Rise of the SNARKs

an introduction to zero-knowledge proofs, zkSNARKs, and `libsnark`

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Blockchain at Berkeley Developers Decal
Spring 2018

Cryptography is a powerful tool for building secure systems.

Much of the cryptography used today offers security properties for **data**.

Confidentiality

Authenticity

What about security properties for **computation**?

Cryptographic proofs offer
privacy-preserving integrity for computation.

Cryptographic Proofs

A powerful defense against malicious behavior, especially, in **decentralized protocols**.

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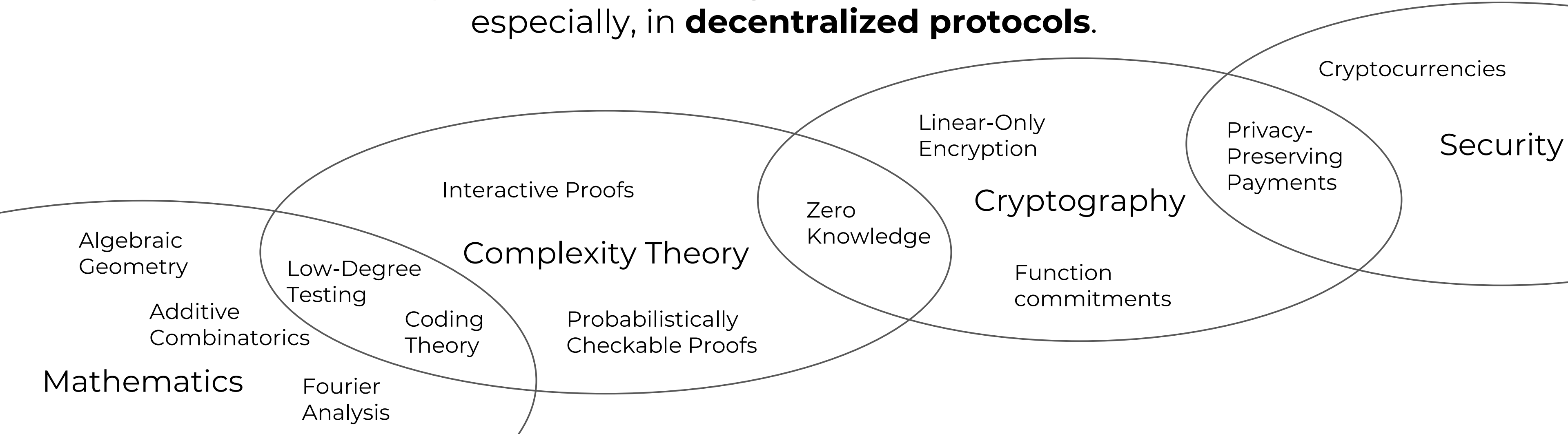
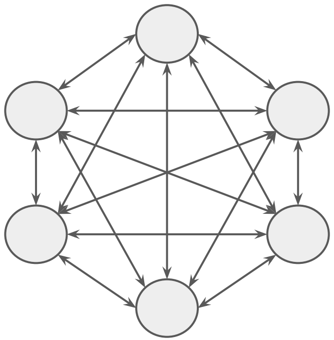


Cryptographic Proofs

1980s Securely compute $y = \boldsymbol{F}(x_1, \ldots, x_n)$ via a multi-party protocol



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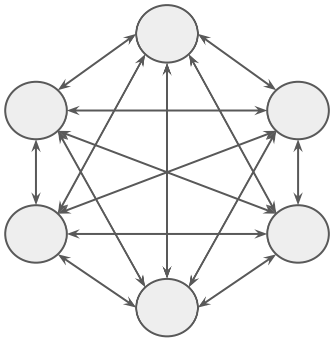

Assumptions
Closed network
All nodes are online
Small number of nodes

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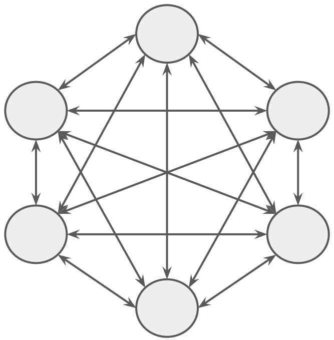


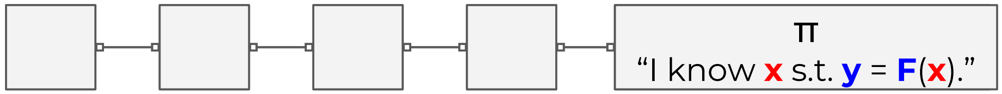
Assumptions

Closed network
All nodes are online
Small number of nodes

Zero-knowledge proof that
every message is sent according to the protocol
(consistent with the input and random tape).

Cryptographic Proofs

2010s Blockchain Technology



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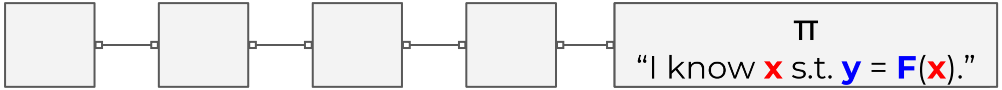

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Open network
Nodes can be online or offline
Planetary scale

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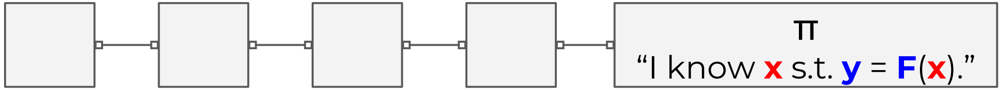

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Desirable Proof Properties

Succinct
Non-Interactive
Publicly Verifiable
Zero Knowledge

Zero-Knowledge Proofs

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Privacy-preserving cryptographic proofs of computational integrity.

Zero-Knowledge Proofs

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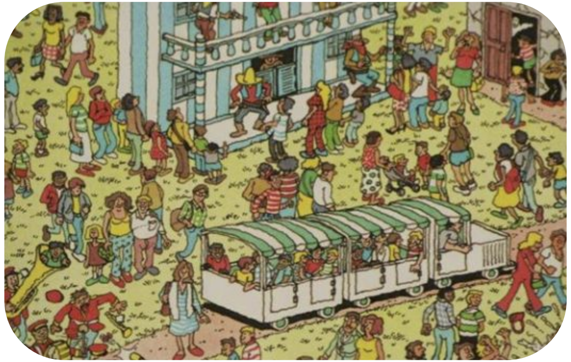
I can't tell you the secret,
but I can prove to you that I know the secret.

Zero-Knowledge Proofs

Privacy-preserving cryptographic proofs of computational integrity.

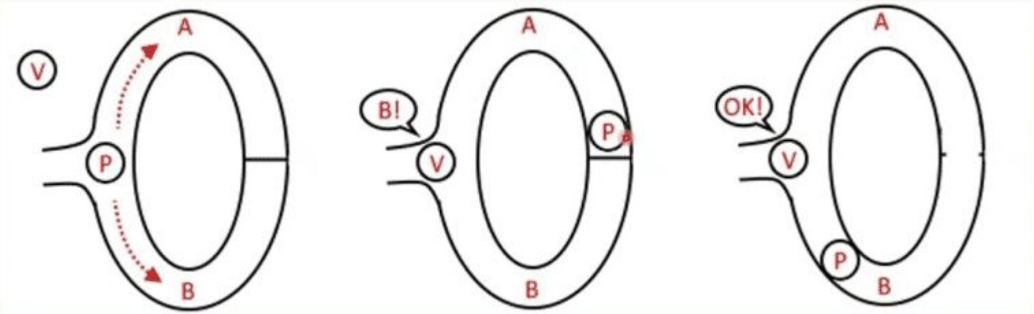


Can you prove to me where Waldo is,
without saying anything about where he is?

Zero-Knowledge Proofs

Privacy-preserving cryptographic proofs of computational integrity.

The Ali Baba Cave



from *“How to Explain Zero-Knowledge Protocols to Your Children”*

Zero-Knowledge Proofs

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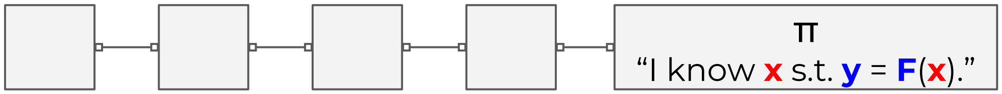

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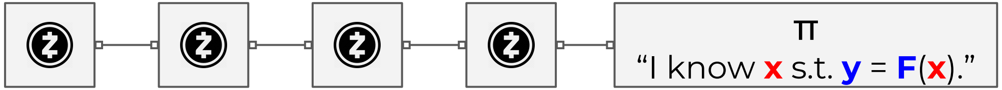
Zero-Knowledge Proofs

2010s Zerocash Protocol (Zcash)



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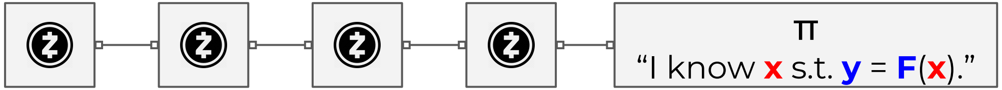

A cryptographic protocol achieving a digital currency that is:

Zero-Knowledge Proofs

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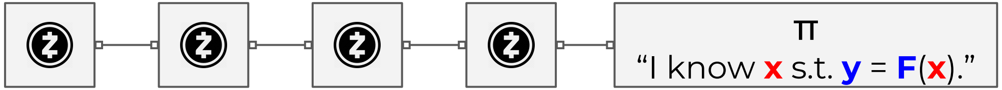

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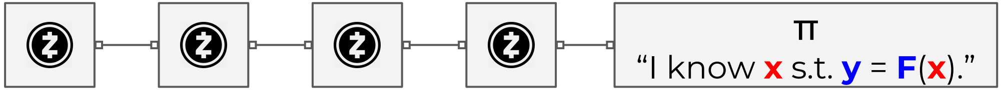

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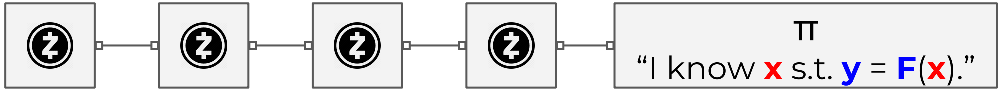


