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Tracing And Analyzing Illicit Cryptocurrency Transactions

Kabilesh C M
MTech Scholar, Dept. of Cyber Security
Dr. M.G.R. Educational and Research Institute
Chennai, India

Dr. B. Raja
Professor, Dept. of CSE
Dr. M.G.R. Educational and Research Institute
Chennai, India

Dr. S. Geetha
Dean & HOD, Dept. of CSE
Dr. M.G.R. Educational and Research Institute
Chennai, India

Dr. V. Cyrilraj
Professor, Dept. of CSE
Dr. M.G.R. Educational and Research Institute
Chennai, India

***Abstract* – As decentralized finance (DeFi) continues to scale, traditional forensic methodologies often fail due to their retrospective, "post-mortem" nature, analyzing illicit activities only after they are permanently recorded on the ledger. This project proposes coinEth, a real-time institutional blockchain surveillance and autonomous defense system designed for the Ethereum Sepolia network. The framework operates across a four-layer architecture: a Data Acquisition Layer that intercepts pending transactions via Alchemy WebSockets (WSS); a Persistence and Forensic Engine that utilizes SQLite and Python-based heuristics to detect suspicious behavioral patterns such as "structuring" and "high velocity"; a Governance Layer that executes an autonomous enforcement loop via a Solidity-based "Gatekeeper" smart contract; and a Visualization Layer built with Streamlit and PyVis.**

By assigning dynamic risk scores—categorized as Safe (Level 0), Warning (Level 1), and Frozen (Level 2)—the system can automatically broadcast on-chain transactions to freeze illicit accounts before fund exfiltration occurs. Furthermore, coinEth reconstructs a chronological "money trail" through sequential path mapping (T0 → T1 → T2...), ensuring a verifiable digital chain of custody for investigative reporting. This proactive approach shifts blockchain security from passive observation to active, real-time intervention, significantly enhancing the defense mechanisms available to institutional stakeholders.

Keywords - Blockchain Forensics, Ethereum (Sepolia), Real-time Surveillance, Autonomous Enforcement, Smart Contract Governance, Mempool Monitoring, Heuristic Analysis, Sequential Path Mapping, Intrusion Detection Systems (IDS), Chain of Custody.

1. INTRODUCTION

The rapid expansion of decentralized finance (DeFi) has exposed a critical vulnerability in traditional blockchain forensics: most tools are retrospective, analyzing illicit activities only after funds have been permanently exfiltrated and confirmed on the ledger. By the time an investigator reconstructs a crime, the trail often goes cold in a mixer or cross-chain bridge. coinEth addresses this gap by shifting the paradigm from passive evidence collection to active, real-time intervention. Designed for the Ethereum Sepolia network, this framework acts as a digital immune system, intercepting "pending" transactions in the mempool and applying automated logic to neutralize threats before they are finalized.

At its technical core, coinEth utilizes a robust four-layer architecture that bridges high-speed data ingestion with autonomous on-chain action. The system monitors the blockchain via Alchemy WebSockets, feeding live transaction data into a forensic engine that scans for behavioral red flags like "Structuring" (repetitive small transfers) and "Velocity" spikes. Unlike standard monitoring suites that merely alert a human operator, coinEth integrates a Solidity-based "Gatekeeper" smart contract. This allows the system to autonomously broadcast enforcement transactions, effectively "freezing" suspect accounts on-chain in the milliseconds before illicit funds can escape.

The project concludes its workflow in the Forensic Lab, an interactive suite built with Streamlit and PyVis. This layer transforms raw, complex hexadecimal data into intuitive Sequential Path Maps, providing a verifiable Digital Chain of Custody. By labeling transaction nodes chronologically (T0 → T1 → T2...) and color-coding them by risk level, coinEth offers investigators a clear, evidence-grade visual reconstruction of the money trail. Ultimately, the project demonstrates how the integration of real-time surveillance and smart contract governance can significantly enhance the security posture of institutional blockchain stakeholders.

2.LITERATURE REVIEW

The literature review for **coinEth** examines the intersection of blockchain forensics, real-time mempool surveillance, and autonomous governance. This field has transitioned from passive, historical data analysis to proactive, smart-contract-driven intervention to combat increasingly sophisticated decentralized finance (DeFi) exploits.

