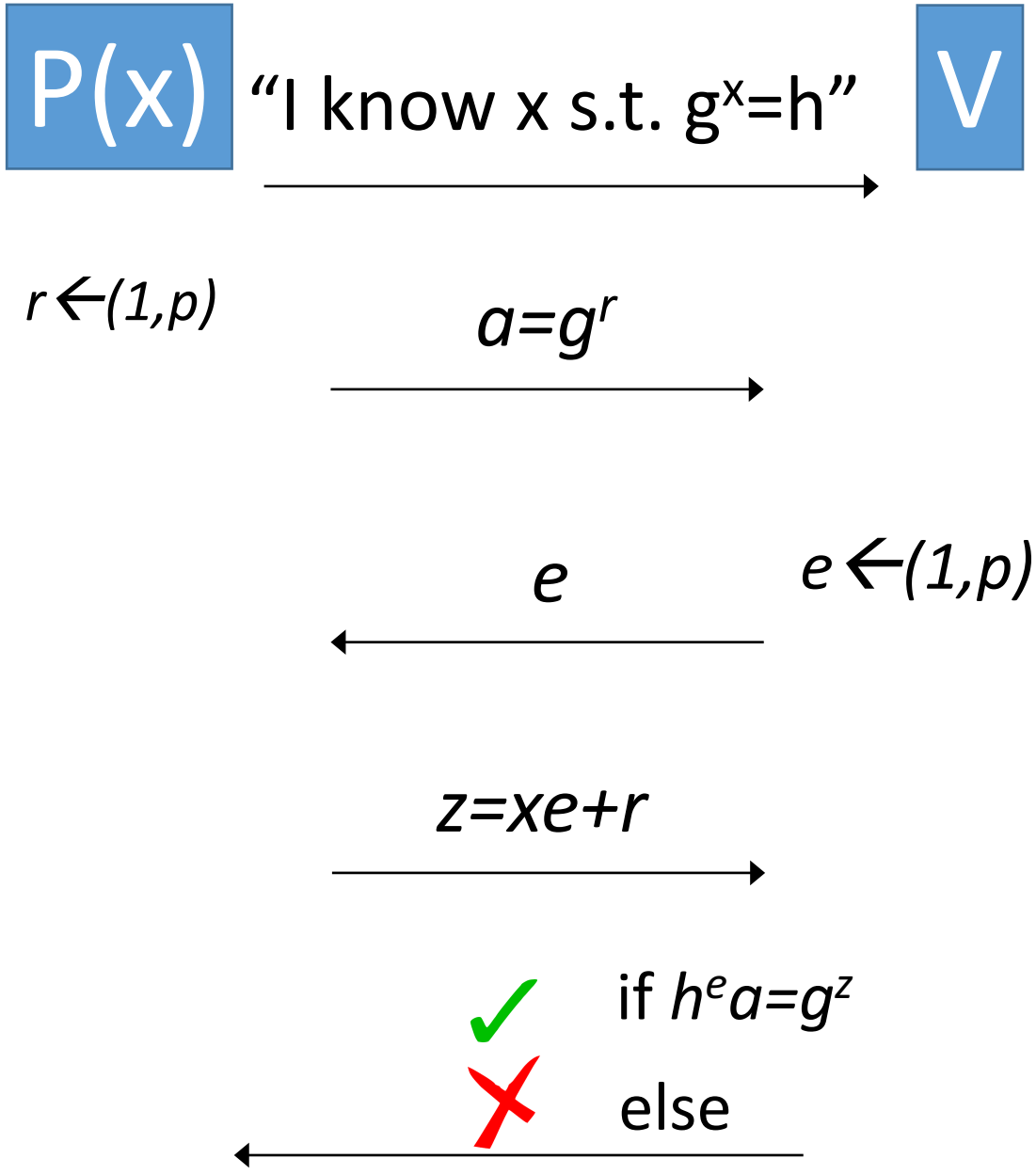
(Honest Verifier) Zero-Knowledge

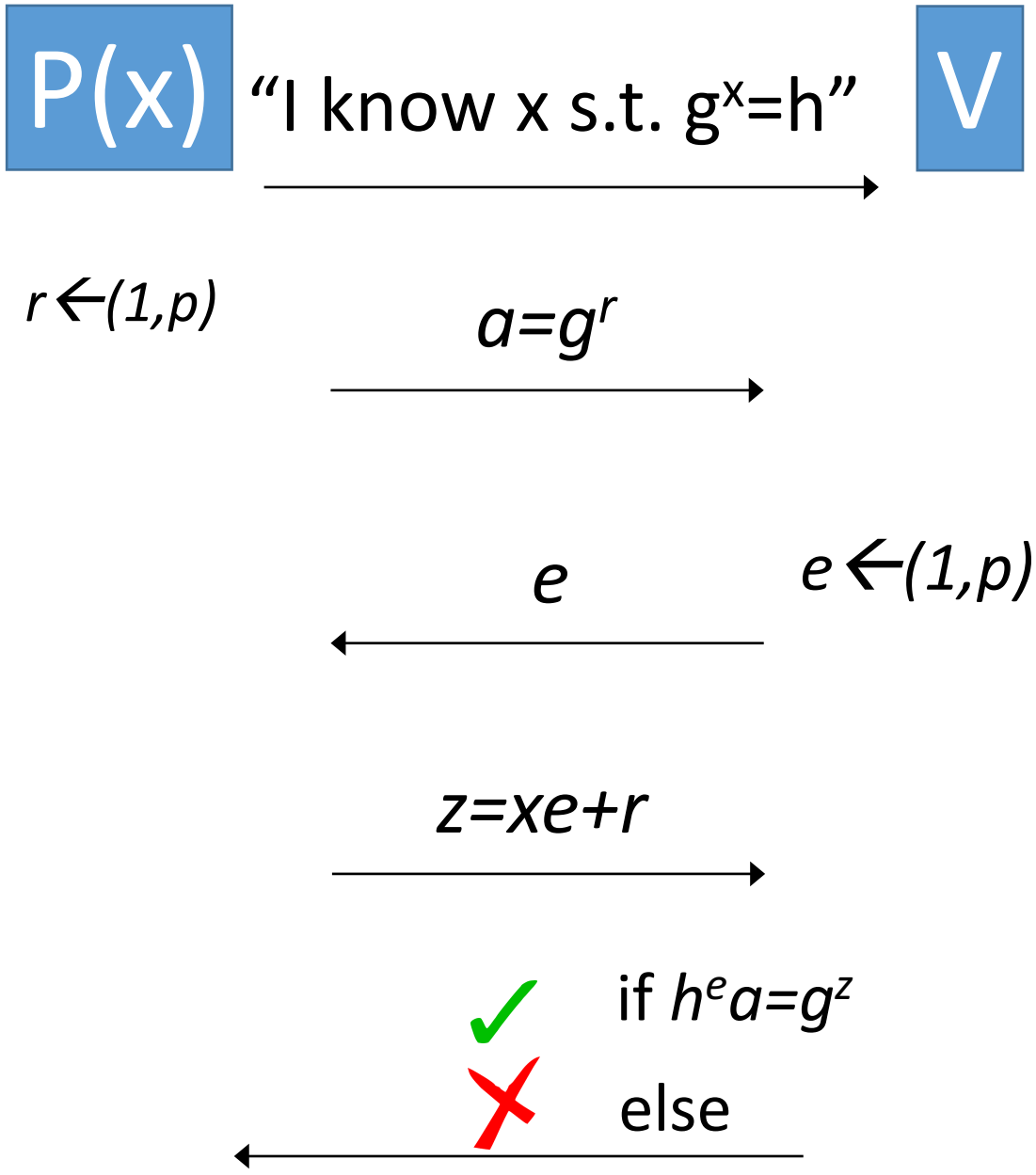
The transcript can be **simulated** without knowing *x*
(hence, it contains no informaiton about x)