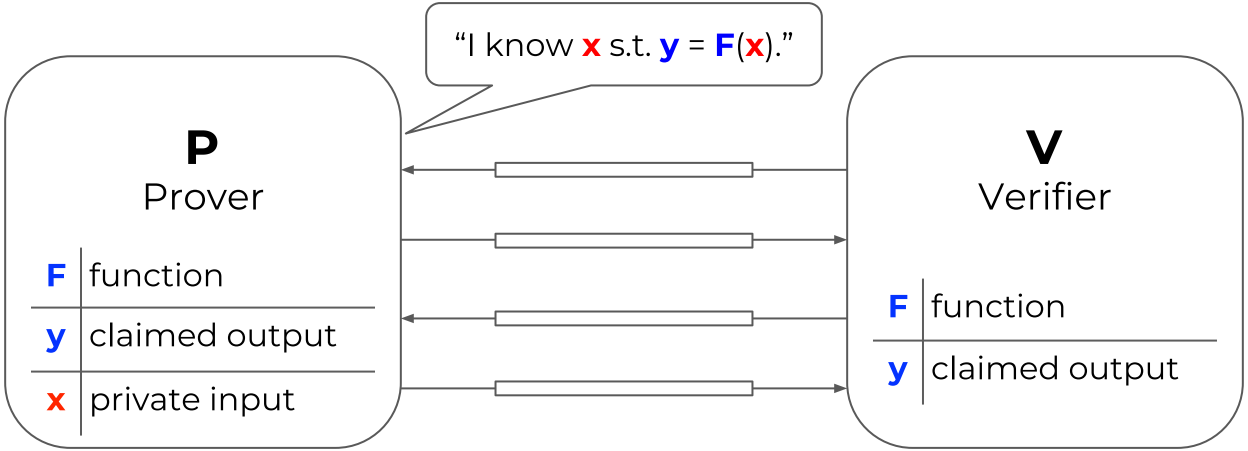
A cryptographic protocol achieving a digital currency that is:

- **Decentralized** - *works when given any (ideal) ledger*
- **Privacy-preserving** - *anyone can post a payment transaction to anyone else, while provably hiding the sender, receiver, and amount*
- **Efficient** - *payment transactions take less than 1 minute to produce, are less than 1 kB in size, and take a few milliseconds to verify*

[GMR89]

Zero-Knowledge Proofs

Privacy-preserving cryptographic proofs of computation integrity.



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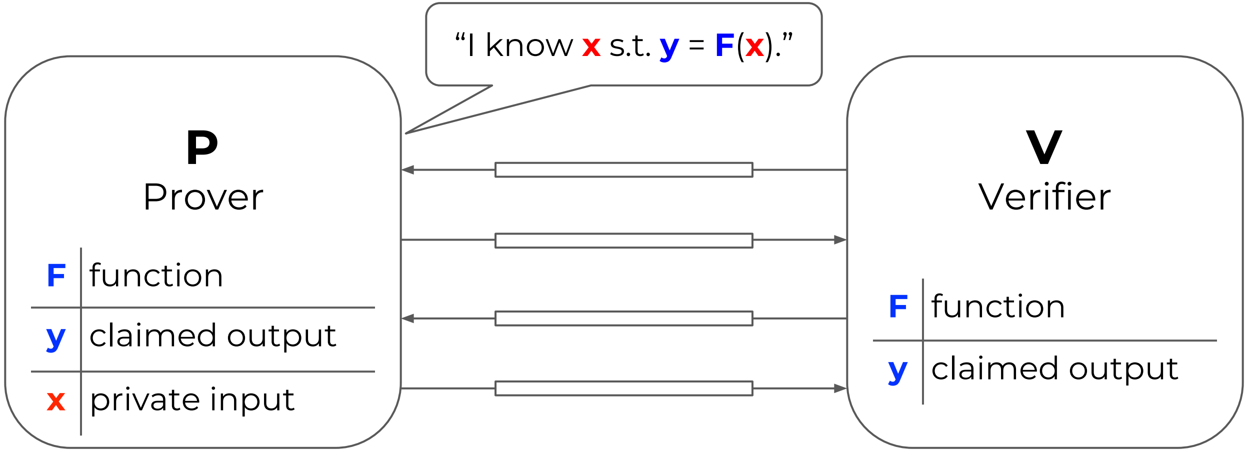

Completeness | $\exists\ \boldsymbol{x}: \boldsymbol{y} = \boldsymbol{F}(\boldsymbol{x}) \rightarrow \Pr[\mathbf{P}(\boldsymbol{F},\boldsymbol{y},\boldsymbol{x})$ convinces $\mathbf{V}(\boldsymbol{F},\boldsymbol{y})]=1$

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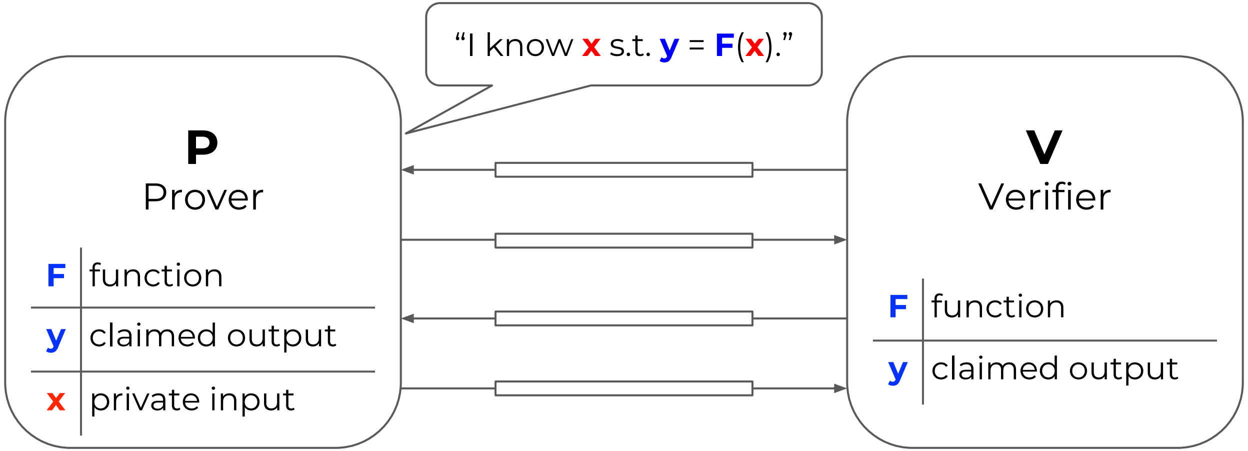

Completeness	$\exists\ x\!: y = F(x) \rightarrow \Pr[\mathbf{P}(F,y,x) \text{ convinces } \mathbf{V}(F,y)]=1$
Soundness	$\nexists\ x\!: y = F(x) \rightarrow \forall\ \mathbf{P'}\ \Pr[\mathbf{P'} \text{ convinces } \mathbf{V}(F,y)]\approx 0$

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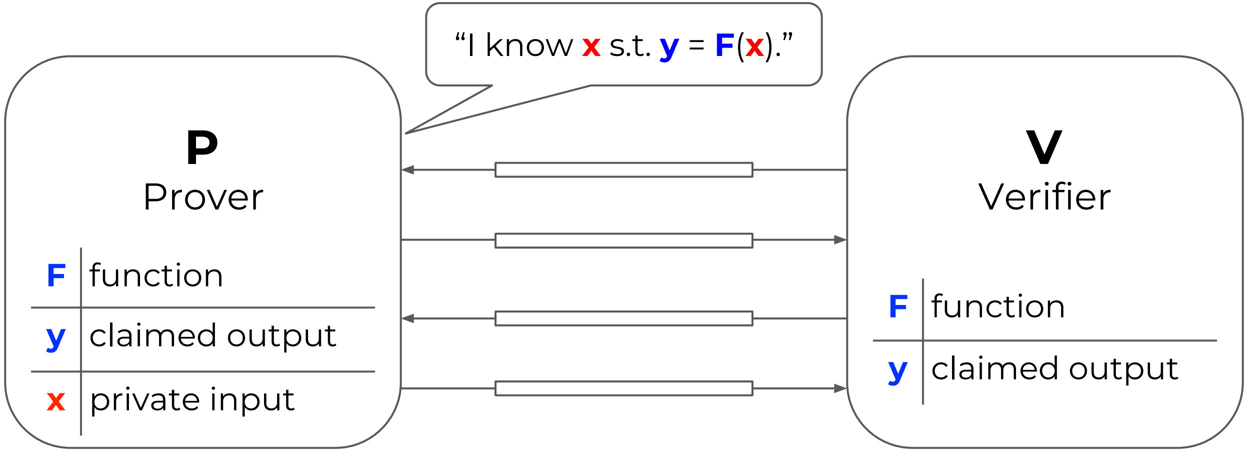

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Zero-Knowledge	$\exists\ x: y = F(x) \rightarrow \underbrace{\mathbf{S}}_{\text{Simulator}}(F,y) \approx \text{view of } \mathbf{V}(F,y) \text{ after talking to } \mathbf{P}(F,y,x)$

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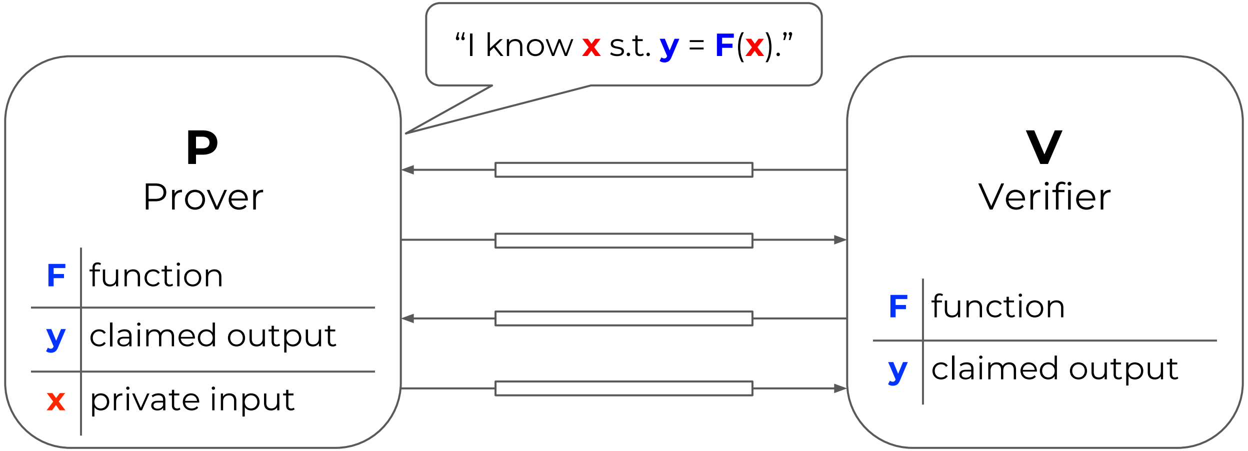


Powerful cryptographic primitive.

