Zero-knowledge proofs and Blockchains

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Tanger Med — April 30, 2025

whoami

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- Cryptographer — Consensys (New York)
- Co-founder of gnark
- Co-founder of linea

Overview

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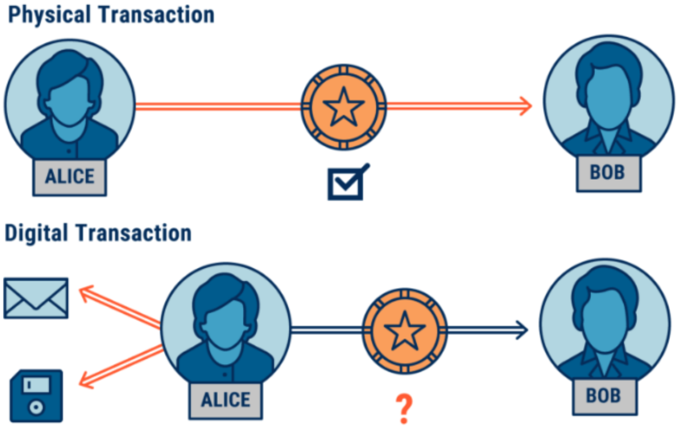
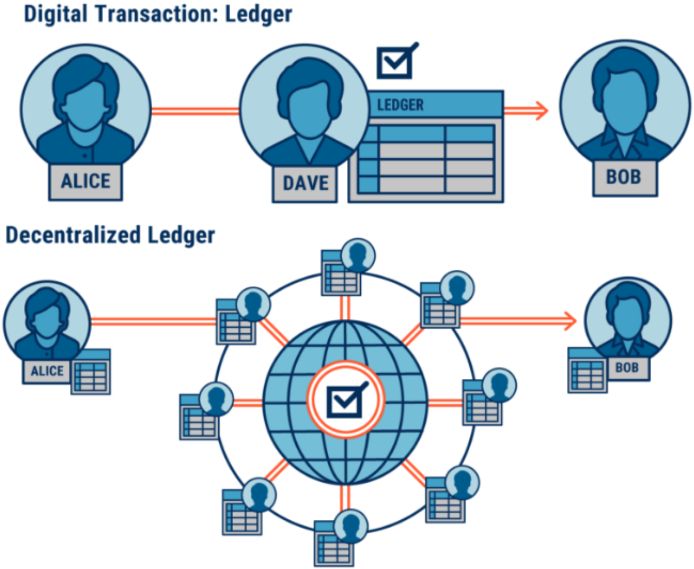
1. Motivation
2. Blockchain
3. Zero-knowledge proofs
4. Applications
5. Research

The story of Alice and Bob



(Courtesy of CBINSIGHTS)

The story of Alice and Bob



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Blockchains

1991

Stuart Haber and W. Scott Stornetta published the first paper to outline the use of a chain of cryptographically secured blocks to preserve the integrity of past information and protect it.

1991

There's too much spam! The concept of proof-of-work was established, seeking to provide countermeasures to spam and other network abuses.

2008

Satoshi Nakamoto released a white paper that ushered in the age of blockchain. The paper was called: ***Bitcoin: A Peer-to-Peer Electronic Cash System***. This paper defined the most commonly known blockchain of today: Bitcoin.

2014

Ethereum is born! It is a distributed world computer that runs on a blockchain. Ethereum is a blockchain that can also be programmed and run computations. Ethereum's world computer is called the *"Ethereum Virtual Machine"*, or EVM.

2015

Bitcoin starts getting serious attention. Harvard Business Review stated *"bitcoin is backed by a widely distributed network"*.

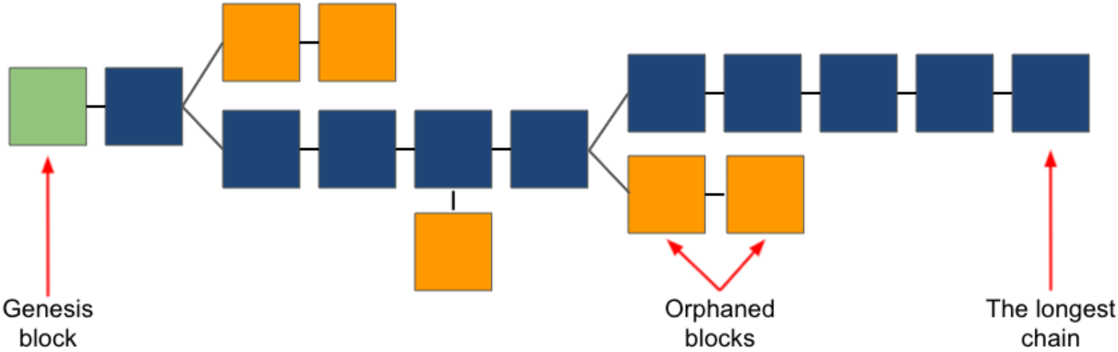
2016

Blockchain embraced by financial industry. JPMorgan Chase, led by CEO Jamie Dimon, is building a new system based on the Ethereum platform.