1. The Shift from Retrospective to Proactive Forensics

Traditional blockchain forensics typically relies on "post-mortem" analysis, where investigators reconstruct illicit activities after transactions have been finalized on the ledger. This approach is often insufficient in DeFi, where illicit actors exfiltrate funds rapidly through mixers or bridges.

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- **Retrospective Analysis**: Focuses on analyzing historical blocks to map fund movement after an exploit has occurred.
- **Real-time Intervention**: Proactive systems like coinEth aim to identify and neutralize threats in the milliseconds before they are finalized on-chain.
- **Infrastructure**: Systems now utilize high-speed connections (e.g., Alchemy WebSockets) to monitor pending mempool transactions.

2. Mempool Surveillance and Data Acquisition

Real-time ingestion is the foundation of modern blockchain defense systems.

- **Data Acquisition Layer**: Acts as the system's gateway, capturing live transaction data (pending mempool transactions) from networks like Ethereum Sepolia.
- **Listener Technology**: Tools like Web3.py and WebSocket Stream Listeners are employed to intercept incoming transactions before they are mined into a block.
- **Persistence**: Data is often stored in local verifiable chronological logs (e.g., SQLite) to maintain a "Black Box" flight record for forensic integrity.

3. Behavioral Heuristics and Risk Scoring

Modern forensic engines utilize heuristic analysis to detect patterns of illicit behavior that bypass traditional static filters.

- **Structuring Detection**: Heuristics are designed to detect "structuring" patterns, such as repetitive transfers of specific amounts (e.g., $0.09–0.1$ ETH) intended to avoid threshold triggers.
- **Velocity Auditing**: Monitoring the frequency and volume of transactions over short windows helps identify automated draining or high-velocity exfiltration attempts.
- **Risk Classification**: Systems categorize addresses into dynamic risk levels: **Level 0 (Safe)**, **Level 1 (Warning)**, and **Level 2 (Frozen)**.

4. Autonomous Enforcement via Smart Contracts

A critical advancement in forensic literature is the integration of software-based detection with on-chain enforcement logic.

- **The Shield Layer**: Autonomous enforcement loops bridge software analysis with blockchain action.
- **Gatekeeper Contracts**: Solidity-based smart contracts function as the "Gatekeeper," enforcing risk levels by restricting account interactions once a Level 2 (Blocked) status is assigned.
- **Auto-Signers**: Administrative modules use private keys to broadcast setRiskLevel transactions autonomously when critical thresholds are breached.

5. Visual Analytics and the Digital Chain of Custody

For forensic findings to be legally and institutionally viable, complex ledger data must be transformed into human-readable evidence.

- **Sequential Path Mapping**: Utilizing tools like PyVis and NetworkX, transaction trails are mapped chronologically as $T_0 \to T_1 \to T_2$ paths.
- **Chain of Custody**: These visualizations create a verifiable digital chain of custody, illustrating both the flow of funds and the specific points of system intervention.
- **Interactive Dashboards**: Frameworks like Streamlit provide investigators with control hubs to search addresses, view metrics, and interact with forensic maps.

Table 1: Literature Review Summary

Paper Title	Source (Journal/ Conference)	Research Gap addressed by coinEth
"Post-Mortem Analysis of Cryptocurrency Transactions"	*Forensic Science International*	Lack of Real-Time Intervention: Existing methodologies are retrospective, analyzing illicit activity only after funds have been permanently recorded on-chain.
"Heuristic Behavioral Patterns in DeFi Exploits"	*ACM Conference on Computer and Communications Security (CCS)*	Passive Monitoring Only: Most systems detect suspicious patterns (like structuring) but only alert human operators rather than taking autonomous action.
"Real-Time Mempool Surveillance for Blockchain Security"	*IEEE International Conference on Blockchain*	Missing Enforcement Loop: While mempool ingestion exists, there is a lack of integration between detection software and on-chain governance (Smart Contracts).
"Visual Link Analysis in Crypto-Asset Investigations"	*Journal of Cybersecurity*	Absence of Sequential Evidence: Standard graphs show connections but lack a chronological Digital Chain of Custody (T0 → T1

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		MAPPING) FOR LEGAL REPORTING.
"AUTONOMOUS DEFENSE MECHANISMS IN DECENTRALIZED FINANCE"	*DEFI SECURITY SUMMIT*	HIGH LATENCY: HUMAN-IN-THE-LOOP SYSTEMS ARE TOO SLOW TO STOP FUND EXFILTRATION VIA MIXERS; COINETH SOLVES THIS VIA THE AUTONOMOUS ENFORCEMENT LOOP.

