The RainbowRoad: Enabling Expressive Cross-Chain Privacy with a Language-Agnostic and Arbitrary Zero-Knowledge Proof System

Cryptskii

1 Introduction

The RainbowRoad project is a comprehensive framework for constructing and verifying zero-knowledge proofs (ZKPs) for arbitrary programs, with a particular focus on smart contracts. ZKPs are a powerful cryptographic primitive that allows a prover to convince a verifier of the truth of a statement without revealing any additional information beyond the statement itself. This has numerous applications in the realm of privacy-preserving computation, secure multi-party computation, and blockchain technologies.

The framework consists of several interrelated components that facilitate the translation of high-level programming languages into a representation amenable to ZKP generation, encoding and decoding mechanisms, proof generation and verification, and various auxiliary tools for visualization and analysis.

2 Framework Components

2.1 Abstract Syntax Tree (AST) and Intermediate Representation (IR)

The first step in the RainbowRoad pipeline is the translation of the input program into an Abstract Syntax Tree (AST) representation. The AST captures the syntactic structure of the program, including function declarations, variable assignments, control flow constructs, and expressions. Formally, an AST node can be defined as:

Definition 1 (AST Node)**.** *An AST node is a recursive data structure representing a programming construct, defined as:*

$$
\begin{aligned}
\boldsymbol{ASTNode} \;=\; & \boldsymbol{FunctionNode}(name, args, body) \\
\mid\; & \boldsymbol{FunctionDecl}(name, params, body) \\
\mid\; & \boldsymbol{VariableDecl}(name, type, initializer) \\
\mid\; & \boldsymbol{VariableAssign}(name, value) \\
\mid\; & \boldsymbol{Operation}(op, operands) \\
\mid\; & \boldsymbol{LiteralValue}(value) \\
\mid\; & \boldsymbol{IfNode}(condition, thenBranch, elseBranch) \\
\mid\; & \boldsymbol{WhileNode}(condition, body) \\
\mid\; & \boldsymbol{Block}(statements) \\
\mid\; & \boldsymbol{FunctionCall}(name, args) \\
\mid\; & \boldsymbol{Variable}(name, type) \\
\mid\; & \boldsymbol{Class}(name, members) \\
\mid\; & \boldsymbol{Enum}(name, values) \\
\mid\; & \boldsymbol{Interface}(name, members) \\
\mid\; & \boldsymbol{Method}(name, body) \\
\mid\; & \boldsymbol{Loop}(type, body) \\
\mid\; & \boldsymbol{Conditional}(type, condition, thenBranch, elseBranch) \\
\mid\; & \boldsymbol{Return}(value) \\
\mid\; & \boldsymbol{Literal}(value) \\
\mid\; & \boldsymbol{Other}(text)
\end{aligned}
$$

The AST is then transformed into an Intermediate Representation (IR), which is a language-independent representation of the program's semantics. The IR is designed to facilitate subsequent stages of the pipeline, such as encoding, proof generation, and verification.

Definition 2 (Intermediate Representation (IR))**.** *The Intermediate Representation (IR) is a recursive data structure capturing the semantics of a program, defined as:*

$$
\begin{aligned}
\boldsymbol{IR} \;=\; & \boldsymbol{IRFunction}(name, params, body)\\
& \mid \boldsymbol{IRVariableDecl}(name, type, initialValue)\\
& \mid \boldsymbol{IRVariableAssign}(name, newValue)\\
& \mid \boldsymbol{IROperation}(op, operands)\\
& \mid \boldsymbol{IRLiteral}(value)\\
& \mid \boldsymbol{IRIf}(condition, thenBranch, elseBranch)\\
& \mid \boldsymbol{IRWhile}(condition, body)\\
& \mid \boldsymbol{IRReturn}(value)\\
& \mid \boldsymbol{IRBlock}(statements)\\
& \mid \boldsymbol{IRFunctionCall}(name, args)\\
& \mid \boldsymbol{IRComment}(text)\\
& \mid \boldsymbol{IRSequence}(ir\_sequence)\\
& \mid \boldsymbol{IRUnknown}(text)
\end{aligned}
$$

The IR is a crucial intermediate step in the RainbowRoad pipeline, as it serves as a bridge between the high-level programming language and the low-level representations required for ZKP generation.

2.2 Encoding and Decoding Mechanisms

Once the program has been translated into the IR, it must be encoded into a format suitable for ZKP generation and verification. The RainbowRoad framework provides several encoding mechanisms, including:

1. **Smart Contract Encoding**: This module translates the IR into a low-level representation suitable for smart contract execution environments, such as the Ethereum Virtual Machine (EVM).
2. **Op-Code Encoding**: This module encodes the IR into a sequence of operation codes (op-codes) that can be directly executed by a virtual machine or interpreted by a proof generation system.
3. **Character Encoding**: This module encodes the IR as a sequence of characters, enabling efficient storage and transmission of the program representation.
4. **Programming Language Encoding**: This module encodes the IR into a specific programming language representation, such as JavaScript or Solidity, allowing for easy integration with existing toolchains and development environments.

The encoded program representation is then passed to the RainbowCode module, which transforms it into a format known as the RainbowCode. The RainbowCode is a compact and efficient representation of the program, designed specifically for ZKP generation and verification.

Definition 3 (RainbowCode). *The RainbowCode is a compact and efficient representation of a program, consisting of a sequence of hexadecimal values. Each hexadecimal value represents a specific instruction or data element in the program.*

The RainbowCode can be decoded back into the original program representation using the RainbowDecoder module. This module takes the RainbowCode as input and applies the appropriate decoding mechanisms to recover the original IR or programming language representation.

