Pairing-Based SNARKs. Pinocchio And Groth16

October 22, 2024

Distributed Lab

zkdl-camp.github.io

github.com/ZKDL-Camp

Plan

Recap

Recap. R1CS

Each **constraint** in the Rank-1 Constraint System must be in the form:

$$\langle \boldsymbol{a}, \boldsymbol{w} \rangle \times \langle \boldsymbol{b}, \boldsymbol{w} \rangle = \langle \boldsymbol{c}, \boldsymbol{w} \rangle$$

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Where $\langle \boldsymbol{u}, \boldsymbol{v} \rangle$ is a dot product.

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Thus

$$\left(\sum_{i=1}^{n} a_i w_i \right) \times \left(\sum_{j=1}^{n} b_j w_j \right) = \sum_{k=1}^{n} c_k w_k$$

That is, actually, a quadratic equation with multiple variables.

Recap. R1CS

Consider the simplest program:

```
def example(a: F, b: F, c: F) -> F:
    if a:
        return b * c
    else:
        return b + c
```

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$$x_2 \times x_3 = \text{mult} \tag{2}$$

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The witness vector: $\boldsymbol{w} = (1, r, x_1, x_2, x_3, \text{mult}, \text{selectMult})$.

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The coefficients vectors:

$$\begin{aligned}
\boldsymbol{a}_1 &= (0,0,1,0,0,0,0), & \boldsymbol{b}_1 &= (0,0,1,0,0,0,0), & \boldsymbol{c}_1 &= (0,0,1,0,0,0,0) \\
\boldsymbol{a}_2 &= (0,0,0,1,0,0,0), & \boldsymbol{b}_2 &= (0,0,0,0,1,0,0), & \boldsymbol{c}_2 &= (0,0,0,0,0,1,0) \\
\boldsymbol{a}_3 &= (0,0,1,0,0,0,0), & \boldsymbol{b}_3 &= (0,0,0,0,0,1,0), & \boldsymbol{c}_3 &= (0,0,0,0,0,0,1) \\
\boldsymbol{a}_4 &= (1,0,-1,0,0,0,0), & \boldsymbol{b}_4 &= (0,0,0,1,1,0,0), & \boldsymbol{c}_4 &= (0,1,0,0,0,0,-1)
\end{aligned}$$

Recap. QAP

R1CS provides us with the following constraint vectors:

$$\boldsymbol{a}_1, \boldsymbol{a}_2, \dots, \boldsymbol{a}_m, \quad \boldsymbol{b}_1, \boldsymbol{b}_2, \dots, \boldsymbol{b}_m, \quad \boldsymbol{c}_1, \boldsymbol{c}_2, \dots, \boldsymbol{c}_m,$$

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Of course, they form corresponding matrices:

$$A = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \dots & a_{mn} \end{bmatrix}, \text{ same goes for } B \text{ and } C$$

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An example of a single “if“ statement:

$$\begin{aligned} \boldsymbol{a}_1 &= (0, 0, 1, 0, 0, 0, 0) \\ \boldsymbol{a}_2 &= (0, 0, 0, 1, 0, 0, 0) \\ \boldsymbol{a}_3 &= (0, 0, 1, 0, 0, 0, 0) \\ \boldsymbol{a}_4 &= (1, 0, -1, 0, 0, 0, 0) \end{aligned}$$

$$\begin{array}{cc} & \begin{array}{ccccccc} & & 3 & & & & \end{array} \\ \begin{array}{c} \\ \\ \\ 4 \end{array} & \left[\begin{array}{ccccccc} 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & \boxed{-1} & 0 & 0 & 0 & 0 \end{array}\right] \end{array}$$

Recap. QAP

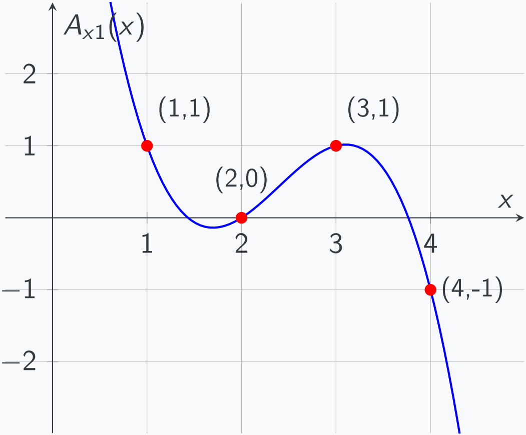

Illustration: The Lagrange inteprolation polynomial for points $\{(1,1),(2,0),(3,1),(4,-1)\}$ visualized over $\mathbb{R}$.

Recap. QAP

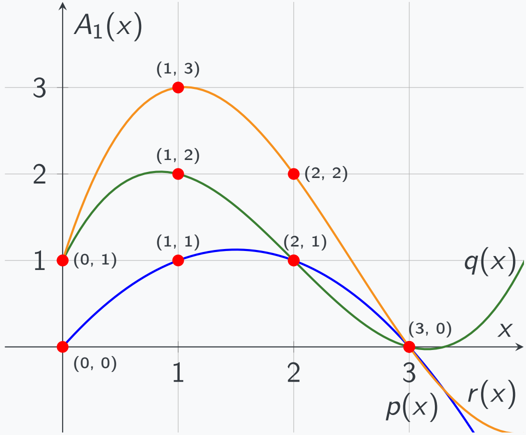

Figure: Addition of two polynomials

Now, using coefficients encoded with polynomials, we can build a constraint number $x \in \{1, \ldots, m\}$ in the next way:

$$
\begin{aligned}
&(w_1 A_1(x) + w_2 A_2(x) + \cdots + w_n A_n(x)) \times \\
\times &(w_1 B_1(x) + w_2 B_2(x) + \cdots + w_n B_n(x)) = \\
= &(w_1 C_1(x) + w_2 C_2(x) + \cdots + w_n C_n(x))
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\end{aligned}
$$

Or written more concisely:

$$
\left(\sum_{i=1}^{n} w_i A_i(x)\right) \times \left(\sum_{i=1}^{n} w_i B_i(x)\right) = \left(\sum_{i=1}^{n} w_i C_i(x)\right)
$$

$$
A(x) \times B(x) = C(x)
$$

Recap. QAP

Now, we can define a **master polynomial** $M(x)$, that has zeros at all elements from the set $\Omega = \{1, \ldots, m\}$

$$M(x) = A(x) \times B(x) - C(x)$$

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It means, that $M(x)$ can be divided by **vanishing polynomial** $Z_\Omega(x)$ without a remainder!

$$Z_\Omega(x) = \prod_{i=1}^{m}(x - i), \qquad H(x) = \frac{M(x)}{Z_\Omega(x)} \text{ is a polynomial}$$

Encrypted Verification

Current Point

We've managed to encode into **a single polynomial** an entire computation (a program), of any size, independent of how much data it consumes.