2017

Blockchain named a "foundational technology".

Blockchains



Blockchains

- How is a tx included in a block?
- How is the longest chain is agreed upon?

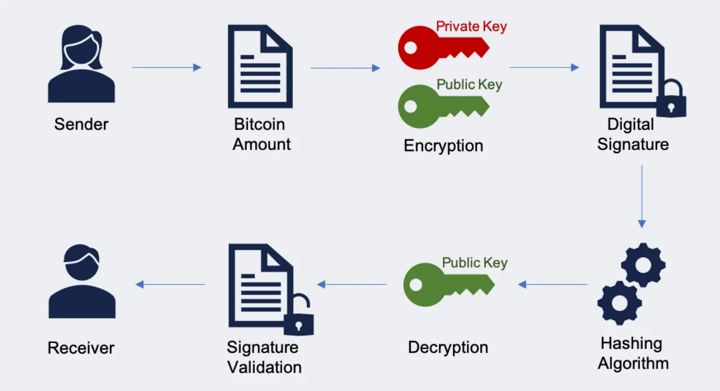
Blockchains

- How is a tx included in a block?
  - Signatures verification (Bitcoin: ECDSA/Schnorr, Ethereum: ECDSA/BLS)
- How is the longest chain is agreed upon?
  - Consensus (Bitcoin: proof-of-work, Ethereum: proof-of-stake)

Blockchains

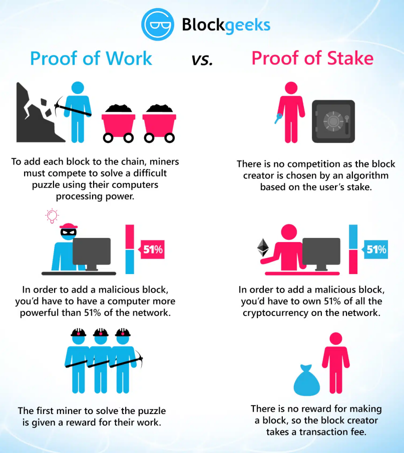
Digital signatures:

- Public-key cryptography: Shcnorr but patented until 2020
- ECDSA as a workaround but with caveats
- Ethereum chooses BLS for aggregation and Bitcoin Schnorr for simplicity



Blockchains

Consensus:



Proof of Work vs. Proof of Stake

To add each block to the chain, miners must compete to solve a difficult puzzle using their computers processing power.

There is no competition as the block creator is chosen by an algorithm based on the user's stake.

In order to add a malicious block, you'd have to have a computer more powerful than 51% of the network.

In order to add a malicious block, you'd have to own 51% of all the cryptocurrency on the network.

The first miner to solve the puzzle is given a reward for their work.

There is no reward for making a block, so the block creator takes a transaction fee.

Examples: proof-of-work, proof-of-stake, proof-of-space, proof-of-authority, proof-of-burn...

Blockchains

A blockchain is a public peer-to-peer *decentralized*, *transparent, immutable, paying* ledger.

- *Transparent*: everything is visible to everyone
- *Immutable*: nothing can be removed once written
- *Paying*: everyone should pay a fee to use

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$$\begin{aligned}
\text{Transparent} &\xrightarrow[\text{Problem}]{} \text{confidentiality} &&\xrightarrow[\text{Solution}]{} ?\\
\text{Immutable} &\xrightarrow[\text{Problem}]{} \text{scalability} &&\xrightarrow[\text{Solution}]{} ?\\
\text{Paying} &\xrightarrow[\text{Problem}]{} \text{cost} &&\xrightarrow[\text{Solution}]{} ?
\end{aligned}$$

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Zero-knowledge proofs (ZKP)

Alice

I know the solution to
this complex equation

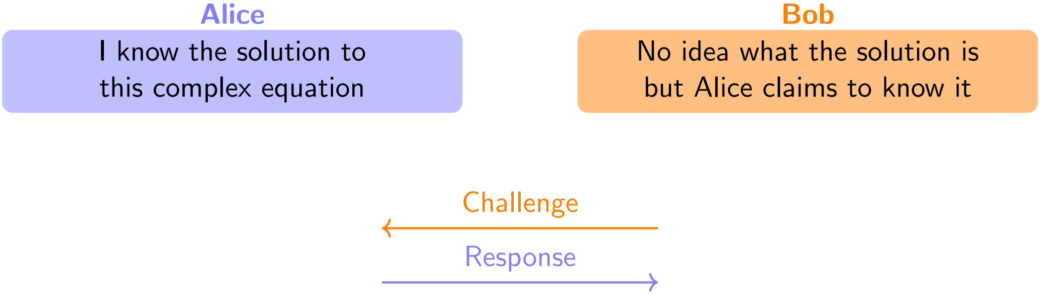
Bob

No idea what the solution is
but Alice claims to know it


Challenge

Response

Zero-knowledge proofs (ZKP)



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- **Sound**: **Alice** has a wrong solution $\implies$ **Bob** is not convinced.