2.3 Proof Generation and Verification

The core of the RainbowRoad framework is the PLONK (Permutations over Lagrange-bases for Oecumenical Noninteractive arguments of Knowledge) proof system, which is used for generating and verifying ZKPs.

Definition 4 (PLONK Proof System). *The PLONK proof system is a zero-knowledge proof protocol that allows a prover to convince a verifier of the truth of a statement, represented as a circuit constraint system, without revealing any additional information beyond the statement itself. The PLONK proof system consists of the following components:*

- ***Circuit Constraint System:*** *A circuit constraint system C is a tuple (F, V, C_S), where F is a finite field, V is a set of variables, and C_S is a set of polynomial constraints over F involving the variables in V.*
- ***Satisfying Assignment:*** *A satisfying assignment α for a circuit constraint system $C = (F, V, C_S)$ is a function $\alpha : V \to F$ such that all constraints in C_S are satisfied when the variables in V are assigned the values specified by α.*
- ***Proving Key:*** *The proving key pk is a set of values derived from the circuit constraint system C, which is used by the prover to generate a PLONK proof.*
- ***Verification Key:*** *The verification key vk is a set of values derived from the circuit constraint system C, which is used by the verifier to verify a PLONK proof.*
- ***PLONK Proof:*** *A PLONK proof π is a tuple (a, b, c) of values in F, which is generated by the prover using the proving key pk and a satisfying assignment α for the circuit constraint system C.*

The PLONK proof system has the following properties:

- ***Completeness:*** *If a prover has a satisfying assignment α for a circuit constraint system C, and generates a PLONK proof π using the proving key pk, then the verifier will accept the proof π when using the verification key vk.*

- ***Soundness:*** *If a prover does not have a satisfying assignment for a circuit constraint system C, then no matter what values they use as a PLONK proof π, the verifier will reject the proof with high probability when using the verification key vk.*

- ***Zero-Knowledge:*** *A PLONK proof π does not reveal any information about the satisfying assignment α used by the prover, beyond the fact that such an assignment exists.*

The RainbowRoad framework provides modules for generating and verifying PLONK proofs, as well as for constructing and manipulating the underlying circuit constraint systems. These modules interact with the RainbowCode representation of the program, allowing for seamless integration of the proof generation and verification processes into the overall pipeline.

2.4 Auxiliary Tools

In addition to the core components for AST/IR translation, encoding/decoding, and proof generation/verification, the RainbowRoad framework includes several auxiliary tools to aid in the development and analysis of ZKP-based applications.

2.4.1 Visualization Aid

The Visualization Aid module provides a graphical representation of the program's AST, IR, and circuit constraint system. This can be particularly useful for debugging and understanding the various transformations and representations involved in the ZKP generation process.

2.4.2 Plonky2 Integration

The Plonky2 Integration module facilitates the use of the Plonky2 library, a high-performance implementation of the PLONK proof system. This module provides a seamless interface between the RainbowRoad framework and the Plonky2 library, enabling efficient proof generation and verification.

2.4.3 Zero-Knowledge Recursive Subgraph Hash Circuit

The Zero-Knowledge Recursive Subgraph Hash Circuit module implements a novel approach for constructing circuit constraint systems for programs involving recursive data structures, such as trees and graphs. This module leverages the properties of zero-knowledge proofs to efficiently represent and verify the integrity of recursive data structures, without revealing sensitive information about their contents.

3 Applications and Future Directions

The RainbowRoad framework has numerous applications in the realm of privacy-preserving computation, secure multi-party computation, and blockchain technologies. Some potential use cases include:

- Privacy-preserving smart contract execution: By generating ZKPs for smart contract execution, the RainbowRoad framework enables the verification of contract execution without revealing sensitive input data or contract logic.
- Secure computation outsourcing: The framework can be used to outsource computationally intensive tasks to untrusted parties, while ensuring the correctness and privacy of the computation through ZKPs.
- Anonymous credentials and identity management: ZKPs can be used to prove the possession of certain credentials or attributes without revealing the underlying identity, enabling privacy-preserving identity management systems.
- Decentralized privacy-preserving data analysis: The RainbowRoad framework can facilitate the analysis of sensitive data in a decentralized and privacy-preserving manner, by combining ZKPs with secure multi-party computation protocols.

Future research directions for the RainbowRoad framework include:

- Improved performance and scalability: Optimizations and parallelization techniques can be explored to enhance the efficiency and scalability of the ZKP generation and verification processes.
- Support for additional programming languages and paradigms: The framework can be extended to support a wider range of programming languages and paradigms, such as functional and logic programming.
- Integration with blockchain platforms: Tighter integration with various blockchain platforms and smart contract execution environments can enable seamless deployment and execution of ZKP-based applications.
- Advanced circuit optimization techniques: Novel circuit optimization techniques can be developed to reduce the complexity and size of the circuit constraint systems, leading to more efficient ZKP generation and verification.
- Formal verification and security analysis: Rigorous formal verification and security analysis of the various components and protocols used in the RainbowRoad framework can further strengthen the robustness and trustworthiness of the system.

4 Comparison with Existing Cross-Chain Methods

While the proposed system shares some high-level goals with existing cross-chain solutions, such as enabling communication and value transfer across different blockchain networks, it differs significantly in its approach and underlying mechanisms. Here, we provide an in-depth comparison of the proposed system with three prominent cross-chain methods: Layer Zero, Cosmos IBC, and Wormhole. The analysis focuses on the key differences, advantages, and limitations of each approach, highlighting the unique features and capabilities of the proposed system.

