

# MERCURY: A multilinear Polynomial Commitment Scheme with constant proof size and no prover FFTs

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## Abstract

We construct a pairing-based polynomial commitment scheme for multilinear polynomials of size  $n$  where constructing an opening proof requires  $O(n)$  field operations, and  $2n + O(\sqrt{n})$  scalar multiplications. Moreover, the opening proof consists of a constant number of field elements. This is a significant improvement over previous works which would require either

1.  $O(n \log n)$  field operations; or
2.  $O(\log n)$  size opening proof.

The main technical component is a new method of verifiably folding a witness via univariate polynomial division. As opposed to previous methods, the proof size and prover time remain constant *regardless of the folding factor*.

## 1 Introduction

Polynomial Commitment Schemes (PCSs)[KZG10] allow a party to commit to a polynomial and later prove an evaluation of the polynomial is correct. That is, for a commitment  $\text{cm}$  and values  $a, b$ ; a prover  $\mathbf{P}$  can produce a proof that  $\text{cm} = \text{com}(f(X))$  and  $f(a) = b$ . PCSs form an essential part of most modern Succinct Non-interactive ARguments of Knowledge (SNARKs). They allow a protocol designer to focus on designing a so-called polynomial Interactive Oracle Proof which can then be compiled, via a PCS, to a SNARK (see [BFS19, GWC19, CHM<sup>+</sup>19] for descriptions of such compilers). In fact,

many of the most important properties of a SNARK, like proof size, verifier complexity, and cryptographic assumptions, follow primarily from the PCS. The earliest polynomial commitment schemes [KZG10] supported univariate polynomials and were used to construct SNARKs like Plonk [GWC19] and Marlin [CHM<sup>+</sup>19] with  $O(n \log n)$  prover complexity and constant proof size. A different class of SNARKs [Set19, CBBZ22] arising from the sumcheck protocol [LFKN92] have linear prover time, but require *multilinear* Polynomial Commitment Schemes (ml-PCS’s).

## 1.1 Our results

Existing transformations from a univariate PCS to ml-PCS are either linear time but require a logarithmic opening proof size, like **gemini** [BCHO22] and **zeromorph** [KT23], or have constant size opening proofs but incur an additional  $O(n \log n)$  prover cost to perform univariate polynomial multiplication via FFT’s. We propose a new protocol that goes beyond this tradeoff: **mercuryl** has constant proof size and only  $O(n)$  prover operations (in addition to the  $O(\lambda n / (\log(\lambda n)))$  operations for multi-scalar multiplications arising in KZG commitments). It is also concretely more efficient than existing schemes with similar verifier complexity<sup>1</sup> in terms of the required scalar multiplications, as can be seen in table 1.

Table 1: Comparison of pairing-based ml-PCS.  $\mathbb{G}$  denotes a scalar multiplication. All verifiers below additionally require two pairings. Proof size is measured in elements of  $\mathbb{F}$ , and uses the fact that a  $\mathbb{G}$ -element is encoded by two  $\mathbb{F}$ -elements.

Scheme	Proof size	Prover Work	Verifier Work
univariate-based e.g. [PH23]	$O(1)$	$O(n \log n) \mathbb{F}, O(n) \mathbb{G}$	$O(\log n) \mathbb{F}, O(1) \mathbb{G}$
<b>gemini</b> [BCHO22]	$O(\log n)$	$O(n) \mathbb{F}, 3n \mathbb{G}$	$O(\log n) \mathbb{F}, O(\log n) \mathbb{G}$
<b>zeromorph</b> [KT23]	$O(\log n)$	$O(n) \mathbb{F}, 2.5n \mathbb{G}$	$O(\log n) \mathbb{F}, O(\log n) \mathbb{G}$
<b>mercuryl</b> (this work)	$O(1)$	$O(n) \mathbb{F}, 2n + O(\sqrt{n}) \mathbb{G}$	$O(\log n) \mathbb{F}, O(1) \mathbb{G}$

## 2 Overview of technique

*In this overview, we use some of the notation defined in Sections 3.1 and 3.2.*

Our technique is best thought of as an improvement of the **gemini** ml-PCS [BCHO22]. Let’s start by recalling how **gemini** works. **gemini** commits to a multilinear function as a *univariate* KZG commitment [KZG10]. Specifically, fix a vector  $f \in \mathbb{F}^n$  describing the function’s values on the boolean cube  $\mathbf{B}_s$  where  $s = \log n$ . That is, we think of  $f$  as

<sup>1</sup>The ml-PCS from [KZHB25] requires only  $O(\sqrt{n})$  scalar multiplications. However, it requires  $O(\log n)$  proof length and  $O(\log n)$  verifier pairings whereas all schemes in table 1 require only two.

representing the multilinear

$$M(X_0, \dots, X_{s-1}) = \sum_{i < n} \mathbf{eq}(i, X_0, \dots, X_{s-1}) f_i.$$

(Here, as explained in Section 3.2, we interpret  $i$  as its binary decomposition  $(i_0, \dots, i_{s-1})$  when used as input to  $\mathbf{eq}$ .) Let  $\mathbf{srs} = \{[x^i]\}_{i < n}$  be a KZG structured reference string. **gemini** outputs  $\mathbf{cm} = [f(x)] = \sum_{i < n} f_i [x^i]$  as a commitment to  $M$ .