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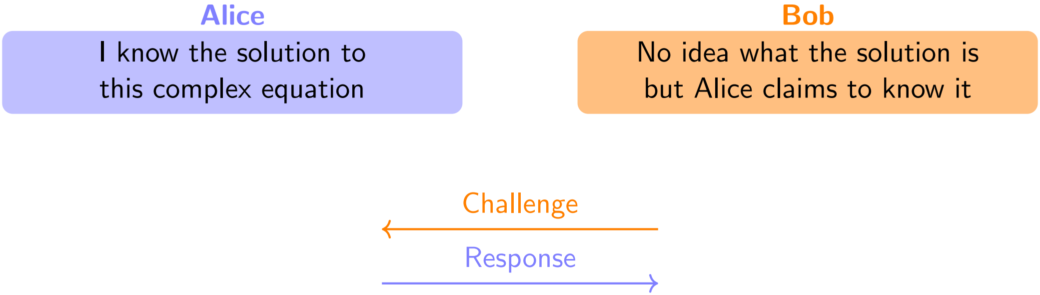

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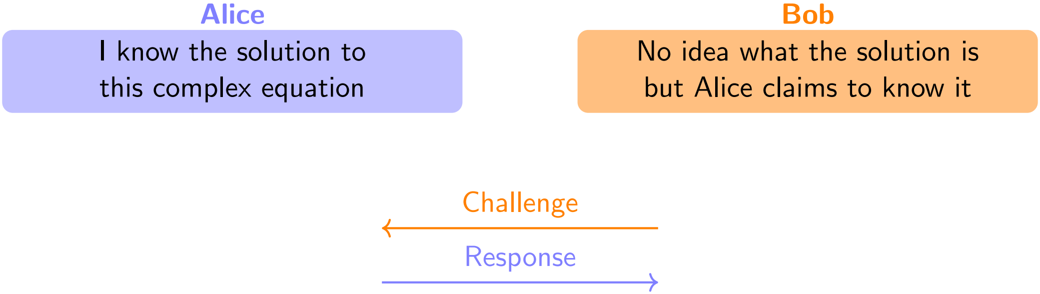

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Response

- **Sound**: **Alice** has a wrong solution $\implies$ **Bob** is not convinced.
- **Complete**: **Alice** has the solution $\implies$ **Bob** is convinced.
- **Zero-knowledge**: **Bob** does NOT learn the solution.

Toy example

?

Example: Sigma protocol

Alice

Bob

I know x such that $g^x = y$

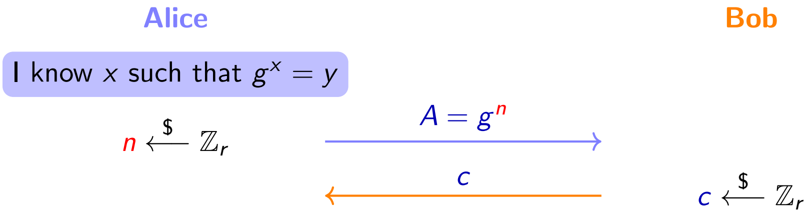
Example: Sigma protocol

Alice **Bob**

I know x such that $g^x = y$

$n \xleftarrow{\$} \mathbb{Z}_r$ $\xrightarrow{A = g^n}$

Example: Sigma protocol



Alice

Bob

I know x such that $g^x = y$

$n \xleftarrow{\$} \mathbb{Z}_r$

$\xrightarrow{A = g^n}$

$\xleftarrow{c}$

$c \xleftarrow{\$} \mathbb{Z}_r$

Example: Sigma protocol

Alice | **Bob**

I know x such that $g^x = y$

$n \xleftarrow{\$} \mathbb{Z}_r$ $\xrightarrow{A = g^n}$

$\xleftarrow{c}$ $c \xleftarrow{\$} \mathbb{Z}_r$

$s = n + c \cdot x$ $\xrightarrow{s}$

Example: Sigma protocol

Alice　　　　　　　　**Bob**

I know x such that $g^x = y$

$n \xleftarrow{\$} \mathbb{Z}_r$　$\xrightarrow{A = g^n}$

$\xleftarrow{c}$　$c \xleftarrow{\$} \mathbb{Z}_r$

$s = n + c \cdot x$　$\xrightarrow{s}$　$g^s \overset{?}{=} A \cdot y^c$

with $A \cdot y^c = g^n \cdot g^{x \cdot c}$

then $g^n \cdot g^{x \cdot c} = g^{n + x \cdot c}$

Non-Interactive Zero-Knowledge (NIZK) Sigma protocol

Alice

Bob

I know x such that $g^x = y$

$$n \xleftarrow{\$} \mathbb{Z}_r$$

$$A = g^n$$

$$c = H(A, y)$$

$$s = n + c \cdot x$$

$$\xrightarrow{\pi = (A, c, s)}$$

$$g^s \stackrel{?}{=} A \cdot y^c$$

$$c \stackrel{?}{=} H(A, y)$$

Non-Interactive Zero-Knowledge (NIZK) Sigma protocol

Alice

Bob

I know x such that $g^x = y$

$$n \xleftarrow{\$} \mathbb{Z}_r$$

$$\underbrace{g}_{\text{Setup}} ; A = g^n$$

$$\underbrace{\begin{array}{c} c = H(A, y) \\ s = n + c \cdot x \end{array}}_{\text{Prove}}$$