4.1 Layer Zero

Layer Zero [1] is a decentralized network that aims to facilitate cross-chain communication and asset transfers. It utilizes a combination of smart contracts and a specialized consensus mechanism called "Zeroverse" to enable cross-chain functionality. The Zeroverse consensus mechanism is based on a multi-chain proof-of-stake (PoS) protocol, where validators are required to stake tokens on multiple chains to participate in the consensus process [?].

4.1.1 Key Differences from the Proposed System

The proposed system differs from Layer Zero in several crucial aspects:

- **Network Architecture**: Layer Zero relies on a separate network and consensus mechanism (Zeroverse) to facilitate cross-chain communication and asset transfers. In contrast, the proposed system leverages the PLONK zk-SNARK circuit [2] and zero-knowledge proofs for cross-chain computation and verification, eliminating the need for a dedicated cross-chain network.

- **Smart Contract Deployment**: Layer Zero requires the deployment of smart contracts on each participating blockchain to enable cross-chain functionality. The proposed system, on the other hand, encodes the source code into Rainbow Code [?] and uses the PLONK circuit for verification, providing a more flexible and efficient approach to cross-chain computation.

- **Confidentiality and Privacy**: Layer Zero does not inherently provide confidentiality or privacy for cross-chain computations or data transfers. In contrast, the proposed system offers built-in confidentiality and privacy features through the encoding and hashing of the source code, ensuring that sensitive information remains protected during cross-chain interactions.

Theorem 1 formalizes the lack of confidentiality in Layer Zero compared to the proposed system.

Theorem 1 (Layer Zero Confidentiality)**.** *Given a cross-chain computation C executed through Layer Zero, an adversary $\mathcal{A}$ with access to the Layer Zero network can observe the input data x and output data y of the computation, i.e., $\mathcal{A}(C) = (x, y)$.*

Proof. In Layer Zero, cross-chain computations are executed through smart contracts deployed on each participating blockchain. These smart contracts interact with the Layer Zero network to facilitate communication and data transfer between chains.

Consider a cross-chain computation C that takes input data x from chain A and produces output data y on chain B. An adversary $\mathcal{A}$ with access to the Layer Zero network can observe the input data x being passed to the smart contract on chain A and the output data y being returned on chain B.

Since Layer Zero does not employ any confidentiality or privacy mechanisms, such as encryption or zero-knowledge proofs, the input and output data are visible to the adversary $\mathcal{A}$. Therefore, $\mathcal{A}(C) = (x, y)$, demonstrating the lack of confidentiality in Layer Zero cross-chain computations. □

4.2 Cosmos IBC (Inter-Blockchain Communication)

Cosmos IBC [3] is a protocol that enables communication and value transfer between different blockchains within the Cosmos ecosystem. It follows a hub-and-spoke model, where independent blockchains (zones) can connect to a central hub and communicate with each other through relay and packet-handling mechanisms.

The Cosmos IBC protocol defines a set of standardized interfaces and message formats for cross-chain communication. It utilizes a combination of light clients, relayers, and packets to facilitate the transfer of data and assets between chains [4]. Light clients are responsible for verifying the state and consensus of remote chains, relayers handle the transmission of IBC packets between chains, and packets encapsulate the cross-chain messages and data.

4.2.1 Key Differences from the Proposed System

The proposed system differs from Cosmos IBC in several key aspects:

- **Ecosystem Scope**: Cosmos IBC is primarily designed for communication and value transfer within the Cosmos ecosystem, limiting its applicability to blockchains that are part of the Cosmos network. The proposed system, in contrast, aims to enable cross-chain computation and verification across different blockchain networks, regardless of their underlying architecture or consensus mechanism.

- **Confidentiality and Privacy**: Cosmos IBC does not provide inherent mechanisms for ensuring the confidentiality or privacy of cross-chain data or computations. The proposed system, on the other hand, employs Rainbow Code encoding and zero-knowledge proofs to protect sensitive information during cross-chain interactions, providing a higher level of confidentiality and privacy.

- **Computation Capabilities**: Cosmos IBC focuses on enabling communication and value transfer between blockchains, but it does not provide native support for arbitrary cross-chain computations. The proposed system leverages the PLONK zk-SNARK circuit to perform arbitrary computations across different blockchains while maintaining the confidentiality of the computation and data.

Algorithm 1 outlines the high-level steps involved in the Cosmos IBC cross-chain communication process.

Algorithm 1 Cosmos IBC Cross-Chain Communication

```
1: Input: Source chain $S$, destination chain $D$, data $x$
2: Output: Data $y$ on destination chain $D$
3: $S$ creates an IBC packet $p$ containing data $x$
4: $S$ sends the IBC packet $p$ to the relayer $R$
5: $R$ verifies the validity of the IBC packet $p$
6: $R$ forwards the IBC packet $p$ to the destination chain $D$
7: $D$ receives the IBC packet $p$ and extracts the data $x$
8: $D$ processes the data $x$ and generates the output $y$
9: return $y$
```

In contrast, the proposed system enables arbitrary cross-chain computations while maintaining confidentiality and privacy through the use of Rainbow Code encoding and zk-SNARK proofs, as outlined in Algorithm 2.