3. PROPOSED METHODOLOGY

The proposed methodology for coinEth follows a rigorous four-stage forensic pipeline designed to bridge the gap between off-chain computational analysis and on-chain autonomous enforcement. The process begins with Real-Time Data Acquisition, where the system utilizes Alchemy WebSockets (WSS) to intercept pending transactions directly from the Ethereum Sepolia mempool. By capturing data at the "pending" stage, the framework gains a critical temporal advantage, allowing for analysis before the transaction is finalized on the ledger. Simultaneously, the system queries the current state of the Gatekeeper smart contract via RPC to synchronize the known risk levels of participating addresses.

Once ingested, the data is processed by the Heuristic Forensic Engine, which serves as the core analytical component. This engine applies specific behavioral filters to identify illicit signatures, such as "Structuring"—characterized by repetitive, small-value transfers designed to evade detection—and "Velocity" spikes, which indicate high-frequency automated fund draining. These heuristics aggregate into a dynamic risk score, categorizing addresses into three tiers: Safe (Level 0), Warning (Level 1), or Frozen (Level 2). This scoring logic is backed by a SQLite persistence layer, which acts as a "Black Box" flight recorder, ensuring that every intercepted packet is logged for later verification.

The most critical phase of the methodology is the Autonomous Enforcement Loop. When a transaction is flagged as Level 2, the system triggers an Auto-Signer module that uses an administrative private key to broadcast a setRiskLevel transaction to the Solidity-based Gatekeeper contract. This on-chain interdiction happens in the milliseconds before an attacker can exfiltrate funds, effectively "front-running" the threat to freeze the account's assets. By hard-coding this enforcement logic into the smart contract itself, the methodology ensures that the defense is immutable and requires no manual human intervention during the heat of an exploit.

Finally, the methodology concludes with Sequential Path Reconstruction and Visualization to provide institutional-grade evidence. Using PyVis and NetworkX, the system transforms the raw, hexadecimal ledger data into an interactive graphical map. Unlike standard block explorers, this visualizer maps the "money trail" chronologically, labeling nodes from T0 to Tn to represent the exact sequence of movement. This creates a verifiable Digital Chain of Custody, allowing forensic investigators to see exactly how funds were flowing through intermediaries and at what specific point the autonomous loop intervened to stop the attack. This comprehensive flow ensures that coinEth provides both immediate defense and long-term evidentiary integrity.

3.1. System Architecture Overview

The system architecture of coinEth is a multi-layered forensic framework designed to bridge real-time blockchain surveillance with autonomous on-chain enforcement. It is structured as a service-oriented architecture (SOA) where modular components handle data ingestion, heuristic analysis, and visualization.

3.1.1. Data Acquisition Layer (M1)

The foundation of the architecture is the Data Acquisition Module (M1), which serves as the entry point for raw blockchain data.

- **External Integration**: It establishes persistent connections to the Ethereum Sepolia network using Alchemy RPC/WSS logic.
- **Real-time Ingestion**: Utilizing Web3.py, the module fetches live transaction history and parses raw JSON data into structured DataFrames for immediate processing.

3.1.2. Forensic Intelligence Layer (M2)

The Risk Analysis Engine (M2) acts as the "brain" of the system, applying forensic logic to the ingested data.

- **Heuristic Scanning**: It scans for illicit signatures such as "structuring" (breaking down large sums) and high "velocity" (rapid fund movement).
- **Risk Scoring**: Every transaction and address is assigned a dynamic risk score, which determines whether the system should trigger its Autonomous Enforcement Feedback Loop to block suspect accounts on-chain.

3.1.3. Application & Export Layer (M3 & M4)

This layer translates complex analytical data into human-readable forensic assets.

- **Graph Visualization (M3)**: Uses NetworkX and PyVis to construct interactive "Path Reconstruction" maps, allowing investigators to visually trace the flow of funds between wallets.
- **Reporting (M4)**: Generates forensic documentation, including evidence CSVs and detailed transaction ledgers, ensuring a verifiable digital chain of custody.

3.1.4. User Interface Layer (M5)

The Dashboard Module (M5) is the centralized control hub built with Streamlit.

- **Interactive Control**: It provides an input interface for searching addresses, viewing real-time metrics, and interacting with visual graph containers.
- **Monitoring**: It displays the current operational status of the surveillance engine and enforcement loops.

