

\mathbf{cq}^* Cached quotients for fast lookups

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Abstract

We present a protocol for checking the values of a committed polynomial $f(X) \in \mathbb{F}_{<N}[X]$ over a multiplicative subgroup $\mathbb{H} \subset \mathbb{F}$ of size n are contained in a table $\mathbf{t} \in \mathbb{F}^N$. After an $O(N \log N)$ preprocessing step, the prover algorithm runs in time $O(n \log n)$. Thus, we continue to improve upon the recent breakthrough sequence of results [ZBK⁺22, PK22, GK22, ZGK⁺22] starting from Caulk [ZBK⁺22], which achieve sublinear complexity in the table size N . The two most recent works in this sequence [GK22, ZGK⁺22] achieved prover complexity $O(n \cdot \log^2 n)$.

Moreover, \mathbf{cq} has the following attractive features.

1. As in [ZBK⁺22, PK22, ZGK⁺22] our construction relies on homomorphic table commitments, which makes them amenable to vector lookups in the manner described in Section 4 of [GW20].
2. As opposed to [ZBK⁺22, PK22, GK22, ZGK⁺22] the \mathbf{cq} verifier doesn't involve pairings with prover defined \mathbb{G}_2 points, which makes recursive aggregation of proofs more convenient.
3. The construction can be altered to a version we call \mathbf{cq}^* that loses the mentioned aggregatability, increase preprocessing time to $O(n \cdot N)$, and in return reduce prover complexity to a *linear* number of field and group operations!

1 Introduction

The *lookup problem* is fundamental to the efficiency of modern zk-SNARKs. Somewhat informally, it asks for a protocol to prove the values of a committed polynomial $\phi(X) \in \mathbb{F}_{<n}[X]$ are contained in a table T of size N of predefined legal values. When the table T corresponds to an operation without an efficient low-degree arithmetization in \mathbb{F} , such a protocol produces significant savings in proof construction time for programs containing the operation. Building on previous work of [BCG⁺18], **lookup** [GW20] was the first to explicitly describe a solution to this problem in the polynomial-IOP context.

*Pronounced “seek you”.

lookup described a protocol with prover complexity quasilinear in both n and N . This left the intriguing question of whether the dependence on N could be made *sublinear* after performing a preprocessing step for the table T . Caulk [ZBK⁺22] answered this question in the affirmative by leveraging bi-linear pairings, achieving a run time of $O(n^2 + n \log N)$. Caulk+ [PK22] improved this to $O(n^2)$ getting rid of the dependence on table size completely.

However, the quadratic dependence on n of these works makes them impractical for a circuit with many lookup gates. We resolve this issue by giving a protocol called **cq** that is quasi-linear in n and has no dependence on N after the preprocessing step.

1.1 Comparison of results

Table 1: Scheme comparison. n = witness size, N = Table size, “Aggregatable” = All prover defined pairing arguments in \mathbb{G}_1

Scheme	Preprocessing	Proof size	Prover Work	Verifier Work	Homomorphic?	Aggregatable?
Caulk [ZBK ⁺ 22]	$O(N \log N) \mathbb{F}, \mathbb{G}_1$	$14 \mathbb{G}_1, 1 \mathbb{G}_2, 4 \mathbb{F}$	$3n + m - \ell \mathbb{G}_1 \text{ exp,}$ $n \mathbb{G}_2 \text{ exp}$	$2 \mathbb{G}_1, 1 \mathbb{G}_2$	✓	✗
Caulk+ [PK22]	$O(N \log N) \mathbb{F}, \mathbb{G}_1$	$7 \mathbb{G}_1, 1 \mathbb{G}_2, 2 \mathbb{F}$	$18n \mathbb{G}_1 \text{ exp}$	$4 \mathbb{G}_1, 2 \mathbb{F}$	✓	✗
flookup [GK22]	$O(N \log^2 N) \mathbb{F}, \mathbb{G}_1$	$6 \mathbb{G}_1, 1 \mathbb{G}_2, 4 \mathbb{F}$	$273n \mathbb{G}_1 \text{ exp}$	$20 \mathbb{G}_1, 16 \mathbb{F}$	✗	✗
baloo [ZGK ⁺ 22]	$O(N \log N) \mathbb{F}, \mathbb{G}_1$	$12 \mathbb{G}_1, 1 \mathbb{G}_2, 4 \mathbb{F}$	$8n \mathbb{G}_1 \text{ exp}$	$6 \mathbb{G}_1, 4 \mathbb{F}$	✓	✗
cq	$O(N \log N) \mathbb{F}, \mathbb{G}_1$	$8 \mathbb{G}_1, 4 \mathbb{F}$	$11n + 11a \mathbb{G}_1 \text{ exp,}$ $\approx 54(n+a) \log(n+a) \mathbb{F} \text{ mul}$	$7 \mathbb{G}_1, 6 \mathbb{F}$	✓	✓
cq*	$O(N \log N + N \cdot n \log n) \mathbb{F}, \mathbb{G}_1$ $O(n \log n) \mathbb{G}_2$	$6 \mathbb{G}_1, 1 \mathbb{G}_2, 1 \mathbb{F}$	$9n + 9a \mathbb{G}_1 \text{ exp,}$ $\approx 54(n+a) \log(n+a) \mathbb{F} \text{ mul}$	$9 \mathbb{G}_1, 6 \mathbb{F}$	✓	✗

