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Formal Verification of the c-kzg library: Establishing the Basis

Audit Report

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1. Audit Report

The goal of this audit report is to determine the adherence of the structure of the c-kzg implementation to the structure of its stated reference, the Polynomial Commitments section of the Python Deneb consensus specification (Python KZG Specification, hereafter) which encodes the KZG commitment scheme.

Identifying similarities and possible discrepancies between the two structures is key to the next two phases of this project. This comparison will guide us in structuring the Cryptol version of the Python KZG Specification in a way that enables subsequent verification against both the Python KZG specification itself and the c-kzg implementation.

It is important to note that determining the correctness of the c-kzg implementation with respect to the Python KZG Specification is beyond the scope of this document

1.1. Audit of the c-kzg Implementation

The Python KZG Specification entails 28 functions from four categories: Bit-reversal permutation, BLS12-381 helpers, Polynomials, and KZG. The following table identifies all of these functions, according to their category, with the GitHub references to Python specification and the c-kzg implementation.

In most cases the names of the functions in the Python specification match the c-kzg implementation. The differences include:

1. The Python function `multi_exp` is represented in the c-kzg implementaion by splitting multiplication into two functions, `g1_mul` and `g2_mul`, to have separate functions handle multiplication for the two groups, G1 and G2, separately, followed by a call to `blst_doub`;

2. A naming convention difference between the Python function `bls_field_to_bytes` and the c-kzg implementation function `bytes_from_bls_field`;

3. Two instances where the c-kzg implementation provides two implementing functions (for speed reasons) with `g1_lincomb_naive` and `g1_lincomb_fast` for Python function `g1_lincomb`, and similarly in the case of functions `blst_fr_inverse` and `blst_fr_eucl_inverse` for Python function `blst_modular_inverse` (though there appears currently to be no difference between these two BLST imported functions as defined in the BLST repository).

In addition, there are a couple of other slight differences. The computation specified in the Python function `compute_quotient_eval_within_domain` is handled inside the c-kzg implementation of the function `compute_kzg_proof_impl` instead of as a subroutine.

Another difference is that the function `blst_modular_inverse` uses the builtin Python function `pow`, whereas the corresponding BLST functions, as implented in `reciprocal_fr`, use BLST utility functions `ct_inverse_mod_256`, `redc_mont_256`, and `mul_mont_sparse_256`.

1.2. Table 1: Comparing c-kzg vs. Python KZG Specification

Category	Python KZG Specification	c-kzg implementation
Bit-reversal permutation	is_power_of_two reverse_bits bit_reversal_permutation	is_power_of_two reverse_bits bit_reversal_permutation
BLS12-381 helpers	multi_exp hash_to_bls_field bytes_to_bls_field bls_field_to_bytes validate_kzg_g1 bytes_to_kzg_commitment bytes_to_kzg_proof blob_to_polynomial compute_challenge bls_modular_inverse div g1_lincomb compute_powers compute_roots_of_unity	g1_mul , g2_mul hash_to_bls_field bytes_to_bls_field bytes_from_bls_field validate_kzg_g1 bytes_to_kzg_commitment bytes_to_kzg_proof blob_to_polynomial compute_challenge blst_fr_inverse , blst_fr_eucl_inverse div g1_lincomb_naive , g1_lincomb_fast compute_powers compute_roots_of_unity
Polynomials	evaluate_polynomial _in_evaluation_form	evaluate_polynomial _in_evaluation_form
KZG	blob_to_kzg_commitment verify_kzg_proof verify_kzg_proof_impl verify_kzg_proof_batch compute_kzg_proof compute_quotient _eval_within_domain compute_kzg_proof_impl compute_blob_kzg_proof verify_blob_kzg_proof verify_blob_kzg_proof_batch	blob_to_kzg_commitment verify_kzg_proof verify_kzg_proof_impl verify_kzg_proof_batch compute_kzg_proof compute_kzg_proof_impl compute_kzg_proof_impl compute_blob_kzg_proof verify_blob_kzg_proof verify_blob_kzg_proof_batch

2. Next Steps

The next phase of this grant's work is to create a Cryptol specification that matches the Python KZG Specification.

After this second milestone, we will create a test bench that will verify the Cryptol specification against the Python specification, using the Python as the oracle for property based testing of the Cryptol. We will also verify properties for KZG correct construction, e.g. calling `compute_kzg_proof` with valid inputs for `blob` and `z_bytes` always results in successful verification when the output proof is passed to `verify_kzg_proof`.

After this third milestone, we will create a script using the Software Analysis Workbench (SAW) to attempt to formally verify and prove one or more of the Python KZG Specification functions as implemented in c-kzg is functionally equivalent to the corresponding Cryptol specification function, as well as memory safe.

After this fourth milestone, we will deliver a final report with our results and conclusions.