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Where the knowledge of the correct witness is a knowledge of the quotient polynomial $H(x)$.

$$M(x) = H(x) \times Z_{\Omega}(x)$$

Remark

Further, for brevity, we will denote $Z_{\Omega}(x)$ as $Z(x)$.

Notation Preliminaries: Groups

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- ✓ Group of points on elliptic curve denoted as $\mathbb{G}$ of prime order q with a generator g.
- ✓ The symmetric pairing function $e : \mathbb{G} \times \mathbb{G} \to \mathbb{G}_T$, where $(\mathbb{G}_T, \times)$ is a target group (typically, just a scalar from extension $\mathbb{F}_{p^k}$).

Recall

The core property of the pairing function e is the **bilinearity**:

$$e(g^\alpha, g^\beta) = e(g^{\alpha\beta}, g) = e(g, g^{\alpha\beta}) = e(g, g)^{\alpha\beta}.$$

Here, g^α is the same as "scalar multiplication of a generator by a scalar $\alpha \in \mathbb{Z}_q$".

Notation Preliminaries: QAP

Recall that the core equation to be proven:

$$\left(\sum_{i=1}^{n} w_i A_i(x)\right) \times \left(\sum_{i=1}^{n} w_i B_i(x)\right) - \left(\sum_{i=1}^{n} w_i C_i(x)\right) = Z(x)H(x)$$

Here, we will change notation a bit: instead of A and B, we are going to use L and R, while C becomes O.

So equation becomes:

$$\underbrace{\left(\sum_{i=1}^{n} w_i L_i(x)\right)}_{\text{left wires encoding}} \times \underbrace{\left(\sum_{i=1}^{n} w_i R_i(x)\right)}_{\text{right wires encoding}} - \underbrace{\left(\sum_{i=1}^{n} w_i O_i(x)\right)}_{\text{output encodings}} = Z(x)H(x)$$

Naive Proof

Suppose, we are given a circuit $\mathcal{C}$ with a maximum degree d of polynomials used underneath.

Thus, all parties additionally know the target polynomial $Z(x)$ and QAP polynomials $\{L_i(x)\}_{i\in[n]}, \{R_i(x)\}_{i\in[n]}, \{O_i(x)\}_{i\in[n]}$, where n is number of witness elements.

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Prover

✓ Provides witness $\boldsymbol{w}$ to a Verifier.

Verifier

✓ Checks $(\sum_{i=1}^{n} w_i L_i(x)) \times (\sum_{i=1}^{n} w_i R_i(x)) = (\sum_{i=1}^{n} w_i O_i(x))$

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We, definitely, need to encrypt the witness data $\boldsymbol{w}$ somehow...

Let's define the *encryption* operation as follows:

$$\mathsf{Enc} : \mathbb{Z}_q \to \mathbb{G}, \quad \mathsf{Enc}(x) := g^x$$

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Essentially, $\mathsf{Enc}(p(\tau))$ is the **KZG Commitment** $\mathsf{com}(p)$.

Example

Consider the polynomial: $p(x) = x^2 - 5x + 2$, the encryption of $p(\tau)$ can be found as follows:

$$\mathsf{Enc}(p(\tau)) = g^{p(\tau)} = g^{\left(\tau^2 - 5\tau + 2\right)} = \left(g^{\tau^2}\right)^1 \cdot \left(g^{\tau^1}\right)^{-5} \cdot \left(g^{\tau^0}\right)^2$$

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Question

KZG Commitment requires encrypted powers of τ: $\{g^{\tau^i}\}_{i \in [d]}$. But where the prover can take them?

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This way, we can find the KZG commitment for each polynomial. For example:

$$\mathsf{com}(L) \triangleq g^{L(\tau)} = g^{\sum_{i=0}^{d} L_i\tau^i} = \prod_{i=0}^{d}(g^{\tau^i})^{L_i},$$

Now, we can calculate the following KZG commitments (or, synonymously, encryptions):

$$g^{L(\tau)}, g^{R(\tau)}, g^{O(\tau)}, g^{H(\tau)}, g^{Z(\tau)}$$

But how can we verify $H(x)Z(x) = L(x)R(x) - O(x)$ in the encrypted space?

Well, first notice that, according to the **Schwarz-Zippel Lemma**, *with overwhelming probability* the check is equivalent to:

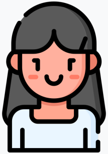
$$L(\tau)R(\tau) = Z(\tau)H(\tau) + O(\tau).$$

So, we can check this equality as follows:

$$e(\mathrm{com}(L), \mathrm{com}(R)) = e(\mathrm{com}(Z), \mathrm{com}(H)) \cdot e(\mathrm{com}(O), g),$$

Trusted Setup: $\tau \xleftarrow{R} \mathbb{F}$, $\{g^{\tau^i}\}_{i\in[d]}$, $g^{Z(\tau)}$, $\textbf{delete}(\tau)$.

Prover $\mathcal{P}$

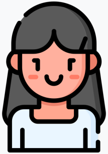


Verifier $\mathcal{V}$

Trusted Setup: $\tau \xleftarrow{R} \mathbb{F}$, $\{g^{\tau^i}\}_{i\in[d]}$, $g^{Z(\tau)}$, **delete**(τ).

✓ $H(x) = \frac{L(x)\times R(x) - O(x)}{Z(x)}$.

Prover $\mathcal{P}$



Verifier $\mathcal{V}$

Trusted Setup: $\tau \xleftarrow{R} \mathbb{F}$, $\{g^{\tau^i}\}_{i\in[d]}$, $g^{Z(\tau)}$, **delete**(τ).

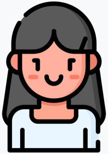
✓ $H(x) = \frac{L(x)\times R(x) - O(x)}{Z(x)}$.

