

# Helios: A Lightweight Path-driven Execution Engine for Hyper-Optimized EVM Clients

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## ABSTRACT

Smart contract execution remains a primary scalability bottleneck for Ethereum Virtual Machine (EVM) blockchains. Existing optimization strategies, such as Just-In-Time (JIT) compilation and path-driven speculative execution, face a "performance paradox" where the overhead of detailed tracing and artifact management often negates performance gains on modern, highly optimized clients like Revm. We present **Helios**, a path-driven execution engine designed to resolve this trade-off through lightweight asynchronous tracing and persistent frame-level caching. Unlike transaction-level approaches, Helios exploits the strong path locality of individual contract calls to maximize reuse across different transactions, transforming raw traces into Static Single Assignment (SSA) graphs off the critical path. By restricting optimization to static-cost instructions, the system guarantees gas-semantic equivalence by construction, eliminating the economic risks associated with aggressive compilation. Evaluation on Ethereum mainnet workloads demonstrates that Helios achieves a median speedup of 6.60× over the state-of-the-art client Revm in Replay Mode, making it ideal for archive node acceleration. In Online Mode, frequency-based filtering enables effective acceleration of hot paths with negligible storage overhead. These findings establish Helios as a scalable, safe foundation for next-generation EVM infrastructure.

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## 1 INTRODUCTION

Public blockchains supporting smart contracts, such as Ethereum and its Layer-2 rollups [6, 7, 15, 28, 35], fundamentally operate as replicated state machines. From a data management perspective, each node functions as a deterministic transaction processor handling two distinct workloads. These workloads comprise the real-time processing of incoming transactions and the re-execution of

historical transactions to verify global state transitions. As throughput and contract complexity increase, execution becomes a primary scalability bottleneck for both scenarios.

Recent acceleration strategies face distinct limitations on modern execution engines [1, 3]. Just-In-Time (JIT) compilation introduces security risks, such as JIT bombs, and causes gas accounting discrepancies [2, 5, 9, 11, 33]. Transaction-level speculative execution degrades performance on fast engines due to the *Performance Paradox* [14, 36]. In this phenomenon, the overhead of instrumentation, tracing, and artifact management frequently exceeds the latency of transaction execution itself. Similarly, operation-level concurrent execution incurs tracing or synchronization costs that frequently outweigh parallel gains [27, 29].

Overcoming the performance paradox on hyper-optimized EVM clients necessitates addressing three fundamental conflicts. **First**, the tension between instrumentation overhead and execution latency. On sub-microsecond engines such as Revm [1], the cost of synchronous tracing often exceeds the execution time itself. Capturing sufficient data dependencies without introducing latency that negates the speedup is non-trivial. **Second**, the trade-off between artifact granularity and reuse capability. Existing transaction-level approaches suffer from a combinatorial explosion of unique execution paths, rendering cached artifacts ephemeral. The challenge lies in identifying a stable granularity that exhibits high locality across diverse transactions while maintaining manageable storage costs. **Third**, the conflict between optimization aggressiveness and strict semantic preservation. Standard compiler transformations such as instruction reordering inherently alter observable execution steps and violate the EVM's gas accounting rules. Achieving significant opcode reduction without complex runtime compensation logic remains a critical hurdle.

To assess whether these challenges can be surmounted, we analyzed Ethereum mainnet workloads and derived three critical insights. **First**, on hyper-optimized clients, native memory and storage management is already highly efficient; capturing full execution state incurs prohibitive I/O overhead while offering negligible optimization utility. Critical dependencies for valid optimization are therefore sparse and confined to stack operations, making lightweight stack-only tracing the optimal design point. **Second**, we observe pronounced frame-level path locality. The top 1% of unique paths accounts for over 70% of total execution time, indicating that shifting granularity from transactions to frames unlocks high cache hit rates across diverse workloads. **Third**, optimizing dynamic state-access operations inherently alters the observable gas schedule, risking consensus divergence. However, such operations are relatively sparse along hot paths, while fixed-cost computational instructions dominate. A path-driven accelerator can therefore safely

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bypass dynamic operations and delegate them to the native handler, focusing acceleration on the computation-heavy majority to ensure correctness by construction.

Guided by these observations, Helios introduces a new design point centered on three architectural principles. **First**, to break the performance paradox, we propose lightweight asynchronous tracing. By offloading stack-only analysis to background threads, Helios decouples trace generation from the critical path, ensuring that optimization overhead never blocks live transaction processing. **Second**, to maximize reuse, we exploit frame-level persistent caching. Unlike transaction-level approaches, Helios organizes optimization artifacts at the granularity of individual call frames, allowing diverse transactions to composably reuse cached paths. This transforms the combinatorial complexity of transaction traces into a manageable set of reusable frame graphs. **Third**, to guarantee safety, we adopt a hybrid execution model with correctness by construction. By restricting optimization to static-cost instructions and delegating dynamic-cost operations to the native engine, Helios preserves exact gas semantics inherently, eliminating the risk of economic discrepancies.

In summary, this paper makes the following contributions:

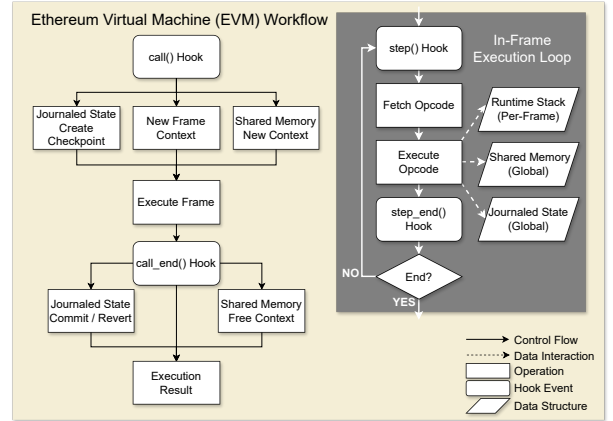
- We investigate the limitations of transaction-level speculation and operation-level concurrency on modern execution engines to formulate the *Performance Paradox*, where auxiliary overheads negate optimization gains. We further identify frame-level path locality and the separation of static and dynamic costs as key levers to resolve this paradox.
- We propose a novel architecture that decouples optimization from critical execution paths via asynchronous lightweight tracing and maximizes artifact reuse through frame-level caching. This approach ensures minimal instrumentation overhead and high cache hit rates.
- We develop the high-performance Helios Engine utilizing a register-based interpreter and bulk gas deduction to minimize execution overhead. It ensures intrinsic gas consistency through a hybrid model that strictly separates static optimizations from dynamic costs. This engine serves as the versatile runtime powering both deterministic replay and speculative execution within our unified framework.
- We implement a prototype of Helios on Revm and evaluate it using Ethereum mainnet workloads. The results demonstrate a median speedup of 6.60× over the native baseline on historical workloads while providing effective acceleration for incoming transactions.

## 2 BACKGROUND & MOTIVATION

### 2.1 The EVM Execution Model

The EVM operates as a quasi-Turing-complete stack machine [35]. Unlike register-based architectures, the EVM performs all computations on a transient runtime stack using specific manipulation instructions such as DUP and SWAP to manage operand placement. This design necessitates frequent stack operations that incur significant execution overhead.

Execution is compartmentalized into a hierarchy of call frames. Each frame maintains an isolated memory context and stack while



**Figure 1: The EVM execution workflow. The process is partitioned into a high-level frame management lifecycle (left) and a low-level, per-opcode execution loop (right).**

sharing persistent storage access with other frames in the transaction. Resource consumption is metered via Gas, which functions as both a validator incentive and a security mechanism against denial-of-service attacks. Gas costs fall into two distinct categories. Static costs are fixed at compile time for computational operations. Dynamic costs depend on runtime states such as memory expansion or storage access frequency. This distinction enables optimization strategies that aggregate static costs while delegating dynamic accounting to the native handling logic.