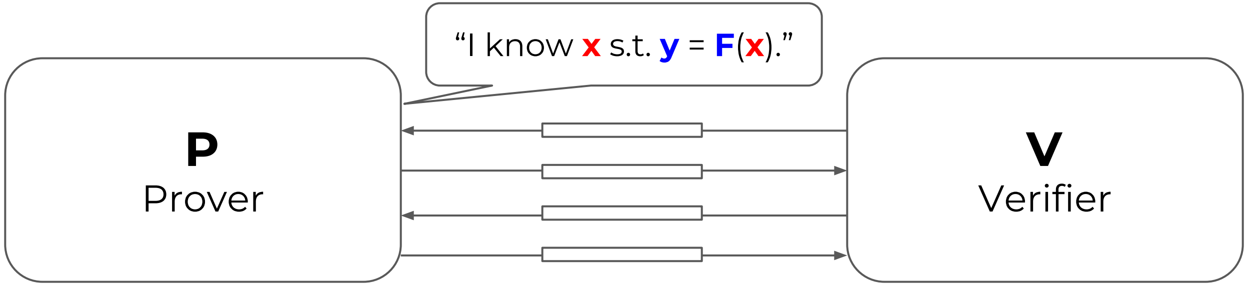
However, it is
interactive, not succinct, and has bad concrete efficiency.

Communication complexity & verification complexity are proportional to time(F)

Relies on PCPs (probabilistically checkable proofs)

Zero-Knowledge Succinct Proofs

Privacy-preserving cryptographic **succinct** proofs of computation integrity.



[Killian92]

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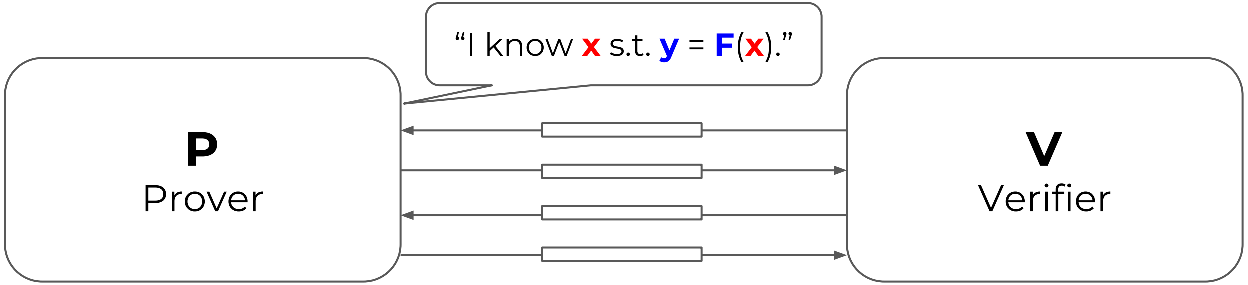
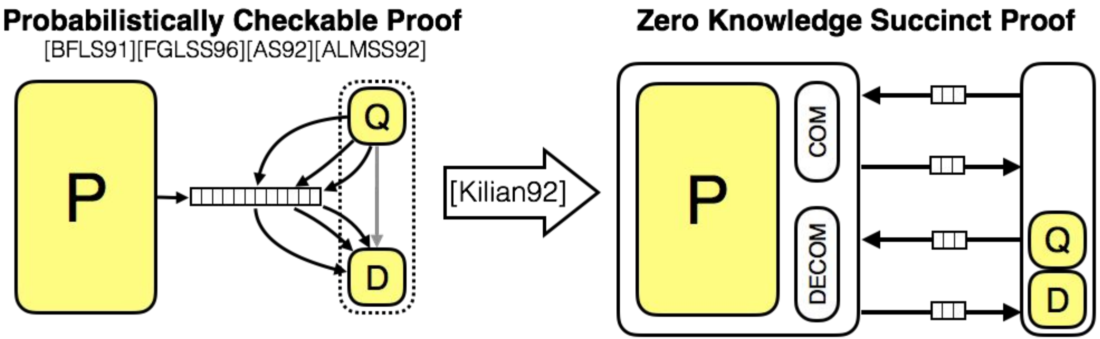


Achieving Succinctness



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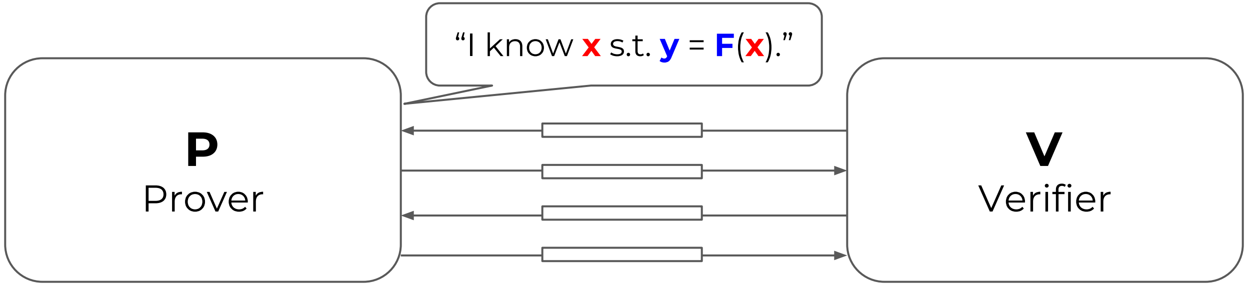

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Zero-knowledge	$\exists\ x: y = F(x) \rightarrow \mathbf{S}(F,y) \approx$ view of $\mathbf{V}(F,y)$ after talking to $\mathbf{P}(F,y,x)$
Succinctness	$\mathbf{V}(F,y)$ runs in time proportional to $\lvert F\rvert+\lvert y\rvert$ (not F's runtime)

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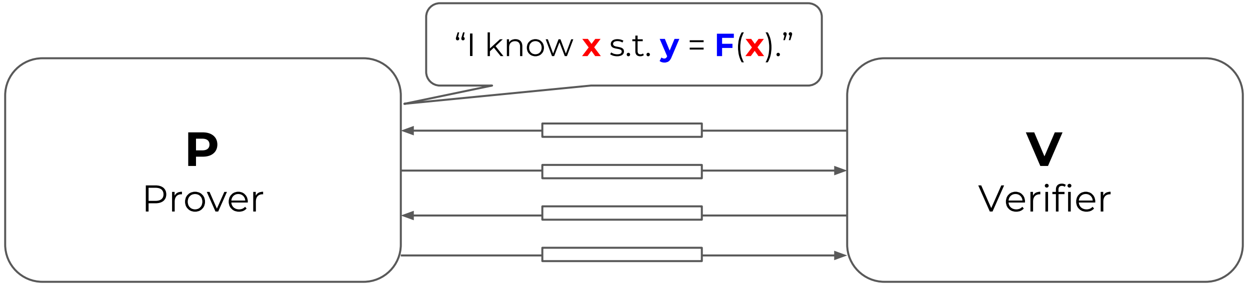

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[Micali94]

Zero-Knowledge Succinct Non-Interactive Proofs

Privacy-preserving cryptographic succinct,
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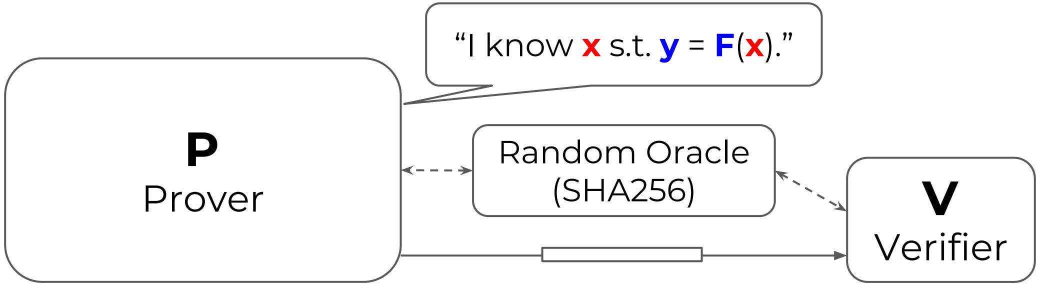

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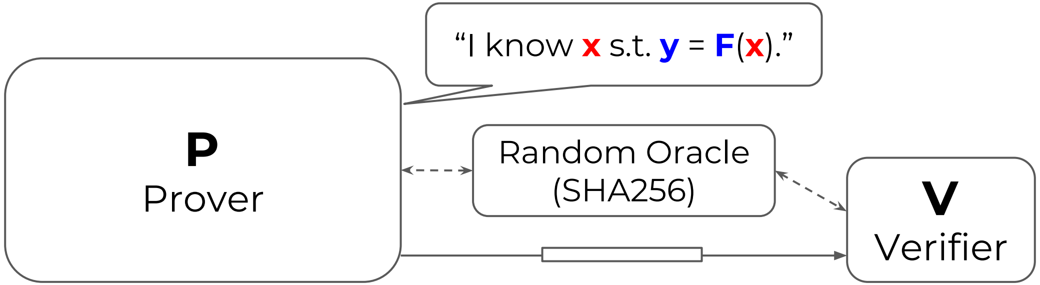

Zero-**K**nowledge **S**uccinct **N**on-interactive **Ar**gument of **K**nowledge