Algorithm 2 Proposed System Cross-Chain Computation

```
1: Input: Source code $C$, input data $x$ from chain $A$, input data $y$ from chain $B$
2: Output: Computation result $z$ on chain $B$
3: Encode source code $C$ into Rainbow Code $R_C$
4: Hash the Rainbow Code $H_C = \mathcal{H}(R_C)$
5: Encode input data $x$ into Rainbow Code $R_x$ and hash it $H_x = \mathcal{H}(R_x)$
6: Encode input data $y$ into Rainbow Code $R_y$ and hash it $H_y = \mathcal{H}(R_y)$
7: Generate PLONK proof $\pi$ using $H_C$, $H_x$, and $H_y$
8: Send the PLONK proof $\pi$ to chain $B$
9: Chain $B$ verifies the PLONK proof $\pi$
10: Chain $B$ executes the computation and obtains the result $z$
11: return $z$
```

4.3 Wormhole

Wormhole [5] is a cross-chain bridge that enables the transfer of assets and data between different blockchain networks, including Ethereum, Solana, and others.

It employs a combination of smart contracts, trusted validators, and specialized messaging protocols to facilitate cross-chain communication.

In Wormhole, a set of trusted validators, called Guardians, are responsible for verifying and attesting to the validity of cross-chain transactions. These Guardians sign and broadcast VAA (Verified Action Approval) messages, which contain the necessary information for the receiving chain to process the cross-chain transaction [?].

4.3.1 Key Differences from the Proposed System

The proposed system differs from Wormhole in several key aspects:

- **Primary Focus**: Wormhole primarily focuses on enabling asset transfers and data communication between different blockchain networks. The proposed system, in contrast, aims to enable arbitrary cross-chain computations and verification using the PLONK zk-SNARK circuit and zero-knowledge proofs, providing a more versatile and expressive framework for cross-chain interactions.

- **Trust Assumptions**: Wormhole relies on a set of trusted validators (Guardians) to verify and attest to the validity of cross-chain transactions. The proposed system eliminates the need for trusted intermediaries by leveraging the cryptographic properties of the PLONK circuit and hashed Rainbow Code for secure computation and verification, enhancing the decentralization and security of cross-chain interactions.

- **Confidentiality and Privacy**: Wormhole does not provide inherent confidentiality or privacy for cross-chain transactions or data transfers. The proposed system, on the other hand, ensures the confidentiality and privacy of cross-chain computations by encoding the source code and using zero-knowledge proofs, protecting sensitive information from being revealed during the process.

Theorem 2 formalizes the trust assumptions in Wormhole compared to the proposed system.

Theorem 2 (Wormhole Trust Assumptions)**.** *In Wormhole, the validity of a cross-chain transaction T is dependent on the honesty of the majority of the Guardians $\mathcal{G}$. If more than $\frac{1}{2}$ of the Guardians are compromised, the security of the cross-chain transaction T is violated.*

Proof. Let n be the total number of Guardians in the Wormhole network, and let k be the number of honest Guardians. The validity of a cross-chain transaction T in Wormhole is determined by the majority of the Guardians signing the corresponding VAA (Verified Action Approval) message.

Suppose an adversary $\mathcal{A}$ compromises m Guardians, such that $m > \frac{n}{2}$. In this case, the adversary $\mathcal{A}$ can control the majority of the Guardians and sign arbitrary VAA messages, effectively violating the security of the cross-chain transaction T.

Therefore, the security of cross-chain transactions in Wormhole is dependent on the honesty of the majority of the Guardians. If more than $\frac{1}{2}$ of the Guardians are compromised, the security of the cross-chain transactions is violated. □

In contrast, the proposed system eliminates the need for trusted intermediaries by leveraging the security properties of the PLONK zk-SNARK circuit and hashed Rainbow Code, as formalized in Theorem 3.

Theorem 3 (Proposed System Security)**.** *In the proposed system, the security of a cross-chain computation C is based on the soundness and zero-knowledge properties of the PLONK zk-SNARK circuit and the collision resistance of the hash function $\mathcal{H}$ used for hashing the Rainbow Code.*

Proof. The security of the proposed system relies on two main components: the PLONK zk-SNARK circuit and the hashed Rainbow Code.

First, the soundness property of the PLONK zk-SNARK circuit ensures that if a prover generates a valid proof π for a statement x, then the statement x is true with overwhelming probability [2]. This means that a valid proof π generated for a cross-chain computation C guarantees the correctness of the computation.

Second, the zero-knowledge property of the PLONK zk-SNARK circuit ensures that the proof π does not reveal any information about the witness w used to generate the proof, other than the truth of the statement x [2]. In the context of the proposed system, this means that the proof π does not reveal any information about the source code C or the input data x and y, ensuring the confidentiality of the cross-chain computation.

Finally, the security of the hashed Rainbow Code relies on the collision resistance of the hash function $\mathcal{H}$. Given the hashed Rainbow Code $H_C = \mathcal{H}(R_C)$, it is computationally infeasible for an adversary to find a different Rainbow Code R'_C such that $\mathcal{H}(R'_C) = H_C$, due to the collision resistance property of the hash function [6].

Therefore, the security of cross-chain computations in the proposed system is based on the soundness and zero-knowledge properties of the PLONK zk-SNARK circuit and the collision resistance of the hash function used for hashing the Rainbow Code. □

4.4 Comparative Analysis

Table **??** provides a comparative summary of the proposed system and the existing cross-chain methods discussed above.

Feature	Proposed System	Layer Zero	Cosmos IBC	Wormhole
Cross-chain computation	✓			
Confidentiality & privacy	✓			
Zero-knowledge proofs	✓			
Arbitrary computations	✓			
Decentralized verification	✓	✓		
Asset transfer	✓	✓	✓	✓
Data communication	✓	✓	✓	✓
Ecosystem agnostic	✓			✓

Table 1: Comparative summary of cross-chain methods (corrected)

As evident from the comparative analysis, the proposed system offers several unique advantages over existing cross-chain methods. Its ability to perform arbitrary cross-chain computations while maintaining confidentiality and privacy through the use of Rainbow Code encoding and zk-SNARK proofs sets it apart from other solutions. The decentralized verification and ecosystem-agnostic nature of the proposed system further enhance its applicability and potential for broad adoption.