✓ KZG commitments:

$\pi_L \leftarrow \text{com}(L)$, $\pi_R \leftarrow \text{com}(R)$,

$\pi_O \leftarrow \text{com}(O)$, $\pi_H \leftarrow \text{com}(H)$,

Prover $\mathcal{P}$



Verifier $\mathcal{V}$

Trusted Setup: $\tau \xleftarrow{R} \mathbb{F}$, $\{g^{\tau^i}\}_{i\in[d]}$, $g^{Z(\tau)}$, **delete**(τ).

✓ $H(x) = \frac{L(x)\times R(x) - O(x)}{Z(x)}$.

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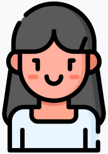
Prover $\mathcal{P}$

$\boldsymbol{\pi} = (\pi_L, \pi_R, \pi_O, \pi_H)$



Verifier $\mathcal{V}$

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✓ $H(x) = \frac{L(x)\times R(x) - O(x)}{Z(x)}$.

✓ KZG commitments:

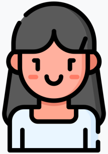
$\pi_L \leftarrow \mathrm{com}(L)$, $\pi_R \leftarrow \mathrm{com}(R)$,

$\pi_O \leftarrow \mathrm{com}(O)$, $\pi_H \leftarrow \mathrm{com}(H)$,

✓ $e(\pi_L, \pi_R) \stackrel{?}{=} e(\mathrm{com}(Z), \pi_H) \cdot e(\pi_O, g)$.

Prover $\mathcal{P}$

$$\boldsymbol{\pi} = (\pi_L, \pi_R, \pi_O, \pi_H) \longrightarrow$$



Verifier $\mathcal{V}$

✓ Succint

✓ Non-Interactive

✓ Zero-Knowledge

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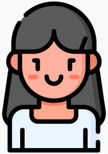
- ✗ Does it work?

Why it doesn't work??

Trusted Setup: $\tau \xleftarrow{R} \mathbb{F}, \quad \{g^{\tau^i}\}_{i \in [d]}, \quad g^{Z(\tau)}$, **delete**$(\tau)$.

Prover $\mathcal{P}$



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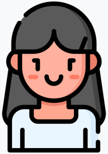

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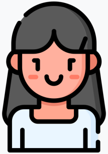
Prover isn't forced to use the values from the trusted setup.

Why it doesn't work??

Trusted Setup: $\tau \xleftarrow{R} \mathbb{F}$, $\{g^{\tau^i}\}_{i\in[d]}$, $g^{Z(\tau)}$, **delete**(τ).

✓ $H'(x) \xleftarrow{R} \mathbb{F}[x]$, $M'(x) = Z(x) \times H'(x)$.

Prover $\mathcal{P}$



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- ✓ $H'(x) \xleftarrow{R} \mathbb{F}[x]$, $M'(x) = Z(x) \times H'(x)$.
- ✓ Finds $L'(x), R'(x), O'(x)$ such that:
  $L'(x) \times R'(x) - O'(x) = M'(x)$

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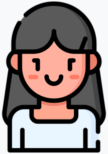

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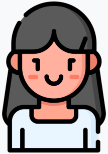
Prover $\mathcal{P}$



Verifier $\mathcal{V}$

Problem

Prover isn't forced to use the values from the trusted setup.

Why it doesn't work??

Trusted Setup: $\tau \xleftarrow{R} \mathbb{F}$, $\{g^{\tau^i}\}_{i\in[d]}$, $g^{Z(\tau)}$, **delete**(τ).

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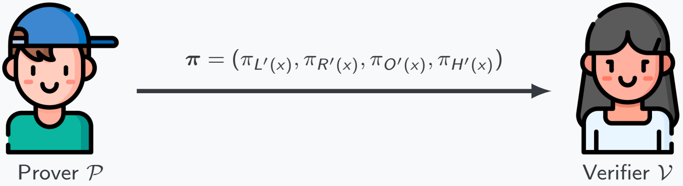

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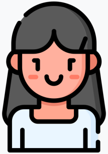
✓ $e(\pi_{L'(x)}, \pi_{R'(x)}) \stackrel{?}{=}$
$e(\text{com}(Z), \pi_H) \cdot e(\pi_{O'(x)}, g)$.

Prover $\mathcal{P}$

$\boldsymbol{\pi} = (\pi_{L'(x)}, \pi_{R'(x)}, \pi_{O'(x)}, \pi_{H'(x)})$



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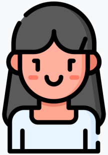

Verifier $\mathcal{V}$

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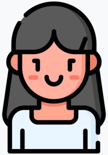

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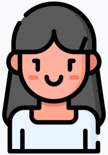

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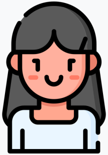
Prover $\mathcal{P}$

$$\boldsymbol{\pi} = (\pi_L, \pi_R, \pi_O, \pi_H, \pi'_L, \pi'_R, \pi'_O, \pi'_H) \longrightarrow$$



Verifier $\mathcal{V}$

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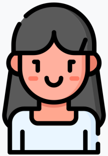

Verifier $\mathcal{V}$

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- ✓ Proof of Exponent:

$$\begin{aligned} e(\pi_L, g^{\alpha}) &= e(\pi'_L, g), \\ e(\pi_R, g^{\alpha}) &= e(\pi'_R, g), \\ e(\pi_O, g^{\alpha}) &= e(\pi'_O, g), \\ e(\pi_H, g^{\alpha}) &= e(\pi'_H, g). \end{aligned}$$

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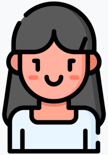

Verifier $\mathcal{V}$

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- ✓ Succint
- ✓ Non-Interactive
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There is no guarantee that the same witness w was used to calculate all the commitments $\pi_L, \pi_R, \pi_O, \pi_H$.

Make It Sound

Additional Optimization

Recal that:

$$L(x) = \sum_{i=0}^{n} w_i L_i(x), \quad R(x) = \sum_{i=0}^{n} w_i R_i(x), \quad O(x) = \sum_{i=0}^{n} w_i O_i(x).$$

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Moreover, it's defined only by the circuit and trusted setup, thus, it can calculated before proof generation as a part of the trusted setup.