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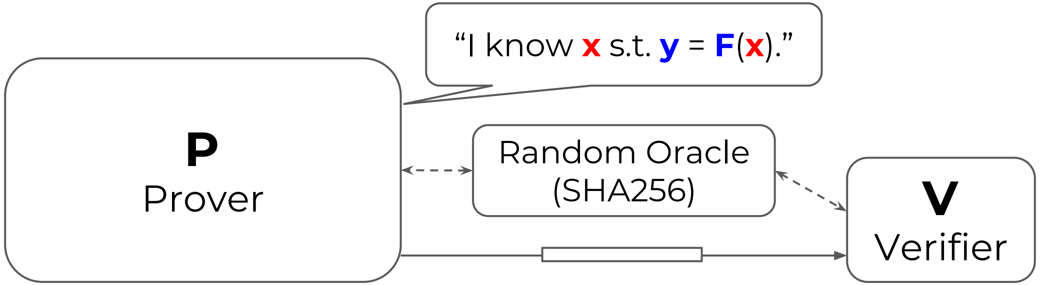

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Zero-knowledge - *Proofs do not reveal the witness*

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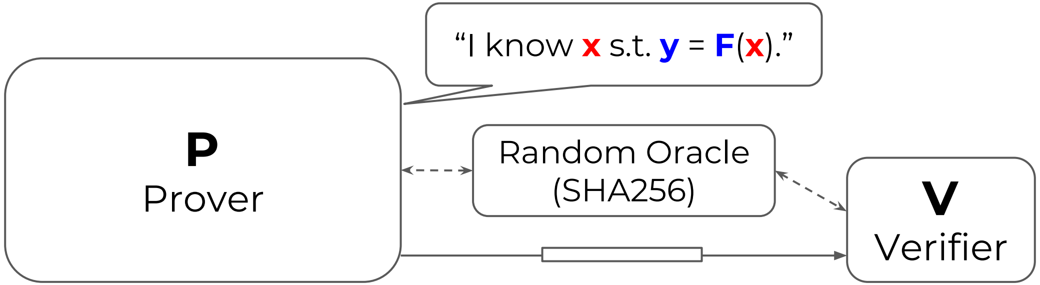

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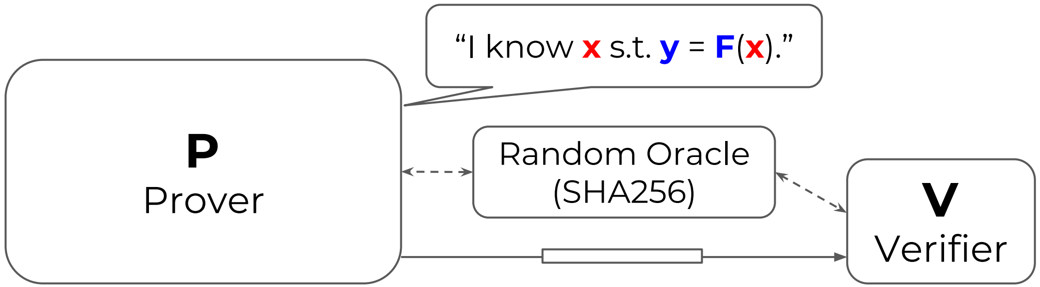

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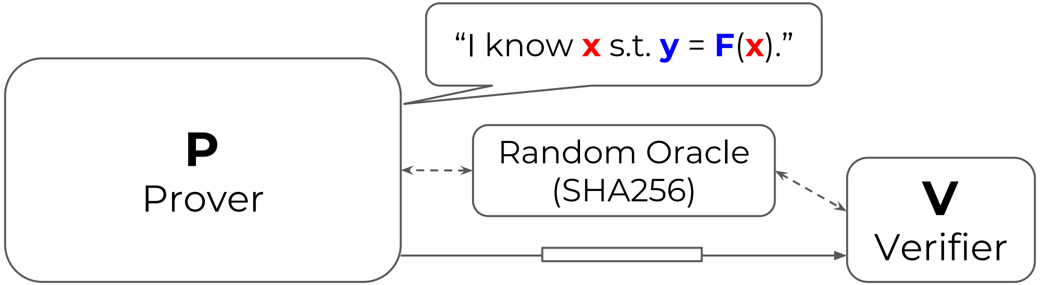

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Non-interactive - *No interaction is necessary between the prover and the verifier*

Argument - *Soundness holds against a polynomially-bounded verifier*

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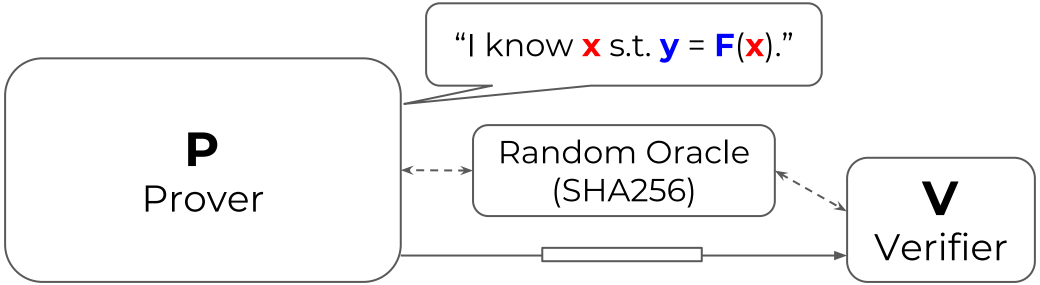

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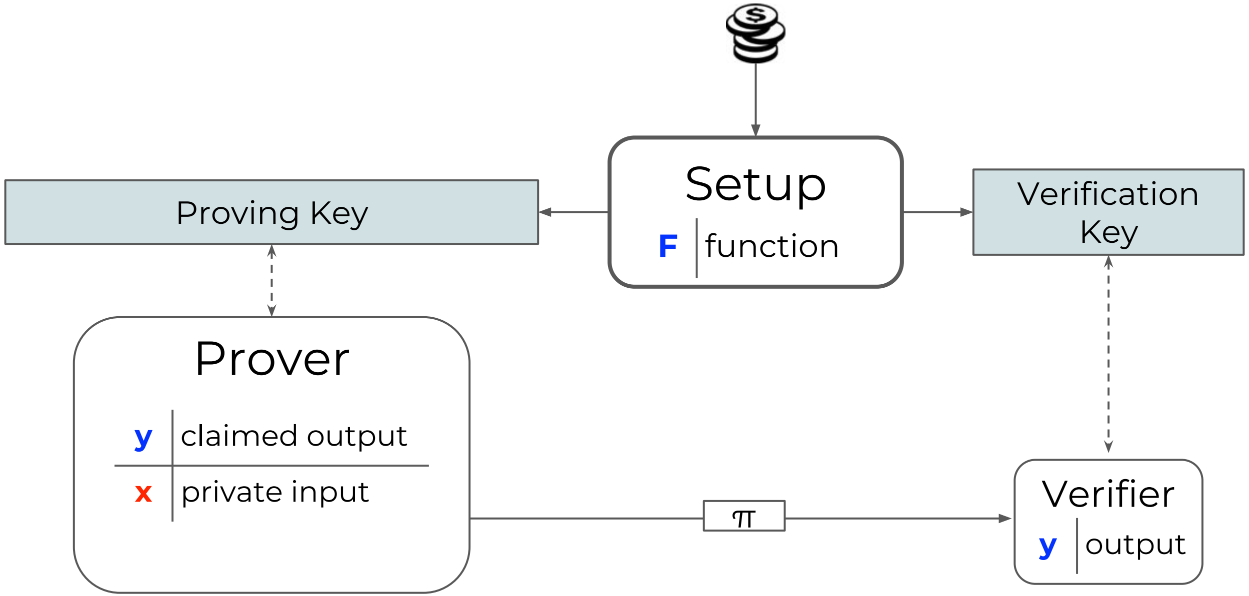
Preprocessing zkSNARKs



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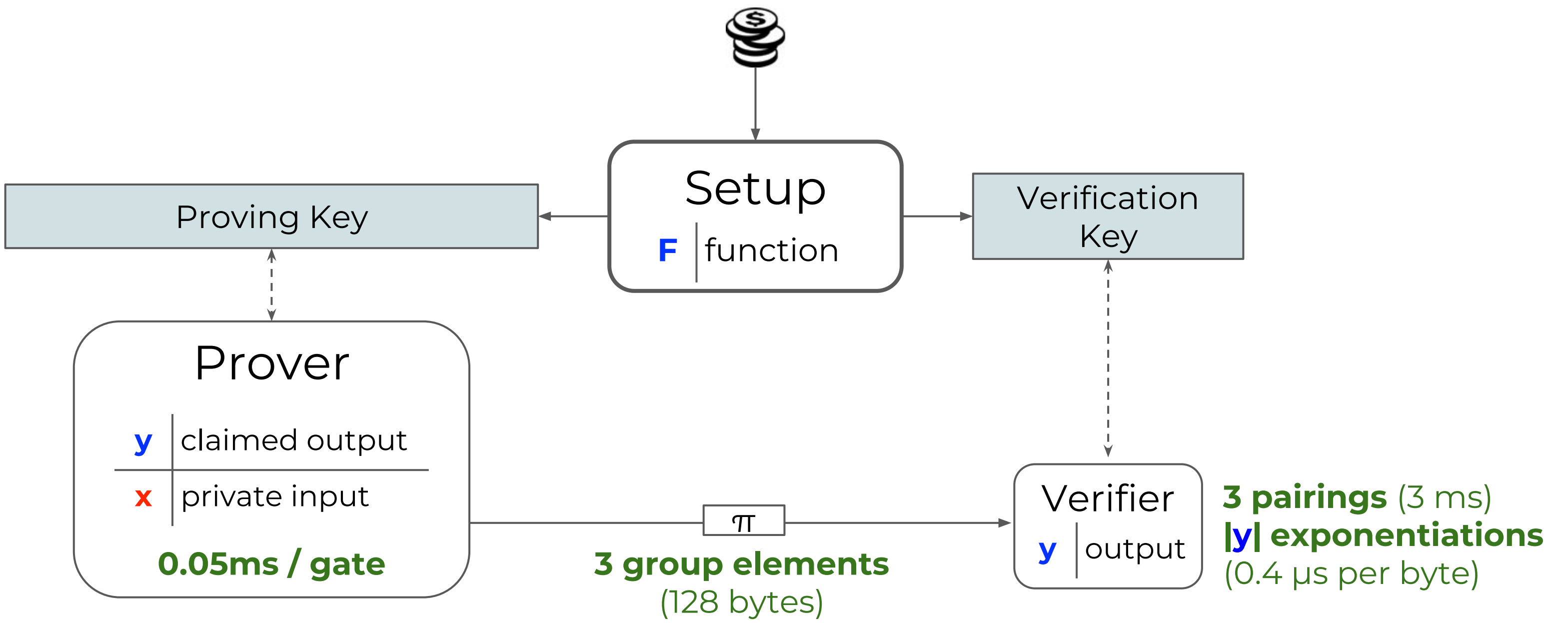

