



PlonK Arithmetization

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Distributed Lab

 zkdl-camp.github.io

 github.com/ZKDL-Camp



Plan

1 Introduction. PlonK: Five Ws

2 PlonK Arithmetization

3 Polynomial Form

- Formulating Conditions
- Permutation Check

Introduction. PlonK: Five Ws

What is PlonK?

PlonK is a type of zkSNARK:

- Groth16
- Halo2
- Marlin
- PlonK
- ...

Who and When invented Plonk?

Ariel Gabizon, Zachary Williamson, Oana Ciobotaru introduced paper “PLONK: Permutations over Lagrange-bases for Oecumenical Noninteractive arguments of Knowledge” in 2019

PlonK: Permutations over Lagrange-bases for Oecumenical Noninteractive arguments of Knowledge

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February 23, 2024

Figure: PlonK Paper. Date in Paper reflects the last update :)

Why use Plonk?

Focus on what you want:

- ZKP for different tasks?
- Efficient proving times?
- Small-medium proof sizes?
- Flexibility?



Where Plonk is used?

zkVMs love Plonk!

- Aztec Protocol (Noir)
 - zkSync
- Dusk Network
- Mina Protocol



PlonK Arithmetization

Arithmetization

Goal: Write some program (computation) into math processing-prone form.

Example

Public Input: $x \in \mathbb{F}$

Private Input: $e \in \mathbb{F}$

Output: $e \times x + x - 1$

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Let's split our program into the sequence of gates with left, right operands and output - circuit.

Example

We need **three gates** to encode our program:

1. **Gate #1:** left e , right x , output $u = e \times x$

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2. **Gate #2:** left u , right x , output $v = u + x$

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1. **Gate #1:** left e , right x , output $u = e \times x$
2. **Gate #2:** left u , right x , output $v = u + x$
3. **Gate #3:** left v , right x , output $w = v + (-1)$

Execution Trace

Then, form *execution trace table* — a matrix T with columns L , R and O .

Example

A	B	C
2	3	6
6	3	9
9	X	8

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Remark

Notice how the last row has no value in B column (marked by X) — this is reasoned by the fact it is not a variable, but rather a constant, meaning it doesn't depend on execution.

Encode the Program

Suppose you were given random matrix T . How could you tell if it is suitable for your circuit?

Solution

Encode the circuit. Check T using encoding:

1. **Gates** (gate constraints) — using matrix Q .
2. **Wires** (copy constraints) — using matrix V .

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Definition (Gate Matrix)

Q matrix has one row per each gate with columns Q_L , Q_R , Q_O , Q_M , Q_C . If columns A , B and C of the execution trace table form valid evaluation of the circuit,

$$A_i Q_{Li} + B_i Q_{Ri} + A_i B_i Q_{Mi} + C_i Q_{Oi} + Q_{Ci} = 0$$

Q Matrix

Example

For our program, we would have a following Q table:

Q_L	Q_R	Q_M	Q_O	Q_C
0	0	1	-1	0
1	1	0	-1	0
1	0	0	-1	-1

You can verify that our claim holds for aforementioned trace matrix:

$$2 \times 0 + 3 \times 0 + 2 \times 3 \times 1 + 6 \times (-1) + 0 = 0$$

$$6 \times 1 + 3 \times 1 + 6 \times 3 \times 0 + 9 \times (-1) + 0 = 0$$

$$9 \times 1 + 0 \times 0 + 9 \times 0 \times 0 + 8 \times (-1) + (-1) = 0$$

V Matrix

Definition

V consists of indices of all inputs and intermediate values, so that if T is a valid trace,

$$\forall i, j, k, l : (V_{i,j} = V_{k,l}) \Rightarrow (T_{i,j} = T_{k,l})$$

Example

For our program, V would look like following:

L	R	O
0	1	2
2	1	3
3		4

Here 0 is an index of e , 1 is an index of x , 2 — u , 3 — v and 4 — output w .