$$\underbrace{\pi = (A, c, s)}_{\text{proof}}$$

$$\longrightarrow$$

$$\underbrace{\begin{array}{c} g^s \stackrel{?}{=} A \cdot y^c \\ c \stackrel{?}{=} H(A, y) \end{array}}_{\text{Verify}}$$

ZKP families

Expressivity

- *specific* statement vs. *general* statement

ZKP families

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Deployability

- *interactive* vs. *non − interactive* protocol
- *trapdoored* setup vs. *transparent* setup
- *Designated* verifier vs. *any* verifier

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Complexity

- prover complexity (Alice)
- verifier complexity (Bob)
- communication complexity (size of the proof and the setup)

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Security

- Cryptographic assumptions
- Cryptographic primitives

Blockchains and ZKP

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Transparent $\xrightarrow[\text{Problem}]{}$ confidentiality $\xrightarrow[\text{Solution}]{}$ *ZKP*

setup, prover?, verifier?

Immutable $\xrightarrow[\text{Problem}]{}$ scalability $\xrightarrow[\text{Solution}]{}$ *ZKP*

Communication complexity

Paying $\xrightarrow[\text{Problem}]{}$ cost $\xrightarrow[\text{Solution}]{}$ *ZKP*

Verifier complexity, *prover*?

ZKP literature landmarks

- First ZKP work [GMR85]
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- “SNARK” terminology and characterization of existence [BCCT12]
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- Pairing-based SNARK with shortest proof and verifier time [Gro16]

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- SNARK with universal and updatable setup [GKM$^+$18, MBKM19, GWC19, CHM$^+$20]

What is a zero-knowledge proof?

"I have a *sound*, *complete* and *zero-knowledge* proof that a statement is true" [GMR85].

Sound

False statement $\implies$ cheating prover cannot convince honest verifier.

Complete

True statement $\implies$ honest prover convinces honest verifier.

Zero-knowledge

True statement $\implies$ verifier learns nothing other than statement is true.

zk-SNARK: Zero-Knowledge Succinct Non-interactive ARgument of Knowledge

"I have a *computationally sound*, *complete*, *zero-knowledge*, **succinct**, **non-interactive** proof that a statement is true and that I know a related secret".

Succinct

A proof is very "short" and "easy" to verify.

Non-interactive

No interaction between the prover and verifier for proof generation and verification (except the proof message).

ARgument of Knowledge

Honest verifier is convinced that a computationally bounded prover knows a secret information.

Preprocessing zk-SNARK for NP language

F: public `NP` program, x, z: public inputs, w: private input

$$z := F(x, w)$$

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A zk-SNARK consists of algorithms S, P, V s.t. for a security parameter λ:

$$\mathit{Setup}: \quad (pk, vk) \quad \leftarrow \quad S(F, 1^\lambda)$$

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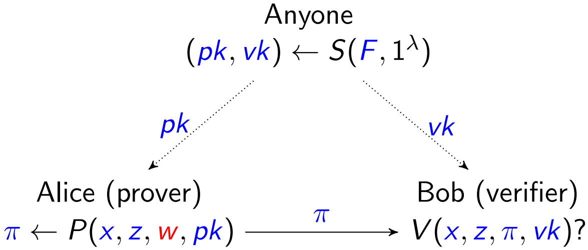

Anyone

$(pk, vk) \leftarrow S(F, 1^\lambda)$

Alice (prover)

$\pi \leftarrow P(x, z, w, pk)$

Bob (verifier)

$V(x, z, \pi, vk)$?

(Trapdoored) preprocessing zk-SNARK for NP language

F: public NP program, x, z: public inputs, w: private input

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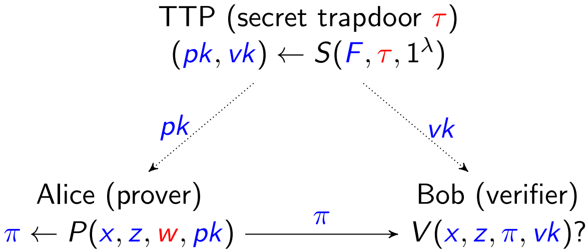
A zk-SNARK consists of algorithms S, P, V s.t. for a security parameter λ:

$$\begin{array}{llll} \textit{Setup}: & (pk, vk) & \leftarrow & S(F, \tau, 1^{\lambda}) \\ \textit{Prove}: & \pi & \leftarrow & P(x, z, w, pk) \\ \textit{Verify}: & \texttt{false/true} & \leftarrow & V(x, z, \pi, vk) \end{array}$$



TTP (secret trapdoor τ)

$(pk, vk) \leftarrow S(F, \tau, 1^{\lambda})$

Alice (prover)

$\pi \leftarrow P(x, z, w, pk)$

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$V(x, z, \pi, vk)$?