Table with relative proof size, prover ops, verifier ops proof-size caulk caulk+ flookup baloo $12 \mathbb{G}_1, 1 \mathbb{G}_2, 4 \mathbb{F}$ this work $6 \mathbb{G}_1, 1 \mathbb{G}_2$

1.2 Technical Overview

We explain our protocol in the context of the line of work starting from [ZBK⁺22].

The innovation of Caulk To restate the problem, we have an input polynomial $f(X)$, a table \mathbf{t} of size N encoded in the values of a polynomial $T(X) \in \mathbb{F}_{<N}[X]$, and wish to show $f|_{\mathbb{H}} \subset \mathbf{t}$, where $|\mathbb{H}| = n \ll N$. We want our prover **P** to perform a number of operations *sublinear* in N , or ideally, a number of operations depending only on n . One natural approach - is to send the verifier **V**, a polynomial T' encoding the n values from \mathbf{t} *actually used in f* , and then run a lookup protocol using T' . The challenging problem is to prove T' *actually encodes values from T* . Speaking impercisely, the “witness” to T' correctness is a quotient Q of degree $N - n$. It would defeat our purpose to actually compute Q - as that would require $O(N)$ operations.

The central innovation of Caulk [ZBK⁺22] is the following observation: If we precompute commitments to certain polynomials, we can compute in a number of operations depending only on n , the *commitment* to Q . Moreover, having only a commitment to Q suffices to check, via pairings, that T' is valid.

This approach was a big step forward, enabling for the first time lookups sublinear in table size. However, it has the following disadvantage: “Extracting” the subtable of values used in f , necessitates interpolation and evaluation of polynomials on arbitrary sets, rather than just subgroups. The corresponding algorithms for working on such sets have asymptotics of $O(n \cdot \log^2 n)$ rather than the $O(n \log n)$ we are used to from FFT’s on subgroups.

Moreover, when desiring to work with a *homomorphic* table commitment, the **Caulk** approach requires working with a T' that encodes the subtable values on a “hidden”, prover-defined set of inputs; consequently requiring more ingenuity and complexity to use the subtable, also after it has been extracted.

Our approach The key difference between **ca** and [ZBK⁺22, PK22, GK22, ZGK⁺22] is that we use the idea of succinct computation of quotient commitments, not to extract a subtable, but to directly run an existing lookup protocol on a large table, in time depending only on n .

Specifically, we use the “logarithmic derivative based lookup” of [?].

It relies on the following lemma from [?]: that says that $f|_{\mathbb{H}} \in \mathfrak{t}$ if and only if for some $m \in \mathbb{F}^N$

$$\sum_{i \in [N]} \frac{m_i}{X + t_i} = \sum_{i \in [n]} \frac{1}{X + f_i}$$

Roughly, the protocol of [?] checks this identity on a random β , by sending polynomials A and B that agree on \mathbb{V} with the rational function values of the LHS and RHS respectively. Given commitments to A, B we can check the equality holds via various sumcheck techniques, e.g. that described in [BCR⁺19]. The RHS is not a problem because it is a sum of size n . Interpolating A , and computing its commitment is actually not a problem either, because the number of non-zero values is at most n . So if we precompute the commitments to the Lagrange base of \mathbb{V} we’re fine.

The main challenge, and innovation, is to convince the verifier \mathbf{V} that A is correctly formed.

This protocol is amenable, because polynomials involved have sparsity depending on witness - For large table problem is computing A that agrees with $m/(\mathfrak{t} + \beta)$ on \mathbb{V}

- Need way to compute A

2 Preliminaries

2.1 Terminology and Conventions

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 λ .

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 λ before all

protocols, and returns all fields and groups used. Specifically, in our protocol $\mathcal{O}(\lambda) = (\mathbb{F}, \mathbb{G}_1, \mathbb{G}_2, \mathbb{G}_t, e, g_1, g_2, g_t)$ where

- \mathbb{F} is a prime field of super-polynomial size $r = \lambda^{\omega(1)}$.
- $\mathbb{G}_1, \mathbb{G}_2, \mathbb{G}_t$ are all groups of size r , and e is an efficiently computable non-degenerate pairing $e : \mathbb{G}_1 \times \mathbb{G}_2 \rightarrow \mathbb{G}_t$.
- g_1, g_2 are uniformly chosen generators such that $e(g_1, g_2) = g_t$.