Crucially, the EVM specification includes a standard hook mechanism to facilitate debugging and tracing. As illustrated in Figure 1, this interface triggers events at key lifecycle points such as opcode execution and frame transitions. This design enables external components to passively observe execution states and capture data dependencies without requiring invasive modifications to the core interpreter logic.

### 2.2 Ethereum Node Workloads

The Ethereum network depends on node archetypes that exhibit divergent operational characteristics [19]. Full nodes operate within fixed block intervals and prioritize the low-latency processing of unpredictable transactions to ensure consensus stability. In contrast, archive nodes maintain the comprehensive ledger history and emphasize execution throughput to facilitate the bulk re-execution of historical states [18, 26]. This operational dichotomy introduces a dual challenge of optimizing for real-time responsiveness while simultaneously accommodating high-volume historical processing [22].

### 2.3 The Performance Paradox

Contract-driven optimization, exemplified by JIT compilation, faces two critical limitations in permissionless blockchains. First, it introduces an attack surface known as "JIT bombs" where attackers construct pathological code patterns, such as deeply nested conditional branches, to trigger exponential compilation complexity.



**Table 1: Performance degradation of path-driven optimization on modern EVMs.**

System	Client	Latency	Tracing	Speedup	Artifact
Native	Geth	398.4 $\mu$ s	–	1.0×	–
Forerunner	Geth	68.1 $\mu$ s	742.6 $\mu$ s	5.8×	910KB
Native	Revm	62.0 $\mu$ s	–	1.0×	–
Forerunner	Revm	39.2 $\mu$ s	381.5 $\mu$ s	1.6×	663KB

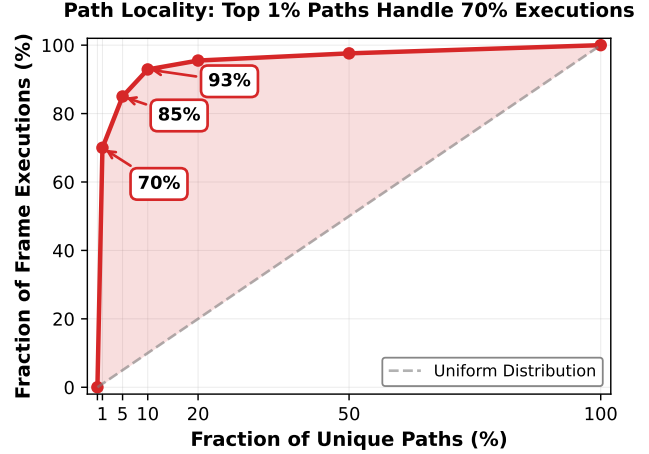
This computational asymmetry allows malicious actors to exhaust validator CPU resources via low-gas transactions and constitutes a Denial-of-Service vector [2, 5, 9, 11, 33].

Second, strict gas-semantic equivalence is a fundamental economic and functional constraint. Any systematic deviation from the canonical gas schedule results in incorrect validator compensation, distorting market incentives and impeding the deployment of production clients. Aggressive compiler optimizations like instruction reordering often alter the observable gas schedule, making consensus preservation difficult without complex runtime compensation. Consequently, path-driven optimization emerges as a safer paradigm by inherently bounding optimization costs to the actual execution trace.

However, existing path-driven schemes encounter a scalability barrier on modern EVM clients, a phenomenon we term the *Performance Paradox*. On slower engines like Geth [10], transaction execution dominates end-to-end latency, rendering the additional instrumentation cost negligible. Conversely, on highly optimized engines like Revm [1], the critical path shifts as execution becomes inexpensive, causing auxiliary tasks such as tracing and artifact management to become the primary bottleneck. Table 1 demonstrates this shift using a Uniswap V2 swap [4]. A prior path-driven system [14] achieves a 5.8 $\times$  speedup on Geth but only 1.6 $\times$  on Revm. Two factors explain this performance degradation. First, synchronous tracing dominates the critical path. On Revm, tracing a transaction is approximately six times slower than native execution and nearly ten times slower than optimized execution, effectively negating the potential benefits. Second, artifact management incurs substantial fixed costs. Loading and parsing a 663 KB artifact to accelerate a task finishing in tens of microseconds introduces I/O latency that does not scale with the underlying execution time. These constraints necessitate two architectural shifts: replacing synchronous tracing with asynchronous optimization off the critical path and substituting large artifacts with lightweight traces to minimize data volume.

## 2.4 The Granularity Mismatch

Beyond tracing overhead, existing strategies predominantly employ transaction-level caching [14, 29, 36]. This approach treats the entire transaction execution trace as the atomic unit of optimization. It faces a combinatorial challenge because slight variations in the sequence of internal contract calls render the entire cached artifact invalid. This dependency enforces a "use-once-discard" lifecycle that limits reuse potential.



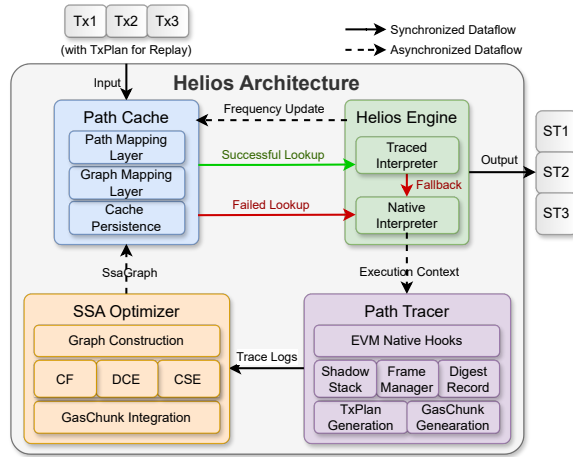
**Figure 2: Path locality in EVM execution exhibits an extreme Pareto distribution. Measured across 5,000 mainnet blocks, the top 1% of unique paths account for 70% of all frame executions, the top 5% handle 85%, and the top 10% handle 93%. The shaded region illustrates the deviation from uniform distribution, demonstrating extreme concentration that enables efficient frame-level caching with minimal storage overhead.**

In contrast, our analysis of Ethereum mainnet workloads reveals significant redundancy at the finer frame granularity. As shown in Figure 2, the distribution of unique frame paths follows a Pareto principle where the top 1% of paths account for over 70% of total executions. This disparity indicates that while unique transaction combinations are vast, the individual contract calls function as repetitive building blocks. Shifting the optimization unit from transactions to frames aligns the caching strategy with this inherent locality and enables the amortization of compilation costs across thousands of invocations.

## 2.5 Design Implications

The preceding analysis suggests three architectural principles for a high-performance EVM accelerator. First, the distinction between static and dynamic gas costs motivates a hybrid execution model. Optimizing only static instructions while delegating dynamic operations to the native handling ensures gas-semantic equivalence by construction. Second, the Performance Paradox necessitates asynchronous lightweight tracing and optimization. Decoupling these tasks from the critical path limits I/O overhead and preserves baseline execution speed. Third, the pronounced path locality implies the need for frame-level persistent caching. This granularity enables compositional artifact reuse across diverse transactions, overcoming the limitations of transaction-level approaches. These principles collectively inform the design of Helios.





**Figure 3: Overview of the Helios architecture.** Overview of the Helios architecture. The system integrates four key components, including Path Cache, Helios Engine, SSA Optimizer, and Path Tracer, to enable path-driven execution. The asynchronous feedback loop (dashed lines) decouples trace generation and optimization from the critical execution path (solid lines), ensuring low-latency transaction processing.

### 3 THE DESIGN OF HELIOS

#### 3.1 Overview

Helios is a path-driven execution engine designed to accelerate EVM transaction processing. Its architecture is built on a continuous feedback loop that integrates four coordinated components: the Path Tracer, the SSA Optimizer, the Path Cache, and the Helios Engine. Notably, path tracing and optimization are performed asynchronously, running in parallel with the primary transaction execution flow. Figure 3 illustrates the system’s high-level architecture and data flow. This asynchronous design eliminates optimization latency from the critical path, ensuring that trace generation and graph compilation do not delay transaction processing.