(Trapdoored) preprocessing zk-SNARK for NP language

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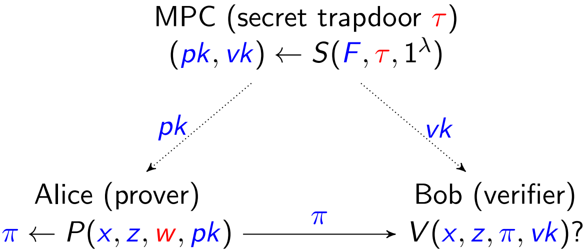
Setup : $(pk, vk) \leftarrow S(F, \tau, 1^\lambda)$

Prove : $\pi \leftarrow P(x, z, w, pk)$

Verify : $\texttt{false/true} \leftarrow V(x, z, \pi, vk)$



MPC (secret trapdoor τ)

$(pk, vk) \leftarrow S(F, \tau, 1^\lambda)$

Alice (prover)

$\pi \leftarrow P(x, z, w, pk)$

Bob (verifier)

$V(x, z, \pi, vk)$?

zk-SNARK

Succinctness: A proof is very "short" and "easy" to verify.

Definition [BCTV14b]

A succinct proof π has size $O_\lambda(1)$ and can be verified in time $O_\lambda(|F| + |x| + |z|)$, where $O_\lambda(.)$ is some polynomial in the security parameter λ.

zk-SNARKs in a nutshell

Main ideas:

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1. Reduce a ”general statement” satisfiability to a polynomial equation satisfiability.

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3. Use homomorphic hiding cryptography to blindly verify the polynomial equation.

zk-SNARKs in a nutshell

Main ideas:

1. Reduce a "general statement" satisfiability to a polynomial equation satisfiability.
2. Use Schwartz-Zippel lemma to succinctly verify the polynomial equation with high probability.
3. Use homomorphic hiding cryptography to blindly verify the polynomial equation.
4. Make the protocol non-interactive.

Arithmetization

Statement → **Arithmetic circuit** → Intermediate representation → Polynomial identities → zk-SNARK proof

$$x^3 + x + 5 = 35 \qquad ({\color{red}x = 3})$$

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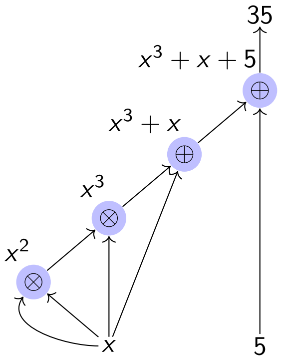

Arithmetization

e.g. R1CS

Statement → Arithmetic circuit → **Intermediate representation** → Polynomial identities → zk-SNARK proof

$$L = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 5 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

$$R = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

$$O = \begin{pmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 & 0 \end{pmatrix}$$

witness:

$$\begin{aligned} \vec{w} &= \begin{pmatrix} \text{one} & x & d & a & b & c \end{pmatrix} \\ &= \begin{pmatrix} 1 & 3 & 35 & 9 & 27 & 30 \end{pmatrix} \end{aligned}$$

$$O \bullet \vec{w} = L \bullet \vec{w} \cdot R \bullet \vec{w}$$

Arithmetization

e.g. Quadratic Arithmetic Program

Statement → Arithmetic circuit → Intermediate representation → **Polynomial identities** → zk-SNARK proof

$$L(X)R(X) - O(X) = H(X)T(X) \qquad (QAP \in \mathbb{F}[X])$$

Arithmetization

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$$L(X)R(X) - O(X) = H(X)T(X) \qquad (QAP \in \mathbb{F}[X])$$

$$L(\tau)R(\tau) - O(\tau) = H(\tau)T(\tau) \qquad (trapdoor\ \tau \xleftarrow{\$} \mathbb{F})$$

Arithmetization

e.g. Quadratic Arithmetic Program

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$$L(X)R(X) - O(X) = H(X)T(X) \qquad (QAP \in \mathbb{F}[X])$$

$$L(\tau)R(\tau) - O(\tau) = H(\tau)T(\tau) \qquad (\textit{trapdoor } \tau \xleftarrow{\$} \mathbb{F})$$

$$C(L(\tau)R(\tau) - O(\tau)) = C(H(\tau)T(\tau)) \qquad (\textit{Homomorphic commitment})$$

Succinct evaluation of polynomials

Instead of verifying the QAP on the whole domain $\mathbb{F}$ → verify it in a single random point $\tau \in \mathbb{F}$.

Schwartz–Zippel lemma

Any two distinct polynomials of degree d over a field $\mathbb{F}$ can agree on at most a $d/|\mathbb{F}|$ fraction of the points in $\mathbb{F}$.