Now suppose prover **P** wants to convince verifier **V** that  $M(z) = v$ , for some  $z = (z_0, \dots, z_{s-1}) \in \mathbb{F}^s$ . In **gemini**, **P** sends commitments  $\mathbf{cm}_1, \dots, \mathbf{cm}_s$  to the  $s$  incremental restrictions leading to evaluation at  $z$ . Namely, to  $M_1 = M(z_0, X_1, \dots, X_{s-1})$ ,  $M_2 = M(z_0, z_1, X_2, \dots, X_{s-1})$ ,  $\dots$ ,  $M_s = M(z_0, \dots, z_{s-1})$ . Assuming **P** sent commitments to the correct functions, all that is needed is to check that  $\mathbf{cm}_s$  is the commitment to the constant  $v$ . Of course, the interesting part is proving the commitments *are* to the correct functions!

For this purpose, **gemini** exploits a connection between  $M$  and its corresponding univariate  $f(X)$ : Write  $f(X) = f_0(X^2) + X f_1(X^2)$ , for  $f_0(X), f_1(X)$  of degree  $< n/2$ . Let  $f_{z_0}(X)$  be the univariate corresponding to  $M_1$  defined above. Then, we have

$$f_{z_0}(X) = (1 - z_0)f_0(X) + z_0 f_1(X).$$

Additionally, we can evaluate  $f_0$  and  $f_1$  via  $f$  using the equations

$$f_0(X^2) = \frac{f(X) + f(-X)}{2}, f_1(X^2) = \frac{f(X) - f(-X)}{2X}$$

Thus, we can perform consistency checks between each pair  $\mathbf{cm}_{i-1}, \mathbf{cm}_i$ , via univariate KZG openings at a random challenge, inductively showing  $\mathbf{cm}_i$  is indeed the commitment to the next desired restriction. Of course, we get  $O(s) = O(\log n)$  proof length due to this sequence of restriction commitments.

Here is a first idea on how to reduce proof length. Protocols based on univariate polynomials allow us to do multilinear evaluation in  $O(n \log n)$  prover time with constant proof size (e.g. Section 5 of [PH23]). Choose a parameter  $t$  and set  $b = 2^t$ . We can run *only the first  $t$  rounds* of **gemini**, reaching a restricted multilinear on  $n - t$  variables. If  $n' = n/b \leq n/\log n$ , we can afford to run a univariate protocol with  $O(n' \log n') = O(n)$  prover time to evaluate  $M_t(z_t, \dots, z_{s-1})$ . This still doesn't take us to overall constant proof size - as we need to use a super-constant  $t$  to reach such  $n'$ . (For us  $t = \log n/2$  will be optimal, although  $t \geq \log \log n$  suffices here.)

This raises the question - can we "skip" the intermediate **gemini** rounds and send *only* the commitment  $\mathbf{cm}_t$ , and directly prove it is consistent with the original  $\mathbf{cm}$ ? Extrapolating the **gemini** strategy in the natural way, we get the answer - yes, but not with constant proof size: We can decompose  $f$  into  $b$  polynomials of degree  $< n/b$ :  $f(X) = \sum_{0 \leq i < b} X^i f_i(X^b)$ . As in the  $b = 2$  case, one can show the univariate  $f'(X)$  corresponding to  $M_t$  is a linear combination of the  $\{f_i(X)\}$ . Moreover, evaluating the  $f_i$  using  $f$  (for the consistency check) can be done. However, it requires  $b$  evaluations of

$f$ . Specifically,  $f_i(r^b)$  is a linear combination of  $\{f(r), f(r\omega), \dots, f(r\omega^{b-1})\}$  where  $\omega$  is a primitive  $b$ 'th root of unity.

Our central innovation is a different way to prove  $\text{cm}_t$  is correct *with* constant proof size. Let's switch notation and denote the opening point as  $u = (u_1, u_2)$  where  $u_1 \in \mathbb{F}^t, u_2 \in \mathbb{F}^{s-t}$ . The (univariate corresponding to the) correct restricted polynomial is

$$h(X) = \sum_{0 \leq i < b} \mathbf{eq}(i, u_1) f_i(X).$$

Let  $g(X) := f(X) \bmod X^b - \alpha$ . Calculation shows

$$g(X) = \sum_{0 \leq i < b} X^i f_i(\alpha).$$

The multilinear  $\hat{g}$  corresponding to  $g(X)$  is

$$\hat{g}(X_0, \dots, X_{t-1}) = \sum_{0 \leq i < b} \mathbf{eq}(i, X_0, \dots, X_{t-1}) f_i(\alpha).$$

In particular, we have

$$\hat{g}(u_1) = \sum_{0 \leq i < b} \mathbf{eq}(i, u_1) f_i(\alpha) = h(\alpha).$$

In words, the evaluation of  $g$  at  $u_1$  as a *multilinear* corresponds to the evaluation of  $h$  at  $\alpha$  as a univariate! We can use standard univariate KZG to open  $\text{cm}_t$  at  $\alpha$ . And, crucially, we can afford to evaluate  $\hat{g}(u_1)$  using the aforementioned univariate protocols as it is of size  $b$  rather than  $n$ . In summary, we can show a committed polynomial corresponds to the correct restriction. And now, again, we can afford to open  $h$  as a multilinear at  $u_2$  using univariate protocols as it has size  $n/b$  rather than  $n$ .

**Comparison to sumcheck** It is instructive to see what happens if we try to get a similar result via a modification of the sumcheck protocol [LFKN92]. Note first that a multilinear evaluation can indeed be written as a sum over the function's values on  $\mathbf{B}_s$  multiplied by the  $\mathbf{eq}$  function:

$$M(u) = \sum_{b \in \mathbf{B}_s} \mathbf{eq}(b, u) M(b).$$

The classic sumcheck protocol, like *gemini*, works by  $\log n$  reductions of the domain size by a factor of two; each round fixing one more variable of the summed function. In the above spirit, we could look at a modified sumcheck protocol, where the first variable ranges over a domain of super-constant size  $b$ . The first round univariate  $P_1$  would thus have degree roughly  $2b$ . To maintain constant proof length, we could send a commitment to  $P_1$  rather than its coefficients (as usually done in sumcheck). However, *computing*  $P_1$  would require superlinear time  $O(n \log b)$  - as we need to perform a  $b$ -size FFT for  $n/b$  values of the second variable appearing in the sum.