Additional Optimization

Updated Trusted Setup:

$$\{g^{\tau^i}\}_{i\in[d]}, \quad \{g^{\alpha\tau^i}\}_{i\in[d]},$$
$$\{g^{L_i(\tau)}\}_{i\in[n]}, \quad \{g^{\alpha L_i(\tau)}\}_{i\in[n]},$$
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Consider the polynomial $L(x) = \sum_{i=0}^{n} w_i L_i(x)$.

$\mathcal{P}$ can compute the KZG commitment π_L and its PoE π'_L as follows:

$$\pi_L \triangleq g^{L(\tau)} = g^{\sum_{i=0}^{n} w_i L_i(\tau)} = \prod_{i=0}^{n} (g^{L_i(\tau)})^{w_i},$$

$$\pi'_L \triangleq g^{\alpha L(\tau)} = g^{\alpha \sum_{i=0}^{n} w_i L_i(\tau)} = \prod_{i=0}^{n} (g^{\alpha L_i(\tau)})^{w_i}.$$

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And we already know how to do that — POE!

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And easy check for verifier:

$$e(\pi_L \pi_R \pi_O, g^{\beta}) = e(\pi_\beta, g).$$

One more time... that doesn't work

If the witness is consistent, the following condition must hold:

$$(w_{L,i}L_i(\tau)+w_{R,i}R_i(\tau)+w_{O,i}O_i(\tau))\beta = w_i\beta(L_i(\tau)+R_i(\tau)+O_i(\tau)) \quad \forall i \in [n]$$

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But, what if $L_i \equiv R_i$. Let's call them q, thus:

$$(w_{L,i} + w_{R,i})q + w_{O,i}O_i(\tau) = w_{\beta,i}(2q + O_i(\tau)) \quad \forall i \in [n]$$

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The adversary can choose $w_{L,i}$, $w_{R,i}$ and $w_{O,i}$ such that:

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Example

$$w = w_O = 5, \quad w_L = 7, \quad w_R = 3$$

$$(7+3)q + 5O(\tau) = 5(2q + O(\tau))$$

$$10q + 5O(\tau) = 10q + 5O(\tau)$$

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So, finally, the trusted setup is updated with:

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Verification:

$$e(\pi_L, g^{\beta_L}) \cdot e(\pi_R, g^{\beta_R}) \cdot e(\pi_O, g^{\beta_O}) = e(\pi_\beta, g)$$

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As the adversary has an access to the public g^{β_L}, g^{β_R}, g^{β_O} he still can cheat verifier by calculating modified π_β.

Example

Consider a constraint $w_1 \times w_1 = w_2$. Let's try to assign 2 and 5 for w_1 in a single constraint. As $2 \times 5 = 10$, the w_2 should contains value 10.

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$$L(x) = 2L_1(x) + 10L_2(x)$$
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Compute π_β as:

$$(g^{(\beta_L \mathbf{L_1}(\tau) + \beta_R \mathbf{R_1}(\tau) + \beta_O \mathbf{O_1}(\tau))})^2 \cdot (g^{\beta_R})^3 \cdot (g^{(\beta_L \mathbf{L_2}(\tau) + \beta_R \mathbf{R_2}(\tau) + \beta_O \mathbf{O_2}(\tau))})^{10}$$

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Proving process isn't changed, unlike verification:

$$e(\pi_L, g^{\beta_L\gamma}) \cdot e(\pi_R, g^{\beta_R\gamma}) \cdot e(\pi_O, g^{\beta_O\gamma}) = e(\pi_\beta, g^{\gamma})$$

That makes it unfeasible to cheat.

Sound SNARK Protocol

Trusted Setup:

$\tau, \alpha, \beta_L, \beta_R, \beta_O, \gamma \xleftarrow{R} \mathbb{F}$, $\{\{g^{\tau^i}, g^{\alpha\tau^i}\}_{i\in[d]}$, $\{g^{(\beta_L L_i(\tau)+\beta_R R_i(\tau)+\beta_O O_i(\tau))}\}_{i\in[n]}\}$,
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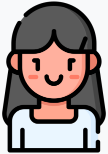
Prover $\mathcal{P}$



Verifier $\mathcal{V}$

Sound SNARK Protocol

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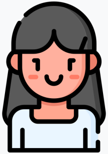

Verifier $\mathcal{V}$

Sound SNARK Protocol

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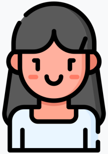
$$\begin{aligned} \pi_L &\leftarrow g^{L(\tau)}, & \pi'_L &\leftarrow g^{\alpha L(\tau)}, \\ \pi_R &\leftarrow g^{R(\tau)}, & \pi'_R &\leftarrow g^{\alpha R(\tau)}, \\ \pi_O &\leftarrow g^{O(\tau)}, & \pi'_O &\leftarrow g^{\alpha O(\tau)}, \\ \pi_H &\leftarrow g^{H(\tau)}, & \pi'_H &\leftarrow g^{\alpha H(\tau)}. \end{aligned}$$

Prover $\mathcal{P}$



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Sound SNARK Protocol

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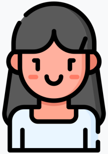

Verifier $\mathcal{V}$

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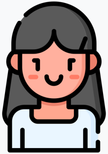
Prover $\mathcal{P}$

$$\boldsymbol{\pi} = (\pi_L, \pi_R, \pi_O, \pi_H, \pi'_L, \pi'_R, \pi'_O, \pi'_H, \pi_\beta) \longrightarrow$$



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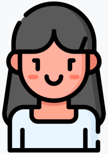

Prover $\mathcal{P}$

Verifier $\mathcal{V}$

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$$\begin{aligned} e(\pi_L, g^{\alpha}) &= e(\pi'_L, g), \\ e(\pi_R, g^{\alpha}) &= e(\pi'_R, g), \\ e(\pi_O, g^{\alpha}) &= e(\pi'_O, g), \\ e(\pi_H, g^{\alpha}) &= e(\pi'_H, g). \end{aligned}$$

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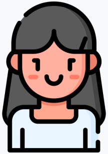

Prover $\mathcal{P}$ Verifier $\mathcal{V}$

Sound SNARK Protocol

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\end{aligned}$$

- ✓ $e(\pi_L, g^{\gamma\beta_L}) \cdot e(\pi_R, g^{\gamma\beta_R}) \cdot$
  $\cdot\, e(\pi_O, g^{\gamma\beta_O}) = e(\pi_\beta, g^{\gamma})$

Prover $\mathcal{P}$

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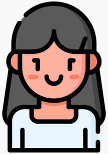

Verifier $\mathcal{V}$

Make it Zero-Knowledge

Why we need modifications?