To quantitatively demonstrate the performance and scalability advantages of the proposed system, we conducted experiments comparing the cross-chain computation latency and throughput of our approach with Layer Zero, Cosmos IBC, and Wormhole. The experiments were performed on a testnet environment simulating multiple blockchain networks.

5 Enabling Complex Cross-Chain DeFi Operations without Token Wrapping

The proposed system's ability to perform arbitrary computations across different blockchains while maintaining confidentiality opens up new possibilities for complex cross-chain DeFi operations without the need for token wrapping. By leveraging the power of Rainbow Code encoding, hashing, and the PLONK zk-SNARK circuit, users can participate in DeFi protocols across different blockchains while preserving the privacy and security of their assets and transaction details.

5.1 Cross-Chain Liquidity Provision Example

Consider a scenario where Alice, a user holding SOL tokens on the Solana blockchain, wants to provide liquidity to a decentralized exchange (DEX) on the Ethereum blockchain without the need for token wrapping or cross-chain bridges.

5.1.1 Problem Statement

Let $\mathcal{S}$ denote the Solana blockchain and $\mathcal{E}$ denote the Ethereum blockchain. Alice, a user on the Solana blockchain, holds a balance of b_A SOL tokens in her wallet address w_A on $\mathcal{S}$. Alice wants to provide liquidity to a decentralized exchange (DEX) on the Ethereum blockchain $\mathcal{E}$ using her SOL tokens. However, directly transferring tokens across different blockchains is not natively supported due to the inherent differences in the underlying blockchain architectures and consensus mechanisms.

The traditional approach to enable cross-chain liquidity provision is through token wrapping or cross-chain bridges. Token wrapping involves creating a wrapped version of the SOL token on the Ethereum blockchain, denoted as $wSOL$, which is backed by the original SOL tokens locked in a smart contract on the Solana blockchain. Cross-chain bridges, on the other hand, rely on trusted intermediaries or multi-sig arrangements to facilitate the transfer of tokens between the Solana and Ethereum blockchains.

However, these approaches introduce additional complexity, risks, and costs. Token wrapping requires the creation and management of additional smart contracts on both blockchains, increasing the attack surface and potential vulnerabilities. Cross-chain bridges rely on trusted intermediaries, introducing counterparty risk and potential points of failure. Moreover, the process of wrapping tokens or using cross-chain bridges often involves multiple transactions and gas fees, adding overhead and costs to the liquidity provision process.

Therefore, the problem statement can be formally defined as follows:

Problem 1. *Given a user Alice with a balance of b_A SOL tokens on the Solana blockchain $\mathcal{S}$, and a decentralized exchange (DEX) on the Ethereum blockchain $\mathcal{E}$, enable Alice to provide liquidity to the DEX using her SOL tokens without the need for token wrapping or cross-chain bridges, while minimizing complexity, risks, and costs.*

The objective is to design a system that allows Alice to securely and efficiently provide liquidity to the Ethereum-based DEX using her SOL tokens from the Solana blockchain, without the need for intermediate token wrapping or reliance on trusted intermediaries. The system should ensure the integrity and confidentiality of the liquidity provision process, while reducing the overall complexity and costs associated with cross-chain liquidity provision.

5.1.2 Proposed Solution

To address the problem of cross-chain liquidity provision without the need for token wrapping or cross-chain bridges, we propose a solution based on Rainbow Code encoding and PLONK zero-knowledge proofs. The proposed system enables Alice to provide liquidity to the Ethereum-based DEX using her SOL tokens from the Solana blockchain in a secure, efficient, and confidential manner. The solution involves the following steps:

1. **Rainbow Code Encoding of SOL Token Balance and Liquidity Provision Parameters:**

   Alice encodes her SOL token balance b_A and the desired liquidity provision parameters p_A into Rainbow Code R_A using the encoding function $\mathcal{R}$:

   $$R_A = \mathcal{R}(b_A, p_A) \tag{1}$$

   where $\mathcal{R}$ is a deterministic function that maps the input data to a unique Rainbow Code representation. The Rainbow Code encoding ensures the confidentiality of Alice's sensitive information, as the original data cannot be easily reverse-engineered from the encoded representation.

2. **Hashing the Rainbow Code:**

   Alice computes the hash of the Rainbow Code R_A using a cryptographically secure hash function $\mathcal{H}$:

   $$H_A = \mathcal{H}(R_A) \tag{2}$$

   where $\mathcal{H}$ is a collision-resistant hash function that maps the Rainbow Code to a fixed-size digest. The hashing step further enhances the security and integrity of the encoded data, as any tampering with the Rainbow Code would result in a different hash value.

3. **Rainbow Code Encoding of DEX Liquidity Pool Parameters and Ethereum-side Data:**

   The Ethereum-based DEX encodes its liquidity pool parameters p_D and the necessary Ethereum-side data d_E into Rainbow Code R_D using the same encoding function $\mathcal{R}$:

   $$R_D = \mathcal{R}(p_D, d_E) \tag{3}$$

   This step ensures that the DEX's liquidity pool parameters and any required Ethereum-specific data are securely encoded and can be used in the subsequent proof generation process.

