

Formalising Groth16 in Lean 4

Daniel Rogozin, for Yatima Inc

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1 Introduction

In this document, we describe the Groth16 soundness formalisation in Lean 4. The text contains the protocol description as well as some comments to its implementation.

Groth16 is a kind of ZK-SNARK protocol introduced in [1]. The latter means that:

- It is *zero-knowledge*. In other words, a prover only has a particular piece of information.
- It is *non-interactive* in order to make secret parameters reusable.

Protocols of this kind have the core characteristics such as:

- *Soundness*, i.e., if a statement does not hold, then the prover cannot convince the verifier.
- *Completeness*, i.e., the verifier is convinced whenever a statement is true.
- *Zero-knowledge*, i.e., the only thing is needed is the truth of a statement.

Generally, non-interactive zero-knowledge proofs relies on the *common reference string* model, that is, a model where a public string is generated in a trusted way and all parties have an access to it.

Let us describe the common scheme that non-interactive zero-knowledge protocols obey, see [2] to have more details. Before that, we need some bits of terminology. Let $p \in F[X]$ be a polynomial, a prover is going to convince a verifier that they know p . In turn, knowing p means that a prover knows some of its roots. As it is well-known, any polynomial might be decomposed as follows whenever it has roots (since fields we consider are finite and they are not algebraically closed):

$$p(x) = \prod_{i < \deg(p)} (x - a_i) \quad (1)$$

for some a_i , $i < \deg(p)$.

Assume that a prover has some values $\{r_i \mid i < n\}$ where each $r_i \in F$ for some $n \leq \deg(p)$. A prover wants to convince a verifier that $p(r_i)$ for each a_i from that set.

If there a_i 's are really roots of p , then the polynomial p can be rewritten as:

$$p(x) = \left(\prod_{i < n} (x - r_i) \right) \cdot h(x) \quad (2)$$

for some $h \in F[X]$.

Denote $(\prod_{i < n} (x - r_i))$ as $t(x)$. We shall call $t(x)$ further a *target polynomial*. So, a verifier accepts only if a target polynomial t divides p .

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*This document may be updated frequently.

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2 Preliminary definitions

We have a fixed finite field F , and $F[X]$ stands for the ring of polynomials over F as usual. The corresponding listing written in Lean:

```
variable {F : Type u} [field : Field F]
```

TODO: listings are rather ugly

In Groth16, we have random values $\alpha, \beta, \gamma, \delta \in F$ that we introduce separately as an inductive data type:

```
inductive Vars : Type
| alpha : Vars
| beta  : Vars
| gamma : Vars
| delta : Vars
```

We also introduce the following parameters:

- $n_{stmt} \in \mathbb{N}$ — the statement size;
- $n_{wit} \in \mathbb{N}$ — the witness size;
- $n_{var} \in \mathbb{N}$ — the number of variables.

In Lean 4, we introduce those parameters as variables in the following way:

```
variable {n_stmt n_wit n_var : Nat}
```

We also define several finite collections of polynomials:

- $u_{stmt} = \{f_i \in F[X] \mid i < n_{stmt}\}$
- $u_{wit} = \{f_i \in F[X] \mid i < n_{wit}\}$
- $v_{stmt} = \{f_i \in F[X] \mid i < n_{stmt}\}$
- $v_{wit} = \{f_i \in F[X] \mid i < n_{wit}\}$
- $w_{stmt} = \{f_i \in F[X] \mid i < n_{stmt}\}$
- $w_{wit} = \{f_i \in F[X] \mid i < n_{wit}\}$

We introduce those collections in Lean 4 as variables as well:

```
variable {u_stmt : Fin n_stmt → F[X]}
variable {u_wit  : Fin n_wit  → F[X]}
variable {v_stmt : Fin n_stmt → F[X]}
variable {v_wit  : Fin n_wit  → F[X]}
variable {w_stmt : Fin n_stmt → F[X]}
variable {w_wit  : Fin n_wit  → F[X]}
```