The system’s functionality is partitioned across these four distinct components. The Path Tracer captures raw execution traces through lightweight, hook-based instrumentation of the native EVM interpreter, producing a linear execution record known as a PathLog. The SSA Optimizer transforms these PathLog entries into an SSA-like intermediate representation [16], termed SsaGraph, by applying a pipeline of classic compiler optimizations to eliminate redundant computations. The Path Cache serves as an in-memory memoization layer, indexing and storing optimized SsaGraph structures for rapid, low-latency retrieval. Finally, the Helios Engine orchestrates the execution of each transaction, determining whether to use a cached SsaGraph for accelerated processing or to delegate the task to the native interpreter as a fallback.

#### 3.2 End-to-End Transaction Lifecycle

Helios operates in distinct Online and Replay modes. Online mode targets real-time processing with unknown execution paths, whereas

Replay mode facilitates high-throughput historical processing using predetermined paths.

**3.2.1 Online Mode: Executing New Transactions.** Online mode addresses the real-time requirements of full nodes and validators handling transactions with unknown execution paths. Upon contract invocation, the Helios Engine generates a path identifier from the contract identity and the call signature to query the Path Cache. A cache hit engages the Traced Interpreter, which performs speculative execution validated by runtime control-flow guards. Conversely, a cache miss or guard failure necessitates a fallback to the Native Interpreter to ensure correctness. This fallback initiates an asynchronous optimization pipeline where the Path Tracer records the execution sequence. The SSA Optimizer subsequently transforms this linear trace into an optimized SsaGraph and associated constants, populating the Path Cache for future reuse.

**3.2.2 Replay Mode: Executing Historical Transactions.** Replay mode targets the high-throughput batch processing needs of archive nodes. In this deterministic environment, the Helios Engine retrieves a pre-computed transaction plan containing an ordered list of execution path identifiers. For each call frame, the engine queries the Path Cache using the specific identifier. Since the plan references only previously verified paths, cache lookups are guaranteed to succeed. The Traced Interpreter executes the retrieved SsaGraph directly, bypassing control-flow guards and the asynchronous optimization pipeline. This approach eliminates speculation overhead and maximizes throughput for historical block reprocessing.

#### 3.3 Key Data Structures

Helios represents, indexes, and orchestrates transaction paths through a small set of data abstractions that govern data flow in both Online and Replay modes.

**Path Representation.** Execution paths are first captured as a PathLog, a raw linear trace produced by the Path Tracer. A PathLog is a sequence of entries, each recording an opcode together with its stack data dependencies, expressed as references to the outputs of preceding operations. The optimization pipeline consumes this representation and transforms it into an SsaGraph, a directed acyclic graph whose nodes denote operations and whose edges denote data dependencies. By making data flow explicit and eliminating the implicit EVM stack, the SsaGraph serves as the executable format for the Traced Interpreter.

**Path Indexing and Retrieval.** Helios employs a multi-key scheme to locate and reuse SsaGraphs. A PathDigest is a 64-bit hash of a path’s opcode sequence acting as a deterministic identifier for the execution logic. A DataKey concatenates a contract’s code hash with the PathDigest to uniquely identify the constant table for a specific contract instance. This separation allows multiple contracts with identical bytecode, such as distinct ERC20 [34] tokens, to share a single SsaGraph while maintaining separate constant tables. Finally, a CallSig is a coarse-grained identifier used for predictive lookup in Online mode, defined as the concatenation of a contract’s code hash and the 4-byte function selector from calldata. A single CallSig may map to multiple PathDigests, corresponding to distinct control-flow branches of the same function, including both successful and revert paths.



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**Algorithm 1: Shadow Stack Tracing**

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**Input:**  $op$ : Current EVM opcode  
**Input:**  $S_{evm}$ : EVM value stack (after opcode execution)  
**Input:**  $S_\ell$ : Shadow stack of LSNs tracking value provenance  
**Output:**  $e$ : Trace log entry containing the opcode, current LSN, input dependencies, and output value  
**Output:** Updated  $S_\ell$

```
// Extract input dependencies from shadow stack
 $D_{in} \leftarrow []$ 
 $k \leftarrow \text{GETINPUTCOUNT}(op)$ 
for  $i \leftarrow 1$  to  $k$  do
     $\ell \leftarrow S_\ell.\text{POP}()$ 
     $D_{in}.\text{APPEND}(\ell)$ 
// Record output value and assign new LSN
if  $op$  produces stack output then
     $v_{out} \leftarrow S_{evm}.\text{TOP}()$ 
     $\ell_{curr} \leftarrow \text{NEXTLSN}()$ 
     $S_\ell.\text{PUSH}(\ell_{curr})$ 
else
     $v_{out} \leftarrow \perp$ ; // No output, e.g., POP, JUMP
     $\ell_{curr} \leftarrow \text{NEXTLSN}()$ 
// Handle stack manipulation instructions
if  $op \in \{\text{DUP1}, \text{DUP2}, \dots, \text{DUP16}\}$  then
     $d \leftarrow op - \text{DUP1} + 1$ 
     $\ell_t \leftarrow S_\ell[d]$ ; // Peek without pop
     $S_\ell.\text{PUSH}(\ell_t)$ ; // Duplicate LSN
if  $op \in \{\text{SWAP1}, \text{SWAP2}, \dots, \text{SWAP16}\}$  then
     $d \leftarrow op - \text{SWAP1} + 1$ 
     $S_\ell.\text{SWAP}(0, d)$ ; // Swap LSNs
// Create log entry
 $e \leftarrow \langle op, \ell_{curr}, D_{in}, v_{out} \rangle$ 
return  $e$ 
```

---

**Execution Metadata.** Helios maintains additional metadata to coordinate cross-frame execution and reduce runtime overhead. A *Transaction Plan* ( $TxPlan$ ) is an ordered sequence of PathDigests that records the path taken by each call frame within a transaction.  $TxPlans$  are produced during Online execution and indexed by block number and transaction index; in Replay mode, they provide a deterministic guide for fetching the correct SsaGraph for every frame. A *GasChunk* is a precomputed scalar capturing the cumulative static gas cost of the instructions lying between two consecutive gas-accounting opcodes. Attached to the corresponding SsaGraph, GasChunks allow the Traced Interpreter to replace per-instruction gas accounting with a single bulk deduction per chunk, thereby reducing overhead while preserving gas-semantic equivalence.

### 3.4 Component Design and Implementation

This section details the internal design and mechanisms of each of Helios’s four primary components. It describes how each component fulfills its role in the end-to-end transaction lifecycle, transforming its inputs into the data structures required by the next stage of the pipeline.

**3.4.1 Path Tracer.** A lightweight instrumentation component observes native EVM execution to produce the raw PathLog data structure,  $TxPlan$ , and GasChunk.

**Instrumentation mechanism.** The tracer attaches to the EVM hook interface and subscribes to six events, including `step` and `step_end` for opcode execution, `call` and `call_end` for external calls, and `create` and `create_end` for contract creation. This hook-based design decouples the tracer from the interpreter and enables passive observation without changing execution semantics.

To capture stack data dependencies, the tracer maintains a shadow stack mirroring the EVM operand stack but storing 32-bit Log Sequence Numbers or LSNs instead of 256-bit values. Each LSN identifies the operation producing the corresponding value. As detailed in Algorithm 1, the tracer pops the required input LSNs to form the dependency list  $D_{in}$  on each `step_end`, allocates a new LSN for the current opcode, and pushes it if the opcode produces a stack result. For stack-manipulation opcodes such as `DUP` and `SWAP` that only reorder values, the tracer applies the same permutation to the shadow stack without creating a new LSN. As a result, only opcodes that actually produce new values become nodes in the PathLog, effectively collapsing substantial stack traffic and yielding PathLog entries that record each operation alongside the LSNs of its true data dependencies.

**PathDigest Calculation.** PathDigest is a rolling hash updated with each executed opcode using the lightweight FNV-1A algorithm [23, 24]. FNV-1A was chosen for its efficiency, involving simple multiplication and XOR operations. This ensures a unique identifier for each execution path and allows fast incremental updates, enabling efficient path comparison and lookup in the PathCache.