We usually let the λ parameter be implicit, i.e. write \mathbb{F} instead of $\mathbb{F}(\lambda)$. We write \mathbb{G}_1 and \mathbb{G}_2 additively. We use the notations $[x]_1 := x \cdot g_1$ and $[x]_2 := x \cdot g_2$.

We often denote by $[n]$ the integers $\{1, \dots, n\}$. We use the acronym e.w.p for “except with probability”; i.e. e.w.p γ means with probability *at least* $1 - \gamma$.

universal SRS-based public-coin protocols We describe public-coin (meaning the verifier messages are uniformly chosen) interactive protocols between a prover and verifier; when deriving results for non-interactive protocols, we implicitly assume we can get a proof length equal to the total communication of the prover, using the Fiat-Shamir transform/a random oracle. Using this reduction between interactive and non-interactive protocols, we can refer to the “proof length” of an interactive protocol.

We allow our protocols to have access to a structured reference string (SRS) that can be derived in deterministic $\text{poly}(\lambda)$ -time from an “SRS of monomials” of the form $\{[x^i]_1\}_{a \leq i \leq b}, \{[x^i]_2\}_{c \leq i \leq d}$, for uniform $x \in \mathbb{F}$, and some integers a, b, c, d with absolute value bounded by $\text{poly}(\lambda)$. It then follows from Bowe et al. [BGM17] that the required SRS can be derived in a universal and updatable setup requiring only one honest participant; in the sense that an adversary controlling all but one of the participants in the setup does not gain more than a $\text{negl}(\lambda)$ advantage in its probability of producing a proof of any statement.

For notational simplicity, we sometimes use the SRS `srs` as an implicit parameter in protocols, and do not explicitly write it.

Aurora lemma

Lemma 2.1. *Let $H \subset \mathbb{F}$ be a multiplicative subgroup of size t . For $f \in \mathbb{F}_{<t}[X]$, we have*

$$\sum_{a \in H} f(a) = n \cdot a(0)$$

2.2 Idealized verifier checks for algebraic adversaries

We introduce some terminology from [GWC19] to capture analysis in the Algebraic Group Model of Fuchsbauer, Kiltz and Loss [FKL18].

First we say our `srs` has *degree* Q if all elements of `srs` _{i} are of the form $[f(x)]_i$ for $f \in \mathbb{F}_{<Q}[X]$ 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 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 $[a_j]_1$.

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

$$[1]_1, [x]_1, \dots, [x^Q]_1, [1]_2, [x]_2, \dots, [x^Q]_2$$

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

Lemma 2.3. *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.*

AGM - real and ideal pairing checks, agm - real and ideal pairing KZG

2.3 log derivative method

Lemma from mvlookup

Lemma 2.4. *Given $f \in \mathbb{F}^n$, and $t \in \mathbb{F}^N$, we have $f \subset t$ as sets if and only if for some $m \in \mathbb{F}^N$ the following identity of rational functions holds*

$$\sum_{i \in [n]} \frac{1}{X + f_i} = \sum_{i \in [N]} \frac{m_i}{X + t_i}.$$

3 Cached quotients

Notation: In this section and the next we use the following conventions. $\mathbb{V} \subset \mathbb{F}$ denotes a multiplicative subgroup of order N which is a power of two. We denote by \mathbf{g} a generator of \mathbb{V} . Hence, $\mathbb{V} = \{\mathbf{g}, \mathbf{g}^2, \dots, \mathbf{g}^N = 1\}$. Given $P \in \mathbb{F}[X]$ and integer $i \in [N]$, we denote $P_i := P(\mathbf{g}^i)$. For $i \in [N]$, we denote by $L_i \in \mathbb{F}_{<N}[X]$ the i 'th Lagrange polynomial of \mathbb{V} . Thus, $(L_i)_i = 1$ and $(L_i)_j = 0$ for $i \neq j \in [N]$.

For a polynomial $A(X) \in \mathbb{F}_{<N}[X]$, we say it is n -sparse if $A_i \neq 0$ for at most n values $i \in [N]$. The *sparse representation* of such A consists of the (at most) n pairs (i, A_i) such that $A_i \neq 0$. We denote $\text{supp}(A) := \{i \in [N] \mid A_i \neq 0\}$.

The main result of this section is a method to compute a commitment to a quotient polynomial - derived from a product with a preprocessed polynomial; in a number of operations depending only on the sparsity of the other polynomial in the product.

The result crucially relies on the following lemma derived from a result of Feist and Khovratovich[FK].