Let $(r_i)_{i < n_{wit}}$ be a collection of elements of F (that is, each $r_i \in F$) parametrised by elements of $\{0, \dots, n_{wit}\}$. Define a polynomial $t \in F[X]$ as:

$$t = \prod_{i < n_{wit}} (x - r_i).$$

Clearly, these r_i 's are roots of t . The definition in Lean 4:

```
variable (r : Fin n_wit → F)

def t : F[X] := Pi i in finRange n_wit ,
  (x : F[X]) - Polynomial.c (r i)
```

3 Properties of t

The polynomial t has the following properties:

Lemma 1.

1. $\deg(t) = n_{wit}$;
2. t is monic, that is, its leading coefficient is equal to 1;
3. If $n_{wit} > 0$, then $\deg(t) > 0$.

We formalise these statements as follows (but we skip proofs):

```
lemma nat_degree_t : (t r).natDegree = n_wit
lemma monic_t : Polynomial.Monic (t r)
lemma degree_t_pos (hm : 0 < n_wit) : 0 < (t r).degree
```

Let $\{a_{wit_i} | i < n_{wit}\}$ and $\{a_{stmt_i} | i < n_{stmt}\}$ be collections of elements of F . A statement witness polynomial pair is a pair of single variable polynomials $(F_{wit_{sv}}, F_{stmt_{sv}})$ such that $F_{wit_{sv}}, F_{stmt_{sv}} \in F[X]$ and

$$\begin{aligned} \bullet F_{wit_{sv}} &= \sum_{i < n_{wit}} a_{wit_i} u_{wit_i}(x) \\ \bullet F_{stmt_{sv}} &= \sum_{i < n_{stmt}} a_{stmt_i} u_{stmt_i}(x) \end{aligned}$$

Their Lean 4 counterparts:

```
def V_wit_sv (a_wit : Fin n_wit → F) : Polynomial F :=
  \sum i in finRange n_wit, a_wit i \bullet u_wit i

def V_stmt_sv (a_stmt : Fin n_stmt → F) : Polynomial F :=
  \sum i in finRange n_stmt, a_stmt i \bullet u_stmt i
```

Define a polynomial sat as:

$$\begin{aligned} sat &= (V_{stmt_{sv}} + V_{wit_{sv}}) \cdot \\ &\quad \cdot ((\sum_{i < n_{stmt}} a_{stmt_i} v_{stmt_i}(x)) + (\sum_{i < n_{wit}} a_{wit_i} v_{wit_i}(x))) - \\ &\quad - ((\sum_{i < n_{stmt}} a_{stmt_i} w_{stmt_i}(x)) + (\sum_{i < n_{wit}} a_{wit_i} w_{wit_i}(x))) \quad (3) \end{aligned}$$

A pair $(F_{wit_{sv}}, F_{stmt_{sv}})$ satisfies *the square span program*, if the remainder of division of sat by t is equal to 0. This requirement is common for ZK-SNARK protocols as we discussed in the first section.

The Lean 4 analogue of the property defined above:

```
def satisfying (a_stmt : Fin n_stmt → F) (a_wit : Fin n_wit → F) :=
  (((\sum i in finRange n_stmt, a_stmt i \bullet u_stmt i)
    + \sum i in finRange n_wit, a_wit i \bullet u_wit i)
  *
  ((\sum i in finRange n_stmt, a_stmt i \bullet v_stmt i)
```

$$\begin{aligned}
& + \sum_{i \text{ in } \text{finRange } n_wit, a_wit \ i} \bullet v_wit \ i) \\
& - ((\sum_{i \text{ in } \text{finRange } n_stmt, a_stmt \ i} \bullet w_stmt \ i) \\
& + \sum_{i \text{ in } \text{finRange } n_wit, a_wit \ i} \bullet w_wit \ i) : F[X]) \%_m (t \ r) = 0
\end{aligned}$$