Simulator

1. Pick e ← (1,p)
2. Pick z ← (1,p)
3. Compute a = h^e/g^z
4. Output (a,e,z)

Example: Schnorr Protocol

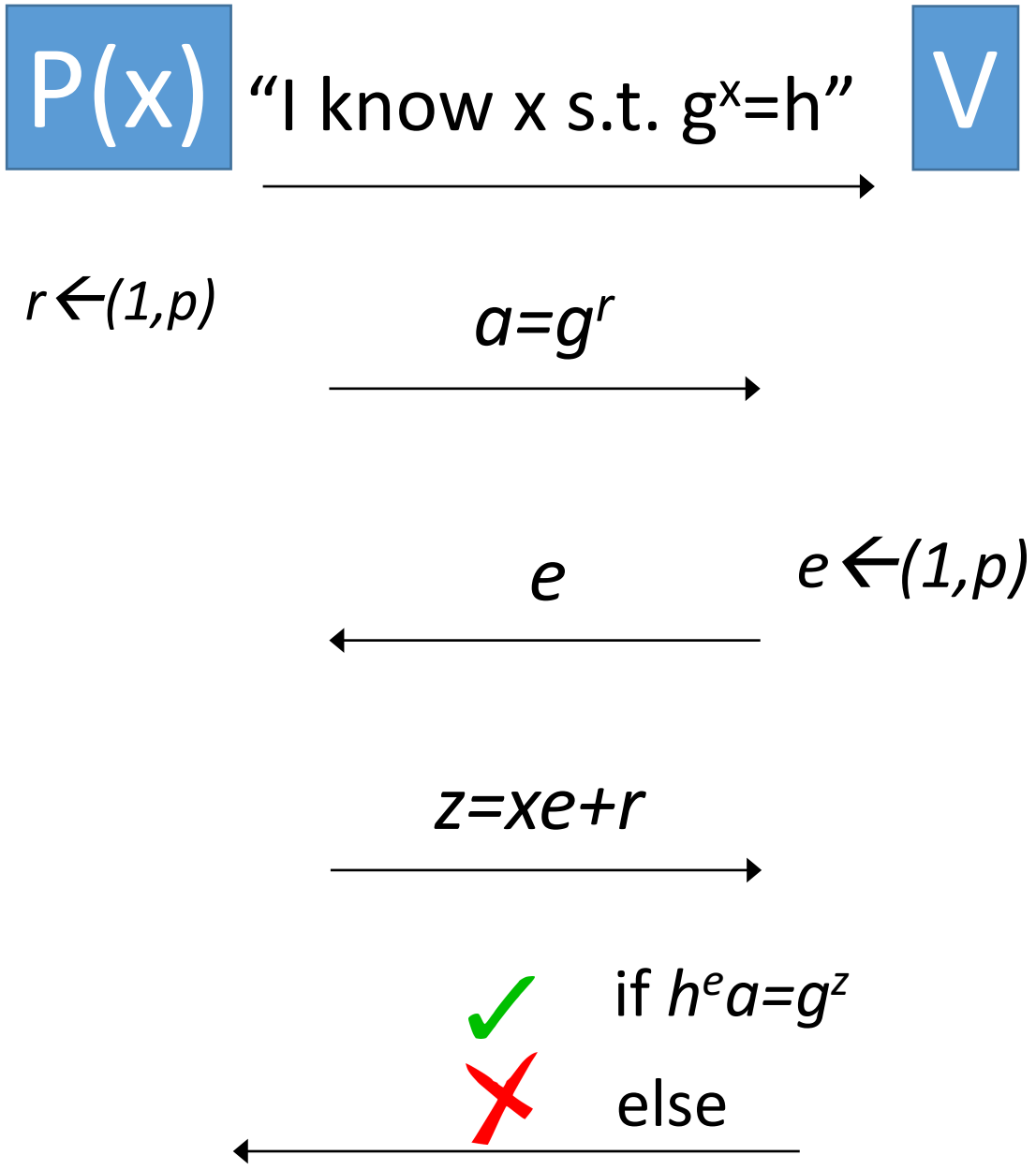




Example: Schnorr Protocol

Completeness

$$g^z = g^{xe+r} = h^e g^r = h^e a$$



Example: Schnorr Protocol

~~**Proof-of-Knowledge**~~

Special Soundness:

From two accepting transcripts

$$(a_1, e_1, z_1), (a_2, e_2, z_2)$$

with $a_1=a_2$ we can **extract** x.

Solve:

$$z_1 = xe_1 + r,$$

$$z_2 = xe_2 + r$$

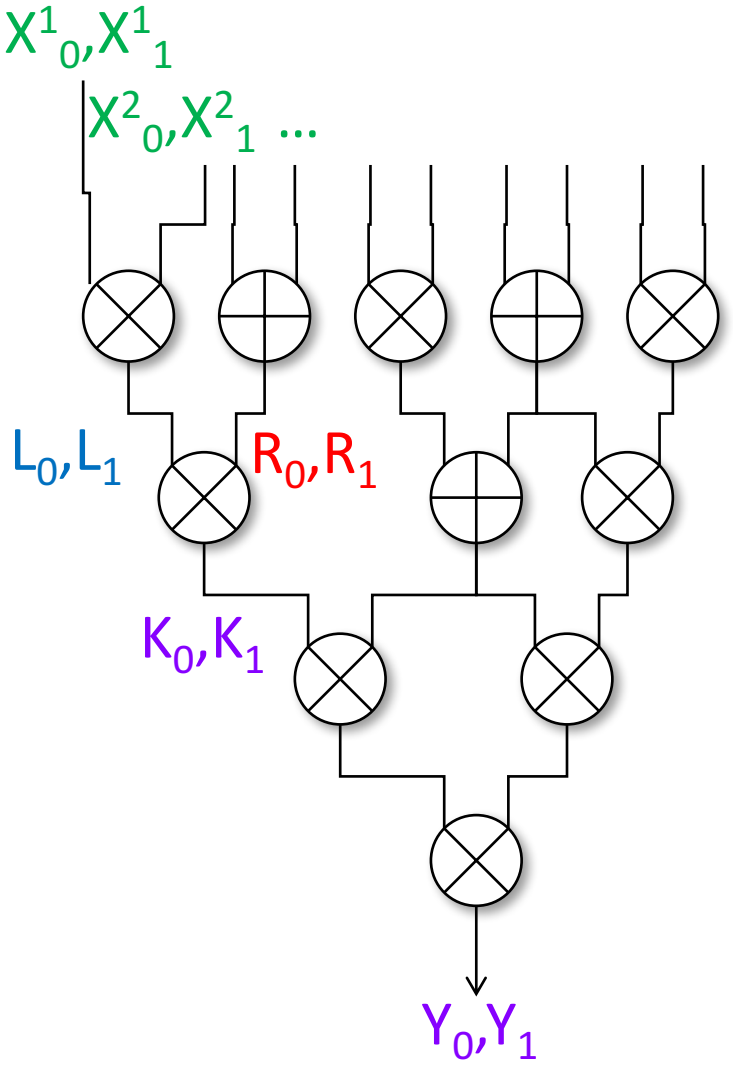
(P can answer 2 different challenges → P knows x)

Example: Schnorr Protocol

Go Back

Example: Privacy Free Garbling

Garbling a Circuit : ([F],e,d)← Gb(f)



- Choose 2 random keys X^i_0, X^i_1 for each input wire
- For each gate g compute
  - $(gg, K_0, K_1) \leftarrow Gb(g, L_0, L_1, R_0, R_1)$
- Output
  - e=(X^i_0, X^i_1) for all input wires
  - d=(Y_0, Y_1)
  - [F]=(gg^i) for all gates i

Encoding and Decoding

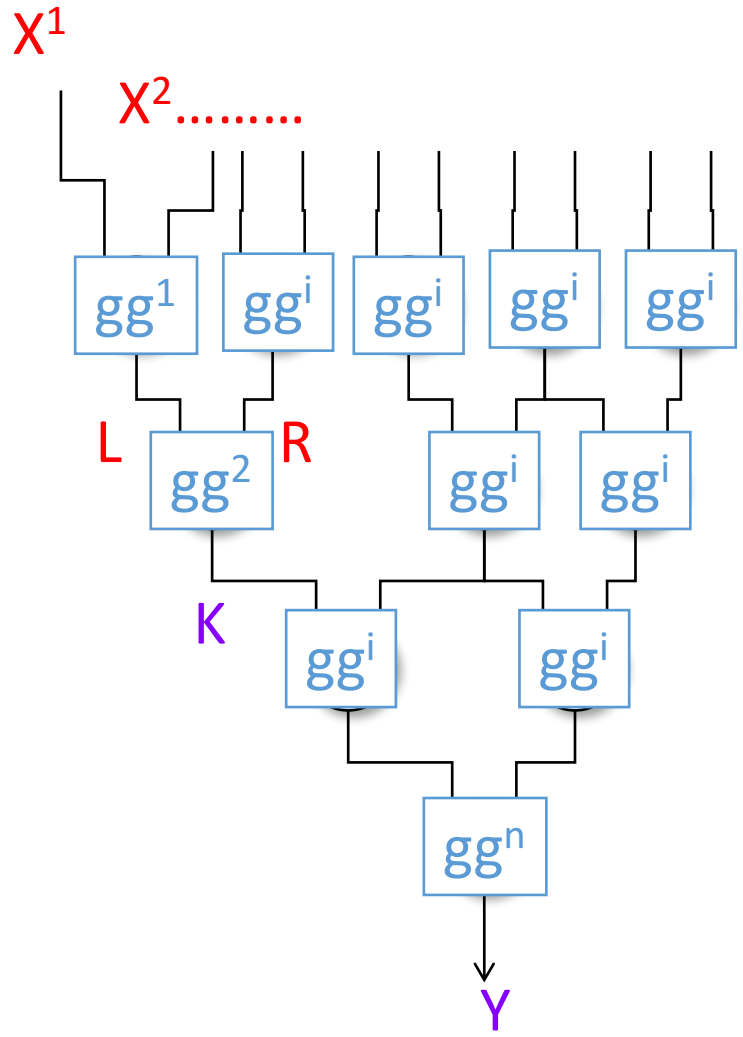
[X] = En(e,x)