Lemma 3.1. *Fix $T \in \mathbb{F}_{<N}[X]$, and a subgroup $\mathbb{V} \subset \mathbb{F}$ of size N . There is an algorithm that given the \mathbb{G}_1 elements $\{[x^i]_1\}_{i \in \{0, \dots, N\}}$ computes for $i \in [N]$, the elements $q_i := [Q_i(x)]_1$ where $Q_i(X) \in \mathbb{F}[X]$ is such that*

$$L_i(X) \cdot T(X) = T_i \cdot L_i(X) + Z_{\mathbb{V}}(X) \cdot Q_i(X)$$

in $O(N \cdot \log N)$ \mathbb{G}_1 operations.

Proof. Recall the definition of the Lagrange polynomial

$$L_i(X) = \frac{Z_{\mathbb{V}}(X)}{Z'_{\mathbb{V}}(\mathbf{g}^i)(X - \mathbf{g}^i)}.$$

Substituting this definition, we can write the quotient $Q_i(X)$ as

$$Q_i(X) = \frac{T(X) - T_i}{Z'_{\mathbb{V}}(\mathbf{g}^i)(X - \mathbf{g}^i)} = Z'_{\mathbb{V}}(\omega^i)^{-1} K_i(X),$$

for $K_i(X) := \frac{T(X) - T_i}{X - \mathbf{g}^i}$. Note that the values $\{[K_i(X)]_1\}_{i \in [N]}$ are exactly the KZG opening proofs of $T(X)$ at the elements of \mathbb{V} . Thus, the algorithm of Feist and Khovratovich [FK, Tom] can be used to compute commitments to all the proofs $[K_i(X)]_1$ in $O(N \log N)$ \mathbb{G}_1 -operations. This works by writing the vector of $[K_i(X)]_1$ as a the product of a matrix with the vector of $[X^i]_1$. This matrix is a DFT matrix times a Toeplitz matrix, both of which have algorithms for evaluating matrix vector products in $O(N \log N)$ operations. Thus, all the KZG proofs can be computed in $O(N \log N)$ field operations and operations in \mathbb{G}_1 .

Finally, the algorithm just needs to scale each $[K_i(X)]_1$ by $Z'_{\mathbb{V}}(\omega^i)$ to compute $[Q_i(X)]_1$. Conveniently, these values admit a very simple description when $Z_{\mathbb{V}}(X) = X^N - 1$ is a group of roots of unity.

$$Z'_{\mathbb{V}}(X)^{-1} = (NX^{N-1})^{-1} \equiv X/N \bmod Z_{\mathbb{V}}(X)$$

In total, the prover computes the coefficients of $T(X)$ in $O(N \log N)$ field operations, computes the KZG proofs for $T(\omega^i) = t_i$ in $O(N \log N)$ group operations, and then scales these proofs by ω^i/n in $O(N)$ group operations. In total, this takes $O(N \log N)$ field and group operations in \mathbb{G}_1 . \square

We're now ready to state the main theorem of this section.

Theorem 3.2. *Fix integer parameters $0 \leq n \leq N$ such that n, N are powers of two. Fix $T \in \mathbb{F}_{<N}[X]$, and a subgroup $\mathbb{V} \subset \mathbb{F}$ of size N . Let $\mathbf{srs} = \{[x^i]_1\}_{i \in [0, \dots, N]}$ for some $x \in \mathbb{F}$. There is an algorithm \mathcal{A} that after a preprocessing step of $O(N \log N)$ \mathbb{F} - and \mathbb{G}_1 -operations starting with \mathbf{srs} does the following.*

Given input $A(X) \in \mathbb{F}_{<N}[X]$ that is n -sparse and given in sparse representation, \mathcal{A} computes in $O(n)$ \mathbb{F} -operations and n \mathbb{G}_1 -operations the element $\mathbf{cm} = [Q(x)]_1$ where $Q \in \mathbb{F}_{<N}[X]$ is such that

$$A(X) \cdot T(X) = Q(X) \cdot Z_{\mathbb{V}}(X) + R(X),$$

for $R(X) \in \mathbb{F}_{<N}[X]$.