Question

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$$\pi_L \stackrel{?}{=} \pi_R^{10}.$$

This works since $\pi_L = g^{L(\tau)}$ and $\pi_R = g^{R(\tau)}$, so

$$\pi_L = \pi_R^{10} \Leftrightarrow g^{L(\tau)} = g^{10R(\tau)} \Leftrightarrow L(\tau) = 10R(\tau) \Leftrightarrow L(x) = 10R(x)$$

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- Therefore, the prover must add some "noise" to the proof, so that the verifier can't use the proof to extract any information about the witness. The randomness of prover is kept secret.
- Simultaneously, this noise would still make the same proof checkable by already defined verification equations.

Question

So how to we represent such "noise" with preserving "homomorphic" properties of the proof?

How do we fix that? Doing stuff

Idea #1

Let prover pick random values $\delta_R, \delta_O, \delta_L, \delta_H \xleftarrow{R} \mathbb{F}$ and calculate the "distorted" values:

$$\pi_L \leftarrow g^{L(\tau)+\delta_L}, \quad \pi_R \leftarrow g^{R(\tau)+\delta_R}, \quad \text{same for } \pi_O, \pi_H$$

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Problem (informally): To make previous verification mechanism work, δ_H must be picked "carefully". However, it's impossible to do so with this construction.

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Idea #2

Let prover pick random values $\delta_R, \delta_O, \delta_L \xleftarrow{R} \mathbb{F}$ and calculate:

$$\pi_L \leftarrow g^{L(\tau)+\delta_L Z(\tau)}, \quad \pi_R \leftarrow g^{R(\tau)+\delta_R Z(\tau)}, \quad \pi_O \leftarrow g^{O(\tau)+\delta_O Z(\tau)}$$

Making Idea Practical

This expression can be easily evaluated. For example,

$$\pi_L = g^{L(\tau)} \cdot \left(g^{Z(\tau)}\right)^{\delta_L} = \mathrm{com}(L) \cdot \mathrm{com}(Z)^{\delta_L}$$

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Idea #3

Our "noise" must be controlled! This can be achieved by calculating π_H as $g^{H(\tau)+\Delta_H}$ where Δ_H depends on $\delta_L, \delta_R, \delta_O$ (and possibly other public parameters).

Making Idea Practical

Check $e(\pi_L, \pi_R) = e(\mathrm{com}(Z), \pi_H) \cdot e(\pi_O, g)$ is now equivalent to:

$$(L(x)+\delta_L Z(x))(R(x)+\delta_R Z(x)) = (H(x)+\Delta_H)Z(x)+(O(x)+\delta_O Z(x)),$$

Making Idea Practical

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which, by expanding, gives us the following equation:

$$\begin{aligned} \cancel{L(x)R(x)} + \delta_R L(x)Z(x) + \delta_L Z(x)R(x) + \delta_L\delta_R Z(x)^2 \\ = \cancel{H(x)Z(x) + O(x)} + \Delta_H Z(x) + \delta_O Z(x) \end{aligned}$$

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where we can cancel out $L(x)R(x)$ and $H(x)Z(x) + O(x)$ terms since they are equal based on initial construction. This way, we get the following expression for Δ_H:

$$\boxed{\Delta_H = \delta_O + \delta_R L(x) + \delta_L R(x) + \delta_L\delta_R Z(x)}$$

Witness consistency proof

Finally, let us not forget about π_β! Previously, we had:

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Therefore, our new π_β becomes:

$$\pi_\beta = \left(g^{\beta_L Z(\tau)}\right)^{\delta_L} \left(g^{\beta_R Z(\tau)}\right)^{\delta_R} \left(g^{\beta_O Z(\tau)}\right)^{\delta_O} g^{\beta_L L(\tau) + \beta_R R(\tau) + \beta_O O(\tau)}$$

Overall protocol

Trusted Setup:

$\tau, \alpha, \beta_L, \beta_R, \beta_O, \gamma \xleftarrow{R} \mathbb{F}$, $\{\{g^{\tau^i}, g^{\alpha\tau^i}\}_{i\in[d]}$, $\{g^{\beta_L L_i(\tau)}, g^{\beta_R R_i(\tau)}, g^{\beta_O O_i(\tau)}\}_{i\in[n]}\}$,
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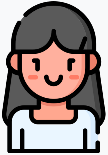
Prover $\mathcal{P}$



Verifier $\mathcal{V}$

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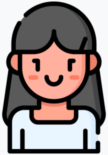
✓ $H(x) = \frac{L(x)\times R(x) - O(x)}{Z(x)}$.

Prover $\mathcal{P}$



Verifier $\mathcal{V}$

Overall protocol

Trusted Setup:

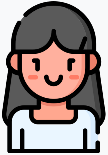
$\tau, \alpha, \beta_L, \beta_R, \beta_O, \gamma \xleftarrow{R} \mathbb{F}$, $\{\{g^{\tau^i}, g^{\alpha\tau^i}\}_{i\in[d]}$, $\{g^{\beta_L L_i(\tau)}, g^{\beta_R R_i(\tau)}, g^{\beta_O O_i(\tau)}\}_{i\in[n]}\}$,
$\{g^{Z(\tau)}, g^{\alpha}, g^{\beta_L}, g^{\beta_R}, g^{\beta_O}, g^{\beta_L\gamma}, g^{\beta_R\gamma}, g^{\beta_O\gamma}, g^{\gamma}\}$, **delete**$(\tau, \alpha, \beta_L, \beta_R, \beta_O, \gamma)$.

✓ $H(x) = \frac{L(x)\times R(x) - O(x)}{Z(x)}$.