Blind evaluation of polynomials

Statement → Arithmetic circuit → Intermediate representation → Polynomial identities → **zk-SNARK proof**

Let's take the example of polynomial L:

Blind evaluation of polynomials

Statement → Arithmetic circuit → Intermediate representation → Polynomial identities → **zk-SNARK proof**

Let's take the example of polynomial L:

- Alice can send L to Bob and he computes $L(\tau)$ → breaks the zero-knowledge.

Blind evaluation of polynomials

Statement → Arithmetic circuit → Intermediate representation → Polynomial identities → **zk-SNARK proof**

Let's take the example of polynomial L:

- Alice can send L to Bob and he computes $L(\tau)$ → breaks the zero-knowledge.
- Bob can send τ to Alice and she computes $L(\tau)$ → breaks the soundness.

Blind evaluation of polynomials

Statement → Arithmetic circuit → Intermediate representation → Polynomial identities → **zk-SNARK proof**

Let's take the example of polynomial L:

- Alice can send L to Bob and he computes $L(\tau)$ → breaks the zero-knowledge.
- Bob can send τ to Alice and she computes $L(\tau)$ → breaks the soundness.

$\Longrightarrow$ homomorphic cryptography to evaluate $L(X)$ at τ without Bob learning L nor Alice learning τ.

Blind evaluation of polynomials

$$L(\tau) = l_0 + l_1\tau + l_2\tau^2 + \cdots + l_d\tau^d \in \mathbb{F}$$

$$C(L(\tau)) = l_0 C(1) + l_1 C(\tau) + l_2 C(\tau^2) + \cdots + l_d C(\tau^d)$$

Somewhat homomorphic commitment w.r.t.:

- depth-d **additions** (arbitrary d)
- depth-1 **multiplications** (for $L(\tau) \cdot R(\tau)$ and $H(\tau) \cdot T(\tau)$).

Blind evaluation of polynomials

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Blind evaluation of polynomials

Somewhat homomorphic commitment w.r.t.:

- depth-d **additions** (arbitrary d)

$$C(\tau) = \tau G \qquad (DL)$$

$$L(\tau)G = l_0 G + l_1 \tau G + l_2 \tau^2 G + \cdots + l_d \tau^d G$$

Blind evaluation of polynomials

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- depth-d **additions** (arbitrary d)

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$$C(\tau_1) = \tau_1 G;\ C(\tau_2) = \tau_2 G$$
$$C(\tau_1) \cdot C(\tau_2) = C(\tau_1 \cdot \tau_2) \qquad (?)$$

Blind evaluation of polynomials

Somewhat homomorphic commitment w.r.t.:

- depth-d **additions** (arbitrary d)

$$C(\tau) = \tau G \qquad (DL)$$
$$L(\tau)G = l_0 G + l_1 \tau G + l_2 \tau^2 G + \cdots + l_d \tau^d G$$

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$$C(\tau_1) = \tau_1 G;\ C(\tau_2) = \tau_2 G$$
$$C(\tau_1) \cdot C(\tau_2) = C(\tau_1 \cdot \tau_2) \qquad (?)$$
$$\underbrace{e(C(\tau_1), C(\tau_2))}_{\text{product of commitments}} = \underbrace{Z^{\tau_1 \cdot \tau_2}}_{\substack{\text{new commitment to } \tau_1 \cdot \tau_2 \\ \text{(where } Z = e(G,G) \neq 1)}} \qquad \text{(bilinear pairing)}$$

Blind evaluation of QAP

Blind evaluation can be achieved with *black-box* pairings:

$$
\begin{aligned}
e(C(H(\tau)), C(T(\tau)) \cdot e(C(O(\tau)), C(1)) &= e(C(L(\tau)), C(R(\tau))) \\
e(H(\tau)G, T(\tau)G) \cdot e(O(\tau)G, G) &= e(L(\tau)G, R(\tau)G) \\
e(G, G)^{H(\tau)T(\tau)} \cdot e(G, G)^{O(\tau)} &= e(G, G)^{L(\tau)R(\tau)} \\
Z^{H(\tau)T(\tau)+O(\tau)} &= Z^{L(\tau)R(\tau)}
\end{aligned}
$$

Somewhat homomorphic commitment

Elliptic curves (DL):

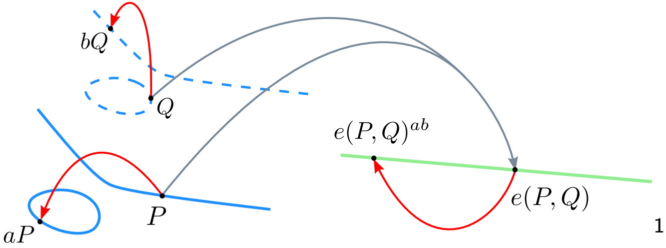
- $E\colon y^2 = x^3 + ax + b$ elliptic curve defined over $\mathbb{F}_q$, q a prime power.
- r prime divisor of $\#E(\mathbb{F}_q) = q + 1 - t$, t Frobenius trace.

