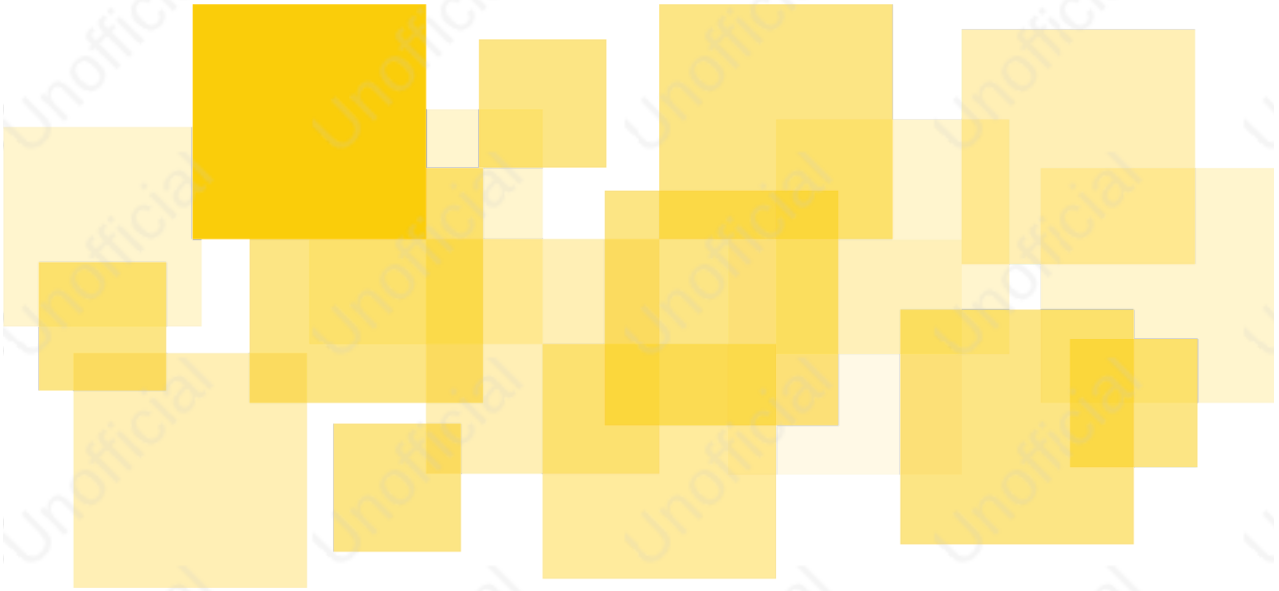
zkEVM Formal Verification Project

Project Review & Outcomes Ethereum

Delivered: August 21th, 2025



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Executive Summary

Project Overview and Goals

This project review documents Runtime Verification's comprehensive formal verification work for the Ethereum Foundation's zkEVM Formal Verification project, delivered in August 2025. The Ethereum Foundation launched this initiative to achieve the highest possible level of assurance for zkEVMs, with the ultimate goal of creating bug-free zero-knowledge Ethereum Virtual Machines.

The overarching goal of the project was to establish mathematical equivalence between zkEVMs used for execution and formal models that have been tested against the EVM conformance test suite, providing the rigorous verification foundation needed for safe zkEVM deployment, and addressing the challenge that many RISC-V based zkEVM approaches rely on REVM (Rust-based EVM implementation) compiled to RISC-V.

Key Deliverables

1. Lean 4 Backend (`klean` Tool)

- **Repository**: runtimeverification/k (`pyk.klean` module)
- **Purpose**: Bridge between K Framework and Lean 4 theorem proving ecosystems
- **Achievement**: Developed command-line tool that generates Lean 4 programs from kompiled K definitions, enabling translation of EVM specifications into theorem-provable format for enhanced verification rigor. The technical innovation of exporting K definitions to Lean 4 proved successful, providing broader ecosystem value by making K semantics accessible to the Lean 4 community.

2. EVM Equivalence Verification Framework

- **Repository**: runtimeverification/evm-equivalence
- **Purpose**: Mathematically prove equivalence between Runtime Verification's KEVM and Nethermind's EvmYul models
- **Achievement**: Established formal proof methodology for opcode-by-opcode equivalence verification, providing mathematical guarantees that different EVM implementations behave identically—crucial for zkEVM trustworthiness

3. EVM Opcode Summarization System

- **Repository**: runtimeverification/evm-semantics
- **Purpose**: Generate atomic, single-step execution rules for EVM opcodes to accelerate verification
- **Achievement**: Created comprehensive summarization framework covering 68 EVM opcodes with 7,225 lines of standardized summary rules, dramatically improving symbolic execution efficiency for zkEVM verification

4. zkEVM Testing and Verification Workflow

- **Repository**: runtimeverification/zkevm-harness
- **Purpose**: Formally verify real-world EVM implementations (REVM) through RISC-V compilation and zero-knowledge toolchains
- **Achievement**: Implemented end-to-end pipeline that compiles Rust EVM code to RISC-V using RISC Zero and SP1 toolchains, then performs both concrete and symbolic verification using K Framework

5. RISC-V Semantics for zkEVM Verification

- **Repository**: runtimeverification/riscv-semantics
- **Purpose**: Enable formal verification of complex zkEVM implementations compiled to RISC-V architecture
- **Achievement**: Implemented complete RISC-V instruction set coverage and semantic optimizations, which crucial because REVM verification relies on compiling REVM to RISC-V, which in turn requires formal verification-ready RISC-V semantics.

Infrastructure Components Delivered

REVM ↔ KEVM Verification Infrastructure

- RISC-V semantics
- zkEVM harness supporting RISC Zero and SP1 compilation toolchains
- Comprehensive test suite covering all major EVM opcode categories

Cross-Framework Verification Capabilities

- `klean` tool enabling K Framework to Lean 4 translation
- Support for equivalence verification between KEVM and CLEAR models
- Extensible architecture for additional formal verification frameworks

Automated Verification Systems

- EVM opcode summarization reducing complex multi-step operations to atomic rules
- Scalable CI pipeline architecture for continuous re-verification
- Performance optimizations enabling practical verification of large-scale systems

Impact on zkEVM Ecosystem

This work directly addresses Runtime Verification's stated mission to "show that the EVMs used for zkEVM execution are correct." The delivered infrastructure provides:

- **Mathematical Guarantees**: Formal proofs that different zkEVM implementations behave equivalently

- **Practical Verification**: Tools for verifying real-world zkEVM implementations like those used by major projects
- **Ecosystem Standardization**: Common verification frameworks promoting consistency across zkEVM development
- **Scalable Infrastructure**: Systems capable of handling the complexity of production zkEVM verification

The project establishes the rigorous formal verification foundation necessary for the zkEVM ecosystem to achieve the Ethereum Foundation's goal of bug-free implementations, while maintaining the security and compatibility guarantees essential for Ethereum's scaling through zero-knowledge rollups.

The Lean 4 Backend

The following section presents `klean`, a tool to generate Lean 4 programs from kompiled K definitions.

klean

The `pyk.klean` module enables Lean 4 code generation from a kompiled KORE definition.