### 3 Preliminaries

#### 3.1 Terminology and conventions

**Fields and Groups** We assume our field  $\mathbb{F}$  is of prime order. We denote by  $\mathbb{F}_{<d}[X]$  the set of univariate polynomials over  $\mathbb{F}$  of degree smaller than  $d$ . We assume all algorithms described receive as an implicit parameter the security parameter  $\lambda$ .

Whenever we use the term *efficient*, we mean an algorithm running in time  $\text{poly}(\lambda)$ . Furthermore, we assume an *object generator*  $\mathcal{O}$  that is run with input  $\lambda$  before all protocols, and returns all fields and groups used. Specifically, in our protocol  $\mathcal{O}(\lambda) = (\mathbb{F}, \mathbb{G}, \mathbb{G}_2, \mathbb{G}_t, e, \mathcal{g}, \mathcal{g}_2, \mathcal{g}_t)$  where

- $\mathbb{F}$  is a prime field of super-polynomial size  $r = \lambda^{\omega(1)}$ .
- $\mathbb{G}, \mathbb{G}_2, \mathbb{G}_t$  are all groups of size  $r$ , and  $e$  is an efficiently computable non-degenerate pairing  $e : \mathbb{G} \times \mathbb{G}_2 \rightarrow \mathbb{G}_t$ .
- $\mathcal{g}, \mathcal{g}_2$  are uniformly chosen generators such that  $e(\mathcal{g}, \mathcal{g}_2) = \mathcal{g}_t$ .

We usually let the  $\lambda$  parameter be implicit, i.e. write  $\mathbb{F}$  instead of  $\mathbb{F}(\lambda)$ . We write  $\mathbb{G}$  and  $\mathbb{G}_2$  additively. We use the notations  $[x] := x \cdot \mathcal{g}$  and  $[x]_2 := x \cdot \mathcal{g}_2$ .

**Vectors and polynomials** We work with integer parameter  $n$  that we'll assume throughout the paper is of the form  $n = 2^{2t}$  for integer  $t > 0$ . We'll denote its square root by  $b := 2^t = \sqrt{n}$ . We index vectors starting from zero. For example, for  $g \in \mathbb{F}^b$  we have  $g = (g_0, \dots, g_{b-1})$ . We associate vectors with univariate polynomials in the following natural way: Given  $g \in \mathbb{F}^b$  we denote  $g(X) := \sum_{0 \leq i < b} g_i X^i$ .

We make the convention that integer ranges in sums begin at zero if not specified otherwise. Thus, we write  $g(X) = \sum_{i < b} g_i X^i$ .

We assume vectors of size  $n$  are indexed by two indices ranging over  $\{0, \dots, b-1\}$ . Thus, for  $f \in \mathbb{F}^n$ , we have  $f = (f_{0,0}, \dots, f_{0,b-1}, \dots, f_{b-1,0}, \dots, f_{b-1,b-1})$ . For  $0 \leq i < b$ , we denote by  $f_i$  the vector  $(f_{0,i}, \dots, f_{b-1,i})$ .

In particular, for  $f \in \mathbb{F}^n$  we have under these notations that

$$f(X) := \sum_{i < b} X^i f_i(X^b) = \sum_{i < b} \sum_{j < b} f_{i,j} X^{i+j \cdot b}$$

For integer  $m > 0$ , we denote by  $\mathbf{B}_m$  the binary cube  $\{0, 1\}^m \subset \mathbb{F}^m$  of dimension  $m$ .

#### 3.2 Multilinear polynomials

Let  $n = 2^{2t}$ , and  $s = 2t$ . We define the well-known **eq** multilinear polynomial in  $2s$  variables.

$$\mathbf{eq}(x, y) := \prod_{i=0}^{s-1} (x_i y_i + (1 - x_i)(1 - y_i))$$

We have for  $x, y \in \mathbf{B}_s$ ,  $\mathbf{eq}(x, y) = 1$  when  $x = y$  and  $\mathbf{eq}(x, y) = 0$  otherwise.

We use the convention that an integer  $0 \leq i < n$  can be used as an input to  $\mathbf{eq}$  by interpreting  $i$  as its binary representation. Namely, for  $0 \leq i < n$ ,  $u \in \mathbb{F}^s$ ,  $\mathbf{eq}(i, u) := \mathbf{eq}(i_0, \dots, i_{s-1}, u)$  where  $i = \sum_{j < s} i_j 2^j$ .

For  $f \in \mathbb{F}^n$ , we define  $\hat{f}$  to be the multilinear polynomial obtaining  $f$ 's values on the boolean cube. Namely,

$$\hat{f}(X_0, \dots, X_{s-1}) := \sum_{i < n} \mathbf{eq}(i, X_0, \dots, X_{s-1}) \cdot f_i.$$

**Decomposing  $\mathbf{eq}$**  We'll overload  $\mathbf{eq}$  to also denote the analogous equality function for  $x, y \in \mathbf{B}_t$ . With this overloading, given  $w_1, w_2, u_1, u_2 \in \mathbf{B}_t$  we have the convenient decomposition

$$\mathbf{eq}((w_1, w_2), (u_1, u_2)) = \mathbf{eq}(w_1, u_1) \mathbf{eq}(w_2, u_2).$$

### 3.3 The algebraic group model

We introduce some terminology from [GWC19] to capture analysis in the Algebraic Group Model of Fuchsbauer, Kiltz and Loss [FKL18]. In this subsection, we use the notation  $\mathbb{G}_1 = \mathbb{G}$ . In our protocols, by an *algebraic adversary*  $\mathcal{A}$  in an SRS-based protocol we mean a  $\text{poly}(\lambda)$ -time algorithm which satisfies the following.