**Metadata generation.** The tracer also constructs GasChunk and TxPlan metadata. For GasChunks, it treats GAS and terminating opcodes such as `RETURN`, `STOP`, `REVERT`, `CREATE`, and `CREATE2` as gas delimiters. It accumulates the static gas cost of instructions between two delimiters and emits a GasChunk with the aggregate cost upon reaching a delimiter. If a path ends without an explicit delimiter, the system inserts a synthetic `STOP` to close the final chunk.

The TxPlan is built using placeholders. When a new frame is entered via the `call` or `create` hook, the tracer appends a placeholder entry. When the frame completes at `call_end` or `create_end`, it computes the frame’s PathDigest and replaces the placeholder. The resulting TxPlan records the final per-frame path sequence in transaction order.

**Path Validation and Filtering.** To restrict resource allocation to reusable paths, the tracer executes a health check during the `call_end` hook by inspecting the frame’s exit status. The system discards paths resulting from VM-level exceptions, particularly out-of-gas errors, while retaining deterministic application-level terminations such as successful returns and `REVERT` operations. This distinction is critical because `REVERT` paths correspond to reproducible control-flow branches, including failed assertions or balance validations, which exhibit high reusability across transactions. Conversely, VM-level exceptions are non-deterministic and may manifest at any instruction depending on the gas limit. Tracking every potential out-of-gas point for a sequence of  $n$  opcodes would generate  $O(n)$  distinct failure paths, leading to cache fragmentation without benefiting deterministic execution. Consequently, the tracer formats only deterministically terminated paths into PathLog entries for the SSA Optimizer.



**3.4.2 SSA Optimizer.** A pure-function component transforms a raw PathLog into an optimized, gas-annotated SsaGraph through a pipeline of graph construction, redundancy elimination, gas integration, and final compaction.

**Graph construction.** For each PathLog entry, the optimizer creates a node in the SsaGraph and connects it to its data-dependency predecessors using the  $D_{in}$  LSN list, yielding a graph representation of the linear trace.

**Optimization passes.** The graph then undergoes three side-effect-aware passes: constant folding, dead-code elimination, and common-subexpression elimination. First, PUSH nodes are converted into constant-table entries and their values are propagated through side-effect-free nodes; computations that become fully constant are removed and recorded as constants. Second, a backward scan from side-effecting nodes removes any node whose result is unused, iterating to a fixed point. Third, the optimizer merges redundant side-effect-free operations by assigning each one a fingerprint consisting of its opcode and input LSNs; nodes with identical fingerprints are unified and all consumers are redirected to the canonical node.

**GasChunk Integration.** Following the optimization pipeline, the optimizer integrates the GasChunk metadata collected by the Path Tracer. It retrieves the list of GasChunks from the PathLog and attaches each pre-computed gas cost to its corresponding delimiter node within the SsaGraph. This annotation embeds the gas accounting information directly into the executable graph structure.

**Graph Compaction and Output.** In the final stage, the optimizer physically deletes all nodes previously marked as REMOVED to produce a compact graph. It finalizes the constant table, containing all immediate values and folded constants from the optimization phase. The resulting SsaGraph, its constant table, and associated identifiers are then transmitted to the Path Cache for storage.

**3.4.3 Path Cache.** A two-tier architecture separates prediction logic from canonical storage to efficiently support both probabilistic Online lookups and deterministic Replay retrieval.

**Tiered Architecture.** The Path Mapping Layer (PML) operates as a frequency-based prediction index for Online mode. It maintains a dual-index structure for each CallSig comprising a frequency map  $M_{freq}$  for  $O(1)$  access and a priority queue  $I_{sorted}$  for  $O(\log k)$  maximum frequency retrieval. To minimize guard validation overhead, the PML prioritizes precision by returning a prediction only if a single *PathDigest* holds the unique maximum frequency. The Graph Mapping Layer (GML) acts as the deterministic backing store mapping PathDigests to reusable SsaGraphs and DataKeys to contract-specific constant tables.

**Query and Update Protocols.** Query logic adapts to the operational mode. In Online mode, as detailed in Algorithm 2, the engine requests a high-confidence prediction from the PML. A successful hit yields a PathDigest that combines with the contract code hash to retrieve execution artifacts from the GML. In contrast, Replay mode bypasses the PML to perform direct lookups in the GML using the TxPlan.

Cache updates occur through two mechanisms formalized in Algorithm 3. First, the SSA Optimizer populates the GML and initializes the PML entry upon generating a new graph. Second, successful online executions trigger a feedback loop where the engine signals

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#### Algorithm 2: Online Mode: Path Lookup

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**Notation:**  $S_\sigma$  denotes a PathStore for CallSig  $\sigma$ , maintaining  $M_{freq}$  (PathDigest  $\rightarrow$  frequency map) and  $I_{sorted}$  (frequency  $\rightarrow$  PathDigest set, sorted index).  
**Input:**  $\sigma$ : CallSig (code hash || function selector)  
**Input:**  $h_c$ : Contract code hash for DataKey construction  
**Input:**  $\mathcal{P}$ : Path Cache with PML and GML layers  
**Output:**  $(G, C, \ell)$ : Cached graph, constant table, and PathDigest; or  $\perp$  if prediction fails

```

// Phase 1: Query Path Mapping Layer for hot path
if  $\sigma \notin \mathcal{P}.PML$  then
    return  $\perp$ ; // Cold start: CallSig never observed
 $S_\sigma \leftarrow \mathcal{P}.PML[\sigma]$ ; // Retrieve PathStore
ACQUIREREADLOCK( $S_\sigma$ )
// Get unambiguous maximum frequency path
 $(f_{max}, P_{max}) \leftarrow I_{sorted}.LASTENTRY()$ 
if  $|P_{max}| \neq 1$  then
    RELEASEREADLOCK( $S_\sigma$ )
    return  $\perp$ ; // Ambiguous: multiple paths share max frequency
 $\ell \leftarrow P_{max}.FIRST()$ ; // Extract the unique hot path
RELEASEREADLOCK( $S_\sigma$ )
// Phase 2: Query Graph Mapping Layer for artifacts
if  $\ell \notin \mathcal{P}.GML.graphs$  then
    return  $\perp$ ; // Path not yet optimized
 $k_{data} \leftarrow h_c || \ell$ ; // Construct DataKey
if  $k_{data} \notin \mathcal{P}.GML.data$  then
    return  $\perp$ ; // Constant table missing
 $G \leftarrow \mathcal{P}.GML.graphs[\ell]$ 
 $C \leftarrow \mathcal{P}.GML.data[k_{data}]$ 
return  $(G, C, \ell)$ ; // Successful prediction

```

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the PML to increment the path's access frequency. This mechanism adapts predictions to evolving traffic patterns. Fine-grained read-write locks manage concurrency by permitting parallel reads for hot path prediction while bounding write contention.

**Persistence and Recovery.** The system serializes cache state to disk via periodic checkpoints to ensure durability. A configurable pruning policy manages storage by evicting CallSigs below a frequency threshold. Upon node restart, indices are reconstructed from checkpoints in  $O(N \log k)$  time to enable immediate high-accuracy prediction. The system handles paths absent from the checkpoint via lazy regeneration.

**3.4.4 Helios Engine.** A central orchestrator supports transaction execution in both Online and Replay mode.

It integrates with the host EVM client by replacing the per-frame execution loop while reusing the client's state and memory management. In our Revm integration, Helios inherits arena-based memory allocation, cached and prewarmed storage access, and the transaction-local journal for atomic commits. This allows the engine to focus on optimizing intra-frame computation while leaving state handling unchanged. For each frame, Helios chooses between its Traced Interpreter and Native Interpreter based on the execution mode and the Path Cache output.