Custom Gates

Default PlonK: **addition** and **multiplication** gates. How to make it more *interesting*?

Solution

Q with it's 5 columns already allows for custom gates, however it is possible to include out own columns.

Example

Our entire program may be encoded as one custom gate.

$$Q: \begin{array}{|c|c|c|c|c|} \hline Q_L & Q_R & Q_M & Q_o & Q_c \\ \hline 0 & 1 & 1 & -1 & -1 \\ \hline \end{array} \quad V: \begin{array}{|c|c|c|} \hline L & R & O \\ \hline 0 & 1 & 2 \\ \hline \end{array} \quad T: \begin{array}{|c|c|c|} \hline A & B & C \\ \hline 2 & 3 & 8 \\ \hline \end{array}$$

$$2 \times 0 + 3 \times 1 + 2 \times 3 \times 1 + 8 \times (-1) + (-1) = 0$$

Public Inputs

Also need to encode public inputs.

Idea

Consider, as if we added new *selector* rows to Q and tied them in V and T .

Example

Q:	Q_L	Q_R	Q_M	Q_o	Q_c
	-1	0	0	0	3
	-1	0	0	0	8
	1	1	1	-1	1
	1	-1	0	0	0

V:	L	R	O
	0		
	1		
	2	0	3
	1	3	

T:	A	B	C
	3		
	8		
	2	3	8
	8	8	

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$Q:$	Q_L	Q_R	Q_M	Q_o	Q_c
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	1	1	1	-1	1
	1	-1	0	0	0

$V:$	L	R	O
	0		
	1		
	2	0	3
	1	3	

$T:$	A	B	C
	3		
	8		
	2	3	8
	8	8	

Now Q and V are not independent of evaluations.

Solution

We introduce another one-column matrix named Π (public inputs).

Wrap-Up

Example

With only Q modified, we have:

Π	Q_L	Q_R	Q_M	Q_o	Q_c
3	-1	0	0	0	0
8	-1	0	0	0	0
0	1	1	1	-1	1
0	1	-1	0	0	0

Wrap-Up

Example

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Π	Q_L	Q_R	Q_M	Q_o	Q_c
3	-1	0	0	0	0
8	-1	0	0	0	0
0	1	1	1	-1	1
0	1	-1	0	0	0

Q :

Definition (Interim Summary)

Matrix T with columns A , B and C encodes correct execution of the program, if the following two conditions hold:

1. $\forall i : A_i Q_{Li} + B_i Q_{Ri} + A_i B_i Q_{Mi} + C_i Q_{Oi} + Q_{ci} + \Pi_i = 0$
2. $\forall i, j, k, l : (V_{i,j} = V_{k,l}) \Rightarrow (T_{i,j} = T_{k,l})$

Polynomial Form

Matrices to Polynomials

Encode matrices into a few equations on polynomials.

Let ω be a primitive N -th root of unity and let $\Omega = \{\omega^j : 0 \leq j < N\}$. Let $a, b, c, q_L, q_R, q_M, q_O, q_C, \pi$ be polynomials of degree at most N that interpolate corresponding columns from matrices at the domain Ω . This means, that $\forall j : a(\omega^j) = A_j$ and the same for other columns.

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Proposition

Now we can reduce down our first condition to checking valid execution trace into the following claim over polynomials:

$$\exists t \in \mathbb{F}[X] : aq_L + bq_R + abq_M + cq_O + q_C + \pi = z_\Omega t,$$

where $z_\Omega(X)$ is the vanishing polynomial $X^N - 1$.

Copy constraints in polynomial form.

Spoiler: we can use the concept of permutation to encode V wirings.

A permutation is a rearrangement of the set:

$$\mathcal{I} = \{(i, j) : \text{such that } 0 \leq i < N, \text{ and } 0 \leq j < 3\}$$

Permutation of the set is commonly denoted as σ .

Copy constraints in polynomial form.