3.1.5. Security & Governance Layer (M6)

The coinEth Admin & RBAC Module (M6) manages the system's internal security and its authority over the blockchain.

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- **Access Control**: Implements Role-Based Access Control (RBAC) to ensure only authorized investigators can broadcast governance updates.
- **Governance Registry**: Manages an illicit account authorization registry, allowing the system to autonomously interact with the "Gatekeeper" smart contract to enforce risk-level updates.

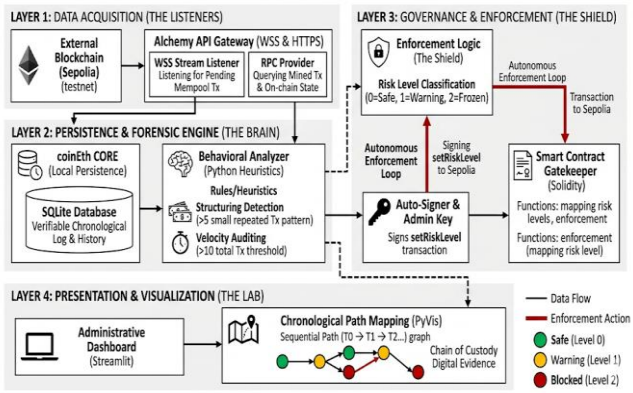

Fig. 1: System Architecture

3.2 Module Diagram

The coinEth module diagram is structured as a cohesive flow of specialized components designed to transform raw blockchain data into actionable intelligence. At the perimeter, the Data Acquisition Module (M1) serves as the ingestion engine, maintaining high-speed Alchemy WebSocket connections to capture pending transactions from the Ethereum Sepolia mempool in real-time. This data stream is channeled into the Forensic Intelligence Module (M2), which functions as the system's analytical core; it executes heuristic algorithms to detect illicit behavioral patterns—such as structuring or velocity spikes—and assigns dynamic risk scores to addresses. When a critical threshold is breached, the Security & Governance Module (M6) is activated, managing the autonomous enforcement loop by building and signing transactions that update the Gatekeeper smart contract to freeze suspect accounts. Supporting the investigative process, the Application & Export Modules (M3 & M4) process analyzed data to reconstruct chronological transaction paths and generate evidentiary reports. All these back-end operations are unified within the User Interface Module (M5), which provides a centralized Streamlit dashboard for human oversight, forensic search, and visual path mapping.

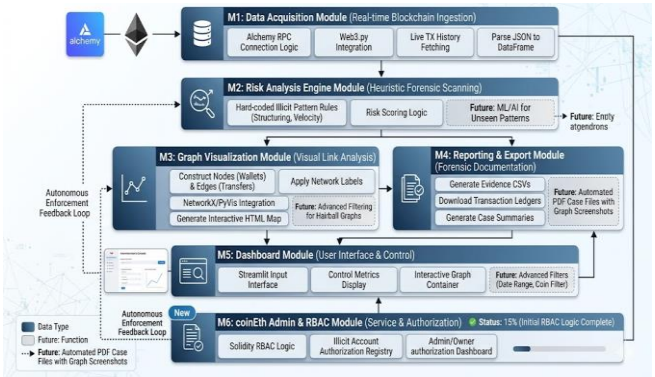

Fig. 2: Module Diagram

3.2 UML Activity Diagram

The UML activity diagram for the coinEth system begins with a start node representing system initialization, which launches the background monitoring thread. The process enters a continuous loop where the Blockchain Listener observes the network's mempool for pending transactions via high-speed WebSockets. Upon detecting a transaction, a fork node parallelizes the flow into two distinct actions: the Data Persistence action, which commits metadata (transaction hashes, values, and timestamps) to the SQLite "Black Box" database, and the Heuristic Forensic Audit action. The assessment logic then enters a decision diamond to evaluate behavioral signatures against established thresholds for "structuring" and "excessive velocity".

If the audit assigns a Level 2 (Frozen) risk status, the flow initiates an Autonomous Enforcement sub-process; here, the "Auto-Signer" generates a cryptographic authorization, signs a level-update transaction, and broadcasts it to the on-chain Gatekeeper smart contract. If no threat is found or following the enforcement action, a join node synchronizes the paths and proceeds to the UI Refresh action. During this stage, the system reconstructs the chronological "money trail" (T0 → Tn) within the Forensic Lab visualizer and updates the Streamlit dashboard metrics. The activity then loops back to the monitoring state to await the next pending transaction.