**Transaction-scoped execution.** Helios executes at transaction granularity. If a traced execution encounters a cache miss, guard



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**Algorithm 3: Path Frequency Update (Feedback Loop)**

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**Notation:** Symbols follow Algorithm 2. Additionally,  $k$  denotes the number of distinct frequencies in  $I_{sorted}$ .  
**Input:**  $\sigma$ : CallSig corresponding to the executed path  
**Input:**  $\ell$ : PathDigest that was successfully executed  
**Input:**  $\mathcal{P}$ : Path Cache with PML  
**Output:** Updated frequency statistics in  $\mathcal{S}_\sigma$   
// Retrieve or create PathStore for this CallSig  
 $\mathcal{S}_\sigma \leftarrow \mathcal{P}.PML.GETORCREATE(\sigma)$   
 $ACQUIREWRITELOCK(\mathcal{S}_\sigma)$ ; // Exclusive access for update  
// Phase 1: Get current frequency  
 $fold \leftarrow M_{freq}.GET(\ell)$  or 0; // Default to 0 for new paths  
 $f_{new} \leftarrow fold + 1$ ; // Increment with saturation  
// Phase 2: Update sorted index  
**if**  $fold > 0$  **then**  
     $P_{old} \leftarrow I_{sorted}[fold]$ ; // Get old frequency bucket  
     $P_{old}.REMOVE(\ell)$   
    **if**  $P_{old} = \emptyset$  **then**  
         $I_{sorted}.REMOVE(fold)$ ; // Clean empty bucket  
// Phase 3: Update sorted index  
 $P_{new} \leftarrow I_{sorted}.ENTRY(f_{new}).ORINSERTEMPTY()$   
 $P_{new}.INSERT(\ell)$   
// Phase 4: Update frequency map  
 $M_{freq}[\ell] \leftarrow f_{new}$   
 $RELEASEWRITELOCK(\mathcal{S}_\sigma)$

---

violation, or out-of-gas condition, the engine discards all partial work and restarts the transaction on the Native Interpreter. This design avoids fine-grained checkpointing or rollback and relies on the EVM's transaction-level atomicity for correctness.

**Traced Interpreter.** When the Path Cache returns a valid SsaGraph, the engine dispatches execution to the Traced Interpreter, whose loop is given in Algorithm 4. It differs from a standard EVM interpreter in three ways.

First, it replaces the EVM stack with a register-like array indexed by LSN. Each SsaGraph node writes its result to its assigned slot, and consumers read operands directly from this array, eliminating DUP/SWAP and other stack manipulation overhead.

Second, in Online mode, it enforces speculative control-flow guards. Before executing JUMP or JUMPI, the interpreter computes the runtime target and checks it against the cached target in the SsaGraph. Any mismatch triggers an immediate transaction-level fallback. In Replay mode, all control-flow targets are fixed by the TxPlan, so these guards are never violated by construction.

Third, it uses chunked gas accounting for static-cost instructions. Instructions accumulate static cost within their GasChunk, and the interpreter deducts the aggregated amount at delimiter nodes in a single operation. Instructions with dynamic gas cost perform individual gas calculations and deductions, preserving exact gas semantics while reducing the number of checks on the hot path.

### 3.5 Security Considerations

Beyond the JIT Bomb resistance established through the path-driven paradigm in §2, Helios's design inherently mitigates path explosion attacks. An adversary might attempt to degrade system performance by constructing malicious contracts that generate

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**Algorithm 4: Traced Interpreter Execution**

---

**Input:**  $\mathcal{G} = (V, E)$ : Optimized SSA graph  
**Input:**  $C : \mathbb{N} \rightarrow \mathbb{U}_{256}$ : Constant value table  
**Input:**  $\Gamma$ : Execution context (mutable)  
**Input:**  $g_{lim}$ : Gas limit  
**Output:**  $\langle \Gamma, g_{used} \rangle$  or  $\perp$  (fallback)  
// Initialize virtual register file and gas counter  
 $\mathcal{R} : \mathbb{N} \rightarrow \mathbb{U}_{256} \leftarrow \text{new Array}[|V|]$   
 $g_{rem} \leftarrow g_{lim}$ ; // Remaining gas initialized to limit  
// Execute vertices in topological order  
**foreach**  $v \in V$  **in topological order** **do**  
     $\vec{v} \leftarrow \langle \rangle$ ; // Operand vector  
    **foreach**  $\ell \in in(v)$  **do**  
        **if**  $\ell \in C$  **then**  
             $\vec{v} \leftarrow \vec{v} \cdot \langle C[\ell] \rangle$ ; // Constant operand  
        **else**  
             $\vec{v} \leftarrow \vec{v} \cdot \langle \mathcal{R}[\ell] \rangle$ ; // Register operand  
    // Control flow guard verification  
    **if**  $op(v) \in \{JUMP, JUMPI\}$  **then**  
         $pc \leftarrow COMPUTETARGET(op(v), \vec{v}, \Gamma)$   
         $\hat{pc} \leftarrow target(v)$ ; // Cached target from PathLog  
        **if**  $pc \neq \hat{pc}$  **then**  
            **return**  $\perp$ ; // Guard violation - trigger fallback  
    // Chunked gas accounting at delimiters  
    **if**  $op(v) \in \{GAS, RETURN, STOP, REVERT, CREATE, CREATE2\}$  **then**  
         $\delta_s \leftarrow chunk(v)$ ; // Accumulated static gas cost  
        **if**  $g_{rem} < \delta_s$  **then**  
            **return**  $\perp$ ; // Gas anomaly - verify natively  
         $g_{rem} \leftarrow g_{rem} - \delta_s$   
    // Execute opcode and update execution context  
     $\rho \leftarrow EXEC(op(v), \vec{v}, \Gamma)$   
    // Deduct dynamic gas costs  
    **if**  $ISDYNAMIC(op(v))$  **then**  
         $\delta_d \leftarrow DYNAMICGAS(op(v), \vec{v}, \Gamma)$   
        **if**  $g_{rem} < \delta_d$  **then**  
            **return**  $\perp$ ; // Out of gas  
         $g_{rem} \leftarrow g_{rem} - \delta_d$   
    // Store result in virtual register  
    **if**  $\rho \neq \epsilon$  **then**  
         $\mathcal{R}[\ell(v)] \leftarrow \rho$ ; // Map LSN to result value  
    // Check for execution termination  
    **if**  $op(v) \in \{RETURN, STOP, REVERT\}$  **then**  
        **return**  $\langle \Gamma, g_{lim} - g_{rem} \rangle$   
**return**  $\langle \Gamma, g_{lim} - g_{rem} \rangle$

---

millions of unique execution paths for a single function signature, potentially flooding the cache and consuming optimization resources.

Helios's architecture naturally defends against this attack vector through three complementary mechanisms. The frequency-based Path Mapping Layer ensures that only paths with demonstrated reusability are predicted and accelerated. Attack-generated paths remain perpetually classified as cold paths due to low execution



counts, excluded from the prediction model. The checkpoint pruning mechanism evicts CallSigs with access frequencies below a configurable threshold, preventing malicious cold paths from consuming long-term storage while retaining legitimate hot paths. The transaction-scoped execution model ensures that cache misses simply trigger fallback to the Native Interpreter, maintaining correctness and baseline performance for unpredicted paths.

Consequently, path explosion attacks impose only bounded costs on asynchronous tracing and temporary cache occupancy without degrading performance for legitimate transactions. This robustness emerges naturally from the frequency-based filtering and bounded resource allocation inherent to Helios’s design.

## 4 EVALUATION

We evaluate Helios under microbenchmarks and Ethereum mainnet workloads to answer three questions: **RQ1** (Optimization Overhead): What are the time and space costs of Helios’s tracing and optimization? **RQ2** (Performance Gains): How much speedup does Helios achieve over modern EVM interpreters and existing optimizations? **RQ3** (System Applicability): How well do Replay and Online modes serve their respective deployment scenarios?