Command Line Interface

After installation of the `kframework` package, the code generator is available on the command line under the `klean` command.

```
usage: klean [-h] [-o DIR] [-l NAME] [-r LABEL] [--derive-beq] [--derive-decidableeq] DEFN_DIR PKG_NAME

Generate a Lean 4 project from a K definition

positional arguments:
  DEFN_DIR              definition directory
  PKG_NAME              name of the generated Lean 4 package (in kebab-case)

options:
  -h, --help            show this help message and exit
  -o, --output DIR      output directory (default: .)
  -l, --library NAME    name of the generated Lean library (default: package name in PascalCase)
  -r, --rule LABEL      labels of rules to include (default: all)
  --derive-beq          derive BEq for all types
  --derive-decidableeq  derive DecidableEq for all types except SortKItem and its dependents
```

The `-r` flag can be provided multiple times, each time with a rule label, to include only those rules (and their transitive dependencies) in the generated output.

Example

In the following, all example commands assume the following:

- Lean 4 is installed, `lake` is on `$PATH`.
- The K Framework is installed, the correct version of `kompile` is on `$PATH`.
- The `runtimeverification/k` repository is cloned, `$PWD` is the `pyk` directory.

```
$ kompile src/tests/integration/test-data/k-files/imp.k  # kompile the IMP definition
$ uv run klean imp-kompiled klean-imp                    # generate the Lean 4 project
```

The command produces the following files:

```
$ tree klean-imp
klean-imp
├── KleanImp
│   ├── Func.lean
│   ├── Inj.lean
│   ├── Prelude.lean
│   ├── Rewrite.lean
│   └── Sorts.lean
├── KleanImp.lean
├── lakefile.toml
└── lean-toolchain
```

File	Description
`KleanImp.lean`	Main library file.
`KleanImp/Prelude.lean`	A prelude with basic declarations shared between all generated projects.
`KleanImp/Sorts.lean`	Type declarations for all relevant[1] sorts in the K definition.
`KleanImp/Inj.lean`	A definition for the `inj` function based on the subsort relation using instances.
`KleanImp/Func.lean`	Axioms for all relevant[1] function signatures in the K definition.
`KleanImp/Rewrite.lean`	A dependent type that encodes the rewrite relation over configurations[2].

The generated files constitute a `lake` project:

```
# klean-imp/lakefile.toml

name = "klean-imp"
version = "0.1.0"
defaultTargets = ["KleanImp"]
weakLeanArgs = [
    "-D maxHeartbeats=10000000"
]

[[lean_lib]]
name = "KleanImp"
```

The command `lake build` builds the project:

```
$ lake -d klean-imp build
info: klean-imp: no previous manifest, creating one from scratch
info: toolchain not updated; already up-to-date
Build completed successfully.
```

1. With regards to the incuded rewrite rules. ↩ ↩[2]
2. To be more precise, it encodes an over-approximation of the relation, as it does not take rule priorities into consideration. ↩

Code Generation

The following describes the technical details of the code generator.

Code Generation Workflow

The starting point of code generation is a kompiled `definition.kore` file. After parsing the definition, as an optimization step, the model is minimized to only contain sorts, symbols, and rule axioms that are relevant with respect to rewrite rules. These sorts, symbols, and axioms are then mapped to Lean 4 concepts. To support this, parts of the Lean 4 syntax, in particular modules and declarations, are modeled as `dataclass` -es whose `__str__` method serializes the object to Lean 4 code (implementation). The model is not complete; i.e., not all syntactic elements are modeled, and not all facets of a modeled syntactic element are represented. Notably, terms are not represented structurally.

The rest of the section describes the Lean 4 artifacts generated by `klean` in detail.

Prelude

The code generator defines a prelude that provides an interpretation (and in some cases, an axiomatic interface) for relevant sorts and hooked functions from K's `domains.md` . The prelude is included verbatim in each project generated by `klean` .

Sorts

Each non-primitive K sort is mapped to a Lean 4 type definition.

Cell sorts are mapped to `structure` -s. If the cell has no subcells (and therefore, wraps a single value), the field name is `val` .

K	Lean 4
`configuration` `  <statusCode> .StatusCode </statusCode>`	`structure SortStatusCodeCell : Type where` `  val : SortStatusCode`

If the cell has subcells, each field name is derived from the sort of a corresponding subcell.

K	Lean 4

`configuration`
`  <callState>`
`    <program>    .Bytes     </program>`
`    <jumpDests>  .Bytes     </jumpDests>`
`    <id>         .Account   </id>`
`    <caller>     .Account   </caller>`
`    <callData>   .Bytes     </callData>`
`    <callValue>  0          </callValue>`
`    <wordStack>  .WordStack </wordStack>`
`    <localMem>   .Bytes     </localMem>`
`    <pc>         0          </pc>`
`    <gas>        0:Gas      </gas>`
`    <memoryUsed> 0          </memoryUsed>`
`    <callGas>    0:Gas      </callGas>`
`    <static>     false      </static>`
`    <callDepth>  0          </callDepth>`
`  </callState>`
	`structure SortCallStateCell : Type where`
	`  program : SortProgramCell`
	`  jumpDests : SortJumpDestsCell`
	`  id : SortIdCell`
	`  caller : SortCallerCell`
	`  callData : SortCallDataCell`
	`  callValue : SortCallValueCell`
	`  wordStack : SortWordStackCell`
	`  localMem : SortLocalMemCell`
	`  pc : SortPcCell`
	`  gas : SortGasCell`
	`  memoryUsed : SortMemoryUsedCell`
	`  callGas : SortCallGasCell`
	`  static : SortStaticCell`
	`  callDepth : SortCallDepthCell`

`List`, `Set`, and `Map` are special-cased (i.e., syntax is not mapped directly), and are also mapped as `structure`.

K	Lean 4

`syntax List ::= List List       [...]`
`syntax List ::= ".List"         [...]`
`syntax List ::= ListItem(KItem) [...]`
	`structure SortList : Type where`
	`  coll : List SortKItem`

`syntax Set ::= Set Set        [...]`
`syntax Set ::= ".Set"         [...]`
`syntax Set ::= SetItem(KItem) [...]`
	`structure SortSet : Type where`
	`  coll : List SortKItem`

`syntax Map ::= Map Map           [...]`
`syntax Map ::= ".Map"           [...]`
`syntax Map ::= KItem "|->" KItem [...]`
	`structure SortMap : Type where`
	`  coll : List (SortKItem × SortKItem)`

Cell collections follow the same pattern, except the element / key-value types are cell types.

K

```
configuration
  <accounts>
    <account multiplicity="*" type="Map">
      <acctID>           0                  </acctID>
      <balance>          0                  </balance>
      <code>             .Bytes:AccountCode </code>
      <storage>          .Map               </storage>
      <origStorage>      .Map               </origStorage>
      <transientStorage> .Map               </transientStorage>
      <nonce>            0                  </nonce>
    </account>
  </accounts>
```

Lean 4

```
structure SortAccountsCell : Type where
  val : SortAccountCellMap

structure SortAccountCellMap : Type where
  coll : List (SortAcctIDCell × SortAccountCell)

structure SortAccountCell : Type where
  acctID : SortAcctIDCell
  balance : SortBalanceCell
  code : SortCodeCell
  storage : SortStorageCell
  origStorage : SortOrigStorageCell
  transientStorage : SortTransientStorageCell
  nonce : SortNonceCell
```

All other (non-primitive) sorts are translated as `inductive`, where the constructors are induced by subsort and symbol productions.