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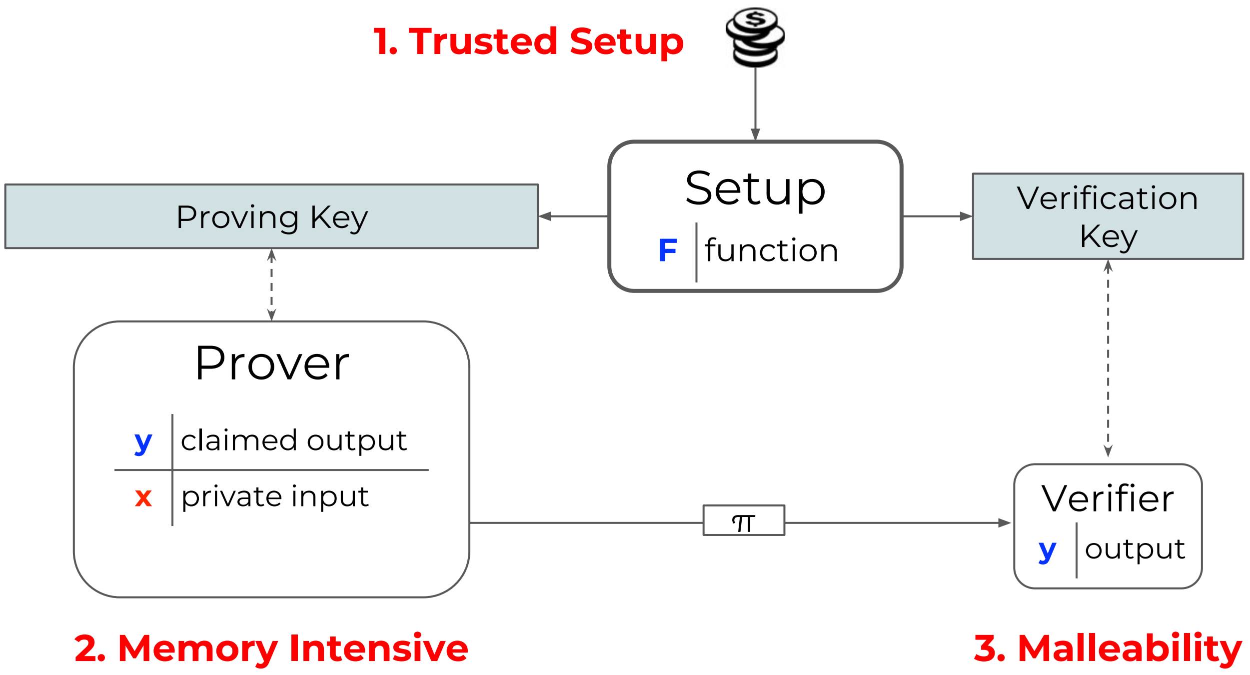

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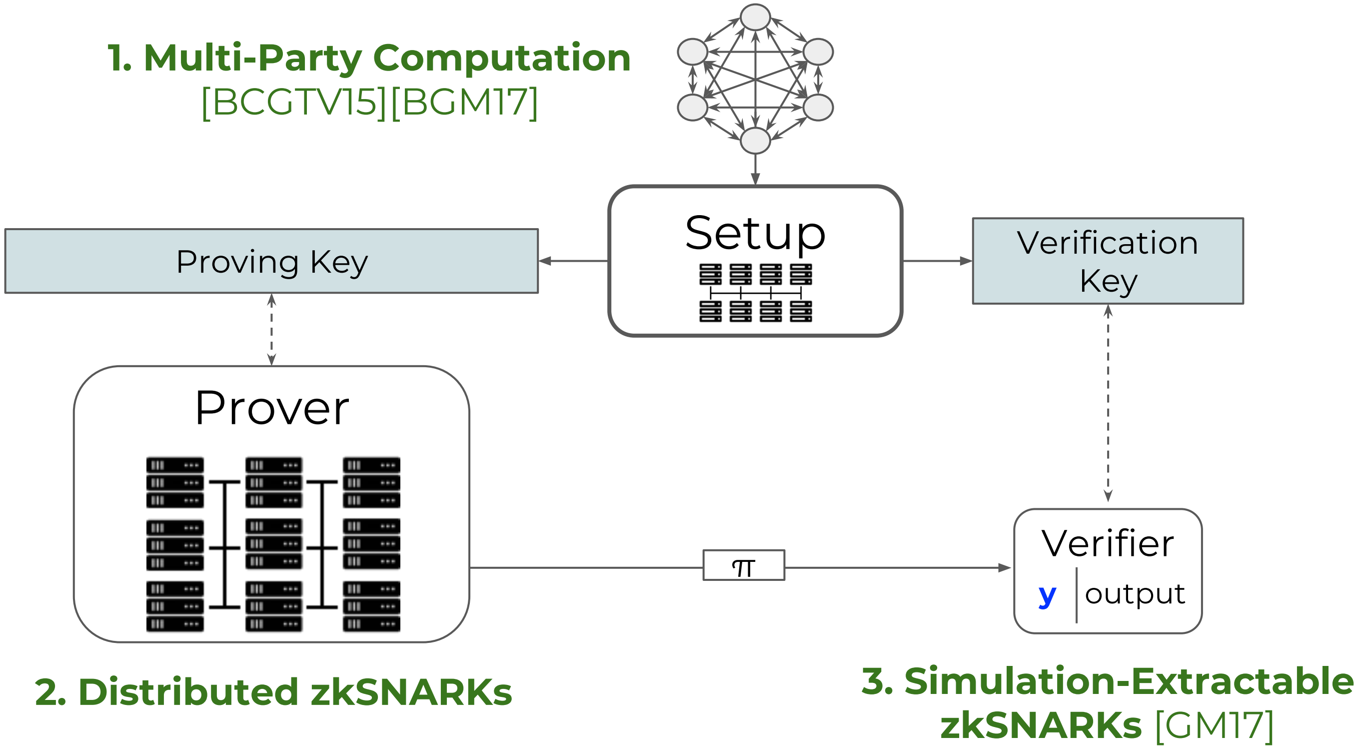

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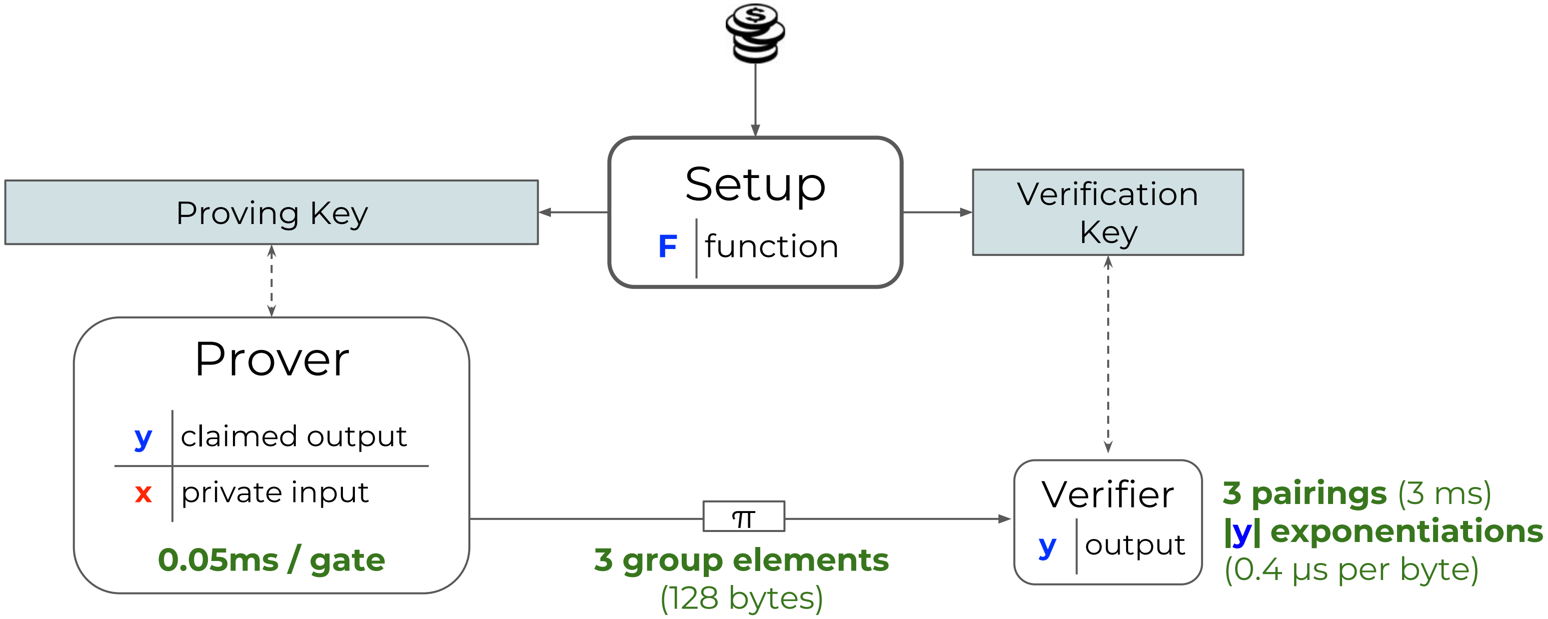