Proof. The preprocessing step consists of computing the quotient commitments $[Q_i(X)]_1$ in $O(N \log N)$ operations, as described in Lemma 3.1. As stated in the lemma, for each $i \in [N]$ we have

$$L_i(X) \cdot T(X) = T_i \cdot L_i(X) + Z_{\mathbb{V}}(X) \cdot Q_i(X).$$

By assumption, the polynomial $A(X)$ can be written as a linear combination of at most n summands in the Lagrange basis of \mathbb{V} .

$$A(X) = \sum_{i \in \text{supp}(A)} A_i \cdot L_i(X)$$

Substituting this into the product with $T(X)$, and substituting each of the products $L_i(X)T(X)$ with the appropriate cached quotient $Q_i(X)$ we find

$$\begin{aligned} A(X)T(X) &= \sum_{i \in \text{supp}(A)} A_i \cdot L_i(X)T(X) = \sum_{i \in \text{supp}(A)} A_i \cdot T_i L_i(X) + A_i \cdot Z_{\mathbb{V}}(X) Q_i(X) \\ &= \sum_{i \in \text{supp}(A)} A_i \cdot T_i L_i(X) + Z_{\mathbb{V}}(X) \cdot \sum_{i \in \text{supp}(A)} A_i \cdot Q_i(X). \end{aligned}$$

Observing that the terms of the first sum are all of degree smaller than N , we get that

$$\begin{aligned} Q(X) &= \sum_{i \in \text{supp}(A)} A_i \cdot Q_i(X) \\ R(X) &= \sum_{i \in \text{supp}(A)} A_i T_i \cdot L_i(X) \end{aligned}$$

Hence, commitments to both the quotient $Q(X)$ and remainder $R(X)$ can be computed in at most n group operations as

$$\begin{aligned} [Q(X)]_1 &= \sum_{i \in \text{supp}(A)} A_i \cdot [Q_i(X)]_1 \\ [R(X)]_1 &= \sum_{i \in \text{supp}(A)} A_i T_i \cdot [L_i(X)]_1 \end{aligned}$$

□

4 $\mathfrak{c}\mathfrak{q}$ - our main protocol

Definition 4.1. $\text{gen}(\mathfrak{t}, N, \text{srs}_0 = ([x^i]_1, [x^i]_2)_{i \in [0, \dots, d]}):$

1. $[Z_{\mathbb{V}}(x)]_2, [T(x)]_2$.

2. Compute for $i \in [N]$:

(a) $q_i = [Q_i(x)]_1$ such that

$$L_i(X) \cdot T(X) = \mathfrak{t}_i \cdot L_i(X) + Z_{\mathbb{V}}(X) \cdot Q_i(X).$$

(b) $[L_i(x)]_1, [x^{d-N} L_i(x)]_1, [x^{d-n}]_1$

(c) $\left[\frac{L_i(x) - L_i(0)}{x} \right]_1$.

Tuple $\text{gen}, \text{IsInTable}_{\mathbb{H}}$

• $\text{gen}(\mathfrak{t}, N, \text{srs}_0) \rightarrow \text{srs}$

• $\text{IsInTable}_{\mathbb{H}}$ an interactive public coin protocol between \mathbf{P} and \mathbf{V} where \mathbf{P} has input $f \in \mathbb{F}_{<n}[X]$, \mathbf{V} has $[f(x)]_1$. Both have \mathfrak{t} and srs . such that

- Completeness: If $f|_{\mathbb{H}} \subset \mathfrak{t}$ then \mathbf{V} outputs acc with probability one.
- Knowledge soundness in the algebraic group model: For any $\mathfrak{t} \in \mathbb{F}^n$, the probability of any algebraic \mathcal{A} to win the following game is $\text{negl}(\lambda)$
 1. We generate for uniform $x \in \mathbb{F}$, $\text{srs}_0 = ([x^i]_1, [x^i]_2)_{i \in [0, \dots, d]}$.
 2. \mathcal{A} chooses $\mathfrak{t} \in \mathbb{F}^N$.
 3. We compute $\text{srs} = \text{gen}(\mathfrak{t}, N, \text{srs}_0)$.
 4. \mathcal{A} sends a message cm and values f_1, \dots, f_n such that $\text{cm} = \sum_{i \in [n]} f_i \cdot [L_i(x)]_1$.
 5. \mathcal{A} and \mathbf{V} engage in the protocol $\text{IsInTable}_{\mathbb{H}}(\mathfrak{t}, \text{cm})$ with \mathcal{A} taking the role of \mathbf{P} .
 6. \mathcal{A} wins if
 - * \mathbf{V} outputs acc , and
 - * $f|_{\mathbb{H}} \not\subset \mathfrak{t}$.

Main protocol: Preprocessed inputs: $[Z_{\mathbb{V}}(x)]_2, [T(x)]_2$ Input (cm, f) .

Round 1: Committing to the multiplicities vector

1. **P** computes poly $m \in \mathbb{F}_{<N}[X]$ such that $m_i = \text{number of times } \mathbf{t}_i \text{ appears in } f|_{\mathbb{H}}$
2. **P** sends $\mathbf{m} := [m(x)]_1$.