4. **Hashing the DEX Rainbow Code:**

   The DEX computes the hash of the Rainbow Code R_D using the same cryptographically secure hash function $\mathcal{H}$:

   $$H_D = \mathcal{H}(R_D) \tag{4}$$

   The DEX makes the hashed value H_D publicly available, allowing Alice to use it in the proof generation process without revealing the actual liquidity pool parameters or Ethereum-side data.

5. **PLONK Proof Generation:**

Alice constructs a PLONK proof π using the hashed Rainbow Codes H_A and H_D, proving the correctness of the liquidity provision operation without revealing her SOL token balance or the specific parameters:

$$\pi = \mathsf{PLONK.Prove}(H_A, H_D) \tag{5}$$

where $\mathsf{PLONK.Prove}$ is the proof generation function of the PLONK zero-knowledge proof system. The proof π attests to the validity of the liquidity provision operation, including the correctness of Alice's SOL token balance, the desired liquidity provision parameters, and the compatibility with the DEX's liquidity pool parameters and Ethereum-side data.

6. **Proof Submission and Verification:**

   Alice sends the PLONK proof π to the Ethereum-based DEX for verification. The DEX verifies the proof using the PLONK verification function $\mathsf{PLONK.Verify}$:

$$v = \mathsf{PLONK.Verify}(\pi) \tag{6}$$

   where v is a boolean value indicating the validity of the proof. If the verification succeeds ($v = 1$), the DEX can be assured that Alice's liquidity provision operation is valid and compatible with its liquidity pool parameters and Ethereum-side requirements, without learning the specific details of Alice's SOL token balance or liquidity provision parameters.

7. **Liquidity Provision Execution and LP Token Issuance:**

   If the proof verification succeeds, the DEX executes the liquidity provision operation, effectively adding Alice's SOL tokens to the liquidity pool on the Ethereum blockchain. The DEX updates its internal state to reflect the increased liquidity and mints the corresponding liquidity provider (LP) tokens t_{LP} to Alice's Ethereum wallet address w_E:

$$t_{LP} \to w_E \tag{7}$$

   The LP tokens represent Alice's share of the liquidity pool and can be used for future redemptions or trading on the Ethereum-based DEX.

To ensure that Alice's tokens are secured and cannot be spent on Solana while providing liquidity on Ethereum, we need a mechanism to lock or freeze the tokens on the Solana blockchain. Rainbow Code encoding alone does not provide a direct solution to this problem, as it focuses on the confidentiality and integrity of the encoded data rather than the locking of tokens.

However, we can extend the proposed solution to include a token locking mechanism on the Solana blockchain without the need for wrapping the tokens. This can be achieved through the use of a time-lock contract or a conditional locking mechanism directly on the Solana blockchain.

Here's an extended version of the proposed solution that incorporates token locking:

1. **Token Locking on Solana:**

   Before initiating the liquidity provision process, Alice locks her SOL tokens on the Solana blockchain using a time-lock contract or a conditional locking mechanism. The locking contract ensures that the tokens cannot be spent or transferred until a specific condition is met or a certain time period has elapsed.

   For example, Alice can create a time-lock contract on Solana that locks her SOL tokens for a predetermined period, such as the duration of the liquidity provision. The contract can be designed to release the tokens back to Alice's wallet once the liquidity is withdrawn from the Ethereum-based DEX or after a specified time period.

   Alternatively, a conditional locking mechanism can be used, where the tokens are locked until a specific condition is met, such as the confirmation of the liquidity provision on the Ethereum blockchain. This can be achieved through a cross-chain communication mechanism, such as a decentralized oracle or a trusted relay, that verifies the state of the liquidity provision on Ethereum and triggers the release of the locked tokens on Solana.

2. **Rainbow Code Encoding and Hashing:**

   Alice encodes her locked SOL token balance b_A, the desired liquidity provision parameters p_A, and the locking contract details l_A into Rainbow Code R_A using the encoding function $\mathcal{R}$:

   $$R_A = \mathcal{R}(b_A, p_A, l_A) \tag{8}$$

   She then computes the hash of the Rainbow Code R_A using a cryptographically secure hash function $\mathcal{H}$:

   $$H_A = \mathcal{H}(R_A) \tag{9}$$

3. **PLONK Proof Generation and Verification:**

   The subsequent steps of the liquidity provision process remain the same as described in the previous solution. Alice generates a PLONK proof π using the hashed Rainbow Codes H_A and H_D, and sends it to the Ethereum-based DEX for verification.

   The DEX verifies the proof and executes the liquidity provision operation if the verification succeeds. The proof verification process now includes an additional check to ensure that the locked SOL token balance b_A matches the liquidity provision parameters p_A and the locking contract details l_A.

4. **Liquidity Withdrawal and Token Release:**

   When Alice decides to withdraw her liquidity from the Ethereum-based DEX, she initiates a liquidity withdrawal request. The DEX processes the withdrawal request and sends a confirmation to the Solana blockchain through a cross-chain communication mechanism.

Upon receiving the confirmation, the locking contract on the Solana blockchain verifies the authenticity of the confirmation and releases the locked SOL tokens back to Alice's wallet. The release of the tokens can be triggered automatically based on the predefined conditions or time period specified in the locking contract.

By incorporating a token locking mechanism on the Solana blockchain, the extended solution ensures that Alice's SOL tokens are secured and cannot be spent while providing liquidity on Ethereum. The locking contract or conditional locking mechanism prevents Alice from double-spending her tokens or withdrawing them prematurely.

The use of Rainbow Code encoding and hashing enhances the confidentiality and integrity of the locked token balance and liquidity provision parameters. The PLONK proof system enables the verification of the liquidity provision operation and the locked token balance without revealing the specific details.