- e={ X^i_0, X^i_1}
- x= { x_1,…,x_n }
- [X]={X^1_{x1},…,X^n_{xn}}

y=De(d,[Y])

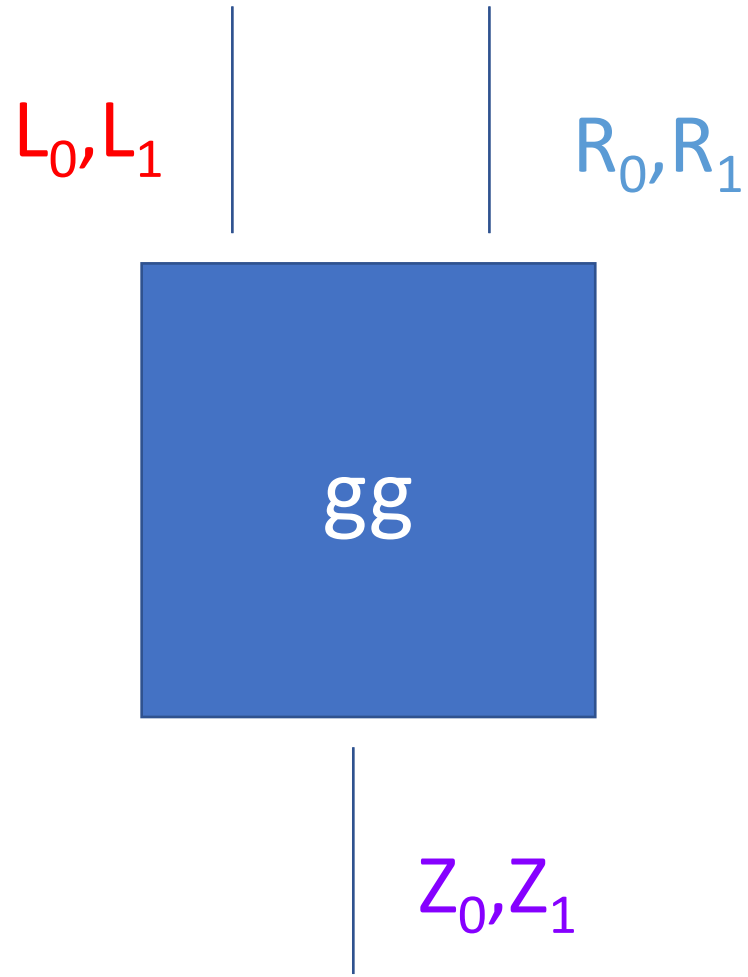
- d = { Y_0,Y_1 }
- [Y] = { K }
- y=
  - 0 if K=Y_0,
  - 1 if K=Y_1,
  - “abort” else

Evaluating a GC : [Y]← Ev([F],[X])



- Parse [X]={X^1,…,X^n} // x is known
- Parse [F]={gg^i}
- For each gate i compute
  - $K_{g(a,b)}$ ← Ev(gg^i,L,a,R,b) //a,b known!
- Output
  - Y //y is known!