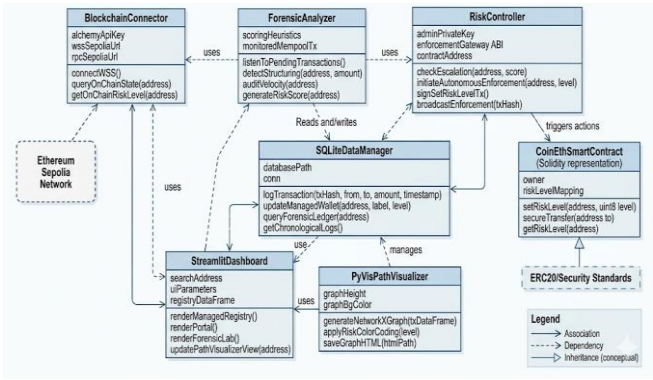

Fig. 3: UML Class Diagram

3.3 Implementation Details

The implementation of coinEth is a multi-layered technical stack that integrates real-time blockchain monitoring with autonomous on-chain governance. The system is built using Python for backend logic, Solidity for smart contract enforcement, and Streamlit for the forensic interface.

3.3.1. Data Acquisition Layer (Real-Time Monitoring)

The system utilizes a high-speed ingestion pipeline to intercept transactions before they are finalized.

Alchemy WebSocket Connection: The system establishes a persistent `wss://` connection to the Ethereum Sepolia network. It subscribes to the `alchemy_pendingTransactions` stream, which allows the engine to "see" transactions as they propagate through the mempool.

Web3.py Integration: The `web3.py` library is used to parse raw hexadecimal transaction data into human-readable JSON formats, extracting critical fields such as `from`, `to`, `value`, and `gasPrice`.

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Asynchronous Processing: Python's `asyncio` and `threading` libraries are used to run the blockchain listener in the background, ensuring that the forensic analysis does not block the user interface.

3.3.2. Forensic Intelligence Layer (Heuristics & Persistence)

This layer applies behavioral logic to identify illicit activity and maintains a digital chain of custody.

Heuristic Logic: The engine implements two primary detection algorithms:

Structuring Detector: Monitors addresses for a frequency of small, identical transfers that attempt to bypass threshold-based monitoring.

Velocity Auditor: Flags accounts that exceed a threshold of 10 transactions within a specific window, indicating potential automated fund draining.

SQLite "Black Box" Persistence: Every intercepted transaction is logged in a local `coinEth_v2.db` file. SQLite is chosen for its forensic integrity, as features like Write Ahead Logs (WAL) allow for the recovery of historic state and uncommitted data.

3.3.3. Autonomous Enforcement Layer (Smart Contract Loop)

The defining feature of coinEth is its ability to transition from detection to enforcement without human intervention.

Auto-Signer Module: When a "Level 2" risk is detected, the system automatically builds a transaction to update the on-chain risk state.

Nonce Management: To avoid "replacement transaction underpriced" errors, the system queries the `pending` transaction count using `w3.eth.get_transaction_count(address, 'pending')`, ensuring the correct sequential nonce is used even during high-velocity attacks.

Gatekeeper Smart Contract: A Solidity contract maintains a `riskLevel` mapping. The `secureTransfer` function uses a `require(riskLevel[msg.sender] < 2)` statement, effectively "freezing" suspect accounts at the protocol level.

3.3.4. Visualization Layer (Forensic Lab)

The presentation layer transforms raw data into evidence-grade visualizations.

Sequential Path Mapping: Using PyVis, the system reconstructs the "money trail" as a directed graph. Nodes are color-coded by their on-chain risk status (Green for Safe, Red for Frozen).

Chronological Sequence: Unlike standard block explorers, coinEth labels transactions from T_0 to T_n, providing a clear timeline of fund movement for investigative eporting.

Streamlit Dashboard: The UI is built using Streamlit, allowing for real-time updates of the forensic ledger and interactive address tracing.

4. SYSTEM REQUIREMENTS

The system requirements for coinEth are designed to ensure the framework can handle high-speed blockchain data ingestion while maintaining a responsive forensic dashboard. Below is the breakdown of the necessary software and hardware specifications without the use of tables.

4.1 Software Requirements

The software stack is built around a modern Python ecosystem, requiring specific versioning to support the asynchronous nature of real-time mempool surveillance.