4 Common reference string elements

Assume we interpreted α , β , γ , and δ somehow with elements of F , say crs_α , crs_β , crs_γ , and crs_δ , that is, in Lean 4:

```
def crs_alpha (f : Vars → F) : F := f Vars.alpha
```

```
def crs_beta (f : Vars → F) : F := f Vars.beta
```

```
def crs_gamma (f : Vars → F) : F := f Vars.gamma
```

```
def crs_delta (f : Vars → F) : F := f Vars.delta
```

For simplicity, we write this interpretation as a function $f : \{\alpha, \beta, \gamma, \delta\} \rightarrow F$ defined by equations:

$$f(a) = crs_a \text{ for } a \in \{\alpha, \beta, \gamma, \delta\}.$$

In addition to those four elements of F we have a collection of degrees for $a \in F$:

$$\{a^i \mid i < n_{var}\}$$

formalised as:

```
def crs_powers_of_x (i : Fin n_var) (a : F) : F := (a)^(i : Nat)
```

We also introduce collections crs_l , crs_m , and crs_n for $a \in F$:

$$crs_l = \frac{((f(\beta)/f(\gamma)) \cdot (u_{stmt_i})(a)) + ((f(\alpha)/f(\gamma)) \cdot (v_{stmt_i})(a)) + w_{stmt_i}(a)}{f(\gamma)} \quad \text{for } i < n_{stmt} \quad (4)$$

$$crs_l = \frac{((f(\beta)/f(\delta)) \cdot (u_{wit_i})(a)) + ((f(\alpha)/f(\delta)) \cdot (v_{wit_i})(a)) + w_{wit_i}(a)}{f(\delta)} \quad \text{for } i < n_{wit} \quad (5)$$

$$crs_l = \frac{a^i \cdot t(a)}{f(\delta)}, \text{ for } i < n_{var} \quad (6)$$

Their Lean 4 version:

```
def crs_l (i : Fin n_stmt) (f : Vars → F) (a : F) : F :=
  ((f Vars.beta / f Vars.gamma) * (u_stmt i).eval (a)
  +
  (f Vars.alpha / f Vars.gamma) * (v_stmt i).eval (a)
  +
  (w_stmt i).eval (a)) / f Vars.gamma.
```

```
def crs_m (i : Fin n_wit) (f : Vars → F) (a : F) : F :=
```

```

((f Vars.beta / f Vars.delta) * (u_wit i).eval (a)
+
(f Vars.alpha / f Vars.delta) * (v_wit i).eval (a)
+
(w_wit i).eval (a)) / f Vars.delta

```

```

def crs_n (i : Fin (n_var - 1)) (f : Vars → F) (a : F) : F :=
  ((a)^(i : Nat)) * (t r).eval a / f Vars.delta

```

Assume we have fixed elements of a field $A_\alpha, A_\beta, A_\gamma, A_\delta, B_\alpha, B_\beta, B_\gamma, B_\delta, C_\alpha, C_\beta, C_\gamma, C_\delta$.

We also have indexed collections $\{A_x \in F \mid x < n_{var}\}, \{B_x \in F \mid x < n_{var}\}, \{C_x \in F \mid x < n_{var}\}, \{A_l \in F \mid l < n_{stmt}\}, \{B_l \in F \mid l < n_{stmt}\}, \{C_l \in F \mid l < n_{stmt}\}, \{A_m \in F \mid m < n_{wit}\}, \{B_m \in F \mid m < n_{wit}\}, \{C_m \in F \mid m < n_{wit}\}, \{A_h \in F \mid h < n_{var-1}\}, \{B_h \in F \mid h < n_{var-1}\}, \{C_h \in F \mid h < n_{var-1}\}$.

```

variable { A_alpha A_beta A_gamma A_delta : F }
variable { B_alpha B_beta B_gamma B_delta : F }
variable { C_alpha C_beta C_gamma C_delta : F }
variable { A_x B_x C_x : Fin n_var → F }
variable { A_l B_l C_l : Fin n_stmt → F }
variable { A_m B_m C_m : Fin n_wit → F }
variable { A_h B_h C_h : Fin (n_var - 1) → F }