Round 2: Interpolating the rational identity at a random β ; checking correctness of A 's values + degree checks for A, B using pairings

1. **V** chooses and sends random $\alpha, \beta \in \mathbb{F}$.
2. **P** computes $A \in \mathbb{F}_{<N}[X]$ such that for $i \in [N]$, $A_i = m_i / (\mathbf{t}_i + \beta)$.
3. **P** sends $\mathbf{a} := [A(x)]_1$.
4. **P** computes $\mathbf{q}_a := [Q_A(x)]_2$ where $Q_A \in \mathbb{F}_{<N}[X]$ is such that

$$A(X)(T(X) + \beta) - m(X) = Q_A(X) \cdot Z_V(X)$$

5. **P** computes $B \in \mathbb{F}_{<n}[X]$ such that for $i \in [n]$, $B_i = 1 / (f_i + \beta)$.
6. **P** sends $\mathbf{q}_b := [B(x)]_1$.
7. **P** computes $Q_B(X)$ such that

$$B(X)(f(x) + \beta) - 1 = Q_B(X) \cdot Z_{\mathbb{H}}(X)$$

8. **P** computes and sends the value $a_0 := A(0)$.
9. **V** sets $b_0 := (N \cdot a_0) / n$.
10. **P** computes and sends $\mathbf{p} = [P(x)]_1$ where

$$P(X) := A(X) \cdot X^{d-N} + \alpha \cdot B(X) \cdot X^{d-n}.$$

11. **V** checks that A encodes the correct values:

$$e(\mathbf{a}, [T(x)]_2 + [\beta]_2) = e(\mathbf{q}_a, [Z_V(x)]_2) \cdot e(\mathbf{m}, [1]_2)$$

12. **V** checks that A, B have the appropriate degrees:

$$e\left(\mathbf{a}, \left[x^{d-N}\right]_2\right) \cdot e\left(\alpha \cdot \mathbf{b}, \left[x^{d-n}\right]_2\right) = e(\mathbf{p}, [1]_2).$$

Round 3: Checking correctness of B at random $\gamma \in \mathbb{F}$

1. \mathbf{V} sends random $\gamma, \eta, \zeta \in \mathbb{F}$.
2. \mathbf{P} sends $b_\gamma := B(\gamma), f_\gamma := f(\gamma)$.
3. As part of checking the correctness of B , \mathbf{V} computes $Z_{\mathbb{H}}(\gamma) = \gamma^n - 1$ and

$$Q_{b,\gamma} := \frac{b_\gamma \cdot (f_\gamma + \beta) - 1}{Z_{\mathbb{H}}(\gamma)}.$$

4. To perform a batched KZG check for the correctness of the values $a_\gamma, b_\gamma, f_\gamma$
 - (a) \mathbf{V} sends random $\eta \in \mathbb{F}$. \mathbf{P} and \mathbf{V} separately compute

$$v := b_\gamma + \eta \cdot f_\gamma + \eta^2 \cdot Q_{b,\gamma}.$$

- (b) \mathbf{P} computes $\pi_\gamma := [h(x)]_1$ for

$$h(X) := \frac{B(X) + \eta \cdot f(X) + \eta^2 \cdot Q_B(X) - v}{X - \gamma}$$

- (c) \mathbf{V} computes

$$\mathbf{c} := \mathbf{b} + \eta \cdot \mathbf{f} + \eta^2 \cdot \mathbf{q}_b$$

and checks that

$$e(\mathbf{c} - [v]_1 + \gamma \cdot \pi_\gamma, [1]_2) = e(\pi_\gamma, [x]_2)$$

5. To perform a batched KZG check for the correctness of the values a_0, b_0
 - (a) \mathbf{P} and \mathbf{V} separately compute

$$u := a_0 + \zeta \cdot b_0.$$

- (b) \mathbf{P} computes and sends $\pi_0 := [h_0(x)]_1$ for

$$h_0(X) := \frac{A(X) + \zeta \cdot B(X)}{X}$$

- (c) \mathbf{V} computes

$$\mathbf{c}_0 := \mathbf{a} + \zeta \mathbf{b}$$

and checks that

$$e(\mathbf{c}_0 - [u]_1, [1]_2) = e(\pi_0, [x]_2)$$

Stats: verifier pairings: 5 - pair \mathbf{a} with random combination of T and $[x^{d-N}]_2$, pair $\mathbf{q_a}$ with $Z_{\mathbb{V}}$. pair \mathbf{b} with $[d-n]_2$ for degree check. Proof size - 8 \mathbb{G}_1 - $\mathbf{a}, \mathbf{b}, \mathbf{p}, \mathbf{m}, \mathbf{q_a}, \mathbf{q_b}$ π_{γ}, π_0 4 \mathbb{F} - $b_{\gamma}, Q_{b,\gamma}, f_{\gamma}, a_0$

Note that we can split \mathbf{p} to two proofs and that reduces a verifier pairing