- For  $i \in \{1, 2\}$ , whenever  $\mathcal{A}$  outputs an element  $A \in \mathbb{G}_i$ , it also outputs a vector  $v$  over  $\mathbb{F}$  such that  $A = \langle v, \mathbf{srs}_i \rangle$ .

First we say our  $\mathbf{srs}$  has *degree*  $Q$  if all elements of  $\mathbf{srs}_i$  are of the form  $[f(x)]_i$  for  $f \in \mathbb{F}_{<Q+1}[X]$  and uniform  $x \in \mathbb{F}$ . In the following discussion let us assume we are executing a protocol with a degree  $Q$  SRS, and denote by  $f_{i,j}$  the corresponding polynomial for the  $j$ 'th element of  $\mathbf{srs}_i$ .

Denote by  $a, b$  the vectors of  $\mathbb{F}$ -elements whose encodings in  $\mathbb{G}_1, \mathbb{G}_2$  an algebraic adversary  $\mathcal{A}$  outputs during a protocol execution; e.g., the  $j$ 'th  $\mathbb{G}_1$  element output by  $\mathcal{A}$  is  $[a_j]$ .

By a “real pairing check” we mean a check of the form

$$(a \cdot T_1) \cdot (T_2 \cdot b) = 0$$

for some matrices  $T_1, T_2$  over  $\mathbb{F}$ . Note that such a check can indeed be done efficiently given the encoded elements and the pairing function  $e : \mathbb{G}_1 \times \mathbb{G}_2 \rightarrow \mathbb{G}_t$ .

Given such a “real pairing check”, and the adversary  $\mathcal{A}$  and protocol execution during which the elements were output, define the corresponding “ideal check” as follows. Since  $\mathcal{A}$  is algebraic when he outputs  $[a_j]_i$ , he also outputs a vector  $v$  such that, from linearity,  $a_j = \sum v_\ell f_{i,\ell}(x) = R_{i,j}(x)$  for  $R_{i,j}(X) := \sum v_\ell f_{i,\ell}(X)$ . Denote, for  $i \in \{1, 2\}$  the vector of polynomials  $R_i = (R_{i,j})_j$ . The corresponding ideal check, checks as a polynomial identity whether

$$(R_1 \cdot T_1) \cdot (T_2 \cdot R_2) \equiv 0$$

The following lemma is inspired by [FKL18]’s analysis of [Gro16], and tells us that for soundness analysis against algebraic adversaries it suffices to look at ideal checks. Before stating the lemma we define the  $Q$ -DLOG assumption similarly to [FKL18].

**Definition 3.1.** Fix integer  $Q$ . The  $Q$ -DLOG assumption for  $(\mathbb{G}_1, \mathbb{G}_2)$  states that given

$$[1], [x], \dots, [x^Q], [1]_2, [x]_2, \dots, [x^Q]_2$$

for uniformly chosen  $x \in \mathbb{F}$ , the probability of an efficient  $\mathcal{A}$  outputting  $x$  is  $\text{negl}(\lambda)$ .

**Lemma 3.2.** Assume the  $Q$ -DLOG for  $(\mathbb{G}_1, \mathbb{G}_2)$ . Given an algebraic adversary  $\mathcal{A}$  participating in a protocol with a degree  $Q$  SRS, the probability of any real pairing check passing is larger by at most an additive  $\text{negl}(\lambda)$  factor than the probability the corresponding ideal check holds.

See [GWC19] for the proof.

### 3.4 Polynomial commitment schemes for multilinear polynomials

We give a formal definition of an ml-PCS secure in the algebraic group model.

**Definition 3.3.** Let  $n = 2^s$ . A multilinear polynomial commitment scheme (ml-PCS) consists of

- $\text{gen}(n)$  - a randomized algorithm that outputs an SRS  $\text{srs}$ .
- $\text{com}(f, \text{srs})$  - that given a polynomial  $f \in \mathbb{F}^n$  returns a commitment  $\text{cm}$  to  $f$ .
- A public coin protocol  $\text{open}(\text{cm}, n, u, v)$  between parties  $\mathbf{P}$  and  $\mathbf{V}$ .  $\mathbf{P}$  is given  $f \in \mathbb{F}^n$ .  $\mathbf{P}$  and  $\mathbf{V}$  are both given integer  $n$ ,  $\text{cm}$  - the purported commitment to  $f$ ,  $u \in \mathbb{F}^s$  and  $v \in \mathbb{F}$  - the purported value  $\hat{f}(u)$ .

such that

- **Completeness:** Suppose that  $\text{cm} = \text{com}(f, \text{srs})$ . Then if  $\text{open}$  is run correctly with values  $n, \text{cm}, u, v = \hat{f}(u)$ ,  $\mathbf{V}$  outputs *accept* with probability one.
- **Knowledge soundness in the algebraic group model:** There exists an efficient  $\mathcal{E}$  such that for any efficient algebraic adversary  $\mathcal{A}$  the probability of  $\mathcal{A}$  winning the following game is  $\text{negl}(\lambda)$  over the randomness of  $\mathcal{A}$  and  $\text{gen}$ .
  1. Given  $\text{srs}$ ,  $\mathcal{A}$  outputs  $n, \text{cm}$ .
  2.  $\mathcal{E}$ , given access to the messages of  $\mathcal{A}$  during the previous step, outputs  $f \in \mathbb{F}^n$ .
  3.  $\mathcal{A}$  outputs  $u \in \mathbb{F}^s$  and  $v \in \mathbb{F}$ .
  4.  $\mathcal{A}$  takes the part of  $\mathbf{P}$  in the protocol  $\text{open}$  with inputs  $n, \text{cm}, u, v$ .
  5.  $\mathcal{A}$  wins if
    - $\mathbf{V}$  outputs *accept* at the end of the protocol.
    - $\hat{f}(u) \neq v$ .