✓ Sample $\delta_L, \delta_R, \delta_O \xleftarrow{R} \mathbb{F}$, compute:

$$\pi_L \leftarrow g^{L(\tau)}(g^{Z(\tau)})^{\delta_L}, \pi'_L \leftarrow g^{\alpha L(\tau)}(g^{\alpha Z(\tau)})^{\delta_L},$$
$$\pi_R \leftarrow g^{R(\tau)}(g^{Z(\tau)})^{\delta_R}, \pi'_R \leftarrow g^{\alpha R(\tau)}(g^{\alpha Z(\tau)})^{\delta_R},$$
$$\pi_O \leftarrow g^{O(\tau)}(g^{Z(\tau)})^{\delta_O}, \pi'_O \leftarrow g^{\alpha O(\tau)}(g^{\alpha Z(\tau)})^{\delta_O},$$
$$\pi_H \leftarrow g^{H(\tau)}(g^{\delta_O})(g^{R(\tau)})^{\delta_L}(g^{L(\tau)})^{\delta_R}(g^{Z(\tau)})^{\delta_L\delta_R}$$

Prover $\mathcal{P}$



Verifier $\mathcal{V}$

Overall protocol

Trusted Setup:

$$\tau, \alpha, \beta_L, \beta_R, \beta_O, \gamma \xleftarrow{R} \mathbb{F}, \quad \{\{g^{\tau^i}, g^{\alpha\tau^i}\}_{i\in[d]}, \quad \{g^{\beta_L L_i(\tau)}, g^{\beta_R R_i(\tau)}, g^{\beta_O O_i(\tau)}\}_{i\in[n]}\},$$
$$\{g^{Z(\tau)}, g^{\alpha}, g^{\beta_L}, g^{\beta_R}, g^{\beta_O}, g^{\beta_L\gamma}, g^{\beta_R\gamma}, g^{\beta_O\gamma}, g^{\gamma}\}, \quad \textbf{delete}(\tau, \alpha, \beta_L, \beta_R, \beta_O, \gamma).$$

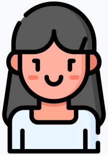
✓ $H(x) = \frac{L(x)\times R(x) - O(x)}{Z(x)}$.

✓ **Sample** $\delta_L, \delta_R, \delta_O \xleftarrow{R} \mathbb{F}$, **compute:**

$$\pi_L \leftarrow g^{L(\tau)}(g^{Z(\tau)})^{\delta_L}, \pi'_L \leftarrow g^{\alpha L(\tau)}(g^{\alpha Z(\tau)})^{\delta_L},$$
$$\pi_R \leftarrow g^{R(\tau)}(g^{Z(\tau)})^{\delta_R}, \pi'_R \leftarrow g^{\alpha R(\tau)}(g^{\alpha Z(\tau)})^{\delta_R},$$
$$\pi_O \leftarrow g^{O(\tau)}(g^{Z(\tau)})^{\delta_O}, \pi'_O \leftarrow g^{\alpha O(\tau)}(g^{\alpha Z(\tau)})^{\delta_O},$$
$$\pi_H \leftarrow g^{H(\tau)}(g^{\delta_O})(g^{R(\tau)})^{\delta_L}(g^{L(\tau)})^{\delta_R}(g^{Z(\tau)})^{\delta_L\delta_R}$$

$\pi_\beta = \ldots$

Prover $\mathcal{P}$



Verifier $\mathcal{V}$

Overall protocol

Trusted Setup:

$$\tau, \alpha, \beta_L, \beta_R, \beta_O, \gamma \xleftarrow{R} \mathbb{F}, \quad \{\{g^{\tau^i}, g^{\alpha\tau^i}\}_{i\in[d]}, \quad \{g^{\beta_L L_i(\tau)}, g^{\beta_R R_i(\tau)}, g^{\beta_O O_i(\tau)}\}_{i\in[n]}\},$$
$$\{g^{Z(\tau)}, g^{\alpha}, g^{\beta_L}, g^{\beta_R}, g^{\beta_O}, g^{\beta_L\gamma}, g^{\beta_R\gamma}, g^{\beta_O\gamma}, g^{\gamma}\}, \quad \textbf{delete}(\tau, \alpha, \beta_L, \beta_R, \beta_O, \gamma).$$

✓ $H(x) = \frac{L(x)\times R(x) - O(x)}{Z(x)}$.

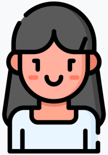
✓ Sample $\delta_L, \delta_R, \delta_O \xleftarrow{R} \mathbb{F}$, compute:

$$\begin{aligned}
\pi_L &\leftarrow g^{L(\tau)}(g^{Z(\tau)})^{\delta_L}, \pi'_L \leftarrow g^{\alpha L(\tau)}(g^{\alpha Z(\tau)})^{\delta_L},\\
\pi_R &\leftarrow g^{R(\tau)}(g^{Z(\tau)})^{\delta_R}, \pi'_R \leftarrow g^{\alpha R(\tau)}(g^{\alpha Z(\tau)})^{\delta_R},\\
\pi_O &\leftarrow g^{O(\tau)}(g^{Z(\tau)})^{\delta_O}, \pi'_O \leftarrow g^{\alpha O(\tau)}(g^{\alpha Z(\tau)})^{\delta_O},\\
\pi_H &\leftarrow g^{H(\tau)}(g^{\delta_O})(g^{R(\tau)})^{\delta_L}(g^{L(\tau)})^{\delta_R}(g^{Z(\tau)})^{\delta_L\delta_R}
\end{aligned}$$

$\pi_\beta = \ldots$

Prover $\mathcal{P}$

$\boldsymbol{\pi} = (\pi_L, \pi_R, \pi_O, \pi_H, \pi'_L, \pi'_R, \pi'_O, \pi'_H, \pi_\beta)$



Verifier $\mathcal{V}$

Overall protocol

Trusted Setup:

$\tau, \alpha, \beta_L, \beta_R, \beta_O, \gamma \xleftarrow{R} \mathbb{F}, \quad \{\{g^{\tau^i}, g^{\alpha\tau^i}\}_{i\in[d]}, \quad \{g^{\beta_L L_i(\tau)}, g^{\beta_R R_i(\tau)}, g^{\beta_O O_i(\tau)}\}_{i\in[n]}\},$
$\{g^{Z(\tau)}, g^{\alpha}, g^{\beta_L}, g^{\beta_R}, g^{\beta_O}, g^{\beta_L\gamma}, g^{\beta_R\gamma}, g^{\beta_O\gamma}, g^{\gamma}\}, \quad \textbf{delete}(\tau, \alpha, \beta_L, \beta_R, \beta_O, \gamma).$

✓ $H(x) = \frac{L(x)\times R(x) - O(x)}{Z(x)}$.