K

```
syntax JSON::= Bool | Int | String
             | "null"           [symbol(JSONnull)]
             | JSONKey ":" JSON [symbol(JSONEntry)]
             | "{" JSONs "}"    [symbol(JSONObject)]
             | "[" JSONs "]"    [symbol(JSONList)]
```

Lean 4

```
inductive SortJSON : Type where
  | inj_SortBool (x : SortBool) : SortJSON
  | inj_SortInt (x : SortInt) : SortJSON
  | inj_SortString (x : SortString) : SortJSON
  | JSONnull : SortJSON
  | JSONEntry (x0 : SortJSONKey) (x1 : SortJSON) : SortJSON
  | JSONObject (x0 : SortJSONs) : SortJSON
  | JSONList (x0 : SortJSONs) : SortJSON
```

Symbol names that contain special characters are quoted using guillemets (« »).

K

```
syntax InternalOp ::= "#next" "[" MaybeOpCode "]" [symbol(#next)]
```

Lean 4

```
inductive SortInternalOp : Type where
  | «#next» (x0 : SortMaybeOpCode) : SortInternalOp
```

In the generated program, declarations are ordered according to the sort dependency relation in two steps.

1. First, sorts are partitioned so that any two sorts of a given class depend on each other. Each such class induces a `mutual` command in the generated program.
2. Classes are then ordered topologically.

Injections

The polymorphic injection and retraction functions are defined in the prelude as follows.

```
class Inj (From To : Type) : Type where
  inj (x : From) : To
  retr (x : To) : Option From

def inj {From To : Type} [inst : Inj From To] := inst.inj
def retr {From To : Type} [inst : Inj From To] := inst.retr
```

For each pair of sorts `S1`, `S2` such that `S1` is a subsort of `S2`, an instance `Inj S1 S2` is generated. It ensures that `inj` is transitive, and that `inj_*` constructors can be retracted into a more specific supersort. This latter is used for subsort matching on the left-hand side of K function rules.

K	Lean 4

`syntax KItem ::= JSON`
`syntax JSON::= Bool | Int | String`
	`inductive SortKItem : Type where`
	`  | inj_SortBool (x : SortBool) : SortKItem`
	`  | inj_SortInt (x : SortInt) : SortKItem`
	`  | inj_SortString (x : SortString) : SortKItem`
	`  | inj_SortJSON (x : SortJSON) : SortKItem`
	
	`inductive SortJSON : Type where`
	`  | inj_SortBool (x : SortBool) : SortJSON`
	`  | inj_SortInt (x : SortInt) : SortJSON`
	`  | inj_SortString (x : SortString) : SortJSON`
	
	`instance : Inj SortJSON SortKItem where`
	`  inj`
	`  | SortJSON.inj_SortBool x => SortKItem.inj_SortBool x`
	`  | SortJSON.inj_SortInt x => SortKItem.inj_SortInt x`
	`  | SortJSON.inj_SortString x => SortKItem.inj_SortString x`
	`  | x => SortKItem.inj_SortJSON x`
	`  retr`
	`  | SortKItem.inj_SortBool x => some (SortJSON.inj_SortBool x)`
	`  | SortKItem.inj_SortInt x => some (SortJSON.inj_SortInt x)`
	`  | SortKItem.inj_SortString x => some (SortJSON.inj_SortInt x)`
	`  | SortKItem.inj_SortJSON x => some x`
	`  | _ => none`

Functions

For each K function symbol not defined in the prelude, a Lean 4 function is declared. In order to support non-total functions, the result type is `Option`.

If the symbol has no corresponding function rules, it is mapped as an `axiom`.

```
axiom «_^Int_;» (x0 : SortInt) (x1 : SortInt) : Option SortInt
```

Otherwise, a `def` is generated that applies the functions generated for each function rule in `priority` order until the first `some` result .

K	Lean 4

`syntax Int ::= Int "up/Int" Int [function, total, symbol(up/Int)]`
 	
`rule _I1 up/Int I2 => 0`
`  requires I2 <=Int 0`
 	
`rule  I1 up/Int 1  => I1`
 	
`rule _I1 up/Int 0  => 0`
 	
`rule  I1 up/Int I2 => (I1 +Int (I2 -Int 1)) /Int I2`
`  requires 1 <Int I2`
	`def _091b7da : SortInt → SortInt → Option SortInt`
	`  | _I1, I2 => do`
	`  let _Val0 <- «_<=Int_» I2 0`
	`  guard _Val0`
	`  return 0`
	
	`def _50d266e : SortInt → SortInt → Option SortInt`
	`  | I1, 1 => some I1`
	`  | _, _ => none`
	
	`def _5321d80 : SortInt → SortInt → Option SortInt`
	`  | _I1, 0 => some 0`
	`  | _, _ => none`
	
	`def _e985b28 : SortInt → SortInt → Option SortInt`
	`  | I1, I2 => do`
	`  let _Val0 <- «_<Int_» 1 I2`
	`  let _Val1 <- «_-Int_» I2 1`
	`  let _Val2 <- «_+Int_» I1 _Val1`
	`  let _Val3 <- «_/Int_» _Val2 I2`
	`  guard _Val0`
	`  return _Val3`
	
	`def «up/Int» (x0 : SortInt) (x1 : SortInt) : Option SortInt :=`
	`  (_091b7da x0 x1) <|>`
	`  (_50d266e x0 x1) <|>`
	`  (_5321d80 x0 x1) <|>`
	`  (_e985b28 x0 x1)`

The definitions are implemented in the `Option` monad to handle non-matching patterns on the left-hand side, unsatisfied preconditions (`guard _Val0`) and undefined subterms (`let _Val3 <- «_/Int_» _Val2 I2`).

If a definition depends on an `axiom` , the `noncomputable` modifier is applied accordingly.

Special handling is necessary to transform complex patterns on the left-hand side of rules supported by the K Framework but not Lean 4, namely, subsort matching, K collection patterns, and for admitting non-unique variables in a pattern. Roughly, processing of such patterns is performed in the following steps.

1. First, all variables[1] in the pattern are renamed to be unique, while tracking equivalence between them. Each pair of such variables, say, `x` and `y` , will conceptually induce a piece of Lean 4 pattern matching code of the form

```
| ..., x, ..., y, ... => match x == y with
  | true => ...
```

2. Then, subsort and collection patterns are recursively abstracted with fresh variables. Each such pair of variable and pattern, say, `x` and `t`, will conceptually induce a piece of Lean 4 pattern matching code of the form

```
| ..., x, ... => match f x with
  | t' => ...
```

   where `f` is a function that implements the logic of matching `t`, and `t'` a pattern capturing a successful match of `x` into `t`.
3. The pattern matching pieces are topologically ordered based on the data dependencies between them. For example, in a K pattern `listHeadInSet(ListItem(X:KItem) _:List, SetItem(X) _:Set)`, `X` is matched in the list, which the nesting of `match` expressions have to reflect (the following snippet simplifies some function names for the ease of exposition):

```
| p1, p2 => match list_head p1 with
  | some x => match in_set p2 x with
    | true => ...
```

The following are examples for the transformation output of each type of complex pattern.

