QAP, PCP, POE

Oct 1, 2024

Distributed Lab

Plan

Recap

Quadratic Arithmetic Program

Probabilistically Checkable Proofs

QAP as a Linear PCP

Recap

Recap: what is zk-SNARK?

Definition

zk-SNARK

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

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✓ **Argument of Knowledge** — a proof that the prover knows the data (witness) that resolves a certain problem, and this knowledge can be “extracted”.

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✓ **Non-interactiveness** — to produce the proof, the prover does not need any interaction with the verifier.

✓ **Zero-Knowledge** — the verifier learns nothing about the data used to produce the proof, despite knowing that this data resolves the given problem and that the prover possesses it.

Recap: Arbitrary Program To Circuits

We can do that in a way like the computer does it — **boolean circuits**.

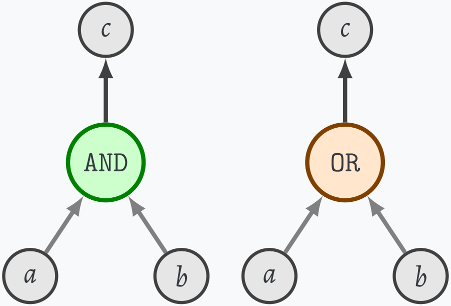

Figure: Boolean AND and OR Gates

But nothing stops us from using something more powerful instead of boolean values...

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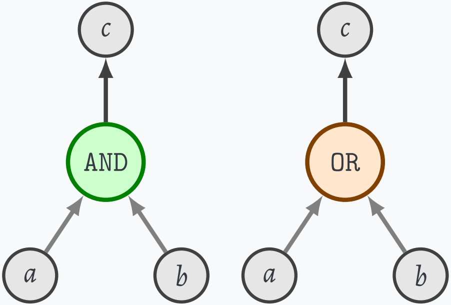

Figure: Boolean `AND` and `OR` Gates

> **100000 gates** just for `SHA256`...

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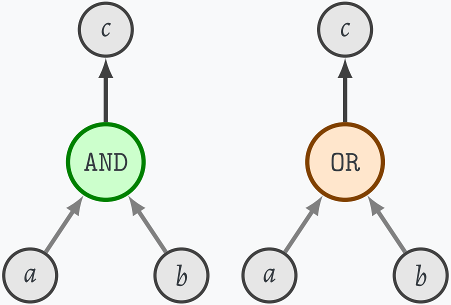

Figure: Boolean AND and OR Gates

> **100000 gates** just for SHA256. . . But nothing stops us from using something more powerful instead of boolean values, gates.

Recap. Arbitrary Program To Circuits

Similar to Boolean Circuits, the **Arithmetic Circuits** consist of gates and wires.

- **Wires**: elements of some finite field $\mathbb{F}$.
- **Gates**: field addition $(+)$ and multiplication $(\times)$.