### 4.1 Experimental Setup

All experiments run on an AWS r7i.2xlarge instance with 8 vCPUs and 64 GB memory. We compare Helios against four baselines representing the state-of-the-art. Geth v1.9.9 [10] serves as the representative Go-based client, while Revm v22.0.1 [1] represents high-performance Rust interpreters. We also evaluate Forerunner [14], applying its full-context tracing to both Geth and Revm. Finally, we include Revmc v0.1.0 [1], a JIT compiler that translates EVM bytecode to Rust. Revmc bundles its own Revm version, which may differ from our standalone Revm baseline.

For microbenchmarks we use three DeFi workloads of increasing complexity: *ERC20-Transfer*, *Uniswap-V2-Swap-1hop*, and *Uniswap-V2-Swap-4hop*. Each transaction is executed 100 times with warm caches and we report medians. For mainnet evaluation we replay 5,000 consecutive Ethereum blocks (#19,476,587–#19,481,586), containing 921,786 transactions, of which 567,372 are contract invocations. Pure ETH transfers are excluded because they do not involve EVM execution.

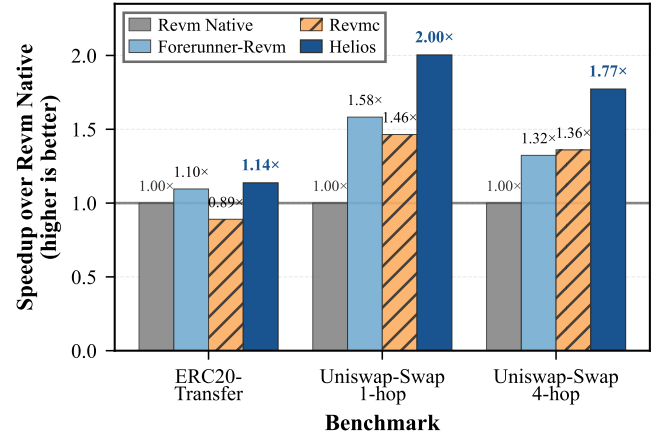
### 4.2 Microbenchmark Performance

**4.2.1 Optimization Overhead (RQ1).** Table 2 summarizes tracing latency and artifact size compared to Forerunner. For ERC20-Transfer, Helios records a path in 23.2  $\mu$ s, yielding a 12.5 $\times$  reduction over Forerunner-Geth and comparable latency to our Forerunner-Revm reimplementations. As contract complexity increases, tracing cost becomes dominated by the number of executed instructions, and Helios still achieves 1.4–2.4 $\times$  lower tracing time than Forerunner-Geth and about 1.2 $\times$  lower than Forerunner-Revm.

The storage savings are more pronounced. For the three benchmarks, Helios reduces artifact size by 82.7 $\times$ , 13.0 $\times$ , and 16.2 $\times$  compared to Forerunner-Geth, and by 9.4–16.4 $\times$  compared to Forerunner-Revm. The resulting artifacts (4.8–122.9 KB) are small enough to be cached in memory, making online management practical.

**Table 2: Tracing Time and Artifact Storage Overhead**

Benchmark	Forerunner		Helios	Reduction	
	Geth	Revm		vs Geth	vs Revm
<i>Tracing Time (<math>\mu</math>s)</i>					
ERC20-Transfer	291.6	26.3	<b>23.2</b>	12.5×	1.1×
Uniswap-Swap-1hop	742.6	381.5	<b>309.9</b>	2.4×	1.2×
Uniswap-Swap-4hop	1317.7	1119.2	<b>943.2</b>	1.4×	1.2×
<i>Artifact Size (KB)</i>					
ERC20-Transfer	393.4	44.7	<b>4.8</b>	82.7×	9.4×
Uniswap-Swap-1hop	910.4	647.5	<b>70.2</b>	13.0×	9.2×
Uniswap-Swap-4hop	1994.3	2017.5	<b>122.9</b>	16.2×	16.4×



**Figure 4: Execution speedup over Revm 22.0.1 baseline. Higher values indicate greater performance improvement.**

**Table 3: Execution Time: Geth-based vs. Revm-based Systems**

System	ERC20 ( $\mu$ s)	1hop ( $\mu$ s)	4hop ( $\mu$ s)
Geth Native	89.11	398.40	966.20
Forerunner-Geth	35.75	68.12	167.38
Revm Native	4.94	62.02	172.49

**4.2.2 Execution Speedup (RQ2).** Table 3 compares Geth-based and Revm-based systems. Forerunner-Geth accelerates Geth Native by up to 5.8 $\times$  but still remains substantially slower than unoptimized Revm on simple workloads, highlighting that optimization benefits are bounded by the efficiency of the underlying interpreter. We therefore focus on Revm-based systems when comparing optimization strategies.

Figure 4 reports speedups over Revm Native. Helios achieves 1.14 $\times$ , 2.00 $\times$ , and 1.77 $\times$  speedup on ERC20-Transfer, Uniswap-1hop, and Uniswap-4hop respectively. Gains are largest on medium and complex swaps, where repetitive arithmetic and control-flow patterns allow the SSA optimizer to eliminate redundant work.



**Table 4: Opcode Reduction and Execution Speedup Across Benchmarks**

Metric	ERC20	1hop	4hop
Native opcode count	492	5,667	18,063
<i>Opcodes Eliminated</i>			
CF	395	4,249	13,604
CSE	10	85	257
DCE	0	9	33
Total eliminated	405	4,343	13,894
Reduction rate	82.3%	76.6%	76.9%
<b>Execution speedup</b>	<b>1.14×</b>	<b>2.00×</b>	<b>1.77×</b>
<i>Predicted speedup</i>	<i>5.66×</i>	<i>4.28×</i>	<i>4.33×</i>

CF: Constant Folding; CSE: Common Subexpression Elimination; DCE: Dead Code Elimination.

**Table 5: Micro-architectural latency breakdown of a hash-intensive workload (ns per iteration).**

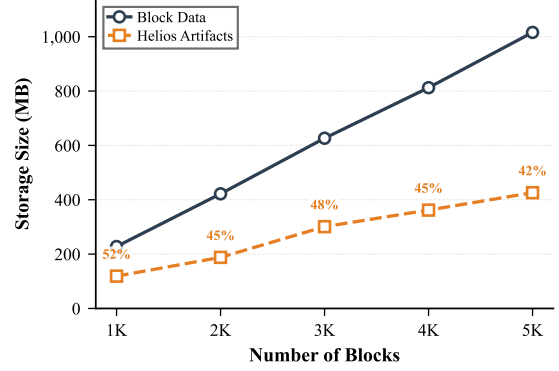
Component	Native EVM	Helios	Reduction
Heavy Ops (Keccak)	314.79	312.33	0.8%
Light Ops	46.49	45.96	1.1%
System Overhead	134.35	93.65	<b>30.3%</b>

Against Forerunner-RevM, Helios improves performance by 4–34% across benchmarks. On Uniswap-1hop, Forerunner-RevM achieves 1.58× speedup, whereas Helios reaches 2.00×, reducing execution time from 39.2  $\mu$ s to 31.0  $\mu$ s. The advantage comes from lightweight artifacts that are faster to load and execute.

Revmc exhibits mixed performance. While it is 11% slower than RevM Native on ERC20-Transfer, it achieves speedups of 1.46× and 1.36× on the two Uniswap workloads, respectively. JIT compilation amortizes better on longer paths, but still underperforms Helios. Interpreter-level SSA specialization thus offers competitive speedups without the runtime costs of code generation.

**4.2.3 Opcode Reduction vs. Speedup (RQ2).** Table 4 indicates that SSA optimization eliminates 76% to 82% of dynamic opcodes across all benchmarks, where constant folding accounts for approximately 98% of the reduction. However, the resulting speedups of 1.14× to 2.00× do not scale linearly with this reduction in instruction count.