K	Lean 4

`syntax Foo  ::= Int | "foo"`
`syntax Bool ::= "foo?" "(" KItem ")" [function, total, symbol(int?)]`
 	
`rule foo?(_:Foo) => true`
`rule foo?(_)     => false [owise]`
	`def _950d09f : SortKItem → Option SortBool`
	`  | _Pat0 => match (@retr SortFoo SortKItem) _Pat0 with`
	`    | some _Gen0 => some true`
	`    | _ => none`
	
	`def _a65c46b : SortKItem → Option SortBool`
	`  | _Gen0 => some false`
	
	`def int? (x0 : SortKItem) : Option SortBool :=`
	`  (_950d09f x0) <|> (_a65c46b x0)`

`syntax KItem ::= head(List) [function, symbol(head)]`
 	
`rule head(ListItem(HEAD) _) => HEAD`
	`noncomputable def _eb9118d : SortList → Option SortKItem`
	`  | _Pat0 => match (ListHook SortKItem).split _Pat0.coll 1 0 with`
	`    | some ([HEAD], _Gen0, []) => some HEAD`
	`    | _ => none`
	
	`noncomputable def head (x0 : SortList) : Option SortKItem := _eb9118d x0`

`syntax Bool ::= Int "eqInt" Int [function, total, symbol(eqInt)]`
 	
`rule I eqInt I => true`
`rule _ eqInt _ => false [owise]`
	`def _b5d6a8f : SortInt → SortInt → Option SortBool`
	`  | I, _Uniq0 => match I == _Uniq0 with`
	`    | true => some true`
	`    | _ => none`
	
	`def _48f6b23 : SortInt → SortInt → Option SortBool`
	`  | _Gen0, _Gen1 => some false`
	
	`def eqInt (x0 : SortInt) (x1 : SortInt) : Option SortBool :=`
	`  (_b5d6a8f x0 x1) <|> (_48f6b23 x0 x1)`

Similarly to sorts, function and function rule definitions are partitioned and topologically ordered with respect to their dependency relation. In the case of mutually recursive definitions, the burden of proving termination (i.e., finding suitable terms for `termination_by` / `decreasing_by`) is on the user.

Rewrite Relation

The rewrite relation is represented as a dependent type

```
inductive Rewrites : SortGeneratedTopCell → SortGeneratedTopCell → Prop
```

where each constructor, except for a special constructor `tran` encoding the transitivity of the relation, represents a rewrite rule. In order to prove a step w.r.t. a given rewrite rule, the `requires` clause and the definedness of subterms have to be proven.

K

```
module COUNTER
  imports INT
  rule [dec]: <k> X:Int => X -Int 1 </k> requires 0 <Int X
endmodule
```

Lean 4

```
inductive Rewrites : SortGeneratedTopCell → SortGeneratedTopCell → Prop where
  | tran
    {s1 s2 s3 : SortGeneratedTopCell}
    (t1 : Rewrites s1 s2)
    (t2 : Rewrites s2 s3)
    : Rewrites s1 s3
  | COUNTER_dec
    {X _Val1 : SortInt}
    {_DotVar0 : SortGeneratedCounterCell}
    {_Val0 : SortBool}
    (defn_Val0 : «_<Int_» 0 X = some _Val0)
    (defn_Val1 : «_-Int_» X 1 = some _Val1)
    (req : _Val0 = true)
    : Rewrites {
      k := {
        val := SortK.kseq ((@inj SortInt SortKItem) X) SortK.dotk
      },
      generatedCounter := _DotVar0
    } {
      k := {
        val := SortK.kseq ((@inj SortInt SortKItem) _Val1) SortK.dotk
      },
      generatedCounter := _DotVar0
    }
```

In the `Rewrites` type definition, rule priorities are not taken into consideration; hence, the generated relation is an overapproximation of the relation induced by the actual rewrite rules.

Potential Uses

The K-to-Lean generator opens several technical directions beyond equivalence verification, which it is used for in this project. One of the promising directions is addressing SMT solver limitations — current verification sometimes falls short on nonlinear arithmetic, modular operations with large bit widths, cryptographic primitives, and complex loop invariants that are common in EVM opcodes. Lean's dependent types and proof

tactics could handle these cases where SMT solvers struggle, with the K backend providing the interface and the initial problem setup and Lean filling verification gaps interactively.

Another valuable application is proving correctness of the lemmas and simplification rules added to speed up K proofs, as well as the REVM proofs implemented in scope of this project, to provide stronger mathematical guarantees of their correctness.

1. To be more precise, all variables that after processing the pattern will end up on the left-hand side. For example, in a pattern `SetItem(X:KItem) S:Set`, `X` will not be part of the Lean 4 pattern, therefore no renaming is necessary. ↩

EVM Equivalence

Executive Summary

This section provides a summary of the runtimeverification/evm-equivalence repository.

Project Overview and Significance

The evm-equivalence repository contains the formal proof of equivalence between two independent mathematical models of the Ethereum Virtual Machine (EVM): Nethermind's EvmYul and Runtime Verification's KEVM. This work aims to mathematically guarantee that these two distinct models of the EVM behave identically.This project provides an additional layer of trust, ensuring that different formal EVM models don't have any behavioral divergences.

Technology Stack

The project leverages a sophisticated stack of formal methods technologies to bridge two different verification paradigms:

- **K Framework**: A rewrite-based executable semantic framework. Runtime Verification's KEVM model, a complete formal specification of the EVM, is written in K. The K Framework excels at defining the operational semantics of a language—how it executes step-by-step.
- **Lean 4**: A functional programming language and interactive theorem prover based on dependent type theory. Nethermind's EvmYul model is written in Lean 4.
- `klean` **Tool**: A command-line utility from K's `pyk` library that serves as the bridge between the two ecosystems. It translates semantic rules from compiled K definitions (like those in KEVM) into corresponding Lean 4 code, enabling the comparison to be performed within a single proof environment.

Work Process and Methodology

The project employs a systematic, multi-stage methodology to prove equivalence on an opcode-by-opcode basis. This "divide and conquer" strategy makes the task of verifying the entire EVM more tractable. The workflow for each opcode can be summarized as follows:

- **Code Generation**: The klean tool is used to translate a specific K rule corresponding to an EVM opcode's semantics (e.g., the rule for `ADD`) into a Lean 4 representation. This generated code resides in the `KEVM2Lean` directory.
- `EvmYul` **Summarization**: Provide the necessary theorems capturing the computational content of the needed opcode within the EvmYul model.
- **State Mapping**: Provide the formal mapping between a state in the KEVM model and a corresponding state in the EvmYul model. The function providing the mapping defines precisely what it means for the two machines to be in an "equivalent" state.

- **Equivalence Proof**: The final proof is constructed entirely within Lean 4. The core of the proof for each opcode is to demonstrate that if the two models start in equivalent initial states, they will transition to equivalent final states after executing that opcode. This proves that the state equivalence property is an invariant preserved by the operation. The individual proofs are contained in files of the `Equivalence` folder.

A Tale of Two Formalisms: KEVM and EvmYul

The core challenge of the `evm-equivalence` project lies in bridging the gap between two distinct and powerful mathematical frameworks. The two EVM models in question, Runtime Verification's KEVM and Nethermind's EvmYul, are implemented using different languages and are based on different approaches to formal methods.