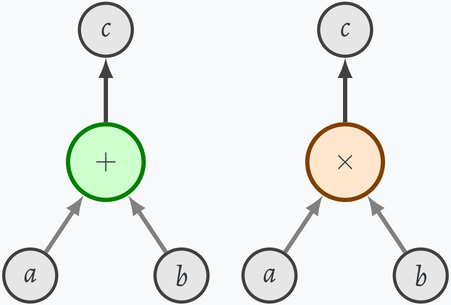

Figure: Addition and Multiplication Gates

Recap. Arbitrary Program To Circuits

Example

How can we translate if statements?

```
def example(a: bool, b: F, c: F) -> F:
    if a:
        return b * c
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        return b + c
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Corresponding equations for the circuit are:

$$r_1 = b \times c, \qquad r_3 = 1 - a, \qquad r_5 = r_3 \times r_2$$
$$r_2 = b + c, \qquad r_4 = a \times r_1, \qquad r = r_4 + r_5$$

Recap. Arbitrary Program To Circuits

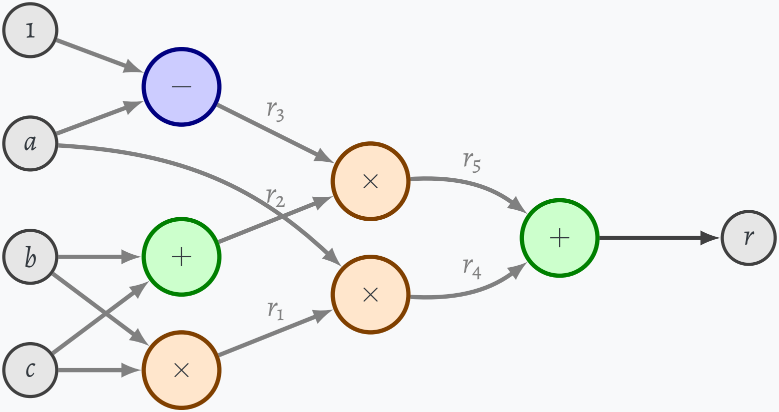

Figure: Example of a circuit evaluating the `if` statement logic.

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Recap. R1CS

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

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

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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

Example

Consider the most basic circuit with one multiplication gate: $x_1 \times x_2 = r$. The witnes vector $\mathbf{w} = (r, x_1, x_2)$. So

$$w_2 \times w_3 = w_1$$
$$(0 + w_2 + 0) \times (0 + 0 + w_3) = w_1 + 0 + 0$$
$$(0w_1 + 1w_2 + 0w_3) \times (0w_1 + 0w_2 + 1w_3) = 1w_1 + 0w_2 + 0w_3$$

Therefore the coefficients vectors are:

$$\mathbf{a} = (0, 1, 0), \quad \mathbf{b} = (0, 0, 1), \quad \mathbf{c} = (1, 0, 0).$$

The general form of our constraint is:

$$(a_1w_1 + a_2w_2 + a_3w_3)(b_1w_1 + b_2w_2 + b_3w_3) = c_1w_1 + c_2w_2 + c_3w_3$$

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$$r = x_1 \times (x_2 \times x_3) + (1 - x_1) \times (x_2 + x_3)$$

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Thus, the next constraints can be build:

$$x_1 \times x_1 = x_1 \quad \text{(binary check)} \tag{1}$$

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

$$x_1 \times \mathsf{mult} = \mathsf{selectMult} \tag{3}$$

$$(1 - x_1) \times (x_2 + x_3) = r - \mathsf{selectMult} \tag{4}$$

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

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The coefficients vectors:

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

Quadratic Arithmetic Program

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✓ Although Rank-1 Constraint Systems provide a powerful method for representing computations, they are not succinct.

✓ We need to transform our computations into a form that is more convenient for proving statements about them.

Notice

A very convenient form for representing computations is **polynomials**!