A non-degenerate bilinear pairing $e : \mathbb{G}_1 \times \mathbb{G}_2 \to \mathbb{G}_T$

non-degenerate: $\forall P \in \mathbb{G}_1,\ P \neq \mathcal{O},\ \exists Q \in \mathbb{G}_2, e(P, Q) \neq 1_{\mathbb{G}_T}$

$\forall Q \in \mathbb{G}_2,\ Q \neq \mathcal{O},\ \exists P \in \mathbb{G}_1, e(P, Q) \neq 1_{\mathbb{G}_T}$

bilinear: $e([a]P, [b]Q) = e(P, [b]Q)^a = e([a]P, Q)^b = e(P, Q)^{ab}$



A pairing-based SNARK

Example: Groth16 [Gro16]

Given an instance $\Phi = (a_0, \ldots, a_\ell) \in \mathbb{F}_r^\ell$ of a public `NP` program F

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- Setup: $(pk, vk) \leftarrow S(F, \tau, 1^\lambda)$ where

$$vk = (vk_{\alpha,\beta}, \{vk_{\pi_i}\}_{i=0}^{\ell}, vk_\gamma, vk_\delta) \in \mathbb{G}_T \times \mathbb{G}_1^{\ell+1} \times \mathbb{G}_2 \times \mathbb{G}_2$$

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- Prove: $\pi \leftarrow P(\Phi, w, pk)$ where

$$\pi = (A, B, C) \in \mathbb{G}_1 \times \mathbb{G}_2 \times \mathbb{G}_1 \qquad (O_\lambda(1))$$

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- Verify: $0/1 \leftarrow V(\Phi, \pi, vk)$ where V is

$$e(A, B) = vk_{\alpha,\beta} \cdot e(vk_x, vk_\gamma) \cdot e(C, vk_\delta) \qquad (O_\lambda(|\Phi|)) \tag{1}$$

  and $vk_x = \sum_{i=0}^{\ell} [a_i] vk_{\pi_i}$ depends only on the instance Φ and $vk_{\alpha,\beta} = e(vk_\alpha, vk_\beta)$ can be computed in the trusted setup for $(vk_\alpha, vk_\beta) \in \mathbb{G}_1 \times \mathbb{G}_2$.

Overview

1. Motivation
2. Blockchain
3. Zero-knowledge proofs
4. Applications
5. Research

Applications

- Privacy: Monero, zcash, Aleo... or Tornado cash...
- Scalability: Mina... or Linea, Aztec...

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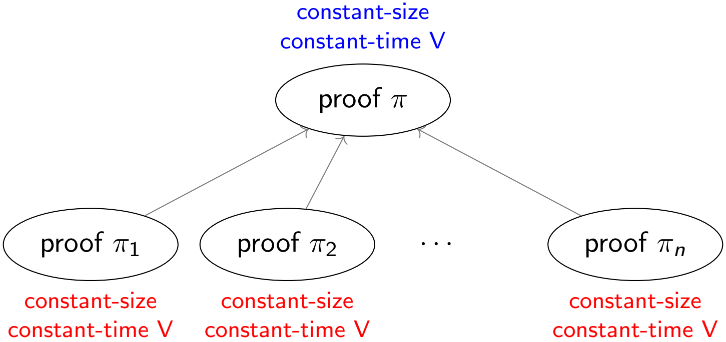
Proof composition: why?

Aggregation:



constant-size

constant-time V

proof π

proof π_1

proof π_2

$\cdots$

proof π_n

constant-size

constant-time V

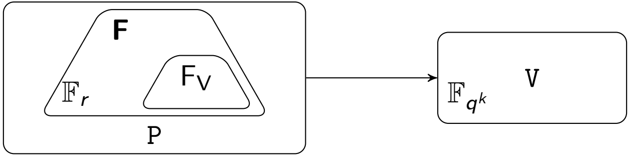
constant-size

constant-time V

constant-size

constant-time V

Proof composition: how?



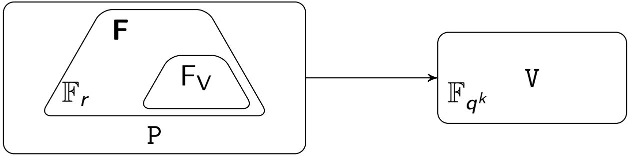
F any program is expressed in $\mathbb{F}_r$

`P` proving is performed over $\mathbb{G}_1$ (and $\mathbb{G}_2$) (of order r)

`V` verification (eq. 1) is done in $\mathbb{F}^*_{q^k}$

F_V program of `V` is natively expressed in $\mathbb{F}^*_{q^k}$ not $\mathbb{F}_r$

Proof composition: how?