The K Framework and KEVM: Executable Specifications

The K Framework is a technology for defining and analyzing programming languages. Its philosophy is that a language's formal specification should be directly executable. K is a rewrite-based system where behavior is defined by transition rules of the form $s_1 \Rightarrow s_2$, describing how a program state s_1 evolves to s_2. A K definition includes syntax, state structure, and transition rules. A key advantage is that a single K definition can generate various language tools like interpreters and verifiers.
KEVM is the application of this framework to the EVM. It is a complete, executable formal specification of the EVM in K, validated against an extensive test suite containing tens of thousands of cases.

Lean 4 and EvmYul: A Proving Ground for Mathematics and Software

Lean 4 is a modern theorem prover and functional programming language used for mathematics formalization and software verification. It is based on the Calculus of Constructions, a dependent type theory, which allows for expressing precise properties about programs. Lean's credibility comes from a small, trusted proof-checking kernel that validates every proof, ensuring a high degree of correctness. Nethermind is using Lean 4 to construct EvmYul, an executable formal model of the EVM and its intermediate language, Yul. The goal is to build a provably correct EVM implementation using interactive theorem proving.

Blueprint and Documentation

For a more in-depth documentation of this project, please refer to the following:

- Blueprint of the project
- Project `README.md`
- Equivalence `README.md`

EVM Opcode Summarization System Technical Report

Executive Summary

The EVM Opcode Summarization System is a framework developed within the KEVM (evm-semantics) project to automatically generate summarized, single-step execution rules for Ethereum Virtual Machine opcodes. This system addresses the critical need for efficient formal verification by condensing complex multi-step opcode executions into atomic, provably correct summary rules. The methodology of this work will be provided in the corresponding academic publication.

Summarization Workflow

The summarization process follows a systematic three-phase approach, as documented in the `KEVMSummarizer` class:

Phase 1: Specification Building (`build_spec`)

The first phase constructs formal specifications for symbolic execution of each opcode:

1.1 Initial State Construction

```
def _build_spec(self, op: str, stack_needed: int, ...):
    # Construct initial EVM state
    _init_subst['K_CELL'] = KSequence([next_opcode, KVariable('K_CELL')])
    _init_subst['WORDSTACK_CELL'] = KEVM.wordstack(stack_needed)
    _init_subst['GAS_CELL'] = KEVM.inf_gas(KVariable('GAS_CELL', 'Gas'))
```

1.2 Opcode-Specific Handling

The system categorizes opcodes and builds specialized specifications as follows:

- **Account Query Opcodes** (`BALANCE` , `EXTCODESIZE` , etc.):

```
if op in ACCOUNT_QUERIES_OPCODES:
    # Create both normal and otherwise cases
    specs.append((..., '_NORMAL'))
    specs.append((..., '_OWISE'))
```

- **Storage Opcodes** (`SLOAD` , `SSTORE` , `TLOAD` , `TSTORE`):

```
elif op in ACCOUNT_STORAGE_OPCODES:
    cell, constraint = accounts_cell('ID_CELL')
    init_subst['ACCOUNTS_CELL'] = cell
```

- **Jump Operations** (`JUMP` , `JUMPI`):

```
elif op == 'JUMPI':
    # Create separate specs for true/false conditions
    specs.append((..., '_FALSE'))
    specs.append((..., '_TRUE'))
```

1.3 Constraint Generation

The system generates constraints for:

- Stack underflow prevention
- Gas cost calculations
- State consistency checks
- Account existence conditions

Phase 2: KCFG Exploration (`explore`)

The second phase performs symbolic execution to explore all possible execution paths:

2.1 Execution Environment Setup

```
def explore(self, proof: APRProof) -> bool:
    with legacy_explore(
        self.kevm,
        kcfg_semantics=KEVMSemantics(allow_symbolic_program=True),
        kore_rpc_command=('kore-rpc-booster',),
        max_depth=1,  # Single-step execution
        max_iterations=300,
    ) as kcfg_explore:
```

2.2 Proof Execution

The system runs the formal prover with a specific configuration:

- **Max depth**: 1 (A debugging value for the number of rewriting steps per iteration; the typical setting is 1000.)
- **Max iterations**: 300 (A debugging value chosen to limit the number of symbolic execution iterations, allowing for a quicker assessment of the verification results and an early decision on proof continuity.)
- **Cut point rules**: All disabled for atomic execution
- **Terminal rules**: Enabled for completion detection

2.3 Result Validation

Each proof is validated to ensure:

- No pending nodes (incomplete execution)
- No stuck nodes (execution failures)
- No bounded nodes (depth limitations)
- Proper terminal states

Phase 3: Rule Summarization (`summarize`)

The final phase transforms the KCFG into clean, usable summary rules:

3.1 KCFG Minimization

```
def summarize(self, proof: APRProof, merge: bool = False):
    proof.minimize_kcfg(KEVMSemantics(allow_symbolic_program=True), merge)
```

3.2 Rule Transformation Pipeline

The system applies multiple transformations to generate clean rules:

1. **Variable Normalization**: `_transform_dash()`
   - Removes underscore prefixes from variable names
   - Standardizes variable naming conventions
2. **Gas Handling**: `_transform_inf_gas()`
   - Converts infinite gas to regular gas calculations
   - Adds appropriate gas constraint guards
3. **Account State Cleanup**: `_transform_dot_account_var()`
   - Simplifies account cell representations
   - Removes redundant account existence checks
4. **Function Abstraction**: `_transform_lhs_functions()`
   - Converts complex LHS functions to variables
   - Adds corresponding equality constraints

3.3 Rule Generation

```
def _to_rules(self, proof: APRProof) -> list[KRule]:
    # Convert KCFG to K rules
    module = APRProofShow(...).kcfg_show.to_module(proof.kcfg)
    for krule in module.sentences:
        # Apply transformations
        body, requires, ensures = _transform_dash(...)
        rule_id = _transform_rule_id(proof.id, requires)
```

```
        # Generate final rule
        krules.append(KRule(body, requires, ensures, atts))
```

3.4 File Generation

The system generates two types of output files:

1. **Individual Summary Files**: `{opcode}-summary.k`
   - Contains rules specific to one opcode
   - Includes necessary imports and dependencies
2. **Master Summary File**: `summaries.k`
   - Imports all individual summary files
   - Provides unified access to all summaries

Workflow Integration

Entry Point Function

```
def summarize(opcode_symbol: str) -> tuple[KEVMSummarizer, list[APRProof]]:
    summarizer = KEVMSummarizer(proof_dir, save_directory)
    proofs = summarizer.build_spec(opcode_symbol)
    for proof in proofs:
        if proof_exists:
            proof = APRProof.read_proof_data(proof_dir, proof.id)
        else:
            summarizer.explore(proof)  # Phase 2
        summarizer.summarize(proof)    # Phase 3
    return summarizer, proofs
```

Batch Processing

```
def batch_summarize(num_processes: int = 4):
    with Pool(processes=num_processes) as pool:
        pool.map(_process_opcode, get_passed_opcodes())
```

Quality Assurance in Workflow

Validation Checks

At each phase, the system performs validation:

1. **Specification Phase**:
   - Stack underflow prevention

- Constraint consistency
- State validity

2. **Exploration Phase**:
   - Proof completion
   - Node state validation
   - Execution path coverage
3. **Summarization Phase**:
   - Rule correctness
   - Transformation validity
   - File generation success

Error Handling

The system includes comprehensive error handling:

```
def _process_opcode(opcode: str) -> None:
    try:
        summarize(opcode)
        _LOGGER.info(f'Successfully processed opcode: {opcode}')
    except Exception as e:
        _LOGGER.error(f'Failed to process opcode {opcode}: {str(e)}')
        _LOGGER.debug(traceback.format_exc())
```

Performance Optimizations

Caching Strategy

- Existing proofs are reused when available
- Proof data is persisted to disk
- Incremental processing supported

Parallel Processing

- Multiple opcodes processed simultaneously
- Configurable process pool size
- Independent opcode processing

Memory Management

- KCFG minimization reduces memory usage
- Temporary data cleanup after processing
- Efficient rule transformation pipelines

This three-phase workflow ensures that each EVM opcode is systematically analyzed, formally verified, and transformed into efficient, single-step execution rules that maintain correctness while optimizing performance for downstream verification tools.