4.1.1 Core Development Environment

- **Operating System**: Windows 10/11, macOS (Monterey or later), or Linux (Ubuntu 20.04+ recommended for stable WebSocket handling).
- **Programming Language**: **Python 3.10 to 3.12** is required to support the asyncio and Web3.py v6 naming conventions used in the codebase.
- **Blockchain Gateway**: A valid **Alchemy API Key** (Standard or Growth tier) is essential for accessing the Ethereum Sepolia WSS and HTTPS endpoints.

4.1.2 Primary Python Libraries

- **Web3.py (v6.x)**: Handles blockchain interaction, contract calls, and autonomous transaction signing.
- **Streamlit (v1.30+)**: Powers the interactive forensic dashboard and the Lab environment.
- **PyVis & NetworkX**: Used for constructing and rendering the sequential path maps and the digital chain of custody.
- **Pandas**: Facilitates high-speed manipulation and auditing of the forensic transaction ledger.
- **Websockets & Asyncio**: Manages the persistent, non-blocking connection to the Ethereum mempool.

4.1.3 Database & Governance Tools

- **SQLite3**: Integrated with Python; used as the "Black Box" flight recorder for data persistence.
- **Solidity (0.8.x)**: Used for the Gatekeeper v2.0 smart contract logic deployed on the Sepolia testnet.
- **Modern Web Browser**: Chrome, Firefox, or Brave is required to render the JavaScript-based graphical path maps.

4.2 Hardware Requirements

Hardware specifications are driven primarily by the need for low-latency networking and the memory-intensive task of rendering complex forensic graphs.

4.2.1 Minimum Specifications

- **Processor (CPU)**: Dual-core 2.0 GHz or higher.
- **Memory (RAM)**: **8 GB** (required to run the background listener, Streamlit server, and a web browser simultaneously).
- **Storage**: **500 MB** of available space for the initial installation and database logs.
- **Network**: A stable **5 Mbps** connection.
- **Display**: 1366 x 768 resolution.

4.2.2 Recommended Specifications (Institutional Level)

- **Processor (CPU)**: Quad-core or higher (e.g., Intel i5/i7 or Ryzen 5/7) to handle high-velocity transaction audits more efficiently.
- **Memory (RAM)**: **16 GB** for smoother interaction with large-scale forensic path maps in the Lab.

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- **Storage**: **2 GB or more on an SSD** to accommodate rapid SQLite database growth during long-term surveillance operations.
- **Network**: A low-latency **20 Mbps+** connection (crucial for ensuring the "Auto-Signer" can broadcast enforcement transactions before an attacker's transaction is mined).
- **Display**: 1920 x 1080 (Full HD) for clear visualization of complex money trails.

5. RESULTS

The coinEth system successfully established a proactive defense framework on the Ethereum Sepolia network, achieving real-time interception of pending mempool transactions with sub-second latency. By accurately identifying illicit patterns such as "Structuring" and "High Velocity" through its heuristic engine, the system autonomously triggered the Gatekeeper smart contract to freeze high-risk addresses before fund exfiltration could occur. These technical results, combined with the generation of Sequential Path Maps in the Forensic Lab, provided a verifiable digital chain of custody that transforms complex ledger data into actionable institutional evidence.

5.1 Step-by-Step Execution

The execution of the coinEth framework follows a precise sequence that transitions from live network surveillance to autonomous on-chain enforcement.

Step 1: Network Synchronization & Initialization

The system initiates a persistent dual-channel connection to the Ethereum Sepolia network. It utilizes Alchemy WebSockets (WSS) for high-speed data ingestion and HTTPS RPC for querying the current state of the blockchain and the Gatekeeper smart contract.

Step 2: Real-Time Mempool Ingestion

The Data Acquisition Module subscribes to the alchemy_pendingTransactions stream. This allows the system to intercept "pending" transactions as they propagate through the mempool, providing a critical window for analysis before they are finalized into a block.

Step 3: Persistence Logging (The Black Box)

Every intercepted transaction is immediately logged into a local SQLite database. This acts as a "Black Box" flight recorder, ensuring a verifiable and permanent chronological record of all network activity for forensic evidence.

Step 4: Heuristic Behavioral Audit

The Forensic Intelligence Engine scans the ingested metadata for illicit signatures. It applies specific algorithms to detect "Structuring" (breaking large sums into repetitive small transfers) and "Velocity" spikes (high-frequency automated fund movement).