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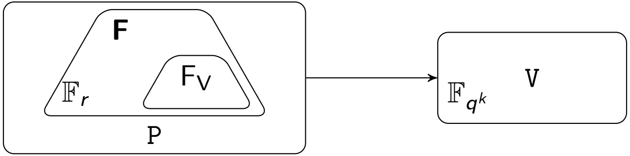

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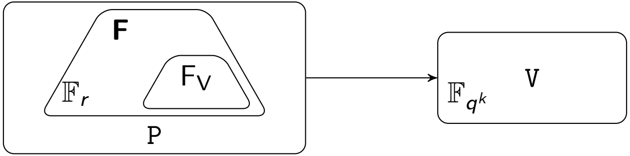

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- 1st attempt: choose a curve for which $q = r$ (impossible)
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- 3rd attempt: use a cycle/chain of pairing-friendly elliptic curves [CFH+15, BCTV14a, BCG+20, EG20, EG22, AEG23]

2-cycles and 2-chains

A 2-cycle of elliptic curves:

$$\begin{tikzcd}
\boxed{E_1(\mathbb{F}_q)} \arrow[d, bend left=60, "\#E_0(\mathbb{F}_p) = q"] \\
\boxed{E_0(\mathbb{F}_p)} \arrow[u, bend left=60, "\#E_1(\mathbb{F}_q) = p"]
\end{tikzcd}$$

A 2-chain of elliptic curves:

$$\begin{tikzcd}
\boxed{E_1(\mathbb{F}_q)} \\
\boxed{E_0(\mathbb{F}_p)} \arrow[u, "\#E_1(\mathbb{F}_q) = h \cdot p"']
\end{tikzcd}$$

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- Blockchain limitations: confidentiality and scalability
- pairing-based zk-SNARKs are a solution (constant-size proof and fast verification)

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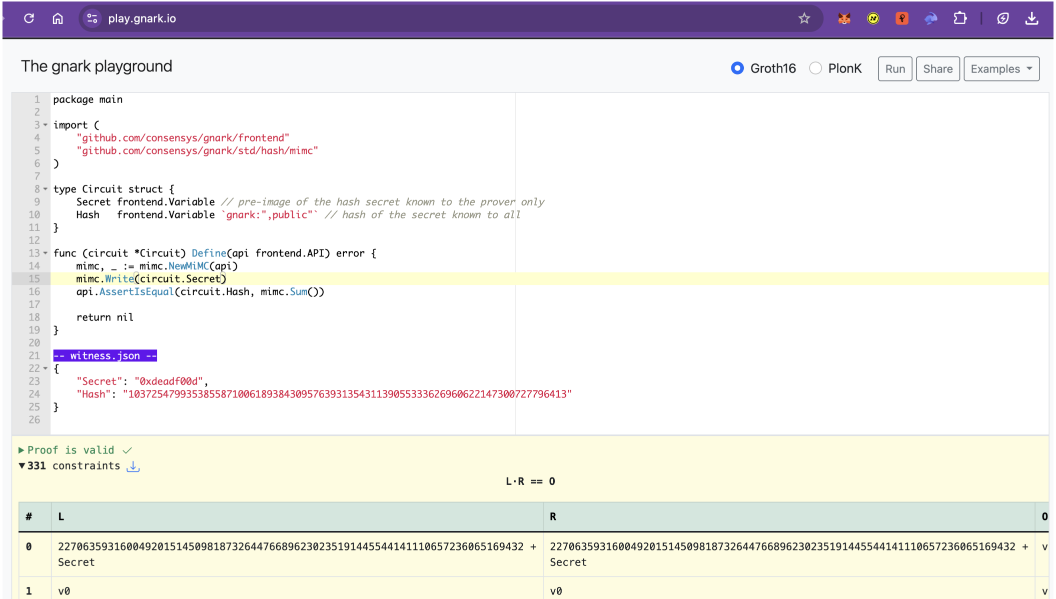
- Implementations: **gnark, linea, arkworks, sonobe, ...**

gnark playground



```
package main

import (
    "github.com/consensys/gnark/frontend"
    "github.com/consensys/gnark/std/hash/mimc"
)

type Circuit struct {
    Secret frontend.Variable // pre-image of the hash secret known to the prover only
    Hash   frontend.Variable `gnark:",public"` // hash of the secret known to all
}

func (circuit *Circuit) Define(api frontend.API) error {
    mimc, _ := mimc.NewMiMC(api)
    mimc.Write(circuit.Secret)
    api.AssertIsEqual(circuit.Hash, mimc.Sum())

    return nil
}

-- witness.json --
{
    "Secret": "0xdeadf00d",
    "Hash": "1037254799353855871006189384309576393135431139055333626960622147300727796413"
}
```

```
▶ Proof is valid ✓
▼331 constraints
```

L·R == 0

#	L	R	O
0	227063593160049201514509818732644766896230235191445544141110657236065169432 + Secret	227063593160049201514509818732644766896230235191445544141110657236065169432 + Secret	v
1	v0	v0	v

Thank you

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- email: `youssef.elhousni@consensys.net`
- telegram: `@ElMarroqui`
- x: `@YoussefElHoun3`
- github: `@yelhousni`

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