Notation



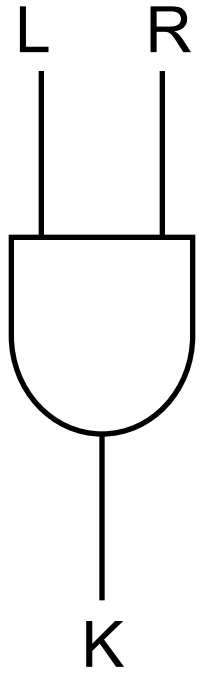
- A *(privacy-free)* garbled gate is a gadget that given two inputs keys gives you the right output key *(and nothing else)*

- $(gg, Z_0, Z_1) \leftarrow Gb(g, L_0, L_1, R_0, R_1)$
- $Z_{g(a,b)} \leftarrow Ev(gg, L, a, R, b)$

- //and not $Z_{1-g(a,b)}$

Yao Garbling

C
$C_1 = H(L_0,R_0) \oplus K_0$
$C_2 = H(L_0,R_1) \oplus K_0$
$C_3 = H(L_1,R_0) \oplus K_0$
$C_4 = H(L_1,R_1) \oplus K_1$



Yao Garbling

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$C_1 = H(L_0,R_0) \oplus K_0$
$C_2 = H(L_0,R_1) \oplus K_0$
$C_3 = H(L_1,R_0) \oplus K_0$
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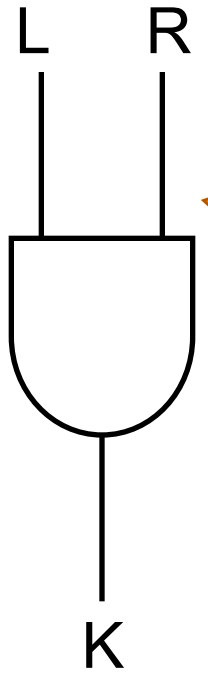
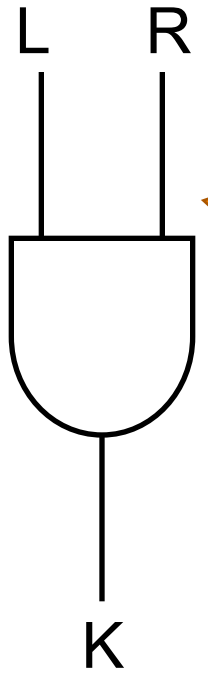


If output is 0 the evaluator should not know why!!!

Privacy-Free Garbling

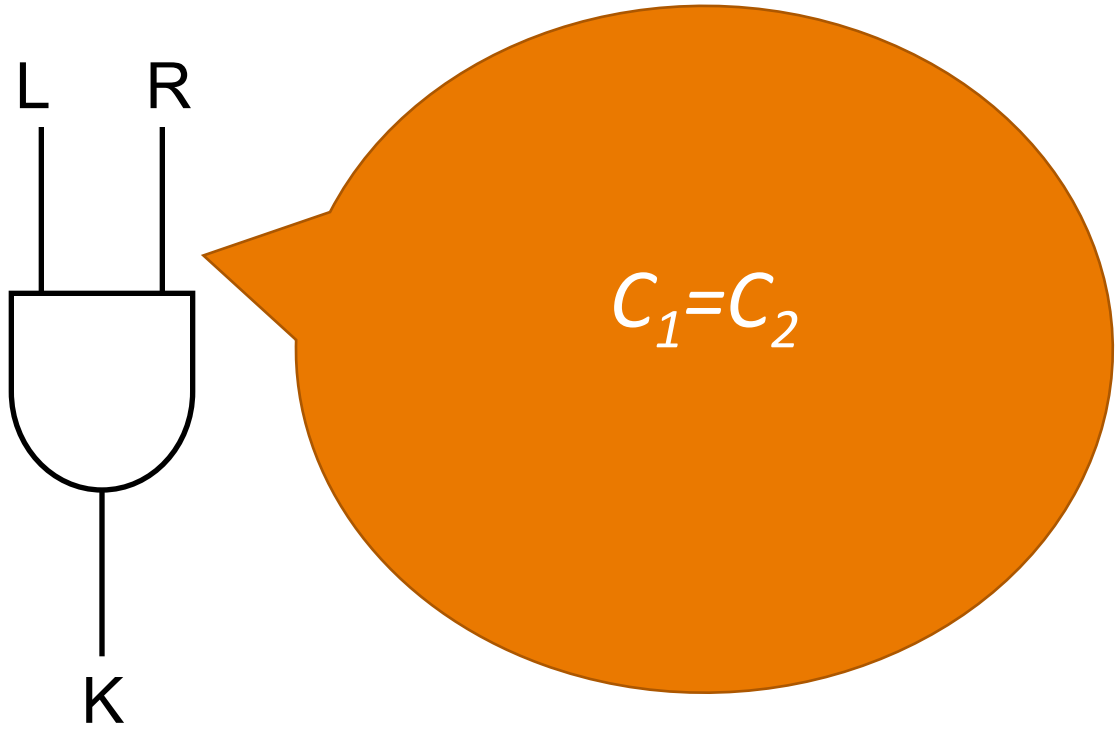
C
$C_1 = H(L_0,R_0) \oplus K_0$
$C_2 = H(L_0,R_1) \oplus K_0$
$C_3 = H(L_1,R_0) \oplus K_0$
$C_4 = H(L_1,R_1) \oplus K_1$