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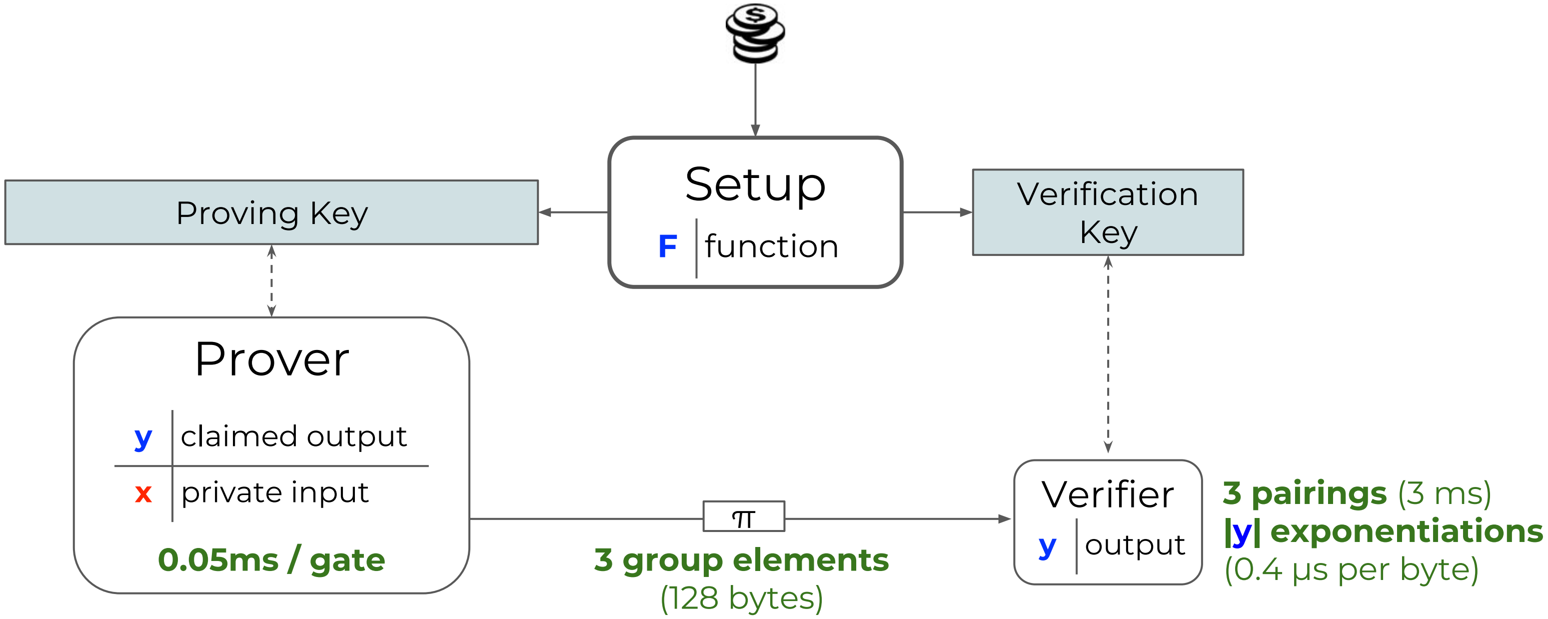
Pairing-based Preprocessing zkSNARKs



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Prime-order bilinear map

G_1, G_2, G_T finite cyclic groups of prime order p

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$e(g^a, h^b) = e(g, h)^{ab}$.

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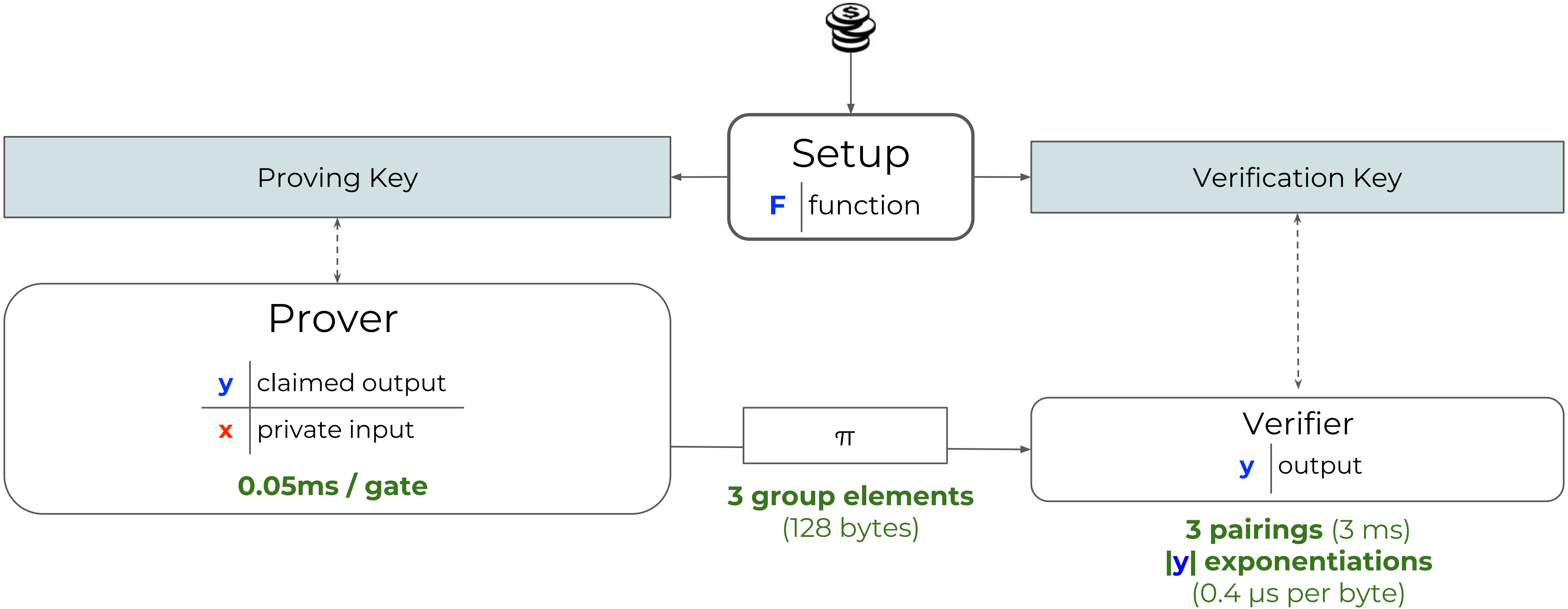
Notation:

$[a]_1 = g^a$ $[b]_2 = h^b$ $[c]_T = e(g, h)^c$

[Groth16]

Pairing-based Preprocessing zkSNARKs



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[Groth16]

Pairing-based Preprocessing zkSNARKs

$$\vec{\sigma}_1 = \left(\alpha, \beta, \delta, \{x^i\}, \left\{\frac{x^i t(x)}{\delta}\right\}, \left\{\frac{\beta u_i(x)+\alpha v_i(x)+w_i(x)}{\gamma}\right\}_{i\leq \ell}, \left\{\frac{\beta u_i(x)+\alpha v_i(x)+w_i(x)}{\delta}\right\}_{i>\ell}\right)$$

Setup

$$\sigma = (\vec{\sigma}_1, \vec{\sigma}_2)$$

$$\vec{\sigma}_2 = \left(\alpha, \beta, \gamma, \delta, \{x^i\}, \left\{\frac{\beta u_i(x)+\alpha v_i(x)+w_i(x)}{\gamma}\right\}_{i\leq \ell}\right)$$

Prover

y	claimed output
x	private input

0.05ms / gate

π

3 group elements
(128 bytes)

Verifier

y	output

3 pairings (3 ms)
|y| exponentiations
(0.4 µs per byte)

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Prover

$$A = \alpha + \sum a_i u_i(x) + r\delta \qquad B = \beta + \sum a_i v_i(x) + s\delta$$

$$C = \sum_{i > \ell} a_i \frac{\beta u_i(x) + \alpha v_i(x) + w_i(x)}{\delta} + \frac{h(x)t(x)}{\delta} + As + rB - rs\delta$$

0.05ms / gate

π

3 group elements
(128 bytes)

Verifier

y | output

3 pairings (3 ms)
|y| exponentiations
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Setup

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$$\vec{\sigma}_1 = \left(\alpha, \beta, \delta, \{x^i\}, \left\{\frac{x^i t(x)}{\delta}\right\}, \left\{\frac{\beta u_i(x) + \alpha v_i(x) + w_i(x)}{\gamma}\right\}_{i \le \ell}, \left\{\frac{\beta u_i(x) + \alpha v_i(x) + w_i(x)}{\delta}\right\}_{i > \ell}\right)$$

$$\vec{\sigma}_2 = \left(\alpha, \beta, \gamma, \delta, \{x^i\}, \left\{\frac{\beta u_i(x) + \alpha v_i(x) + w_i(x)}{\gamma}\right\}_{i \le \ell}\right)$$

Prover

$$A = \alpha + \sum a_i u_i(x) + r\delta \qquad B = \beta + \sum a_i v_i(x) + s\delta$$

$$C = \sum_{i > \ell} a_i \frac{\beta u_i(x) + \alpha v_i(x) + w_i(x)}{\delta} + \frac{h(x)t(x)}{\delta} + As + rB - rs\delta$$

0.05ms / gate

$\pi = ([A]_1, [C]_1, [B]_2)$

3 group elements
(128 bytes)

Verifier

y | output

3 pairings (3 ms)
|y| exponentiations
(0.4 μs per byte)

https://github.com/scipr-lab/libsnark/tree/master/src/zk_proof_systems/ppzksnark/r1cs_gg_ppzksnark

Pairing-based Preprocessing zkSNARKs

Setup

$$\sigma = (\vec{\sigma}_1, \vec{\sigma}_2)$$

$$\vec{\sigma}_1 = \left(\alpha, \beta, \delta, \{x^i\}, \left\{\frac{x^i t(x)}{\delta}\right\}, \left\{\frac{\beta u_i(x)+\alpha v_i(x)+w_i(x)}{\gamma}\right\}_{i\le\ell}, \left\{\frac{\beta u_i(x)+\alpha v_i(x)+w_i(x)}{\delta}\right\}_{i>\ell}\right)$$

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Prover

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0.05ms / gate

$$\pi = ([A]_1, [C]_1, [B]_2)$$

3 group elements
(128 bytes)

Verifier

$$[A]_1 \cdot [B]_2 = [\alpha]_1 \cdot [\beta]_2 + \sum_{i=0}^{\ell} a_i \left[\frac{\beta u_i(x) + \alpha v_i(x) + w_i(x)}{\gamma}\right]_1 \cdot [\gamma]_2 + [C]_1 \cdot [\delta]_2$$

3 pairings (3 ms)
|y| exponentiations
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[Groth16]