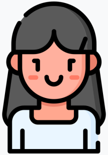
✓ Sample $\delta_L, \delta_R, \delta_O \xleftarrow{R} \mathbb{F}$, compute:

$$\begin{aligned}
\pi_L &\leftarrow g^{L(\tau)}(g^{Z(\tau)})^{\delta_L}, \pi'_L \leftarrow g^{\alpha L(\tau)}(g^{\alpha Z(\tau)})^{\delta_L},\\
\pi_R &\leftarrow g^{R(\tau)}(g^{Z(\tau)})^{\delta_R}, \pi'_R \leftarrow g^{\alpha R(\tau)}(g^{\alpha Z(\tau)})^{\delta_R},\\
\pi_O &\leftarrow g^{O(\tau)}(g^{Z(\tau)})^{\delta_O}, \pi'_O \leftarrow g^{\alpha O(\tau)}(g^{\alpha Z(\tau)})^{\delta_O},\\
\pi_H &\leftarrow g^{H(\tau)}(g^{\delta_O})(g^{R(\tau)})^{\delta_L}(g^{L(\tau)})^{\delta_R}(g^{Z(\tau)})^{\delta_L\delta_R}
\end{aligned}$$

$\pi_\beta = \ldots$

✓ $e(\pi_L, \pi_R) \stackrel{?}{=} e(\mathbf{com}(Z), \pi_H) \cdot e(\pi_O, g)$.

$$\boldsymbol{\pi} = (\pi_L, \pi_R, \pi_O, \pi_H, \pi'_L, \pi'_R, \pi'_O, \pi'_H, \pi_\beta) \longrightarrow$$



Prover $\mathcal{P}$

Verifier $\mathcal{V}$

Overall protocol

Trusted Setup:

$\tau, \alpha, \beta_L, \beta_R, \beta_O, \gamma \xleftarrow{R} \mathbb{F}$, $\{\{g^{\tau^i}, g^{\alpha\tau^i}\}_{i\in[d]}$, $\{g^{\beta_L L_i(\tau)}, g^{\beta_R R_i(\tau)}, g^{\beta_O O_i(\tau)}\}_{i\in[n]}\}$,
$\{g^{Z(\tau)}, g^{\alpha}, g^{\beta_L}, g^{\beta_R}, g^{\beta_O}, g^{\beta_L\gamma}, g^{\beta_R\gamma}, g^{\beta_O\gamma}, g^{\gamma}\}$, **delete**$(\tau, \alpha, \beta_L, \beta_R, \beta_O, \gamma)$.

✓ $H(x) = \frac{L(x)\times R(x) - O(x)}{Z(x)}$.

✓ Sample $\delta_L, \delta_R, \delta_O \xleftarrow{R} \mathbb{F}$, compute:

$$\begin{aligned}
\pi_L &\leftarrow g^{L(\tau)}(g^{Z(\tau)})^{\delta_L}, \pi'_L \leftarrow g^{\alpha L(\tau)}(g^{\alpha Z(\tau)})^{\delta_L},\\
\pi_R &\leftarrow g^{R(\tau)}(g^{Z(\tau)})^{\delta_R}, \pi'_R \leftarrow g^{\alpha R(\tau)}(g^{\alpha Z(\tau)})^{\delta_R},\\
\pi_O &\leftarrow g^{O(\tau)}(g^{Z(\tau)})^{\delta_O}, \pi'_O \leftarrow g^{\alpha O(\tau)}(g^{\alpha Z(\tau)})^{\delta_O},\\
\pi_H &\leftarrow g^{H(\tau)}(g^{\delta_O})(g^{R(\tau)})^{\delta_L}(g^{L(\tau)})^{\delta_R}(g^{Z(\tau)})^{\delta_L\delta_R}
\end{aligned}$$

$\pi_\beta = \ldots$

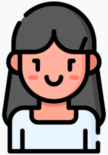
✓ $e(\pi_L, \pi_R) \stackrel{?}{=} e(\mathrm{com}(Z), \pi_H)\cdot e(\pi_O, g)$.

✓ Proof of Exponent:

$$\begin{aligned}
e(\pi_L, g^{\alpha}) &= e(\pi'_L, g),\\
e(\pi_R, g^{\alpha}) &= e(\pi'_R, g),\\
e(\pi_O, g^{\alpha}) &= e(\pi'_O, g),\\
e(\pi_H, g^{\alpha}) &= e(\pi'_H, g).
\end{aligned}$$

Prover $\mathcal{P}$

$\boldsymbol{\pi} = (\pi_L, \pi_R, \pi_O, \pi_H, \pi'_L, \pi'_R, \pi'_O, \pi'_H, \pi_\beta)$ $\longrightarrow$



Verifier $\mathcal{V}$

Overall protocol

Trusted Setup:

$$\tau, \alpha, \beta_L, \beta_R, \beta_O, \gamma \xleftarrow{R} \mathbb{F}, \quad \{\{g^{\tau^i}, g^{\alpha\tau^i}\}_{i\in[d]}, \quad \{g^{\beta_L L_i(\tau)}, g^{\beta_R R_i(\tau)}, g^{\beta_O O_i(\tau)}\}_{i\in[n]}\},$$
$$\{g^{Z(\tau)}, g^{\alpha}, g^{\beta_L}, g^{\beta_R}, g^{\beta_O}, g^{\beta_L\gamma}, g^{\beta_R\gamma}, g^{\beta_O\gamma}, g^{\gamma}\}, \quad \textbf{delete}(\tau, \alpha, \beta_L, \beta_R, \beta_O, \gamma).$$