System Architecture Overview

Core Components

The summarization functionality is concentrated in four main components:

1. **Core Engine**: `summarizer.py` (943 lines) - The main implementation
2. **CLI Integration**: `cli.py` and `__main__.py` - Command-line interface and execution
3. **Testing Framework**: `test_summarize.py` and `test_prove.py` - Validation and verification
4. **Generated Summaries**: `/summaries` directory - 68 individual opcode summary files

Additional Supporting Components

Based on the commit analysis, the system also includes:

- **KEVM Helper Methods**: Extended functionality in the core KEVM system
- **EDSL Modules**: Domain-specific language support for summary generation
- **Build Configuration**: Integration with the K build system through `kdist/plugin.py`
- **Wrapper Functions**: Utility functions for opcode processing
- **Gas Cost Analysis**: Support for gas cost summarization across all opcodes

Technical Architecture

1. KEVMSummarizer Class

The core `KEVMSummarizer` class provides three main functionalities:

```
class KEVMSummarizer:
    def build_spec(self, op: str) -> list[APRProof]:
        """Build specifications for symbolically executing an opcode."""

    def explore(self, proof: APRProof) -> bool:
        """Execute the specification to explore the KCFG."""

    def summarize(self, proof: APRProof, merge: bool = False) -> None:
        """Minimize the KCFG to get summarized rules."""
```

2. Opcode Coverage and Status

The system tracks 68 different EVM opcodes with their implementation status:

```
OPCODES: Final = frozendict({
    'STOP': KApply('STOP_EVM_NullStackOp'),
    'ADD': KApply('ADD_EVM_BinStackOp'),
    'MUL': KApply('MUL_EVM_BinStackOp'),
    # ... additional 65 opcodes
})
```

Each opcode has an associated status in `OPCODES_SUMMARY_STATUS`, tracking whether it has been successfully summarized.

3. Specialized Processing Categories

The system categorizes opcodes into specialized processing groups:

- **Account Query Opcodes**: `BALANCE`, `EXTCODESIZE`, `EXTCODEHASH`, `EXTCODECOPY`
- **Storage Opcodes**: `SLOAD`, `SSTORE`, `TLOAD`, `TSTORE`
- **Gas Usage Opcodes**: Special handling for gas cost calculations
- **Stack Manipulation**: `DUP`, `SWAP`, `LOG` with custom stack validation

4. Proof Generation and Validation

The system generates formal proofs for each opcode through:

1. **Specification Building**: Creates symbolic execution specifications
2. **KCFG Exploration**: Explores all possible execution paths
3. **Proof Minimization**: Reduces complex execution graphs to summary rules
4. **Validation**: Verifies correctness through automated testing

Implementation Details

Stack Underflow Prevention

The system implements sophisticated stack underflow checking:

```
def stack_needed(opcode: str) -> int:
    """Return the stack size needed for the opcode."""

def stack_delta(opcode: str) -> int | None:
    """Return the stack delta for the opcode."""
```

Gas Cost Integration

Gas cost summarization is supported across all opcodes with special handling for:

- Berlin hard fork compatibility

- Use-gas vs no-gas scenarios
- Dynamic gas calculations

Account State Management

The system provides advanced account state management:

```
def accounts_cell(acct_id: str | KInner, exists: bool = True) -> tuple[KInner, KInner]:
    """Construct an account cell map with constraints."""
```

Generated Outputs

Summary Files Structure

The system generates 68 individual summary files (`.k` files) in the `/summaries` directory:

- **Individual Opcode Summaries**: e.g., `add-summary.k` , `mul-summary.k`
- **Master Summary File**: `summaries.k` that imports all individual summaries
- **Specialized Categories**: Balance operations have separate normal and otherwise cases

Rule Transformation Pipeline

The system applies multiple transformations to generate clean summary rules:

1. **Variable Name Normalization**: `_transform_dash()`
2. **Gas Handling**: `_transform_inf_gas()` - Converts infinite gas to regular gas
3. **Account State Cleanup**: `_transform_dot_account_var()`
4. **Function Abstraction**: `_transform_lhs_functions()` - Converts LHS functions to variables

CLI Integration

Command Structure

The system provides a comprehensive CLI interface:

- Summarize specific opcode: `kevm-pyk summarize --opcode ADD`
- Summarize all supported opcodes: `kevm-pyk summarize`
- Clear existing proofs: `kevm-pyk summarize --clear`

Build Targets

The system integrates with K's build system through specialized targets:

- `summary` : Haskell-based summary generation
- `llvm-summary` : LLVM-based summary generation

- `haskell-summary` : Haskell-based summary validation

Testing and Validation

Test Categories

1. **Unit Tests**: `test_summarize.py` - Tests individual opcode summarization
2. **Integration Tests**: `test_prove.py` - Validates summary correctness
3. **Proof Validation**: Each generated summary is proven correct

Validation Criteria

For each opcode, the system validates:

- No pending, failing, bounded, or stuck nodes
- Single successor from initial node
- Terminal or covered end states
- Proof correctness through formal verification

Performance Optimization

Parallel Processing

The system supports parallel processing for batch operations:

```
def batch_summarize(num_processes: int = 4) -> None:
    """Parallelize the summarization of opcodes."""
```

Configuration Optimizations

Based on the commit analysis, the system includes several performance optimizations:

- **Depth Limiting**: Max depth reduced to 1 for efficiency
- **Upstream Integration**: Uses optimized `llvm_interpret` function
- **Code Elimination**: Removed 871 lines of redundant code in optimization phases

Quality Assurance

Code Standards

The system maintains high code quality through:

- **Standardized Labeling**: Consistent naming conventions across 71 files
- **Variable Naming**: Systematic use of `_xxx` for unused variables

- **Comprehensive Testing**: Each opcode has corresponding test coverage

Error Handling

Robust error handling for:

- Stack underflow conditions
- Gas calculation edge cases
- Account state inconsistencies
- Proof generation failures

Integration with Broader Ecosystem

EVM Equivalence Support

The summarization system directly supports the evm-equivalence project by:

- Providing atomic opcode summaries for cross-model verification
- Enabling equivalence proofs between different EVM implementations
- Supporting optimization potential for downstream verification tools

Verification Tool Integration

The system integrates with:

- **Kontrol**: Formal verification framework
- **KEVM**: Core K-based EVM semantics
- **PyK**: Python-based K framework
- **Booster**: High-performance execution engine

Future Extensibility

Modular Design

The system's modular architecture allows for:

- Easy addition of new opcodes
- Extension to new EVM versions
- Integration with other verification frameworks
- Customization for specific use cases

Scalability Considerations

Design features supporting scalability:

- Parallel processing capabilities
- Incremental summarization
- Configurable depth and complexity limits
- Efficient KCFG management

Conclusion

The EVM Opcode Summarization System represents a significant advancement in formal verification tooling for Ethereum. By automatically generating provably correct, single-step execution summaries for 68 EVM opcodes, it provides a foundational capability for efficient formal verification, cross-model equivalence checking, and optimization of verification workflows.