Idea: Instead of checking polynomial equality $P(x) = Q(x)$ at multiple points $Q(x_1), \dots, Q(x_n)$ (essentially, checking each constraint), we check it only once at $\tau \xleftarrow{R} \mathbb{F}$: $P(\tau) = Q(\tau)$. Soundness is guaranteed by the **Schwartz-Zippel Lemma**.

We finished with:

$$\mathbf{a}_1, \mathbf{a}_2, \ldots, \mathbf{a}_m, \quad \mathbf{b}_1, \mathbf{b}_2, \ldots, \mathbf{b}_m, \quad \mathbf{c}_1, \mathbf{c}_2, \ldots, \mathbf{c}_m,$$

We finished with:

$$\mathbf{a_1}, \mathbf{a_2}, \ldots, \mathbf{a_m}, \quad \mathbf{b_1}, \mathbf{b_2}, \ldots, \mathbf{b_m}, \quad \mathbf{c_1}, \mathbf{c_2}, \ldots, \mathbf{c_m},$$

Of course, they form corresponding matrices:

$$A = \begin{bmatrix} a_{11} & a_{12} & \ldots & a_{1n} \\ a_{21} & a_{22} & \ldots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \ldots & a_{mn} \end{bmatrix} \quad B = \begin{bmatrix} b_{11} & b_{12} & \ldots & b_{1n} \\ b_{21} & b_{22} & \ldots & b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ b_{m1} & b_{m2} & \ldots & b_{mn} \end{bmatrix} \quad C = \begin{bmatrix} c_{11} & c_{12} & \ldots & c_{1n} \\ c_{21} & c_{22} & \ldots & c_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ c_{m1} & c_{m2} & \ldots & c_{mn} \end{bmatrix}$$

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An example of a single “if“ statement:

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

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Pleeeeeenty of zeroes, right? And this is just one out of 3 matrices...

The previous witness vector:

$$\mathbf{w} = (1, r, x_1, x_2, x_3, \text{mult}, \text{selectMult})$$

Let's take a closer look at the matrix columns:

$$\begin{array}{c} \begin{array}{ccccccc} & & 3 & & & & \end{array} \\ \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & -1 & 0 & 0 & 0 & 0 \end{bmatrix} \end{array}$$

Consider 4th constraint: $(1 - x_1) \times (x_2 + x_3) = r - \text{selectMult}$

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As we know, such a mapping can be builds using Lagrange interpolation polynomial with the following formula:

$$L(x) = \sum_{i=0}^{n} y_i \ell_i(x), \quad \ell_i(x) = \prod_{j=0, j \neq i}^{n} \frac{x - x_j}{x_i - x_j}.$$

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There are n columns and m constraints. So, it results in n polynomials such that:

$$A_j(i) = a_{i,j}, \ i \in \{1, 2, \ldots, m\}, \ j \in \{1, 2, \ldots, n\}$$

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The same is true for matrices B and C, with $3n$ polynomials in total, n for each of the coefficients matrices:

$$A_1(x), A_2(x), \ldots, A_n(x), B_1(x), B_2(x), \ldots, B_n(x), C_1(x), C_2(x), \ldots, C_n(x)$$

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Note