Example

The matrix V induces a permutation of this set where $\sigma((i,j))$ is equal to the indices of the next occurrence of the value at position (i,j) . So, for our example:

V :

L	R	O
0		
1		
2	0	3
1	3	

$$\sigma((0,0)) = (2,1), \sigma((0,1)) = (0,3), \sigma((0,2)) = (0,2)$$

$$\sigma((0,3)) = (0,1), \sigma((2,1)) = (0,0), \sigma((3,1)) = (2,2)$$

Permutation Check. Having defined permutation, we can now reduce a condition 2 of valid execution trace matrix into the following check:

$$\forall (i, j) \in \mathcal{I} : T_{i,j} = T_{\sigma(i,j)}$$

You may have noticed how this can be reformulated as equality of A and B :

$$A = \{((i, j), T_{i,j}) : (i, j) \in \mathcal{I}\}$$

$$B = \{(\sigma((i, j)), T_{i,j}) : (i, j) \in \mathcal{I}\}$$

We can reduce this check down to polynomial equations.

Suppose we have sets $A = \{a_0, a_1\}$ and $B = \{b_0, b_1\}$. We can consider polynomials $A' = \{a_0 + X, a_1 + X\}$, $B' = \{b_0 + X, b_1 + X\}$. So, $A' = B'$, only if $(a_0 + X)(a_1 + X) = (b_0 + X)(b_1 + X)$. This is true because of linear polynomial unique factorization property, working as prime factors. Now, we can utilize Schwartz-Zippel lemma to replace the latter formula with $(a_0 + \gamma)(a_1 + \gamma) = (b_0 + \gamma)(b_1 + \gamma)$ for some random γ with overwhelming probability. If we wish to generalize this for arbitrary sets $A = \{a_0, \dots, a_{k-1}\}$ and $B = \{b_0, \dots, b_{k-1}\}$, apply the following check:

$$\prod_{i=0}^{k-1} (a_i + \gamma) = \prod_{i=0}^{k-1} (b_i + \gamma)$$

Let Ω be a domain of the form $\{1, \omega, \dots, \omega^{k-1}\}$ for some k -th root of unity ω . Let f and g be polynomials that interpolate the following values at Ω :

$$f : (a_0 + \gamma, \dots, a_{k-1} + \gamma)$$

$$g : (b_0 + \gamma, \dots, b_{k-1} + \gamma)$$

Then $\prod_{i=0}^{k-1} (a_i + \gamma) = \prod_{i=0}^{k-1} (b_i + \gamma)$ if and only if exists a polynomial $Z \in \mathbb{F}[X]$ such that for all $h \in \Omega$ we have $Z(\omega^0) = 1$ and $Z(h)f(h) = g(h)Z(\omega h)$.

Now that we can encode equality of sets of field elements, let's expand this to sets of tuples of field elements. Let $A = \{(a_0, a_1), (a_2, a_3)\}$ and $B = \{(b_0, b_1), (b_2, b_3)\}$, then, similarly:

$$A' = \{a_0 + a_1 Y + X, a_2 + a_3 Y + X\}$$

$$B' = \{b_0 + b_1 Y + X, b_2 + b_3 Y + X\}$$

$$A = B \leftrightarrow A' = B'$$

As before, we can leverage Schwartz-Zippel lemma to reduce this down into sampling random β and γ and checking equality of:

$$(a_0 + \beta a_1 + \gamma)(a_2 + \beta a_3 + \gamma) = (b_0 + \beta b_1 + \gamma)(b_2 + \beta b_3 + \gamma)$$

Let's make (i, j) into one field element, so that we can use statement above for encoding.