Pairing-based Preprocessing zkSNARKs

Efficiency

Proof size: $2G_1$, $1G_2$

Prover: $m + 3n\ E_1, n\ E_2$

Verifier: $\ell\ E_1 + 3P$

Setup

$$\sigma = (\vec{\sigma}_1, \vec{\sigma}_2)$$

$$\vec{\sigma}_1 = \left(\alpha, \beta, \delta, \{x^i\}, \left\{\frac{x^i t(x)}{\delta}\right\}, \left\{\frac{\beta u_i(x) + \alpha v_i(x) + w_i(x)}{\gamma}\right\}_{i \le \ell}, \left\{\frac{\beta u_i(x) + \alpha v_i(x) + w_i(x)}{\delta}\right\}_{i > \ell}\right)$$

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`libsnark`: a C++ library for zkSNARKs

(libsnark.org)

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Algebraic Core			
	Polynomial Interpolation / Evaluation	Fast Fourier Transforms in Finite Fields	Lagrange-Coefficient Computations
	Finite Field Arithmetic	Bilinear Group Arithmetic	Fixed & Variable Base Multi-Exponentiation

libsnark: a C++ library for zkSNARKs

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- **libff**: a C++ library for Finite Fields and Elliptic Curves

(github.com/scipr-lab/libff)

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- **`libfqfft`**: a C++ library for FFTs in Finite Fields

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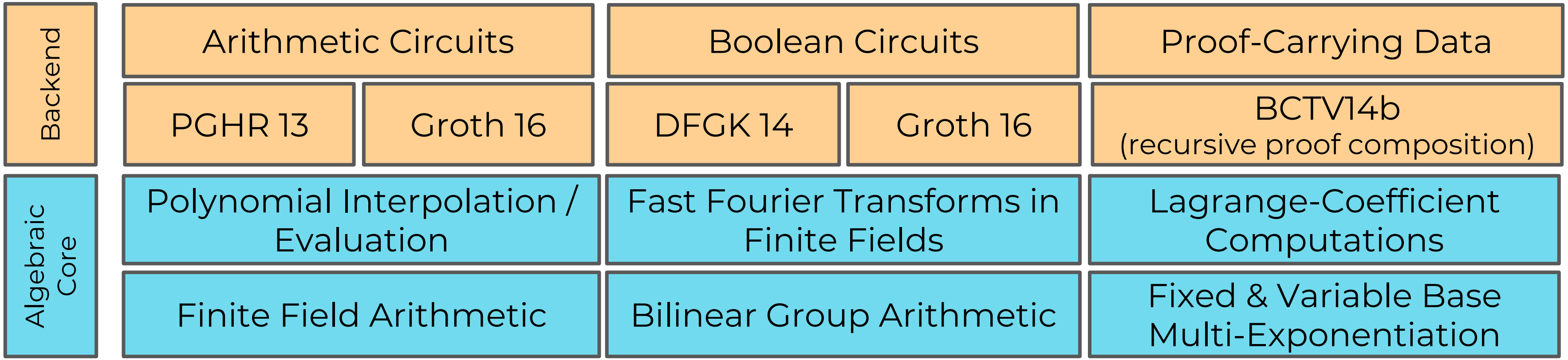

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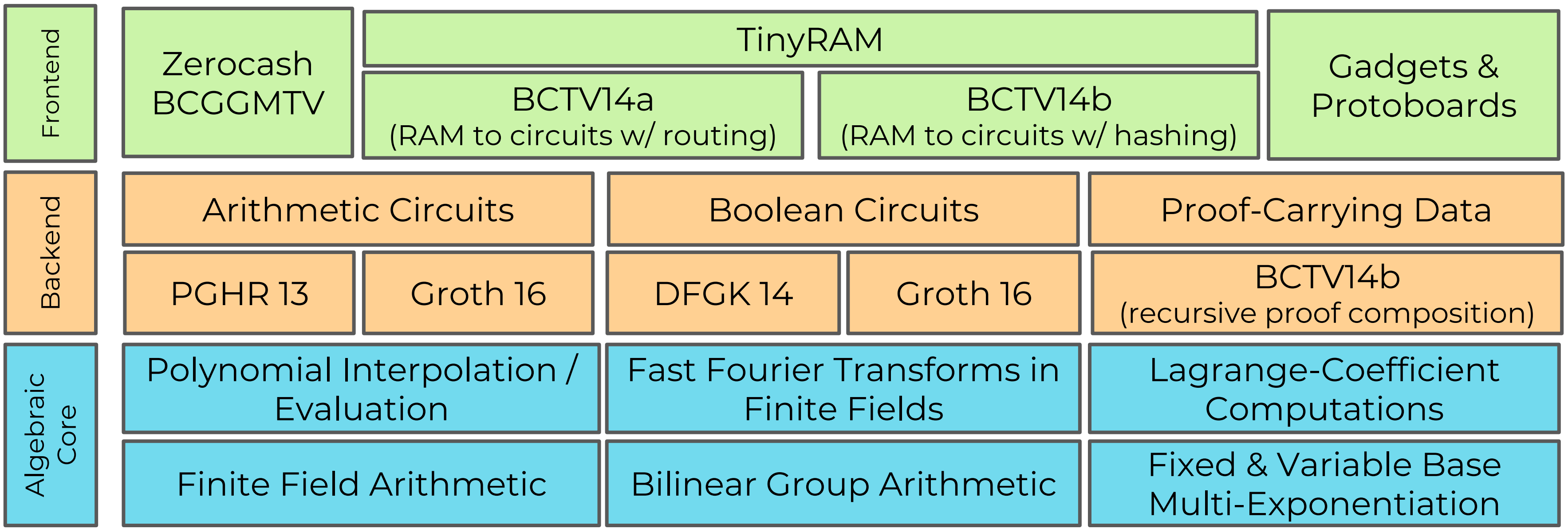

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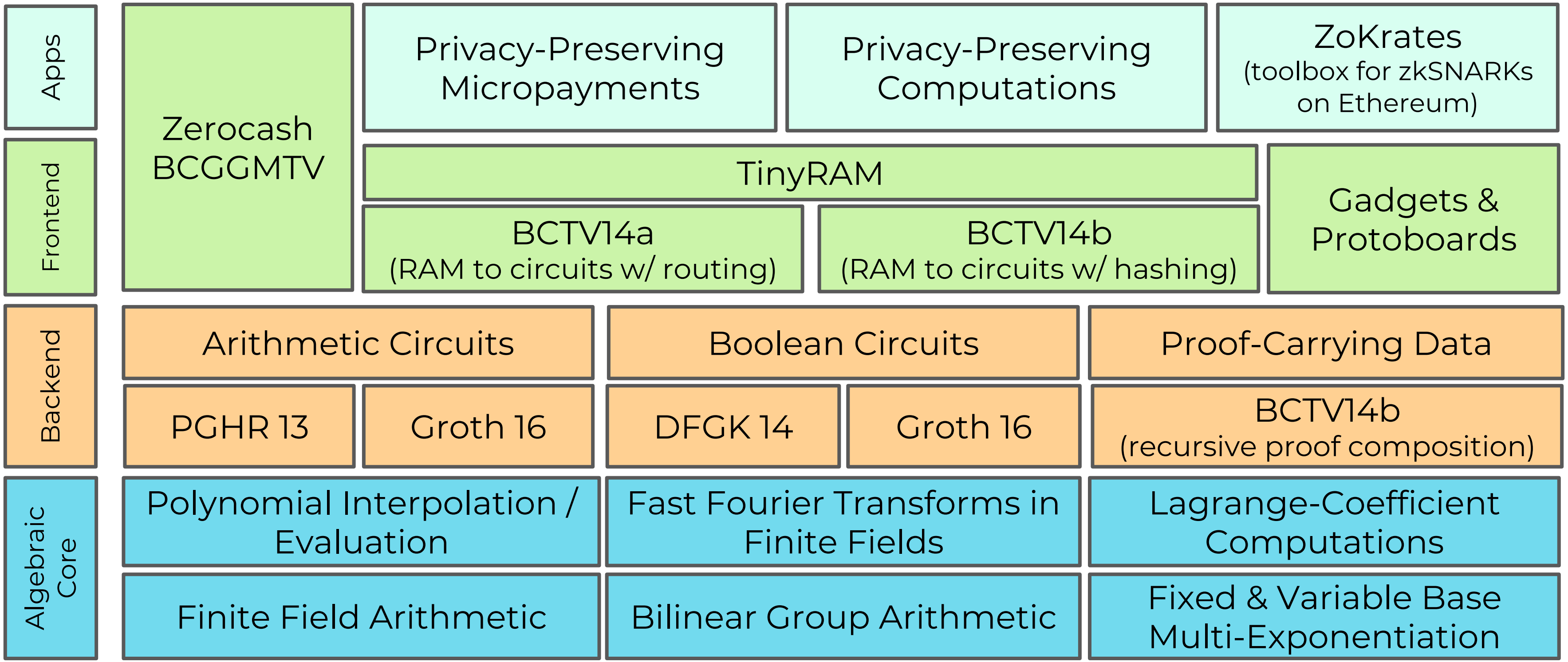

Developing on `libsnark`

`libff`

Choice of elliptic curve implementations

Barreto-Naehrig curve
(~128 bits of security)

Edwards curve
(~80 bits of security)

MNT4 curve
(~80 bits of security)

MNT6 curve
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`libff`

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Bilinear Group Arithmetic

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`libff`

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Bilinear Group Arithmetic

`libfqfft`

Choice of evaluation domains

Standard radix-2
(size $m = 2^k$ & m-th roots of unity)

Extended radix-2
(size $m = 2^{k+1}$ & m-th roots of unity, union a coset of these roots)

Step radix-2
(size $m = 2^k + 2^r$ & 2^k-th roots of unity, union a coset of 2^r-th roots of unity)

Geometric Sequence
(size m & sampled points of $a_n = r^{(n-1)}$)

Arithmetic Sequence
(size m & sampled points of $a_i = a_1 + (i - 1)*d$)

Developing on `libsnark`

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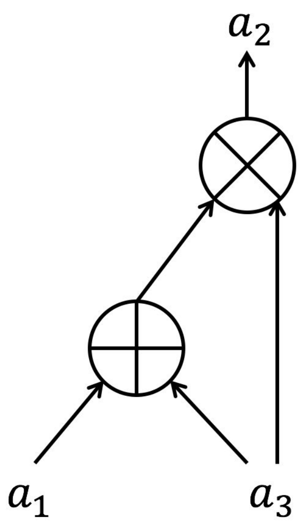
Polynomial Interpolation / Evaluation