Evaluator knows plain inputs/outputs

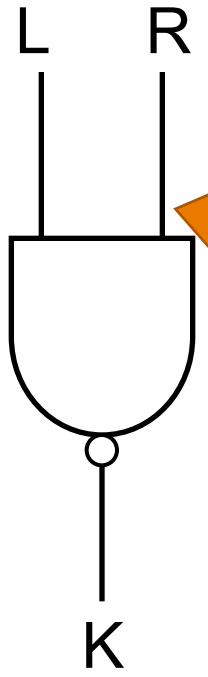
Privacy-Free Garbling

C
$C_1 = H(L_0) \oplus K_0$
$C_2 = H(L_0) \oplus K_0$
$C_3 = H(L_1,R_0) \oplus K_0$
$C_4 = H(L_1,R_1) \oplus K_1$



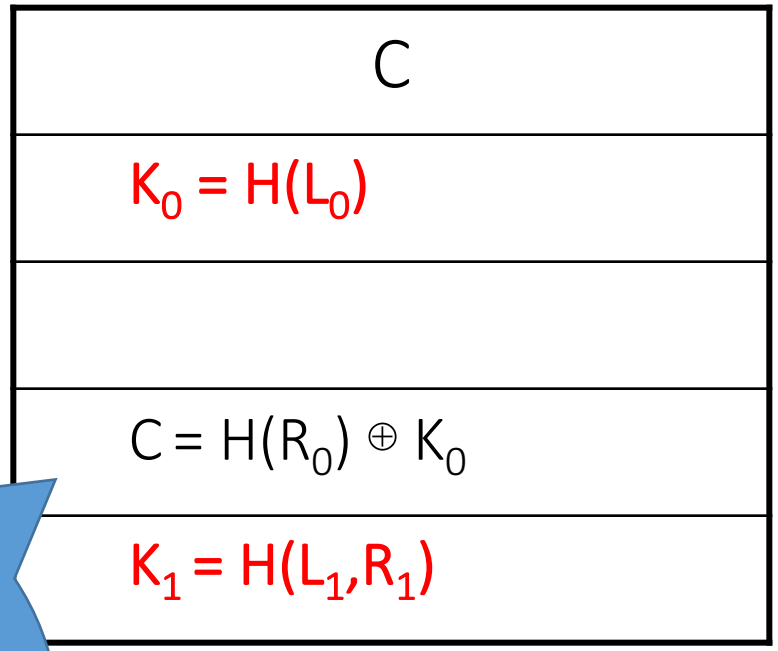
Privacy-Free Garbling

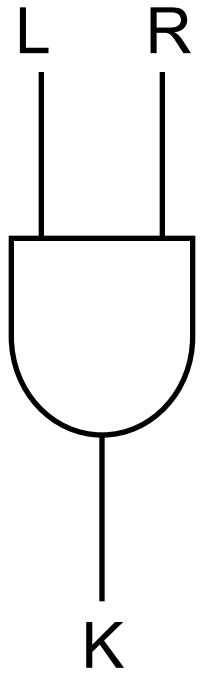
C
$C_1 = H(L_0) \oplus K_0$
$C_3 = H(R_0) \oplus K_0$
$C_4 = H(L_1,R_1) \oplus K_1$



Output is 0
If either input is 0

Privacy-Free Garbling





Standard "row-reduction" technique

Only 1 ciphertext!

Privacy-Free Evaluation

Eval(gg, L,a,R,b)

- If a=0
  - Output $K_0 = H(L_0)$
- If b=0
  - Output $K_0 = C \oplus H(R_0)$
- else
  - Output $K_1 = H(L_1, R_1)$

gg
$C = H(R_0) \oplus K_0$

Example: Privacy Free Garbling

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