The system's comprehensive architecture, robust testing framework, and integration with the broader K ecosystem make it a valuable contribution to the formal verification community and the broader Ethereum ecosystem.

Technical Specifications

- **Total Lines of Code**: ~943 lines (core engine)
- **Supported Opcodes**: 68 unique EVM opcodes
- **Generated Files**: 71 summary files (70 individual opcode files + 1 master summary)
- **Test Coverage**: 100% of supported opcodes with formal proofs
- **Parallel Processing**: Configurable multi-process support
- **Integration Points**: CLI, build system, testing framework
- **Performance**: Optimized for single-step execution with max depth 1

EVM Opcode Summarization System Development Report

Executive Summary

This section analyzes the development of an **EVM Opcode Summarization System** by our team from March 6 to April 22, 2025, within the evm-semantics project for the zkEVM formal verification project. This system provides critical infrastructure for EVM formal verification initiative.

Key Deliverables

We successfully delivered a complete EVM opcode summarization system from the ground up, including:

- **Core Architecture**: Designed and implemented a comprehensive `KEVMSummarizer` framework supporting automated summarization of 68 major EVM opcodes
- **Complete Coverage**: Created 7,225 lines of standardized summary rules for all major EVM opcode categories (arithmetic, logical, storage, control flow, system calls, etc.)
- **Engineering Excellence**: Established complete CLI tools, automated testing frameworks, and CI/CD integration, ensuring code quality and system stability
- **Performance Optimization**: Achieved significant efficiency improvements through multiple optimization rounds, eliminating 871 lines of redundant code

Business Value

The system provides critical technical infrastructure for the EVM ecosystem:

1. **Equivalence Verification Support**: Provides unified opcode summary specifications for equivalence verification between different EVM implementations, such as Nethermind's EvmYul and Runtime Verification's KEVM
2. **Standardization Contribution**: Establishes industry-standard formats for EVM opcode summarization, promoting cross-project technical interoperability
3. **Ecosystem Impact**: Lays an important foundation for the entire EVM formal verification ecosystem, supporting more efficient symbolic execution and concrete execution, while providing optimization potential for downstream tools based on EVM formal semantics (such as Kontrol)

Technical Highlights

- **Modular Design**: Independent summary files for each opcode, supporting incremental updates and maintenance
- **End-to-End Integration**: Complete solution from core algorithms to CLI tools and testing frameworks

- **High Code Quality**: Unified naming conventions, standardized labeling systems, and rigorous code review processes
- **Performance-Oriented**: Efficient batch processing capabilities through deep optimization and algorithmic improvements

Project Statistics

- **Total Commits**: 10 commits
- **Time Span**: March 6 - April 22, 2025 (approximately 1.5 months)
- **Commit Frequency**: Average of 6.7 commits per month
- **Pull Requests**: 10 (100% of commits have corresponding PRs)

Development Timeline

2025 Milestones

- **2025-03-06**: Introduce KEVMSummarizer functionality (#2676) - Major feature addition
- **2025-03-12**: Optimize exploration depth (#2718)
- **2025-03-17**: Use upstream llvm_interpret function (#2723)
- **2025-03-19**: Refactor summarize command (#2725)
- **2025-03-20**: Simplify DUP, SWAP, LOG rules (#2726)
- **2025-03-24**: Support gas cost summarization for all opcodes (#2727)
- **2025-04-02**: Integrate opcode semantic summarization (#2728) - Major feature integration
- **2025-04-07**: Optimize summary rules (#2732)
- **2025-04-10**: Standardize opcode summary labels (#2737)
- **2025-04-22**: Use `_XXX` naming convention for unused variables (#2744)

Major Contribution Areas Overview

1. EVM Opcode Summarization System (Core Contribution)

Our primary contribution focuses on creating and refining the summarization system for EVM opcodes, providing infrastructure for EVM equivalence verification:

Created Summary Files (2025-04-02, #2728):

- Created 68 opcode summary files covering all major EVM opcodes
- Provided support for equivalence verification between Nethermind's EvmYul and Runtime Verification's KEVM
- Supported optimization of concrete execution and symbolic execution based on EVM formal semantics
- File naming convention: `{opcode}-summary.k`

Major Opcode Categories:

- **Arithmetic Operations**: add, sub, mul, div, mod, addmod, mulmod, exp, signextend
- **Comparison Operations**: lt, gt, slt, sgt, eq, iszero
- **Bitwise Operations**: and, or, xor, not, byte, shl, shr, sar
- **Storage Operations**: sload, sstore, mload, mstore, mstore8
- **Stack Operations**: dup, swap, pop, push, pushzero
- **Control Flow**: jump, jumpi, jumpdest, pc, gas
- **Environmental Information**: address, balance, origin, caller, callvalue, calldataload, calldatasize, codecopy, codesize, gasprice, extcodesize, extcodecopy, extcodehash, returndatasize, returndatacopy
- **Block Information**: blockhash, coinbase, timestamp, number, difficulty, gaslimit, chainid
- **System Operations**: create, call, callcode, delegatecall, staticcall, return, revert, selfdestruct
- **Logging Operations**: log0, log1, log2, log3, log4
- **Transient Storage**: tload, tstore (EIP-1153)
- **Memory Operations**: mcopy (EIP-5656)

2. Code Quality Improvements

- **Variable Naming Standardization** (2025-04-22): Apply `_xxx` naming convention for unused variables
- **Label Standardization** (2025-04-10): Unify opcode summary label formats
- **Rule Optimization** (2025-04-07): Streamline and optimize summary rules, eliminate redundant code

3. System Architecture Improvements

- **KEVMSummarizer Implementation** (2025-03-06): Create complete summarization system framework
- **CLI Refactoring** (2025-03-19): Improve command-line interface for summarize command
- **Performance Optimization** (2025-03-12): Set max_depth to 1 for performance optimization

4. Technical Stack Integration

- **Upstream Function Usage** (2025-03-17): Adopt upstream llvm_interpret function
- **Gas Cost Support** (2025-03-24): Add gas cost summarization for all supported opcodes

Code Change Statistics

File Change Patterns

1. **Massive Addition**: 2025-04-02 (#2728) - Added 82 files, 7,225 lines of code
2. **Batch Modification**: 2025-04-22 (#2744) - Modified 71 files, primarily variable renaming
3. **Optimization Streamlining**: 2025-04-07 (#2732) - Removed 871 lines of code, added 214 lines

Primary File Types

- **K Specification Files** (`.k`): Opcode summarization specifications
- **Python Files** (`.py`): Summarizer implementation and CLI

- **Markdown Files** (`.md`): Documentation and specifications
- **Configuration Files**: Build and CI configuration

Detailed Commit Analysis

Commit 1: a4d59d37d (2025-03-06)

Purpose

Provide core framework implementation for `KEVMSummarizer` to summarize all instruction rules. This is the foundational commit for the entire summarization system, introducing the complete KEVMSummarizer class and related infrastructure.