The extended solution provides a secure and transparent way to lock tokens on the Solana blockchain while enabling cross-chain liquidity provision on Ethereum. It eliminates the need for token wrapping and relies on native locking mechanisms on the Solana blockchain, reducing the complexity and risks associated with traditional cross-chain liquidity provision methods.

The token locking mechanism can be customized based on the specific requirements and constraints of the liquidity provision scenario. The locking contract can be designed to support various locking conditions, such as time-based locking, value-based locking, or a combination of both. The cross-chain communication mechanism can be adapted to use different decentralized oracle solutions or trusted relays, depending on the security and trust assumptions of the system.

Overall, the extended solution enhances the security and reliability of cross-chain liquidity provision by ensuring that the tokens are locked on the source blockchain while providing liquidity on the target blockchain. It leverages the power of Rainbow Code encoding, PLONK proofs, and native token locking mechanisms to enable secure, confidential, and efficient cross-chain liquidity provision without the need for token wrapping.

The proposed solution leverages the power of Rainbow Code encoding and PLONK zero-knowledge proofs to enable secure and confidential cross-chain liquidity provision without the need for token wrapping or cross-chain bridges. The Rainbow Code encoding ensures the confidentiality of sensitive information, while the PLONK proof system allows for the verification of the liquidity provision operation without revealing the specific details.

The use of cryptographic hash functions further enhances the security and integrity of the encoded data, making it computationally infeasible for an adversary to tamper with the Rainbow Codes without being detected. The PLONK proof system provides a highly efficient and scalable way to generate and verify proofs, ensuring the practicality and performance of the proposed solution.

By eliminating the need for token wrapping and cross-chain bridges, the proposed system reduces the complexity, risks, and costs associated with traditional cross-chain liquidity provision methods. Alice can securely and efficiently provide liquidity to the Ethereum-based DEX using her SOL tokens from the Solana blockchain, without the need for intermediate steps or reliance on trusted intermediaries.

The proposed solution opens up new possibilities for seamless and secure cross-chain liquidity provision, enabling users to leverage their assets across different blockchain ecosystems without compromising on security, confidentiality, or efficiency. The system can be extended and adapted to support various cross-chain liquidity provision scenarios, promoting interoperability and composability in the decentralized finance (DeFi) ecosystem.

5.1.3 Confidentiality and Security Analysis

The proposed solution ensures the confidentiality and security of Alice's SOL token balance and the liquidity provision parameters throughout the cross-chain operation. The Rainbow Code encoding function $\mathcal{R}$ and the cryptographically secure hash function $\mathcal{H}$ protect the sensitive information from being revealed to the public or the counterparties.

Theorem 4 formalizes the confidentiality guarantee provided by the Rainbow Code encoding.

Theorem 4 (Rainbow Code Confidentiality)**.** *Given a Rainbow Code $R = \mathcal{R}(x)$, where x is the input data, it is computationally infeasible to recover x from R without knowledge of the encoding function $\mathcal{R}$.*

Proof. The confidentiality of the Rainbow Code encoding relies on the security of the encoding function $\mathcal{R}$. Assuming $\mathcal{R}$ is a secure encoding function, an adversary without knowledge of $\mathcal{R}$ cannot efficiently recover the input data x from the Rainbow Code R.

Consider an adversary $\mathcal{A}$ who attempts to recover x from R. To succeed, $\mathcal{A}$ would need to find an inverse function $\mathcal{R}^{-1}$ such that:

$$\mathcal{R}^{-1}(R) = \mathcal{R}^{-1}(\mathcal{R}(x)) = x \tag{10}$$

However, without knowledge of the encoding function $\mathcal{R}$, finding such an inverse function $\mathcal{R}^{-1}$ is computationally infeasible. The security of $\mathcal{R}$ ensures that the input data x cannot be efficiently recovered from the Rainbow Code R.

Therefore, the Rainbow Code encoding provides confidentiality for the input data x. □

Furthermore, the use of the PLONK zk-SNARK circuit ensures the integrity and correctness of the cross-chain liquidity provision operation without revealing the sensitive information. The zero-knowledge property of the PLONK proof π guarantees that no information about Alice's SOL token balance or the specific parameters is leaked during the proof verification process.

Theorem 5 formalizes the zero-knowledge property of the PLONK proof.

Theorem 5 (PLONK Zero-Knowledge Property)**.** *A PLONK proof π for a statement x satisfies the zero-knowledge property if there exists a polynomial-time simulator $\mathcal{S}$ such that for any verifier $\mathcal{V}$, the following two distributions are computationally indistinguishable:*

- $\mathsf{PLONK.Prove}(x, w)$*: The distribution of proofs generated by the honest prover with witness w.*
- $\mathcal{S}(x)$*: The distribution of simulated proofs generated by the simulator $\mathcal{S}$ on input x.*

The zero-knowledge property ensures that the verifier learns nothing beyond the validity of the statement being proven. In the context of the cross-chain liquidity provision operation, the PLONK proof π allows the Ethereum-based DEX to verify the correctness of the operation without gaining any knowledge about Alice's SOL token balance or the specific parameters involved.

5.2 Enabling Seamless Cross-Chain DeFi Operations

The cross-chain liquidity provision example highlights the potential of the proposed system to enable seamless and secure cross-chain DeFi operations. By leveraging the power of Rainbow Code encoding, hashing, and the PLONK zk-SNARK circuit, users can participate in various DeFi protocols across different blockchains while maintaining the confidentiality and integrity of their assets and transaction details.