## 4 Components

In this section we go over known components (with some new optimizations), that will be used in our main protocol in Section 6. The treatment will be semi-formal, and assume basic familiarity with the KZG polynomial commitment scheme [KZG10]. The formal treatment will be part of the description and knowledge soundness proof of the main protocol in Section 6.

### 4.1 Inner products in $O(b \log b)$ time.

Fix polynomials  $g_1(X) = \sum_{i=0}^{d_1} a_i X^i$ ,  $g_2(X) = \sum_{i=0}^{d_2} b_i X^i$  in  $\mathbb{F}[X]$ . We define  $\langle g_1, g_2 \rangle$  to be  $\sum_{i=0}^d a_i b_i$  where  $d := \min\{d_1, d_2\}$ . We present a convenient way to verify inner products  $\langle g_1, g_2 \rangle$  similar to [BCC<sup>+</sup>16, MBKM19]. The basic observation is that  $\langle g_1, g_2 \rangle$  is the constant coefficient of the rational function  $R(X) := g_1(X)g_2(1/X)$ . Thus,  $\langle g_1, g_2 \rangle = v$  is equivalent to the existence of polynomials  $S_1(X), S_2(X)$  such that

$$g_1(X)g_2(1/X) = 1/X \cdot S_1(1/X) + v + X \cdot S_2(X).$$

We can thus send commitments to  $S_1, S_2$  as proof of the correctness of  $v$ . As an optimization, we observe that we can “symmetrize”  $R$  and look instead at the rational function

$$R'(X) := g_1(X)g_2(1/X) + g_1(1/X)g_2(X).$$

The advantage of  $R'$  is that the negative and positive coefficients are equal. Thus,  $\langle g_1, g_2 \rangle = v$  is equivalent to the existence of  $S(X) \in \mathbb{F}[X]$  such that

$$g_1(X)g_2(1/X) + g_1(1/X)g_2(X) = 2v + X \cdot S(X) + (1/X)S(1/X).$$

**Claim 4.1.** *Suppose  $g_1(X), g_2(X) \in \mathbb{F}_{<b}[X]$ . Let  $S(X)$  be as defined above. Then  $S$  can be computed in  $O(b \log b)$   $\mathbb{F}$ -operations.*

*Proof.* When  $g_1(X), g_2(X) \in \mathbb{F}_{<b}[X]$  we multiply the equation above by  $X^{b-1}$  to get

$$X^{b-1}(g_1(X)g_2(1/X) + g_1(1/X)g_2(X)) = X^{b-1}(2v + X \cdot S(X) + (1/X)S(1/X)).$$

We can use an  $O(b \log b)$  time FFT to evaluate the LHS on  $2b$  points. We then do an inverse FFT to get the coefficients  $c_0, \dots, c_{2b-2}$  of the LHS. Now, we can output  $S = (c_b, \dots, c_{2b-2})$ .  $\square$

**Batching inner product checks** Suppose we now have two inner product claims  $\langle g_1, g_2 \rangle = v_1$  and  $\langle h_1, h_2 \rangle = v_2$ . The following claim gives us a way to randomly batch them so that one polynomial  $S(X)$  suffices to prove both.



**Claim 4.2.** Fix polynomials  $g_1, g_2, h_1, h_2 \in \mathbb{F}[X]$  and  $v_1, v_2 \in \mathbb{F}$ . Suppose  $\langle g_1, g_2 \rangle \neq v_1$  or  $\langle h_1, h_2 \rangle \neq v_2$ . Then, e.w.p  $1/|\mathbb{F}|$  over  $\gamma \in \mathbb{F}$  there does not exist  $S(X) \in \mathbb{F}[X]$  such that

$$\begin{aligned} g_1(X)g_2(1/X) + g_1(1/X)g_2(X) + \gamma(h_1(X)h_2(1/X) + h_1(1/X)h_2(X)) \\ = 2(v_1 + \gamma v_2) + X \cdot S(X) + (1/X)S(1/X) \end{aligned}$$

*Proof.* Denote  $(v'_1, v'_2) = (\langle g_1, g_2 \rangle, \langle h_1, h_2 \rangle)$ . The constant coefficient of the LHS is  $v'_1 + \gamma v'_2$ . To satisfy the equation in the claim for some  $S$ , we need

$$v'_1 + \gamma v'_2 = v_1 + \gamma v_2,$$

which can hold for at most one  $\gamma$  when  $(v_1, v_2) \neq (v'_1, v'_2)$ .  $\square$

#### 4.2 Multilinear evaluations as inner products of univariate polynomials.

For  $u \in \mathbf{B}_t$  define the polynomial  $P_u(X) := \sum_{i < b} \mathbf{eq}(i, u)X^i$ . Note that for  $g(X) \in \mathbb{F}_{<b}[X]$ , we have

$$\langle P_u, g \rangle = \sum_{i < b} \mathbf{eq}(i, u)g_i = \hat{g}(u).$$

As leveraged in [BGH19], we have the product formula

$$P_u(X) = \prod_{i=0}^{t-1} (u_i X^{2^i} + 1 - u_i),$$

implying  $P_u(X)$  can be evaluated in  $O(t)$   $\mathbb{F}$ -operations. Hence, a verifier  $\mathbf{V}$  operating in  $O(\log n)$  time can evaluate  $P_u(X)$  itself.