We analyze this discrepancy in Table 5 by decomposing the micro-architectural latency of a hash-intensive workload. The breakdown reveals that computationally expensive operations such as KECCAK256 dominate execution and account for over 60% of the wall-clock latency. Since Helios delegates these operations to the native host to ensure safety, their fixed costs limit the theoretical maximum speedup. Within the optimizable scope, Helios reduces interpretation overhead including stack manipulation and gas metering by 30.5%, which decreases the per-iteration latency from 134ns to 93ns. Consequently, while the register-based model



**Figure 5: Storage growth for block data versus Helios optimization artifacts. Overhead decreases from 52.2% (1,000 blocks) to 41.9% (5,000 blocks) due to path convergence, where new blocks increasingly reuse existing cached artifacts.**

**Table 6: Storage-Coverage Tradeoff for Mainnet Blocks**

Freq Threshold	Storage	Overhead	Exec Coverage	Top-1 Coverage
$\geq 1$ (all paths)	426 MB	42.0%	100.0%	62.2%
$\geq 10$	50 MB	4.9%	96.5%	58.0%
$\geq 50$	38 MB	3.7%	90.0%	52.2%
$\geq 100$	19 MB	1.9%	85.6%	48.6%
$\geq 500$	4 MB	0.3%	69.9%	38.4%

streamlines execution logic, the overall performance gains remain bounded by the inherent computational intensity of cryptographic.

### 4.3 Mainnet Workload Analysis

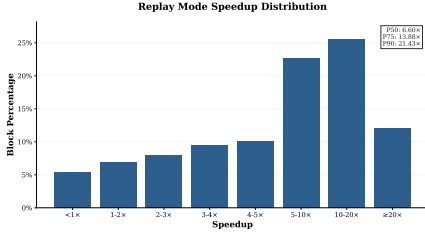
**4.3.1 Storage Overhead and Coverage (RQ1).** We next examine the cost of storing optimization artifacts on real workloads. Caching all unique paths observed in 5,000 blocks yields 426 MB of artifacts, corresponding to 41.9% overhead relative to raw block data (Figure 5). Overhead grows sub-linearly: the first 1,000 blocks incur 52.2% overhead, which drops as later blocks increasingly reuse existing paths.

To exploit path locality, we apply frequency-based filtering and keep only paths that execute at least  $f$  times during the warmup period (Table 6). A threshold of  $f \geq 10$  reduces storage to 50 MB (4.9% overhead) while still covering 96.5% of contract executions and achieving a 58.0% Top-1 prediction hit rate. More aggressive thresholds further shrink storage but lose coverage, so we use  $f \geq 10$  for Online deployment.

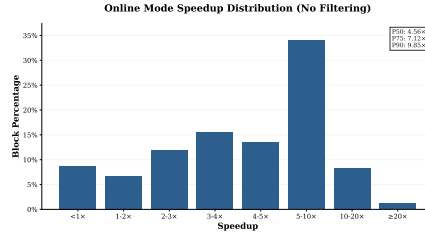
**4.3.2 Replay Mode Performance (RQ2 & RQ3).** Replay mode assumes a precomputed transaction plan and represents the best-case scenario for archive nodes. On the 5,000 evaluated blocks, it achieves a median speedup of 6.60× over RevM Native, with the 75th and 90th percentiles at 13.88× and 21.43× respectively (Figure 6). Only 5.4% of blocks are slower than baseline.

These results indicate that once transaction paths have been traced and optimized, Helios can substantially accelerate repeated

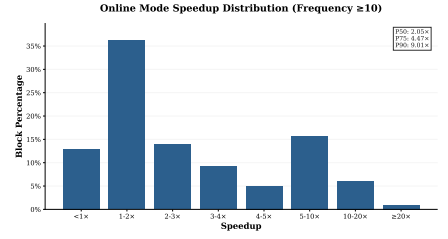




**Figure 6: Replay mode speedup distribution across 5,000 mainnet blocks. 5.4% of blocks exhibit slowdown. The median speedup of 6.60× and 90th percentile of 21.43× demonstrate consistent acceleration.**



**Figure 7: Online mode speedup distribution without filtering achieves median speedup of 4.56×. The distribution remains broad with 34.0% of blocks in the 5-10× range.**



**Figure 8: Online mode speedup distribution with frequency ≥ 10 filtering. Retaining high-frequency paths reduces median speedup to 2.05× but preserves 90th percentile at 9.01×.**

re-execution of historical blocks, making it well-suited for archive node synchronization and analytic workloads.

**4.3.3 Online Mode Effectiveness (RQ2 & RQ3).** Online mode must predict execution paths using only the current CallSig and cached statistics. We evaluate it on 1,000 blocks immediately following the warmup range.

Without filtering (all paths cached), Online mode reaches a median speedup of 4.56×, with 75th and 90th percentiles at 7.12× and 9.85×; 8.8% of blocks are slower than baseline (Figure 7). Applying frequency ≥ 10 filtering reduces the median speedup to 2.05× and the 75th percentile to 4.47×, while the 90th percentile remains high at 9.01× (Figure 8). Thus, frequency-based pruning trades median performance for a substantial drop in storage, but preserves strong acceleration for the hottest blocks.

The remaining gap between Online and Replay performance stems from three factors: (i) Top-1 prediction covers only 58.0% of executions under frequency filtering, so many transactions still fall back to native execution; (ii) Helios uses transaction-level rollback on mispredictions, discarding partially optimized work instead of switching paths mid-execution; and (iii) prediction and cache lookup add fixed per-transaction overhead that becomes visible when optimized paths execute in a few microseconds. We discuss potential extensions such as multi-path caching and finer-grained fallback in §5.

## 5 DISCUSSION

This section interprets the performance results, analyzes the limitations of the current design, and outlines future research directions.

### 5.1 Interpreting the Speedup

Helios achieves a median speedup of 6.60× in Replay Mode. This performance improvement results from the execution of optimized SSA graphs, which eliminates redundant stack operations and simplifies gas accounting for static instructions.

However, the evaluation reveals a disparity between the opcode reduction rate and the actual execution speedup. While SSA optimization removes approximately 80% of instructions, the microbenchmark speedups range from 1.14× to 2.00×. This discrepancy indicates that the overhead of the Traced Interpreter limits

the potential performance gains. The management of execution metadata and the interpretation of the graph structure introduce costs that are comparable to the savings from instruction elimination. Furthermore, unoptimized heavy instructions continue to dominate the execution time in certain workloads.

A promising avenue for future work is implementing JIT or Ahead-Of-Time (AOT) compilation to eliminate interpretation overhead and fully leverage the instruction reduction achieved by our SSA optimizer. The register-based design of the SsaGraph maps naturally to modern CPU architectures, facilitating this transition. Furthermore, unlike traditional bytecode JITs that face "JIT bomb" risks, the acyclic and strictly bounded nature of the SsaGraph offers a unique opportunity for safe compilation, avoiding complexity explosion attacks."

### 5.2 Online Mode Challenges

The performance of Online Mode exhibits a reduction when frequency-based filtering is applied. Our analysis of the coverage table reveals a gap between the coverage achieved by the Top-1 prediction strategy and the actual execution coverage. This suggests that the current simplicity-first selection strategy does not fully utilize the optimized paths.

We explored alternative strategies to address this limitation, including a race-parallel execution model. In this approach, the system caches the Top-K paths and executes them concurrently, committing the result of the first successful path or falling back to native execution if all fail. However, microbenchmarks showed that the overhead of the parallel framework outweighed the benefits. Native execution completed in 60 μs, whereas the race-parallel implementation increased latency to 70 μs, compared to 30 μs for the baseline optimized execution in the Uniswap-1hop case. Efficiently leveraging multi-path caching remains an open problem.

Another factor contributing to the performance degradation is the transaction-scoped fallback mechanism. Currently, a single frame prediction failure triggers a rollback of the entire transaction to the native EVM, resulting in the underutilization of successful frame-level predictions. A potential solution is to implement frame-level fallback, where only the failed frame reverts to native execution while subsequent frames attempt to use cached paths. To mitigate the risk of frequent engine switching, which we term



"de-optimization bombs," an optimization circuit breaker could limit the number of allowed fallbacks per transaction. Furthermore, the system could explore chained predictions, where the output of one optimized frame directly triggers the speculative execution of the next. These strategies represent a trade-off between architectural simplicity and execution coverage that warrants further investigation.