The proposed system's ability to perform arbitrary computations across blockchains opens up new possibilities for cross-chain DeFi, including:

- Cross-chain lending and borrowing without the need for wrapped tokens
- Cross-chain yield farming and liquidity mining
- Cross-chain decentralized exchanges with native token support
- Cross-chain portfolio management and rebalancing
- Cross-chain insurance and risk management protocols

These cross-chain DeFi operations can be performed securely and efficiently using the proposed system, without the need for intermediaries or trust assumptions. The use of Rainbow Code encoding and zk-SNARK proofs ensures that sensitive information remains confidential while enabling trustless verification of the correctness of the operations.

The composability and interoperability benefits brought by the proposed system have the potential to significantly enhance the DeFi ecosystem. By enabling seamless cross-chain interactions and eliminating the need for token wrapping or cross-chain bridges, the system can facilitate greater capital efficiency, reduced friction, and improved user experience across different blockchain networks.

5.2.1 Comparison with Existing Cross-Chain DeFi Solutions

Existing cross-chain DeFi solutions often rely on token wrapping or cross-chain bridges to enable the movement of assets and liquidity across different blockchains. While these solutions have paved the way for cross-chain interoperability, they come with certain limitations and challenges.

Token wrapping involves creating a wrapped version of a token on a different blockchain, which is typically backed by the original token locked in a smart contract on the native blockchain. This process introduces additional complexity, as it requires the creation and management of separate wrapped token contracts on each blockchain involved in the cross-chain operation. Wrapped tokens also introduce counterparty risk, as users need to trust the custodian or smart contract holding the original tokens.

Cross-chain bridges, on the other hand, rely on trusted intermediaries or multi-sig schemes to facilitate the transfer of assets between different blockchains. These bridges often require users to trust the operators or validators responsible for the security and integrity of the bridge. Cross-chain bridges can also be vulnerable to attacks, such as the double-spend problem, where an attacker attempts to spend the same funds on multiple blockchains simultaneously.

In contrast, the proposed system eliminates the need for token wrapping or cross-chain bridges by enabling direct cross-chain DeFi operations through Rainbow Code encoding and zk-SNARK proofs. This approach offers several advantages over existing solutions:

- Trustless Verification: The use of zk-SNARK proofs allows for trustless verification of cross-chain operations without relying on intermediaries or trusted parties.
- Confidentiality: Rainbow Code encoding and hashing ensure that sensitive information, such as asset balances and transaction details, remains confidential throughout the cross-chain DeFi operations.
- Reduced Complexity: By eliminating the need for token wrapping or cross-chain bridges, the proposed system reduces the complexity and overhead associated with cross-chain asset transfers and liquidity provision.
- Enhanced Security: The trustless nature of the proposed system mitigates the risks associated with trusted intermediaries or multi-sig schemes, enhancing the overall security of cross-chain DeFi operations.

5.2.2 Future Research Directions

The proposed system's potential to revolutionize cross-chain DeFi opens up several avenues for future research and exploration. Some potential areas for further investigation include:

- Scalability and Performance Optimization: Exploring techniques to enhance the scalability and performance of the proposed system, such as optimizing the Rainbow Code encoding and zk-SNARK proof generation processes, to support high-throughput cross-chain DeFi applications.

- Interoperability with Existing DeFi Protocols: Investigating the integration of the proposed system with existing DeFi protocols and platforms to enable seamless cross-chain interactions and liquidity flow.
- Cross-Chain Governance and Coordination: Exploring mechanisms for cross-chain governance and coordination to facilitate the management and evolution of cross-chain DeFi protocols and applications.
- Privacy-Preserving Cross-Chain DeFi: Extending the confidentiality features of the proposed system to enable privacy-preserving cross-chain DeFi operations, such as confidential asset transfers and private liquidity provision.
- Formal Verification and Security Analysis: Conducting formal verification and rigorous security analysis of the proposed system to ensure its robustness against potential vulnerabilities and attacks.

These research directions aim to further enhance the capabilities, security, and usability of the proposed system, driving the adoption and growth of cross-chain DeFi in the blockchain ecosystem.

5.2.3 Conclusion

The proposed system's ability to enable complex cross-chain DeFi operations without the need for token wrapping or cross-chain bridges represents a significant advancement in the realm of decentralized finance. By leveraging Rainbow Code encoding, hashing, and zk-SNARK proofs, the system allows users to participate in various DeFi protocols across different blockchains while maintaining the confidentiality and integrity of their assets and transaction details.

The cross-chain liquidity provision example demonstrates the efficiency and practicality of the proposed solution, showcasing its potential to revolutionize the DeFi ecosystem. The trustless verification, confidentiality, reduced complexity, and enhanced security offered by the system make it a promising alternative to existing cross-chain DeFi solutions.

As the DeFi landscape continues to evolve, the proposed system's ability to enable seamless and secure cross-chain interactions will play a crucial role in driving innovation, liquidity, and adoption across multiple blockchain networks. Further research and development in this area will contribute to the growth and maturation of the cross-chain DeFi ecosystem, unlocking new opportunities for decentralized financial applications and services.

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6 Conclusion

The RainbowRoad framework provides a comprehensive and extensible solution for constructing and verifying zero-knowledge proofs for arbitrary programs, with a particular emphasis on smart contracts. By combining advanced cryptographic techniques with state-of-the-art compilers and virtual machine technologies, the framework enables the development of privacy-preserving applications across a wide range of domains. The modular design and extensive set of auxiliary tools make the RainbowRoad framework a valuable asset for researchers, developers, and practitioners working in the fields of privacy-preserving computation, secure multi-party computation, and blockchain technologies.