Using the polynomials  $P_u$ , multilinear evaluations can be proven in a batched manner based on Claim 4.2: Suppose we want to show given committed univariates  $g(X), h(X) \in \mathbb{F}[X]$ ,  $u_1, u_2 \in \mathbb{F}^t$ ,  $v_1, v_2 \in \mathbb{F}$  that  $\hat{g}(u_1) = v_1$  and  $\hat{h}(u_2) = v_2$ .

1.  $\mathbf{V}$  sends random  $\gamma \in \mathbb{F}$ .
2.  $\mathbf{P}$  sends commitment to  $S$  such that

$$\begin{aligned} g(X)P_{u_1}(1/X) + g(1/X)P_{u_1}(X) + \gamma(h(X)P_{u_2}(1/X) + h(1/X)P_{u_2}(X)) \\ = 2(v_1 + \gamma v_2) + X \cdot S(X) + (1/X)S(1/X). \end{aligned}$$

3.  $\mathbf{V}$  chooses a random  $\mathfrak{z} \in \mathbb{F}$ .
4.  $\mathbf{P}$  sends and proves correctness of the values of  $g, h$  and  $S$  on  $\mathfrak{z}, 1/\mathfrak{z}$ .
5.  $\mathbf{V}$  evaluates  $P_{u_1}, P_{u_2}$  at  $\mathfrak{z}, 1/\mathfrak{z}$ .
6.  $\mathbf{V}$  checks the equation in step 2 holds at  $\mathfrak{z}$ .

### 4.3 Degree checks

The idea presented here is from [Tha23]. Suppose  $\mathbf{P}$  wants to prove to  $\mathbf{V}$  that  $\mathbf{cm}$  is a commitment to a polynomial  $g(X) \in \mathbb{F}_{<b}[X]$ . Let  $D(X) := X^{b-1}g(1/X)$ . The idea is that  $D(X)$  is a polynomial if and only if  $g(X)$  has degree  $< b$ . Thus, assuming our structured reference string doesn't contain negative powers,  $\mathbf{P}$  can commit to  $D$  if and only if  $g(X) \in \mathbb{F}_{<b}[X]$ .

This motivates the following protocol.

1.  $\mathbf{P}$  sends a commitment  $\mathbf{d}$  to  $D(X)$ .
2.  $\mathbf{V}$  chooses random  $\mathfrak{z} \in \mathbb{F}$ .
3.  $\mathbf{P}$  sends  $D_{\mathfrak{z}} := D(\mathfrak{z})$ ,  $\bar{g}_{\mathfrak{z}} := g(1/\mathfrak{z})$ , and uses KZG to prove their correctness.
4.  $\mathbf{V}$  can now check  $D$ 's correctness on  $\mathfrak{z}$ , using the equation

$$D_{\mathfrak{z}} \stackrel{?}{=} \mathfrak{z}^{b-1} \bar{g}_{\mathfrak{z}}.$$

## 5 Univariate division

Our protocol crucially relies on the following simple claim about division by a polynomial of the form  $X^b - \alpha$ .

**Claim 5.1.** *Fix integers  $b > 0$  and let  $n = b^2$ . Fix  $\alpha \in \mathbb{F}$ , and  $f(X) \in \mathbb{F}_{<n}[X]$ . Let  $f_0(X), \dots, f_{b-1}(X) \in \mathbb{F}_{<b}[X]$  be such that  $f(X) = \sum_{i < b} X^i f_i(X^b)$ . Let  $g(X) \in \mathbb{F}_{<b}[X]$ ,  $q(X) \in \mathbb{F}[X]$  be such that*

$$f(X) = (X^b - \alpha) \cdot q(X) + g(X).$$

*Then,*

1.  $g(X) = \sum_{i < b} X^i f_i(\alpha)$ .
2. *The coefficients of  $q(X)$  can be computed in  $O(n)$   $\mathbb{F}$ -operations.*

*Proof.* To see the first item, note that reduction mod  $X^b - \alpha$  corresponds to substituting  $\alpha$  into  $X^b$  inside each  $f_i(X^b)$  in the expression  $\sum_{i < b} X^i f_i(X^b)$ . We proceed to the computation of  $q(X)$ . We compute for each  $0 \leq i < b$ , the coefficients of the quotient  $q_i(X) \in \mathbb{F}[X]$  such that

$$f_i(X) = q_i(X)(X - \alpha) + f_i(\alpha).$$

Using Horner's method for division by the linear polynomial  $X - \alpha$  this requires only  $n$  multiplications and additions in  $\mathbb{F}$ . Now, we have that

$$f(X) = \sum_{i < b} X^i f_i(X^b) = \sum_{i < b} X^i \left( q_i(X^b)(X^b - \alpha) + f_i(\alpha) \right) = q(X)(X^b - \alpha) + g(X),$$

for  $q(X) := \sum_{i < b} X^i q_i(X^b)$ . Thus, the coefficients of  $q(X)$  are simply the interleaving of the coefficients of the  $\{q_i(X)\}$ .  $\square$

## 6 Main Construction

**MERCURY** is the tuple  $(\text{gen}, \text{com}, \text{open})$  described next.

gen( $n$ ): Choose random  $x \in \mathbb{F}$  and outputs  $\{[1], [x], \dots, [x^{n-1}], [1]_2, [x]_2\}$

com( $n, f, \text{srs}$ ): Output  $\sum_{i < b} \sum_{j < b} f_{i,j} \cdot [x^{i \cdot b + j}]$ .

open( $n, \text{cm}, u, v; f$ ):

1. Committing to partial sums:

- (a) Let  $u = (u_1, u_2)$  for  $u_1, u_2 \in \mathbf{B}_t$ . **P** computes the polynomial  $h(X) := \sum_{i < b} \mathbf{eq}(i, u_1) f_i(X)$ . Note that the coefficient of  $X^j$  in  $h(X)$  is  $\sum_{i < b} \mathbf{eq}(i, u_1) f_{i,j}$  - hence we think of it as a commitment to partial sums.
- (b) **P** computes and sends  $\mathbf{h} := [h(x)]$ .