```

The adversary's proof representation is defined as the following three sums, for $x \in F$:

$$\begin{aligned}
A = & A_\alpha \cdot crs_\alpha + A_\beta \cdot crs_\beta + A_\gamma \cdot crs_\gamma + A_\delta \cdot crs_\delta + \\
& + \sum_{i < n_{var}} A_{x_i} * x^i + \sum_{i < n_{stmt}} A_{l_i} * crs_l(x) + \\
& + \sum_{i < n_{wit}} A_{m_i} * crs_m(x) + \sum_{i < n_{var-1}} A_{h_i} * crs_n(x) \quad (7)
\end{aligned}$$

$$\begin{aligned}
B = & B_\alpha \cdot crs_\alpha + B_\beta \cdot crs_\beta + B_\gamma \cdot crs_\gamma + B_\delta \cdot crs_\delta + \\
& + \sum_{i < n_{var}} B_{x_i} * x^i + \sum_{i < n_{stmt}} B_{l_i} * crs_l(x) + \\
& + \sum_{i < n_{wit}} B_{m_i} * crs_m(x) + \sum_{i < n_{var-1}} B_{h_i} * crs_n(x) \quad (8)
\end{aligned}$$

$$\begin{aligned}
C = & C_\alpha \cdot crs_\alpha + C_\beta \cdot crs_\beta + C_\gamma \cdot crs_\gamma + C_\delta \cdot crs_\delta + \\
& + \sum_{i < n_{var}} C_{x_i} * x^i + \sum_{i < n_{stmt}} C_{l_i} * crs_l(x) + \\
& + \sum_{i < n_{wit}} C_{m_i} * crs_m(x) + \sum_{i < n_{var-1}} C_{h_i} * crs_n(x) \quad (9)
\end{aligned}$$

Here, we provide the Lean 4 version of A only.

```

def A (f : Vars → F) (x : F) : F :=
  (A_alpha * crs_alpha F f)
+

```

```

A_beta * crs_beta F f
+
A_gamma * crs_gamma F f
+
A_delta * crs_delta F f
+
\sum i in (finRange n_var), (A_x i) * (crs_powers_of_x F i x)
+
\sum i in (finRange n_stmt),
  (A_l i) * (@crs_l F field n_stmt u_stmt v_stmt w_stmt i f x)
+
\sum i in (finRange n_wit),
  (A_m i) * (@crs_m F field n_wit u_wit v_wit w_wit i f x)
+
\sum i in (finRange (n_var - 1)), (A_h i) * (crs_n F r i f x)

```

A proof is called *verified*, if the following equation holds:

$$A \cdot B = crs_\alpha \cdot crs_\beta + \left(\sum_{i < n_{stmt}} a_{stmt_i} \cdot crs_{l_i}(x) \right) \cdot crs_\gamma + C \cdot crs_\delta \quad (10)$$

```

def verified (f : Vars -> F) (x : F) (a_stmt : Fin n_stmt -> F) : Prop :=
  A f x * B f x =
    (crs_alpha F f * crs_beta F f) +
    ((\sum i in finRange n_stmt, (a_stmt i) * @crs_l i f x) *
     (crs_gamma F f) + C f x * (crs_delta F f))

```

5 Modified common reference string elements

We modify common reference string elements from the previous section as multivariate polynomials.

6 Coefficient lemmas

7 Formalised soundness

References

- [1] Jens Groth. On the size of pairing-based non-interactive arguments. In *Annual international conference on the theory and applications of cryptographic techniques*, pages 305–326. Springer, 2016.
- [2] Maksym Petkus. Why and how zk-snark works: Definitive explanation. *arXiv preprint arXiv:1906.07221*, 2019.