Recall that $i \in [0; N - 1]$ and $j \in [0; 2]$; we can take $3N$ -th primitive root of unity η and define our field element as $a_0 = \eta^{3i+j}$:

$$A = \{(\eta^{3i+j}, T_{i,j}) : (i, j) \in \mathcal{I}\}$$

$$B = \{(\eta^{3k+l}, T_{i,j}) : (i, j) \in \mathcal{I}, \sigma((i, j)) = (k, l)\}$$

Let η be a $3N$ -th primitive root of unity, β and γ random field elements. Let $\mathcal{D} = \{1, \eta, \eta^2, \dots, \eta^{3N-1}\}$. Then let f and g interpolate at \mathcal{D} :

$$f : \{T_{i,j} + \eta^{3i+j}\beta + \gamma : (i,j) \in \mathcal{I}\}$$

$$g : \{T_{i,j} + \eta^{3k+l}\beta + \gamma : (i,j) \in \mathcal{I}, \sigma((i,j)) = (k,l)\}$$

So, $\exists Z \in \mathbb{F}[X]$ s.t. $\forall h \in \Omega$ we have $Z(\eta^0) = 1$ and $Z(h)f(h) = g(h)Z(\eta h) \leftrightarrow A = B$ w.h.p.

Notice, that $\omega = \eta^3$ is a primitive N -th root of unity. Let $\Omega = \{1, \omega, \omega^2, \dots, \omega^{N-1}\}$. We will define three polynomials, which interpolate following sets:

$$S_{\sigma 1} : \{\eta^{3k+l} : (i, 0) \in \mathcal{I}, \sigma((i, 0)) = (k, l)\}$$

$$S_{\sigma 2} : \{\eta^{3k+l} : (i, 1) \in \mathcal{I}, \sigma((i, 0)) = (k, l)\}$$

$$S_{\sigma 3} : \{\eta^{3k+l} : (i, 2) \in \mathcal{I}, \sigma((i, 0)) = (k, l)\}$$

Copy constraints via polynomials

Let ω be an N -th root of unity. Let $\Omega = \{1, \omega, \omega^2, \dots, \omega^{N-1}\}$. Let k_1 and k_2 be two field elements such that $\omega^i \neq \omega^j k_1 \neq \omega^l k_2$ for all i, j, l . Let β and γ be random field elements. Let f and g be the polynomials that interpolate, respectively, the following values at Ω :

$$f : \{ (T_{0,j} + \omega^i \beta + \gamma) (T_{1,j} + \omega^i k_1 \beta + \gamma) (T_{2,j} + \omega^i k_2 \beta + \gamma) : 0 \leq i < N$$

$$g : \{ (T_{0,j} + S_{0,1}(\omega^i) \beta + \gamma) (T_{0,j} + S_{0,2}(\omega^i) \beta + \gamma) (T_{0,j} + S_{0,3}(\omega^i) \beta + \gamma)$$

So, $\exists Z \in \mathbb{F}[X]$ such that $\forall d \in \mathcal{D}$ we have $Z(\omega^0) = 1$ and $Z(d)f(d) = g(d)Z(\omega d) \leftrightarrow A = B$ w.h.p.

Summary | Matrices

Definition

Let T be a $N \times 3$ matrix with columns A, B, C and Π a $N \times 1$ matrix where N is the number of gates. They correspond to a valid execution instance with public input given by Π if and only if:

1. $\forall i : A_i Q_{Li} + B_i Q_{Ri} + A_i B_i Q_{Mi} + C_i Q_{Oi} + Q_{Ci} + \Pi_i = 0$
2. $\forall i, j, k, l : V_{i,j} = V_{k,l} \implies T_{i,j} = T_{k,l}$
3. $\forall i > n : \Pi_i = 0$

Summary | Polynomials


Definition

Let $z_\Omega = X^N - 1$. Let T be a $N \times 3$ matrix with columns A, B, C and Π a $N \times 1$ matrix. They correspond to a valid execution instance with public input given by Π if and only if:

1. $\exists t_1 \in \mathbb{F}[X] : aq_L + bq_R + abq_M + cq_O + q_C + \pi = z_\Omega t_1$
2. $\exists t_2, t_3, z \in \mathbb{F}[X] : zf - gz' = z_\Omega t_2$ and $(z - 1)L_1 = z_\Omega t_3$, where $z'(X) = z(X\omega)$.

Thank you for your attention



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