Lemma 4.2. *The element q_A in Step 4 can be computed in $n \log n$ \mathbb{G}_2 -operations and $O(n \log n)$ \mathbb{F} -operations*

Lemma 4.3. *The elements π_0, π_{γ} can be computed in $2 \cdot n \log n$ \mathbb{G}_1 -operations and $O(n \log n)$ \mathbb{F} -operations*

Knowledge soundness proof: Let \mathcal{A} be an efficient algebraic adversary participating in the Knowledge Soundness game from Definition 4.1. We show its probability of winning the game is $\text{negl}(\lambda)$. Let $f \in \mathbb{F}_{<d}[X]$ be the polynomial sent by \mathcal{A} in the first step of the game such that $\mathbf{cm} = [f(x)]_1$. As \mathcal{A} is algebraic, when sending the commitments $\mathbf{m}, \mathbf{a}, \mathbf{b}, \mathbf{p}, \mathbf{q_a}, \mathbf{q_b}, \pi_{\gamma}, \pi_0$ during protocol execution it also sends polynomials $m(X), A(X), B(X), P(X), Q_A(X), Q_B(X), h(X), h_0(X) \in \mathbb{F}_{<d}[X]$ such that the former are their corresponding commitments. Let E be the event \mathbf{V} outputs **acc**. Note that the event that \mathcal{A} wins the game is contained in E . E implies all pairing checks passed. Let $A \subset E$ be the event that one of the corresponding ideal pairing checks didn't pass. According to Lemma 2.3, $\Pr(A) = \text{negl}(\lambda)$. Given A didn't occur, we have

- From step 11

$$A(X)(T(X) + \beta) - M(X) = Q_A(X) \cdot Z_{\mathbb{V}}(X)$$

Which means that for all $i \in [N]$,

$$A_i = \frac{M_i}{T_i + \beta}$$

- From step 12

$$X^{d-N} A(X) + \alpha \cdot X^{d-n} B(X) = P(X),$$

which implies e.w.p. $1/|\mathbb{F}|$ over $\alpha \in \mathbb{F}$, that $\deg(A) < N$ and $\deg(B) < n$.

- From the checks of steps 4c and 2c, e.w.p. $n/|\mathbb{F}|$ over $\eta, \zeta \in \mathbb{F}$ (see e.g. Section 3 of [GWC19] for an explanation of the correctness of batched KZG [KZG10]).
 $b_{\gamma} = B(\gamma), Q_{b,\gamma} = Q_B(\gamma), f_{\gamma} = f(\gamma), a_0 = A(0), b_0 = B(0)$.
- Which implies by how $Q_{b,\gamma}$ is set in step 3 that e.w.p. $(2n)/|\mathbb{F}|$ over γ

$$B(X) \cdot (f(X) + \beta) = 1 + Q_B(X) Z_{\mathbb{H}}(X),$$

which implies for all $i \in [n]$ that $B(\omega^i) = \frac{1}{f(\omega^i) + \beta}$.

- We know have using Lemma 2.1 that

$$N \cdot a_0 = \sum_{i \in [N]} A_i = \sum_{i \in [N]} \frac{m_i}{T_i + \beta}$$

$$n \cdot b_0 = \sum_{i \in [n]} B(\omega^i) = \sum_{i \in [n]} \frac{1}{f(\omega^i) + \beta}$$

Thus e.w.p. $(n \cdot N)/|\mathbb{F}|$ over $\beta \in \mathbb{F}$, we have that

$$\sum_{i \in [N]} \frac{m_i}{T_i + X} = \sum_{i \in [n]} \frac{1}{f(\omega^i) + X},$$

which implies $f|_{\mathbb{H}} \in \mathfrak{t}$.

In summary, we have shown the event that \mathbf{V} outputs acc while $f|_{\mathbb{H}} \not\in \mathfrak{t}$ is contained in a constant number of events with probability $\text{negl}(\lambda)$; and so \mathbf{cq} satisfies the knowledge soundness property.

5 \mathbf{cq}^*

The only point where \mathbf{P} does $O(n \log n)$ operations in \mathbf{cq} is using FFT's to compute $Q_B(X)$. Similarly to what we did with $Q_A(X)$ we could try to only compute the commitment $[Q_B(x)]_1 \text{ gen}(\mathfrak{t}, \text{srs})$

Main protocol: $\text{gen}(\mathfrak{t}, N, \text{srs}_0 = ([x^i]_1, [x^i]_2)_{i \in [0, \dots, d]}):$

1. $[Z_{\mathbb{V}}(x)]_2, [T(x)]_2$.