2. Committing to “folded” polynomial  $g$ :

- (a) **V** sends random  $\alpha \in \mathbb{F}$ .
- (b) **P** computes polynomials  $g(X) \in \mathbb{F}_{<b}[X]$  and  $q(X) \in \mathbb{F}[X]$  such that

$$f(X) = (X^b - \alpha) \cdot q(X) + g(X).$$

- (c) **P** computes and sends  $\mathbf{q} := [q(x)]$  and  $\mathbf{g} := [g(x)]$ .

3. Sending proofs of correctness for  $h$  and the degree of  $g$ :

- (a) **V** sends a random batching challenge  $\gamma \in \mathbb{F}$ .
- (b) **P** computes and sends  $\mathbf{s} = [S(x)]$  where  $S(X) \in \mathbb{F}[X]$  is such that

$$\begin{aligned} g(X)P_{u_1}(1/X) + g(1/X)P_{u_1}(X) + \gamma \cdot (h(X)P_{u_2}(1/X) + h(1/X)P_{u_2}(X)) \\ = 2(h(\alpha) + \gamma \cdot v) + X \cdot S(X) + (1/X)S(1/X). \end{aligned}$$

- (c) **P** computes and sends  $\mathbf{d} := [D(x)]$  where

$$D(X) := X^{b-1}g(1/X).$$

4. KZG evaluations:

- (a) **V** sends a random evaluation challenge  $\mathfrak{z} \in \mathbb{F}$ .
- (b) **P** sends the values  $g_{\mathfrak{z}} := g(\mathfrak{z}), \bar{g}_{\mathfrak{z}} := g(1/\mathfrak{z}), h_{\mathfrak{z}} := h(\mathfrak{z}), \bar{h}_{\mathfrak{z}} := h(1/\mathfrak{z}), h_{\alpha} := h(\alpha), s_{\mathfrak{z}} := S(\mathfrak{z}), \bar{s}_{\mathfrak{z}} := S(1/\mathfrak{z})$ .

- (c)  $\mathbf{V}$  computes the expected values for  $D(\mathfrak{z})$  and  $h(\alpha)$  assuming the equations in steps 3b,3c are satisfied. That is,  $D_{\mathfrak{z}} := \mathfrak{z}^{b-1}\bar{g}_{\mathfrak{z}}$ , and

$$h_{\alpha} := (g_{\mathfrak{z}}P_{u_1}(1/\mathfrak{z}) + \bar{g}_{\mathfrak{z}}P_{u_1}(\mathfrak{z}) + \gamma(h_{\mathfrak{z}}P_{u_2}(1/\mathfrak{z}) + \bar{h}_{\mathfrak{z}}P_{u_2}(\mathfrak{z}) - 2v) - \mathfrak{z}s_{\mathfrak{z}} - (1/\mathfrak{z})\bar{s}_{\mathfrak{z}}) / 2.$$

- (d)  $\mathbf{P}$  computes and sends the KZG opening proof  $\pi_{\mathfrak{z}}$  to check the equation of step 2b at  $\mathfrak{z}$ . That is  $\pi_{\mathfrak{z}} := [H(x)]$  for

$$H(X) := \frac{f(X) - (\mathfrak{z}^b - \alpha)q(X) - g_{\mathfrak{z}}}{X - \mathfrak{z}}.$$

- (e)  $\mathbf{P}$  computes and sends a batched KZG opening proof  $\pi'$  for the values sent in step 4b and computed by  $\mathbf{V}$  in step 4c, as described in Section 4 of [BDFG20].  
(f)  $\mathbf{V}$  checks the proof  $\pi_{\mathfrak{z}}$  via pairings as in [KZG10]:

$$e(\mathbf{cm} - [\mathfrak{z}^b - \alpha] \cdot \mathbf{q} - g_{\mathfrak{z}}, [1]_2) = e(\pi_{\mathfrak{z}}, [x - \mathfrak{z}]_2).$$

- (g)  $\mathbf{V}$  checks the opening proof  $\pi'$  as described in [BDFG20].  
(h) If one of the checks in steps 4f,4g fails,  $\mathbf{V}$  outputs *reject*. Otherwise  $\mathbf{V}$  outputs *accept*.

**Runtime of  $\mathbf{P}$ :** Computing  $q(X)$  in step 2b requires  $O(n)$  operations by Claim 5.1. Computing  $\mathbf{q}$  and  $\pi_{\mathfrak{z}}$  requires two MSMs of size  $n$ . All other steps are on polynomials of size  $O(b) = O(\sqrt{n})$ . Thus, other commitments clearly require  $O(\sqrt{n})$  scalar multiplications. It is easy to see other steps require  $o(n)$   $\mathbb{F}$ -operations. The least trivial of these is perhaps the computation of  $S(X)$  shown to require  $O(b \log b) = o(n)$  operations in Claim 4.1.

**Proving knowledge soundness:** Let  $\mathcal{A}$  be an efficient algebraic adversary participating in the Knowledge Soundness game from Definition 3.3. We show its probability of winning the game is  $\text{negl}(\lambda)$ . We define the extractor  $\mathcal{E}$  to simply output the vector  $f \in \mathbb{F}^n$   $\mathcal{A}$  outputs (as it's algebraic) with  $\text{com}(f) = \mathbf{cm}$  together with  $\mathbf{cm}$ .