Developing on **`libsnark`**

`libsnark` arithmetic circuits

Developing on **`libsnark`**

`libsnark` arithmetic circuits



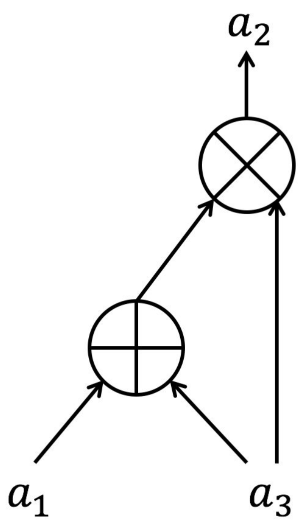
Write as quadratic equation over $\boldsymbol{F}_p$

$$(a_1 + a_3) \cdot a_3 = a_2$$

Arithmetic Circuits

Developing on **`libsnark`**

`libsnark` arithmetic circuits



Write as quadratic equation over $\boldsymbol{F}_p$

$$(a_1 + a_3) \cdot a_3 = a_2$$

Arithmetic circuits can be expressed in the form,

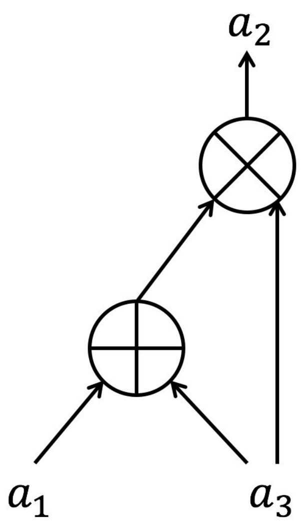
$$\sum a_i u_i \cdot \sum a_i v_i = \sum a_i w_i$$

over variables $a_1, \ldots, a_m$, where by convention $a_0 = 1$.

Arithmetic Circuits

Developing on **`libsnark`**

`libsnark` arithmetic circuits



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$$\sum a_i u_i \cdot \sum a_i v_i = \sum a_i w_i$$

over variables $a_1, \dots, a_m$, where by convention $a_0 = 1$.

An arithmetic circuit defines an *NP-language* with statements $(a_1, \dots, a_\ell)$ and witnesses $(a_{\ell+1}, \dots, a_m)$.

Arithmetic Circuits

Developing on `libsnark`

`libsnark` gadgetlib1 & gadgetlib2

Gadgets &
Protoboards

Developing on **`libsnark`**

`libsnark` gadgetlib1 & gadgetlib2

Low-level libraries which expose all features of the preprocessing zkSNARK

Gadgets & Protoboards

Developing on **`libsnark`**

`libsnark` gadgetlib1 & gadgetlib2

Low-level libraries which expose all features of the preprocessing zkSNARK

Finite Fields

Elliptic Curves

Pairings

Multi-Exponentiation

Hash Functions *(SHA256)*

Merkle Trees *(Authentication Paths)*

CPU Checkers *(TinyRAM)*

zkSNARK verifier

Gadgets & Protoboards

libsnark: a C++ library for zkSNARKs

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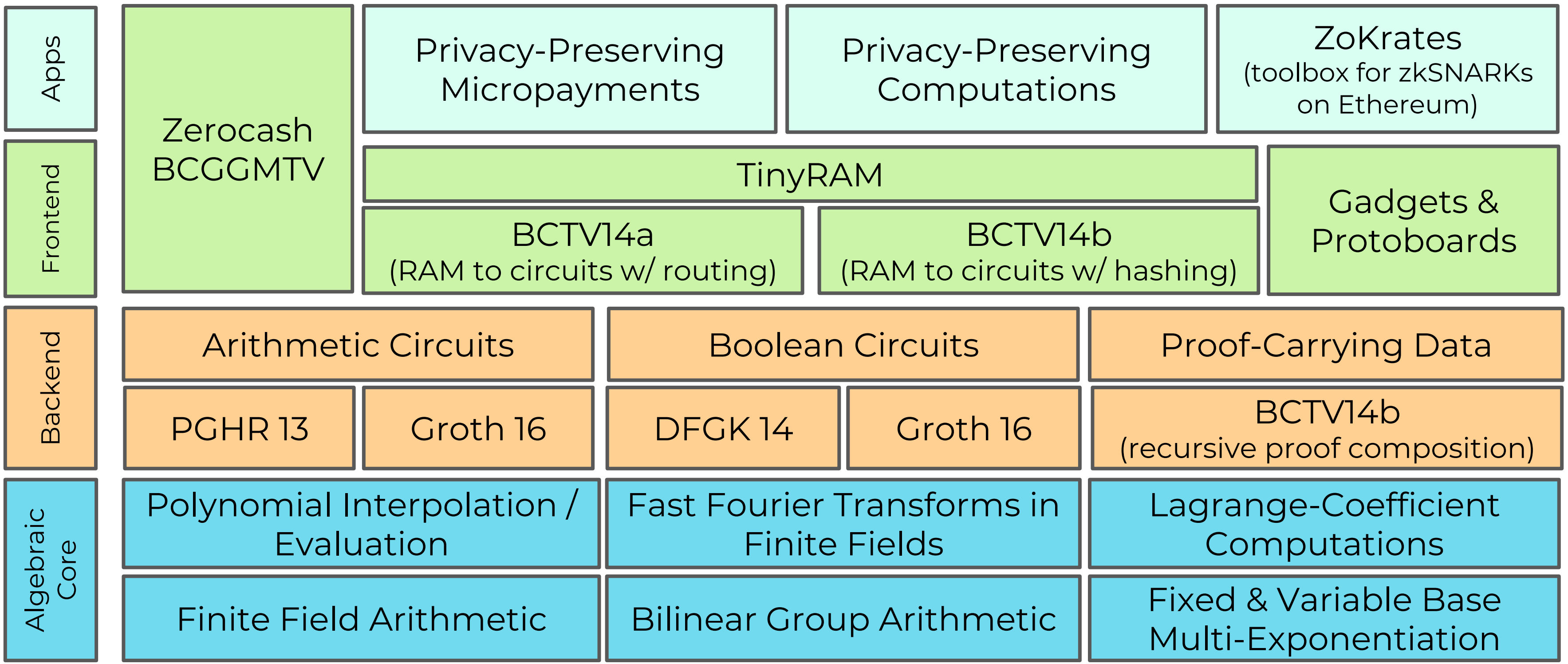

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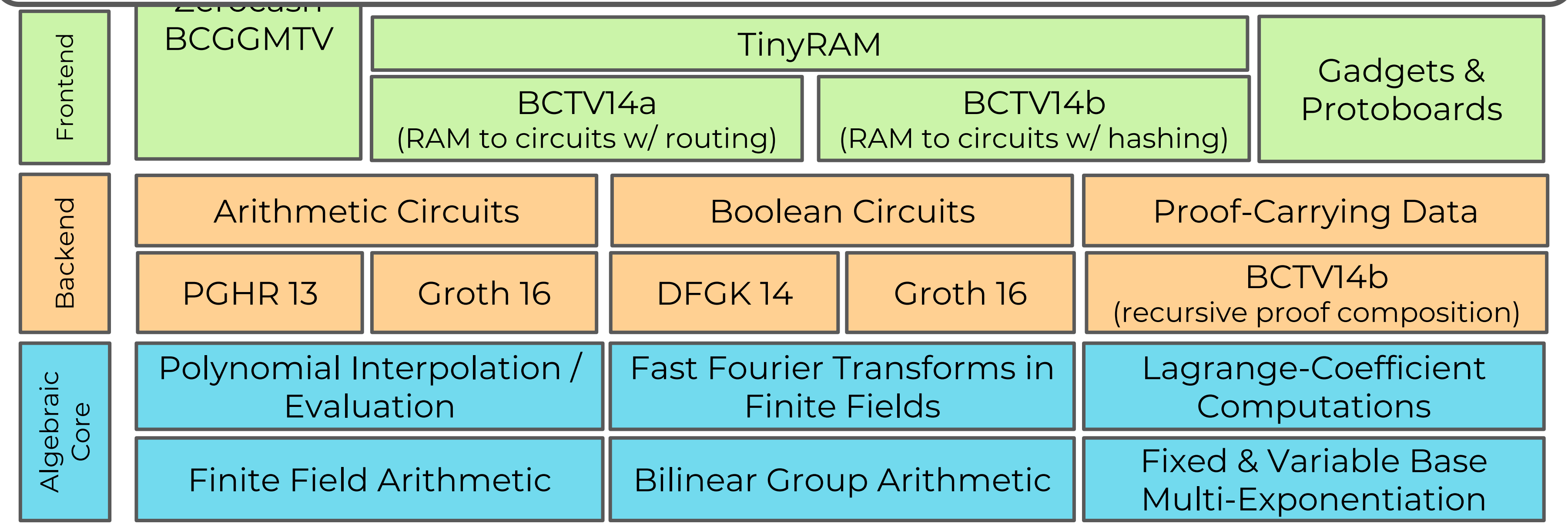
To get started:

`github.com/howardwu/libsnark-tutorial`



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To get involved:

`libsnark.org/get-involved`

Backend	Arithmetic Circuits	Boolean Circuits	Proof-Carrying Data
Backend	PGHR 13 / Groth 16	DFGK 14 / Groth 16	BCTV14b (recursive proof composition)
Algebraic Core	Polynomial Interpolation / Evaluation	Fast Fourier Transforms in Finite Fields	Lagrange-Coefficient Computations
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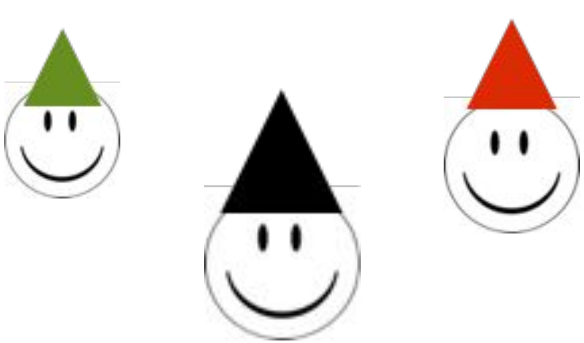

Thanks!