We could have assigned any *unique* index from $\mathbb{F}$ to each constraint (say, t_i for each $i \in \{1, \ldots, m\}$) and interpolate through these points:

$$A_j(t_i) = a_{i,j}, \ i \in \{1, 2, \ldots, m\}, \ j \in \{1, 2, \ldots, n\}$$

Example

Considering the witness vector $\mathbf{w}$ and matrix A from the previous example, for the variable x_1, the next set of points can be derived:

$$\{(1,1),(2,0),(3,1),(4,-1)\}$$

The Lagrange interpolation polynomial for this set of points:

$$\ell_1(x) = -\frac{(x-2)(x-3)(x-4)}{6}, \qquad \ell_2(x) = \frac{(x-1)(x-3)(x-4)}{2},$$
$$\ell_3(x) = -\frac{(x-1)(x-2)(x-4)}{2}, \qquad \ell_4(x) = \frac{(x-1)(x-2)(x-3)}{6}.$$

Thus, the polynomial is given by:

$$\begin{aligned} A_{x_1}(x) &= 1\cdot\ell_1(x) + 0\cdot\ell_2(x) + 1\cdot\ell_3(x) + (-1)\cdot\ell_4(x) \\ &= -\frac{5}{6}x^3 + 6x^2 - \frac{79}{6}x + 9 \end{aligned}$$

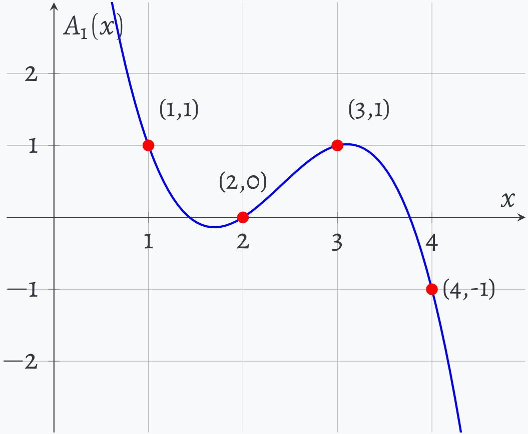

Illustration: The Lagrange inteprolation polynomial for points $\{(1,1),(2,0),(3,1),(4,-1)\}$ visualized over $\mathbb{R}$.

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Consider two polynomials $p(x)$ and $q(x)$:

$$p(x) = -\frac{1}{2}x^2 + \frac{3}{2}x, \qquad q(x) = \frac{1}{3}x^3 - 2x^2 + \frac{8}{3}x + 1.$$

With corresponding sets of points:

$$\{(0,0),(1,1),(2,1),(3,0)\}, \quad \{(0,1),(1,2),(2,1),(3,0)\}$$

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But what does it change? We “exchanged“ $3n$ columns for $3n$ polynomials.

Consider two polynomials $p(x)$ and $q(x)$:

$$p(x) = -\frac{1}{2}x^2 + \frac{3}{2}x, \qquad q(x) = \frac{1}{3}x^3 - 2x^2 + \frac{8}{3}x + 1.$$

With corresponding sets of points:

$$\{(0,0),(1,1),(2,1),(3,0)\}, \quad \{(0,1),(1,2),(2,1),(3,0)\}$$

The sum of these polynomials can be calculated as:

$$r(x) = \frac{1}{3}x^3 - 2\frac{1}{2}x^2 + 4\frac{1}{6}x + 1$$

The resulting polynomial $r(x)$ corresponds to the set of points:

$$\{(0,1),(1,3),(2,2),(3,0)\}$$

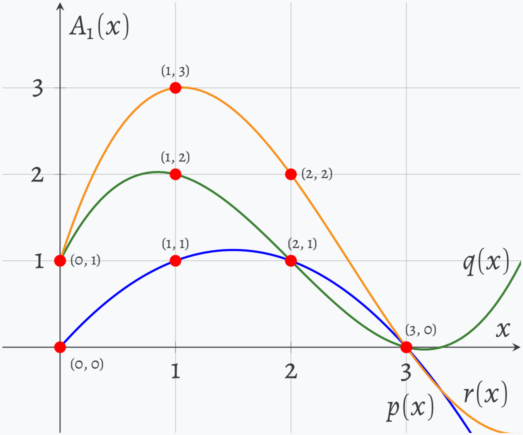

Figure: Addition of two polynomials

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

$$
\begin{aligned}
&(w_1A_1(X) + w_2A_2(X) + \cdots + w_nA_n(X))\times\\
\times&(w_1B_1(X) + w_2B_2(X) + \cdots + w_nB_n(X)) =\\
=&(w_1C_1(X) + w_2C_2(X) + \cdots + w_nC_n(X))
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\end{aligned}
$$

Or written more concisely:

$$
\left(\sum_{i=1}^{n} w_iA_i(X)\right) \times \left(\sum_{i=1}^{n} w_iB_i(X)\right) = \left(\sum_{i=1}^{n} w_iC_i(X)\right)
$$

Hold on, but why does it hold? Let us substitute any $X = j$ into this equation:

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Recall that we interpolated polynomials to have $A_i(j) = a_{j,i}$. Therefore, the equation above can be reduced to:

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But hold on again! Notice that $\sum_{i=1}^{n} w_i a_{j,i} = \langle \mathbf{w}, \mathbf{a}_j \rangle$ and therefore we have:

$$\langle \mathbf{w}, \mathbf{a}_j \rangle \times \langle \mathbf{w}, \mathbf{b}_j \rangle = \langle \mathbf{w}, \mathbf{c}_j \rangle \ \forall j \in \{1, \dots, m\},$$

so we ended up with the initial m constraint equations!

Now let us define polynomials $A(X), B(X), C(X)$ for easier notation:

$$A(X) = \sum_{i=1}^{n} w_i A_i(X), \quad B(X) = \sum_{i=1}^{n} w_i B_i(X), \quad C(X) = \sum_{i=1}^{n} w_i C_i(X)$$

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Therefore:

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

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

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

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

Definition (Quadratic Arithmetic Program)

Suppose that m R1CS constraints with a witness of size n are written in a form

$$A\mathbf{w} \odot B\mathbf{w} = C\mathbf{w}, \qquad (A, B, C \in \mathbb{F}^{m \times n})$$

Then, the **Quadratic Arithmetic Program** consists of $3n$ polynomials $A_1, \dots, A_n, B_1, \dots, B_n, C_1, \dots, C_n$ such that:

$$A_j(i) = a_{i,j}, \ B_j(i) = b_{i,j}, \ C_j(i) = c_{i,j}, \ \forall i \in \{1, \dots, m\} \ \forall j \in \{1, \dots, n\}$$

Then, $\mathbf{w} \in \mathbb{F}^n$ is a valid assignment for the given QAP and **target polynomial** $Z(X) = \prod_{i=1}^{m}(X - i)$ if and only if there exists such a polynomial $H(X)$ such that

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

Probabilistically Checkable Proofs

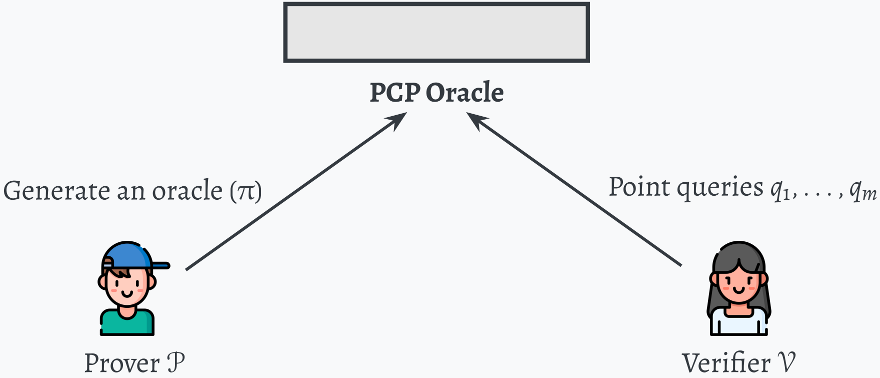
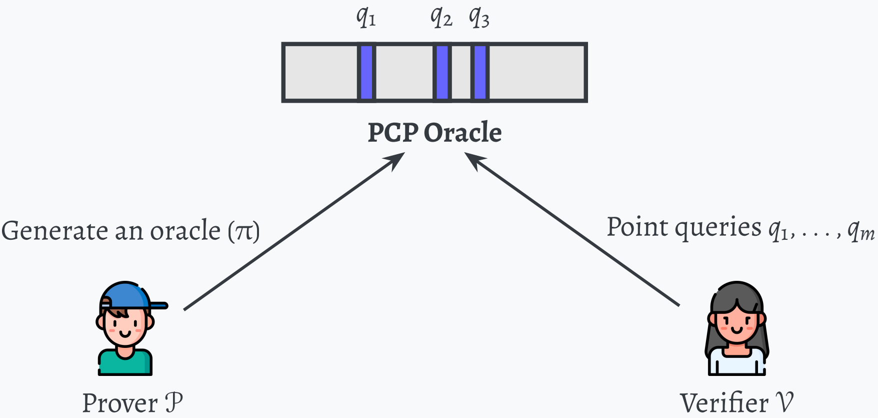


Figure: Illustration of a Probabilistically Checkable Proof (PCP) system. The prover $\mathcal{P}$ generates a PCP oracle π that is queried by the verifier $\mathcal{V}$ at specific points $q_1, \ldots, q_m$.



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Three main extensions of PCPs that are frequently used in SNARKs are:

- **IPCP** (**Interactive PCP**): The prover commits to the PCP oracle and then, based on the interaction between the prover and verifier, the verifier queries the oracle and decides whether to accept the proof.
- **IOP** (**Interactive Oracle Proof**): The prover and verifier interact and on each round, the prover commits to a new oracle. The verifier queries the oracle and decides whether to accept the proof.
- **LPCP** (**Linear PCP**): The prover commits to a linear function and the verifier queries the function at specific points.