As  $\mathcal{A}$  is algebraic, when sending the commitments  $\mathbf{h}, \mathbf{q}, \mathbf{g}, \mathbf{s}, \mathbf{d}, \pi_{\mathfrak{z}}, \pi'$  during protocol execution it also sends polynomials  $h(X), q(X), g(X), S(X), D(X), H(X), Q(X) \in \mathbb{F}_{<n}[X]$  such that the former are their corresponding commitments. Let  $E$  be the event that  $\mathbf{V}$  outputs *accept*. Let  $A$  be the event that  $\mathcal{A}$  wins the knowledge soundness game. Note that by definition  $A \subset E$ , and our goal is to show  $\text{prob}(A) = \text{negl}(\lambda)$ . We will define a constant number of events such that their union contains  $A$  and each has probability  $\text{negl}(\lambda)$ . This implies the knowledge soundness of the protocol.

$E$  implies all pairing checks have passed. Let  $E_0 \subset E$  be the event that one of the corresponding ideal pairing checks as defined in Section 3.3 didn't pass. According to Lemma 3.2,  $\text{prob}(E_0) = \text{negl}(\lambda)$ .

Given that  $E_0$  didn't occur, we have from the knowledge soundness proof of batched KZG in Section 3 of [BDFG20] that the evaluations sent by  $\mathbf{P}$  and computed by  $\mathbf{V}$  are all correct. That is,

1.  $g_{\mathfrak{z}} = g(\mathfrak{z}), \bar{g}_{\mathfrak{z}} = g(1/\mathfrak{z}), h_{\mathfrak{z}} = h(\mathfrak{z}), \bar{h}_{\mathfrak{z}} = h(1/\mathfrak{z}), s_{\mathfrak{z}} = S(\mathfrak{z}), \bar{s}_{\mathfrak{z}} = S(1/\mathfrak{z}),$
2.  $D(\mathfrak{z}) = \mathfrak{z}^{b-1}g(1/\mathfrak{z}),$
- 3.
4.  $2(h(\alpha) + \gamma v) = g(\mathfrak{z})P_{u_1}(1/\mathfrak{z}) + g(1/\mathfrak{z})P_{u_1}(\mathfrak{z}) + \gamma(h(\mathfrak{z})P_{u_2}(1/\mathfrak{z}) + h(1/\mathfrak{z})P_{u_2}(\mathfrak{z})) - \mathfrak{z}S(\mathfrak{z}) - (1/\mathfrak{z})S(1/\mathfrak{z}).$

Note that items 2-4 can be viewed as rational equations evaluated at  $\mathfrak{z}$ . Let  $E_1$  be the event that  $E_0$  didn't occur, and one of the equations in steps 2-4 doesn't hold as a rational identity. Multiplying denominators, we have from the Schwarz-Zippel Lemma that  $E_1$  occurs with probability at most  $2n/|\mathbb{F}| = \text{negl}(\lambda)$  over  $\mathfrak{z} \in \mathbb{F}$ . Assuming  $E_0$  and  $E_1$  didn't occur we have that

1.  $D(X) = X^{b-1}g(1/X),$
- 2.
3.  $2(h(\alpha) + \gamma v) = g(X)P_{u_1}(1/X) + g(1/X)P_{u_1}(X) + \gamma(h(X)P_{u_2}(1/X) + h(1/X)P_{u_2}(X)) - XS(X) - (1/X)S(1/X).$
4.  $g(X) = f(X) - (X^b - \alpha)q(X).$

Let  $E_2$  be the event that  $E_0$  and  $E_1$  don't occur but  $\hat{g}(u_1) \neq h(\alpha)$  or  $\hat{h}(u_2) \neq v$ . According to Claim 4.2, given the equation in item 2,  $E_2$  occurs with probability at most  $1/|\mathbb{F}|$  over  $\gamma$ .

Let  $E_3$  be the event that  $E_0 \cup E_1 \cup E_2$  don't occur and

1.  $h(X) \neq \sum_{i < b} \mathbf{eq}(i, u_1) f_i(X),$
2.  $h(\alpha) = \sum_{i < b} \mathbf{eq}(i, u_1) f_i(\alpha).$

Obviously,  $E_3$  has probability  $\text{negl}(\lambda)$ .

Assume  $E_0 \cup E_1 \cup E_2 \cup E_3$  doesn't occur. We show that  $\hat{f}(u) = v$ , and thus we are outside the event  $A$ . In other words,  $A \subset E_0 \cup E_1 \cup E_2 \cup E_3$ .

Since  $D(X) = X^{b-1}g(1/X)$  we know that  $\deg(g) < b$ . Since  $g(X) = f(X) - (X^b - \alpha)q(X)$ , from Claim 5.1 we know that  $g(X) = \sum_{i < b} f_i(\alpha)X^i$ . Hence, we know that

$$\hat{g}(u_1) = \sum_{i < b} \mathbf{eq}(i, u_1) f_i(\alpha) = h(\alpha).$$

Using  $\neg E_3$  we know that  $h(X) = \sum_{i < b} \mathbf{eq}(i, u_1) f_i(X)$ . Hence, writing  $h(X) = \sum_{j < b} h_j X^j$  we have  $h_j = \sum_{i < b} \mathbf{eq}(i, u_1) f_{i,j}$ . Thus, we have

$$\begin{aligned} \hat{f}(u) &= \sum_{i < b} \sum_{j < b} \mathbf{eq}(i, u_1) \mathbf{eq}(j, u_2) f_{i,j} = \sum_{j < b} \mathbf{eq}(j, u_2) \sum_{i < b} \mathbf{eq}(i, u_1) f_{i,j} \\ &= \sum_{j < b} \mathbf{eq}(j, u_2) h_j = \hat{h}(u_2) = v. \end{aligned}$$

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