- ✓ $H(x) = \frac{L(x)\times R(x) - O(x)}{Z(x)}$.
- ✓ Sample $\delta_L, \delta_R, \delta_O \xleftarrow{R} \mathbb{F}$, compute:

$$\begin{aligned}
\pi_L &\leftarrow g^{L(\tau)}(g^{Z(\tau)})^{\delta_L}, \pi'_L \leftarrow g^{\alpha L(\tau)}(g^{\alpha Z(\tau)})^{\delta_L},\\
\pi_R &\leftarrow g^{R(\tau)}(g^{Z(\tau)})^{\delta_R}, \pi'_R \leftarrow g^{\alpha R(\tau)}(g^{\alpha Z(\tau)})^{\delta_R},\\
\pi_O &\leftarrow g^{O(\tau)}(g^{Z(\tau)})^{\delta_O}, \pi'_O \leftarrow g^{\alpha O(\tau)}(g^{\alpha Z(\tau)})^{\delta_O},\\
\pi_H &\leftarrow g^{H(\tau)}(g^{\delta_O})(g^{R(\tau)})^{\delta_L}(g^{L(\tau)})^{\delta_R}(g^{Z(\tau)})^{\delta_L\delta_R}
\end{aligned}$$

$\pi_\beta = \ldots$

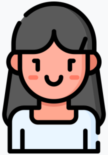
- ✓ $e(\pi_L, \pi_R) \stackrel{?}{=} e(\mathsf{com}(Z), \pi_H)\cdot e(\pi_O, g)$.
- ✓ Proof of Exponent:

$$\begin{aligned}
e(\pi_L, g^{\alpha}) &= e(\pi'_L, g),\\
e(\pi_R, g^{\alpha}) &= e(\pi'_R, g),\\
e(\pi_O, g^{\alpha}) &= e(\pi'_O, g),\\
e(\pi_H, g^{\alpha}) &= e(\pi'_H, g).
\end{aligned}$$

- ✓ $e(\pi_L, g^{\gamma\beta_L})\cdot e(\pi_R, g^{\gamma\beta_R})\cdot$
  $\cdot\, e(\pi_O, g^{\gamma\beta_O}) = e(\pi_\beta, g^{\gamma})$

Prover $\mathcal{P}$

$$\boldsymbol{\pi} = (\pi_L, \pi_R, \pi_O, \pi_H, \pi'_L, \pi'_R, \pi'_O, \pi'_H, \pi_\beta)$$



Verifier $\mathcal{V}$

Real Protocols

Complexity of the Basic Protocol

Overall Complexity

Suppose circuit consists of n gates. Then, the complexity of the basic protocol is as follows:

- **Proof Size:** $O(1)$ — constant number of group elements.
- **Setup Time:** $O(n)$ — calculating powers of τ, evaluations at τ.
- **Prover Time:** $O(n \log n)$ — using FFT and wise choice of Ω.
- **Verifier Time:** $O(1)$ — constant number of pairings.

However, $O(1)$ is not very descriptive for proof and verifier complexities, so let us provide a more detailed analysis.

- **Proof Size:** 9 $\mathbb{G}$ group elements.
- **Verifier Time:** 15 pairings.

We can do better!

Pinocchio Protocol

Idea

In toxic waste, include $\rho_L, \rho_R \xleftarrow{R} \mathbb{F}$, set $\rho_O \leftarrow \rho_L \rho_R$, and define the following generators:

$$g_L \leftarrow g^{\rho_L}, \quad g_R \leftarrow g^{\rho_R}, \quad g_O \leftarrow g^{\rho_O}$$

Reason

Such choice of generators reduce 15 pairings to **11 pairings**. Additionally, we have only **8 group elements** in the proof.

Groth16 Protocol

Idea: Generic Group Model

Use **Generic Group Model** (GGM) technique. Simply put, GGM allows the adversary to only make **oracle requests** to compute the group operations. For example, having a set $\{g^{\alpha R_i(\tau)}\}_{i \in [d]}$, adversary can compute only linear combinations of these values. In the particular case of Groth16, instead of considering $L_i(x)$, $R_i(x)$, and $O_i(x)$ separately, we construct their linear combinations as $Q_i(x) := \beta L_i(x) + \alpha R_i(x) + O_i(x)$, where α and β are toxic parameters.

Groth16 Protocol: Setup Procedure

The proving key is formed as follows:

$$\mathsf{pp} \leftarrow \left(g_1^{\alpha}, g_1^{\beta}, g_1^{\delta}, \left\{g_1^{\tau^i}, \frac{\beta L_i(\tau) + \alpha R_i(\tau) + O_i(\tau)}{\gamma}, \frac{\tau^i Z(\tau)}{\delta}\right\}_{i \in [n]},\right.$$
$$\left. g_2^{\beta}, g_2^{\delta}, g_2^{\gamma}, \{g_2^{\tau^i}\}_{i \in [d]}\right)$$

Groth16 Protocol: Proving Procedure

Sample random $\delta_L, \delta_R \xleftarrow{R} \mathbb{F}$ and compute the following values:

$$\pi_L \leftarrow g_1^{\alpha+\sum_{i=1}^{n} w_i L_i(\tau)+\delta_L\delta}, \quad \pi_R \leftarrow g_2^{\beta+\sum_{i=0}^{n} w_i R_i(\tau)+\delta_R\delta},$$
$$\pi_O \leftarrow g_1^{\frac{Q_{\text{mid}}(\tau)+H(\tau)Z(\tau)}{\delta}+L\delta_R+R\delta_L-\delta_L\delta_R\delta},$$

where by Q_{mid} we denoted the following expression:

$$Q_{\text{mid}}(\tau) = \sum_{i\in\mathcal{I}_{\text{mid}}} w_i Q_i(\tau) = \sum_{i\in\mathcal{I}_{\text{mid}}} w_i(\beta L_i(\tau) + \alpha R_i(\tau) + O_i(\tau))$$

Groth16 Protocol: Verification Procedure

The verifier first calculates the following value:

$$\pi_{\text{io}} \leftarrow g_1^{\sum_{i\in\mathcal{I}_{\text{io}}} w_i(\beta L_i(\tau)+\alpha R_i(\tau)+O_i(\tau))/\gamma},$$

and then checks the following single condition:

$$e(\pi_L,\pi_R) = e(g_1^{\alpha},g_2^{\beta})e(\pi_{\text{io}},g_2^{\gamma})e(\pi_O,g_2^{\delta})$$

Note

$e(g_1^{\alpha},g_2^{\beta})$ can be additionally hard-coded in the verifier, thus reducing the number of pairings to 3. Finally, the proof's size is now reduced to 3 group elements: two from $\mathbb{G}_1$, and one from $\mathbb{G}_2$.

Thank you for your attention

♥

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