### 5.3 System Scalability

Beyond execution logic, system scalability presents additional opportunities for optimization. While our initial exploration of instruction-level parallelism (ILP) [32] did not yield satisfactory results due to synchronization overhead, the potential for parallel execution remains. The current dependency graph modeling could be enhanced by incorporating advanced ILP techniques from compiler theory. Future research could investigate more sophisticated scheduling algorithms or hardware-assisted synchronization primitives to unlock the parallelism inherent in the SsaGraph.

Finally, the current Path Cache implementation prioritizes low storage overhead with a simple persistence and pruning policy. As the system scales to handle larger state histories, more mature caching strategies will be required. Future work could explore tiered storage architectures that balance hit rate, retrieval latency, and storage cost, potentially leveraging external high-performance key-value stores for long-term artifact persistence.

## 6 RELATED WORK

This work focuses on accelerating Ethereum Virtual Machine (EVM) execution, specifically targeting modern, high-performance interpreters such as Revm. Research in this domain can be categorized into smart contract optimization toolchains, path-driven speculative execution systems, and concurrent execution architectures.

### 6.1 Smart Contract Optimization and Compilation

Optimization in the smart contract landscape spans from static source analysis to bytecode rewriting and compilation.

**Program Analysis and Optimization.** Traditional Solidity toolchains provide static analysis capabilities that serve as a foundation for downstream optimization. Tools like Slither [21] generate intermediate representations (SlithIR) and control flow graphs (CFG) to detect vulnerabilities. Rattle [8] lifts EVM bytecode into a SSA form to recover high-level control flow. While Rattle and Helios both leverage SSA to eliminate redundant stack operations, their objectives differ fundamentally. Rattle employs SSA as an intermediate representation for static analysis and decompilation, prioritizing readability without propagating changes back to the executable bytecode. In contrast, Helios utilizes SSA as a dynamic, executable format (SsaGraph) specifically designed for the runtime engine. The Helios optimizer operates on frame-level execution paths rather than static bytecode, generating artifacts for immediate execution acceleration via a specialized interpreter rather than for analysis.

**Superoptimization.** Superoptimization frameworks [12, 13, 30] aim to identify the optimal instruction sequence functionally equivalent to a target sequence but with minimal gas cost. While theoretically capable of producing maximally efficient code, these approaches rely on SMT solvers [17] to verify equivalence. The operational semantics of the EVM—specifically the modeling of memory expansion, storage, and dynamic gas costs—require complex logic encodings that heavily tax SMT solvers. Consequently, the search space for equivalent programs explodes exponentially with instruction count, often necessitating strict timeouts or restricting optimization to basic blocks without memory side-effects. These constraints make superoptimization difficult to apply dynamically at runtime.

**JIT and AOT Compilation.** Just-In-Time (JIT) and Ahead-Of-Time (AOT) compilers attempt to translate EVM bytecode into native machine code. Projects like Revmc [11] generate Rust code from EVM bytecode to bypass the interpreter loop. However, for the microsecond-scale transactions typical of the EVM, the overhead of runtime code generation often outweighs the execution speedup. Helios mitigates this overhead by avoiding full native compilation. Instead, it transforms execution paths into an abstract graph representation replayed by a specialized Traced Interpreter. This approach maintains the micro-architectural optimizations of the underlying host interpreter while reducing the instruction dispatch count.

### 6.2 Path-driven Speculative Execution

As a path-driven execution engine, Helios is directly comparable to systems like Forerunner [14] and Seer [36].

**Comparison with Existing Systems.** Forerunner applies constraint-driven speculative execution, generating "Accelerated Programs" (APs) based on transaction history. Seer employs fine-grained branch prediction and snapshots to manage state dependencies. However, these systems face limitations when applied to modern, fast interpreters due to their tracing strategy. Forerunner relies on full-context tracing, capturing stack frames, memory snapshots, and contract state. On highly optimized engines like Revm, the I/O overhead of loading these large artifacts often exceeds the execution time of the transaction itself. Helios employs **lightweight asynchronous tracing** to address this bottleneck. By recording only stack operations and minimal data dependencies, Helios achieves compression rates of  $9.4\times$  to  $16.4\times$  compared to full-context approaches, rendering online artifact management practical.

**Granularity and Gas Semantics.** Existing systems typically utilize transaction-level caching, which limits reuse to identical transaction sequences. Helios introduces **frame-level caching**, exploiting the observation that individual contract call frames exhibit high path locality even when parent transactions differ. Furthermore, prior works do not explicitly address the preservation of gas semantics during optimization. Helios guarantees gas equivalence by construction: it restricts SSA optimization to static-cost instructions while delegating all dynamic-cost operations (e.g., memory expansion, storage access) to the native EVM, ensuring the economic model remains undisturbed.



### 6.3 Concurrent and Parallel Execution

Various concurrent execution architectures address the sequential bottleneck of the EVM.

**Operation-Level Concurrency.** ParallelEVM [29] enables operation-level concurrency by dynamically generating an SSA Operation Log to track data dependencies. This mechanism allows selective re-execution of conflicting operations rather than aborting entire transactions. While both ParallelEVM and Helios leverage SSA, their objectives differ fundamentally: ParallelEVM employs SSA for concurrency control and conflict resolution, whereas Helios utilizes it for single-thread execution path optimization. Furthermore, ParallelEVM relies on synchronous runtime tracing. Although the reported log generation overhead is approximately 4.5%, Helios posits that on high-performance interpreters like Revm, any synchronous tracing on the critical path introduces non-negligible overhead, limiting net acceleration.

**Parallel Architectures.** Other approaches focus on architectural innovations. PaVM [20] supports both intra-contract and inter-contract parallelism through a specialized runtime system, though it does not explicitly address parallel determinism. Block-STM [25] implements optimistic concurrency control with a collaborative scheduler to execute transaction sets in parallel. Hardware-centric solutions such as MTPU [31] adopt algorithm-architecture co-design, utilizing spatial-temporal scheduling to exploit parallelism.

**Orthogonality Analysis.** Helios is orthogonal to these frameworks. Its core contribution is a lightweight, high-throughput path execution engine that optimizes the fundamental unit of computation—the sequential execution of a contract path. This baseline acceleration can be integrated into parallel frameworks such as ParallelEVM, Block-STM, or PaVM to further maximize system throughput.

### 6.4 Alternative Virtual Machine Environments

The emergence of WebAssembly [37] (WASM) in blockchain has led to new runtime environments like DTVM [38] and Wasmtime, which utilize JIT compilation and "hot-switching" mechanisms to balance startup performance with long-term execution efficiency. Helios adopts a similar philosophy for the EVM, using a dual-mode approach (Online vs. Replay) to adaptively balance the overhead of tracing against the benefits of optimized execution.

## 7 CONCLUSION

We presented Helios, a path-driven execution engine designed to accelerate transaction processing on high-performance EVM clients. We identified a *performance paradox* in existing optimization strategies: on modern, highly optimized interpreters, the overhead of detailed tracing and artifact management often negates the benefits of optimization. Helios addresses this challenge through a novel architecture that combines lightweight asynchronous tracing with frame-level caching. By restricting optimization to static-cost instructions, Helios achieves gas-semantic equivalence by construction, eliminating the economic risks associated with aggressive JIT compilation.

Our evaluation on Ethereum mainnet workloads demonstrates the efficacy of this approach. In Replay Mode, Helios achieves a

median speedup of 6.60× over the baseline Revm interpreter, validating its potential for accelerating archive node synchronization and historical data analysis. In Online Mode, Helios effectively accelerates hot execution paths, leveraging the strong path locality inherent in smart contract execution.

Helios establishes a new design point for blockchain execution engines, prioritizing safety, correctness, and architectural simplicity alongside raw performance. Future work will explore integrating JIT compilation to further reduce interpretation overhead for optimized paths and refining the speculative execution model with frame-level fallback mechanisms to maximize coverage. By decoupling optimization from the critical path, Helios provides a scalable foundation for the next generation of EVM infrastructure.

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