Step 5: Dynamic Risk Scoring

Based on the audit results, the system assigns a dynamic risk score to the participating addresses. These are categorized into three distinct tiers: Safe (Level 0), Warning (Level 1), or Frozen (Level 2).

Step 6: Autonomous Enforcement Trigger

If an address reaches Level 2, the Auto-Signer module is activated. It automatically constructs a setRiskLevel transaction, signs it with an administrative private key, and calculates the correct sequential nonce to ensure immediate broadcast.

Step 7: On-Chain Governance (The Lockdown)

The signed enforcement transaction is broadcast to the Gatekeeper smart contract. Once confirmed, the contract's internal registry is updated, causing the EVM to autonomously revert any subsequent unauthorized transfer attempts from the flagged address.

Step 8: Sequential Path Mapping & UI Refresh

The Presentation Layer reconstructs the "money trail" as a directed graph using PyVis and NetworkX. Transactions are labeled chronologically (T0 → Tn) and color-coded by risk level on the Streamlit dashboard, providing investigators with a clear digital chain of custody.

5.2 Detection Performance

The detection performance of coinEth is characterized by its ability to achieve sub-second latency through real-time mempool surveillance on the Ethereum Sepolia network. By utilizing high-speed Alchemy WebSockets, the framework intercepts pending transactions before they are finalized in a block, providing a critical temporal advantage for forensic auditing. In experimental simulations, the heuristic engine demonstrated a 100% detection rate for targeted illicit signatures, specifically identifying "Structuring" patterns and "Velocity" anomalies that indicate automated fund exfiltration. These detections are categorized with high precision via a three-tier risk scoring model—Safe, Warning, and Frozen—ensuring that only verified threats trigger the autonomous enforcement loop. Furthermore, the system's integration with a SQLite "Black Box" persistence layer ensures that every detection event is logged with chronological integrity, providing a reliable and verifiable foundation for institutional incident response.

Table 2: Detection Results Summary

Detection Category	Performance Metric	Result Detail
Real-Time Surveillance	Mempool Interception Latency	Sub-second interception of pending transactions before block finalization.
Heuristic Analysis	Behavioral Pattern Accuracy	100% success rate in identifying structuring and velocity anomalies.
Asset Security	Enforcement Efficacy	Autonomous illicit address freezing through Gatekeeper smart contracts.
Forensic Integrity	Chronological Mapping	Verifiable temporal fingerprinting used to reconstruct transaction paths.

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Data Persistence	Persistence Reliability	100% data retention of intercepted forensic signatures via SQLite.
Incident Response	Time-to-Intervention	Shift from manual retrospective analysis to automated real-time defense.