2. Compute for $i \in [N]$:

(a) $q_i = [Q_i(x)]_1$ such that

$$L_i(X) \cdot T(X) = \mathfrak{t}_i \cdot L_i(X) + Z_{\mathbb{V}}(X) \cdot Q_i(X).$$

(b) $[L_i(x)]_1, [x^{d-N} L_i(x)]_1, [x^{d-n}]_1$

(c) $\left[\frac{L_i(x) - L_i(0)}{x} \right]_1$.

Preprocessed inputs: $[Z_{\mathbb{V}}(x)]_2, [T(x)]_2$ Input (cm, f) .

Round 1: Committing to the multiplicities vector, and f in \mathbb{G}_2

1. \mathbf{P} computes poly $m \in \mathbb{F}_{<N}[X]$ such that $m_i =$ number of times \mathfrak{t}_i appears in $f|_{\mathbb{H}}$
2. \mathbf{P} sends $\mathfrak{m} := [m(x)]_1$.
3. \mathbf{P} sends $\mathfrak{f}_2 := [f(x)]_2$
4. \mathbf{V} checks correctness of \mathfrak{f}_2 via

$$e(\mathfrak{f}, [1]_2) = e([1]_1, \mathfrak{f}_2).$$

Round 2: Interpolating the rational identity at a random β ; checking correctness of degrees and values of A, B using pairings

1. \mathbf{V} chooses and sends random $\alpha, \beta \in \mathbb{F}$.
2. \mathbf{P} computes $A \in \mathbb{F}_{<N}[X]$ such that for $i \in [N]$, $A_i = m_i/(\mathfrak{t}_i + \beta)$.
3. \mathbf{P} sends $\mathbf{a} := [A(x)]_1$.
4. \mathbf{P} computes $\mathbf{q}_\mathbf{a} := [Q_A(x)]_2$ where $Q_A \in \mathbb{F}_{<N}[X]$ is such that

$$A(X)(T(X) + \beta) - m(X) = Q_A(X) \cdot Z_\mathbb{V}(X)$$

5. \mathbf{P} computes $B \in \mathbb{F}_{<n}[X]$ such that for $i \in [n]$, $B_i = 1/(f_i + \beta)$.
6. \mathbf{P} sends $\mathbf{q}_\mathbf{b} := [B(x)]_1$.
7. \mathbf{P} computes $\mathbf{q}_\mathbf{b} := [Q_B(X)]_1$ such that

$$B(X)(f(x) + \beta) - 1 = Q_B(X) \cdot Z_\mathbb{H}(X)$$

8. \mathbf{P} computes and sends the value $a_0 := A(0)$.
9. \mathbf{V} sets $b_0 := (N \cdot a_0)/n$.
10. \mathbf{P} computes and sends $\mathbf{p} = [P(x)]_1$ where

$$P(X) := A(X) \cdot X^{d-N} + \alpha \cdot B(X) \cdot X^{d-n}.$$

11. \mathbf{V} checks that A encodes the correct values:

$$e(\mathbf{a}, [T(x)]_2 + [\beta]_2) = e(\mathbf{q}_\mathbf{a}, [Z_\mathbb{V}(x)]_2) \cdot e(\mathbf{m}, [1]_2)$$

12. \mathbf{V} checks that B encodes the correct values:

$$e(\mathbf{b}, [\mathfrak{f}]_2 + [\beta]_2) = e(\mathbf{q}_\mathbf{b}, [Z_\mathbb{H}(x)]_2) \cdot e([1]_1, [1]_2)$$

13. \mathbf{V} checks that A, B have the appropriate degrees:

$$e\left(\mathbf{a}, \left[x^{d-N}\right]_2\right) \cdot e\left(\alpha \cdot \mathbf{b}, \left[x^{d-n}\right]_2\right) = e(\mathbf{p}, [1]_2).$$

Round 3: Checking correctness of $A(0), B(0)$

1. **V** sends random $\zeta \in \mathbb{F}$.
2. To perform a batched KZG check for the correctness of the values a_0, b_0
 - (a) **P** and **V** separately compute

$$u := a_0 + \zeta \cdot b_0.$$

- (b) **P** computes and sends $\pi_0 := [h_0(x)]_1$ for

$$h_0(X) := \frac{A(X) + \zeta \cdot B(X)}{X}$$

- (c) **V** computes

$$c_0 := a + \zeta b$$

and checks that

$$e(c_0 - [u]_1, [1]_2) = e(\pi_0, [x]_2)$$

Stats: verifier pairings: 5 - pair **a** with random combination of T and $[x^{d-N}]_2$, pair q_a with $Z_{\mathbb{V}}$. pair **b** with $[d-n]_2$ for degree check. Proof size - 6 \mathbb{G}_1 - $a, b, p, m, q_a, q_b, \pi_0$ 1 \mathbb{G}_2 - f_2 1 \mathbb{F} - a_0

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