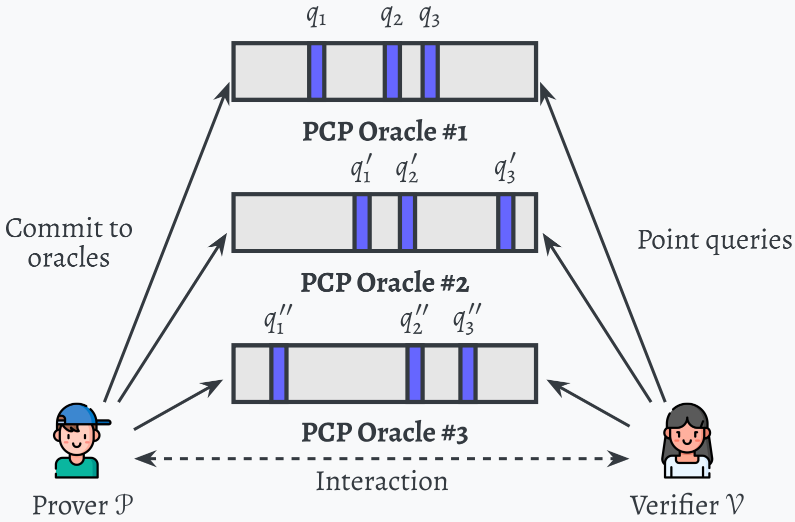

Figure: Illustration of an Interactive Oracle Proof (IOP). On each round i ($1 \leqslant i \leqslant r$), $\mathcal{V}$ sends a message m_i, and $\mathcal{P}$ commits to a new oracle π_i, which $\mathcal{V}$ can query at $\mathbf{q}_i = (q_{i,1}, \ldots, q_{i,m})$.

QAP as a Linear PCP

Definition (Linear PCP)

A **Linear PCP** is a PCP where the prover commits to a linear function $\boldsymbol{\pi} = (\pi_1, \ldots, \pi_k)$ and the verifier queries the function at specific points $\boldsymbol{q}_1, \ldots, \boldsymbol{q}_r$. Then, the prover responds with the values of the function at these points:

$$\langle \boldsymbol{\pi}_1, \mathbf{q}_1 \rangle, \langle \boldsymbol{\pi}_2, \mathbf{q}_2 \rangle, \ldots, \langle \boldsymbol{\pi}_r, \mathbf{q}_r \rangle.$$

Example (QAP as a Linear PCP)

Recall that key QAP equation is:

$$L(x) \times R(x) - O(x) = Z(x)H(x).$$

Now, consider the following **linear PCP for QAP**:

1. $\mathcal{P}$ commits to an extended witness $\mathbf{w}$ and coefficients $\mathbf{h} = (h_1, \ldots, h_n)$ of $H(x)$.
2. $\mathcal{V}$ samples $\gamma \xleftarrow{R} \mathbb{F}$ and sends query $\boldsymbol{\gamma} = (\gamma, \gamma^2, \ldots, \gamma^n)$ to $\mathcal{P}$.
3. $\mathcal{P}$ reveals the following values:

$$\pi_1 \leftarrow \langle \mathbf{w}, \boldsymbol{L}(\gamma) \rangle, \qquad \pi_2 \leftarrow \langle \mathbf{w}, \boldsymbol{R}(\gamma) \rangle,$$
$$\pi_3 \leftarrow \langle \mathbf{w}, \boldsymbol{O}(\gamma) \rangle, \qquad \pi_4 \leftarrow Z(\gamma) \cdot \langle \mathbf{h}, \boldsymbol{\gamma} \rangle.$$

4. $\mathcal{V}$ checks whether $\pi_1 \pi_2 - \pi_3 = \pi_4$.

Question

Why is it safe to use such a check?

The polynomials $L(x)$, $R(x)$ and $O(x)$ are interpolated polynomials using $|C|$ (number of gates) points, so:

$$\deg(L) \leqslant |C|\,, \quad \deg(R) \leqslant |C|\,, \quad \deg(O) \leqslant |C|$$

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Thus, we can estimate the degree of polynomial $M(x) = L(x)R(x) - O(x)$.

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$$\deg(M) \leqslant \max\{\deg(L) + \deg(R), \deg(O)\} \leqslant 2\,|C|$$

If an adversary $\mathcal{A}$ does not know a valid witness $\mathbf{w}$, he can compute a polynomial $(\widetilde{M}(x), \widetilde{H}(x)) \leftarrow \mathcal{A}(\cdot)$ that satisfies a verifier $\mathcal{V}$:

$$\Pr_{s \xleftarrow{R} \mathbb{F}}\left[\widetilde{M}(s) = Z(s)\widetilde{H}(s)\right] \leqslant \frac{2\,|C|}{|\mathbb{F}|}$$

If $|\mathbb{F}|$ is large enough, $2|C|/|\mathbb{F}|$ is *negligible*.

Thanks for your attention!