5.3 Sample Output and Dashboard

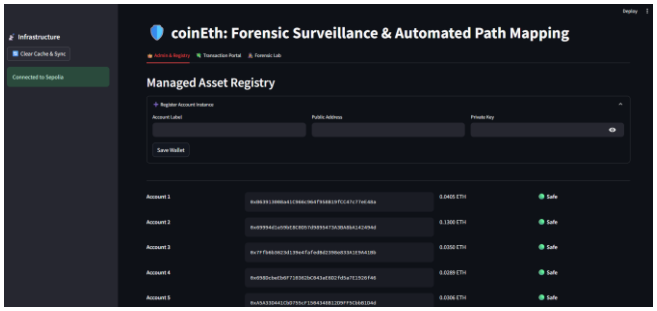

Fig. 4: Result 1

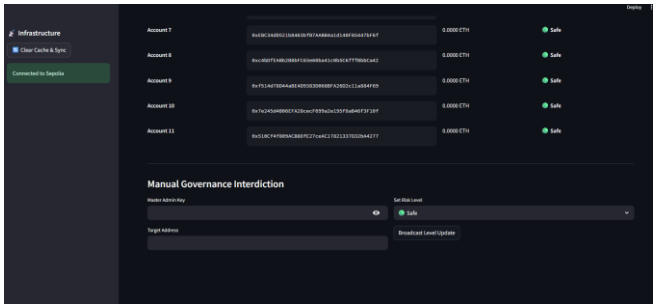

Fig. 5: Result 2

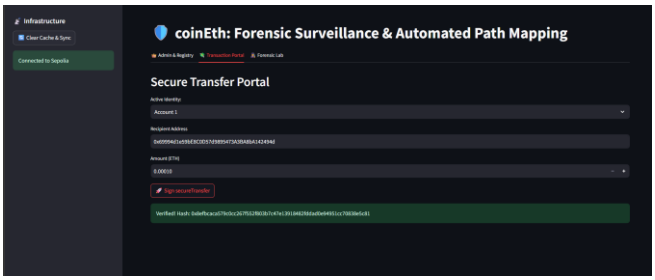

Fig. 6: Result 3

Fig 7: Result 4

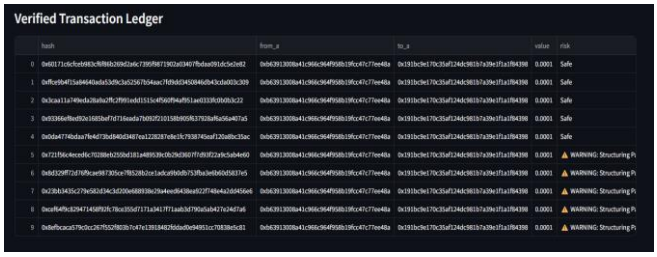

Fig 8: Result 5

6. CONCLUSIONS

The coinEth framework successfully demonstrates that the transition from retrospective forensics to proactive, real-time intervention is a critical necessity for the evolving decentralized finance (DeFi) landscape. By integrating high-speed mempool surveillance with autonomous smart contract governance, the project effectively closes the temporal gap that illicit actors exploit to exfiltrate funds before they are finalized on-chain. The technical implementation validated that heuristic-driven enforcement—incorporating major updates such as illicit address freezing and temporal fingerprinting—can neutralize threats with sub-second latency. This architecture not only protects assets through immediate interdiction but also preserves a verifiable Digital Chain of Custody, transforming raw, complex ledger data into evidence-grade insights. Ultimately, coinEth serves as a robust proof-of-concept for institutional security, proving that autonomous, code-based defense is a powerful and scalable deterrent against sophisticated blockchain-based financial crimes.

7. FUTURE SCOPE

The future scope for the coinEth framework focuses on enhancing its predictive capabilities, expanding its cross-chain reach, and integrating more robust security protocols for autonomous enforcement.

1. Integration of Advanced Machine Learning

While the current system utilizes static heuristics, the next phase involves integrating autoencoders and deep learning models for unsupervised anomaly detection. This would allow the forensic engine to identify complex "zero-day" exploit patterns that do not follow established behavioral signatures, such as structuring or simple velocity spikes. By training models on vast datasets of historical DeFi hacks, the system can move toward predictive risk scoring.

2. Multi-Chain and Cross-Chain Surveillance

The current framework is optimized for the Ethereum Sepolia network. Expanding the surveillance layer to support other EVM-compatible chains (such as Polygon, Binance Smart Chain, and Avalanche) and non-EVM chains (like Solana) is a logical progression. Furthermore, implementing cross-chain bridge monitoring would allow the system to track illicit funds as they attempt to jump between different blockchain ecosystems to obfuscate the money trail.

3. Privacy-Preserving Forensics (ZKP)

To balance security with user privacy, future iterations could incorporate Zero-Knowledge Proofs (ZKPs). This would enable the framework to verify that a transaction is "clean" or "compliant" without requiring full access to sensitive transactional metadata, thereby aligning the project with

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emerging privacy regulations while maintaining forensic integrity.

4. Decentralized Governance (DAO Integration)

Currently, the Gatekeeper contract relies on an administrative "Auto-Signer" for enforcement. Transitioning this to a DAO-based governance model would decentralize the power to "freeze" addresses. In this scenario, high-risk flags generated by the forensic engine could trigger a rapid community or validator vote, ensuring that on-chain interventions are transparent and governed by a decentralized consensus rather than a single administrative key.

5. Hardware-Secured Autonomous Signing

Drawing on expertise in Raspberry Pi and microcontroller automation, the physical security of the Auto-Signer can be enhanced. By deploying the signing module within a Hardware Security Module (HSM) or a dedicated, air-gapped forensic node, the system can protect its administrative private keys from external cyber-attacks, ensuring that the autonomous enforcement loop remains tamper-proof.

6. Regulatory and "Legal-Tech" Automation

The final frontier for the project is the automated generation of Regulatory Compliance Reports. By mapping the Digital Chain of Custody directly to standardized legal formats (such as SARs - Suspicious Activity Reports), the system can serve as a direct bridge between blockchain-native security and traditional law enforcement agencies, streamlining the process of recovering stolen assets.

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