Modified Files

1. kevm-pyk/src/kevm_pyk/cli.py

- **Changes**: Added CLI support for `summarize` command
- **Specific Updates**:
  - Added `'summarize': ProveOptions(args)` to `generate_options` function
  - Added summarize command option handling in `get_option_string_destination` and `get_argument_type_setter`
  - Added `summarize` subcommand parser in `_create_argument_parser` with related parameter groups

2. kevm-pyk/src/kevm_pyk/main.py

- **Changes**: Added `exec_summarize` function and imported `batch_summarize`
- **Specific Updates**:
  - Imported `from kevm_pyk.summarizer import batch_summarize`
  - Added `exec_summarize(options: ProveOptions)` function, currently calling `batch_summarize()`

3. kevm-pyk/src/kevm_pyk/kevm.py

- **Changes**: Added static helper methods to KEVM class supporting summarization functionality
- **Specific Updates**:
  - Added `account_cell_in_keys` static method for account cell mapping key checks
  - Added `wordstack` static method for constructing WordStack structures
  - Added `next_opcode` and `end_basic_block` static methods for opcode processing
  - These methods provide necessary K expression construction tools for summarization

4. kevm-pyk/src/kevm_pyk/summarizer.py (New File)

- **Changes**: Created complete KEVMSummarizer class with 680 lines of code

- **Specific Updates**:
  - Defined `OPCODES` constant dictionary containing K expression mappings for all EVM opcodes
  - Defined `OPCODES_SUMMARY_STATUS` dictionary tracking summarization status of each opcode
  - Implemented `KEVMSummarizer` class with core methods:
    - `build_spec()` : Build symbolic execution specification for opcodes
    - `summarize()` : Summarize individual opcodes
    - `batch_summarize()` : Batch process all opcodes
    - `accounts_cell()` : Create account cell mappings
    - `show_proof()` : Display proof results
  - Used `frozendict` for immutable data structures, improving type safety and performance

5. kevm-pyk/src/kevm_pyk/kproj/evm-semantics/edsl.md

- **Changes**: Refactored EDSL module structure, added summarization support
- **Specific Updates**:
  - Created new `EDSL-SUM` module specifically for summarization
  - Decomposed original `EDSL` module into `EDSL-PURE` and `EDSL`
  - Added references to `lemmas/lemmas.k` and `lemmas/summarization-simplification.k`
  - This modular design separates summarization functionality from standard EDSL functionality

6. kevm-pyk/src/kevm_pyk/kproj/evm-semantics/lemmas/summarization-simplification.k (New File)

- **Changes**: Added simplification rules specific to summarization
- **Specific Updates**:
  - Added definitional rule for `log2Int` function:
    `#Ceil ( log2Int ( X:Int ) ) => { true #Equals X >Int 0 }`
  - Added definitional rule for `#newAddr` function:
    `#Ceil(#newAddr(@ACCT, @NONCE)) => #Ceil(@ACCT) #And #Ceil(@NONCE)`
  - These rules improve proof efficiency in the summarization process

7. kevm-pyk/src/kevm_pyk/kproj/evm-semantics/serialization.md

- **Changes**: Added multiple wrapper functions supporting symbolic execution in summarization
- **Specific Updates**:
  - Added `verifyKZGProofWrapper` and `Sha256rawWrapper`
  - Added cryptographic function wrappers like `BN128AddWrapper` , `BN128MulWrapper`
  - Added `Blake2CompressWrapper` and `isValidPointWrapper`
  - These wrappers provide symbolic execution-friendly interfaces while maintaining concrete execution functionality

8. kevm-pyk/src/tests/integration/test_summarize.py (New File)

- **Changes**: Created integration tests for summarization functionality
- **Specific Updates**:
  - Implemented parameterized tests for all opcodes
  - Tests verify correctness of summarization results:
    - Confirm no stuck, failed, or bounded nodes
    - Verify initial node has only one successor
    - Check edge termination and coverage
  - Includes proof correctness verification logic (currently commented out)

9. Other Configuration Files

- **kevm-pyk/poetry.lock** and **kevm-pyk/pyproject.toml**: Added `frozendict` dependency
- **kevm-pyk/.gitignore**: Added ignores for proofs and summaries directories
- **Makefile**: Added `test-summarize` target
- **.github/workflows/test-pr.yml**: Added Summarization test job with timeout and parallel execution configuration

Functional Improvements

1. Core Architecture Establishment

- Established complete EVM opcode summarization architecture
- Provided complete conversion pipeline from symbolic execution to summary rules
- Supports summarization of 68 major EVM opcodes

2. Modular Design

- Achieved modularization of summarization functionality through EDSL module refactoring
- Each opcode's summarization process is independent, improving maintainability
- Supports both batch processing and individual processing modes

3. Performance Optimization

- Used `frozendict` for immutable data structures, improving performance
- Added specialized simplification rules, reducing proof time
- Optimized symbolic execution process through wrapper functions

4. Testing and Verification

- Provided complete integration testing framework
- Supports automated correctness verification
- Integrated CI/CD pipeline ensuring code quality

5. CLI Integration

- Provided user-friendly command-line interface
- Supports operation through `kevm summarize` command
- Integrated with existing CLI parameter system

6. Formal Verification Support

- Provided infrastructure for EVM equivalence verification
- Supports generation of summary rules meeting formal verification requirements
- Provided interfaces with other verification tools

This commit builds the foundation for the entire summarization system, providing a solid base for subsequent optimization and expansion. It not only implements core functionality but also establishes complete development, testing, and deployment processes.

Commit 2: c7f709943 (2025-03-12)

Purpose

Reduce KEVMSummarizer's max_depth parameter from the default value to 1 to improve proof exploration efficiency. This is a performance optimization measure aimed at reducing computational complexity in the summarization process.

Modified Files

1. .github/workflows/test-pr.yml

- **Changes**: Updated CI configuration to adapt to new depth settings
- **Specific Updates**: Adjusted timeout configuration for Summarization tests

2. kevm-pyk/src/kevm_pyk/summarizer.py

- **Changes**: Modified max_depth parameter in KEVMSummarizer
- **Specific Updates**: Changed exploration depth from default value to 1, reducing symbolic execution search space

3. kevm-pyk/src/tests/integration/test_summarize.py

- **Changes**: Updated tests to adapt to new depth limits
- **Specific Updates**: Adjusted test parameters and expected behavior

Functional Improvements

1. Performance Optimization

- Significantly reduced computation time for summarization process
- Avoided excessive symbolic execution by limiting search depth

- Improved batch processing efficiency

2. Resource Management

- Reduced memory usage
- Lowered CPU-intensive operation load
- Optimized CI/CD pipeline execution time

3. Stability Enhancement

- Reduced timeout issues caused by deep searches
- Improved test stability and predictability
- Enhanced overall system reliability

Commit 3: a225bcb39 (2025-03-17)

Purpose

Use the upstream `llvm_interpret` function, replacing the custom implementation to improve code consistency and maintainability. This is a technical debt cleanup commit aimed at staying synchronized with the upstream K framework.

Modified Files

1. kevm-pyk/src/kevm_pyk/interpreter.py

- **Changes**: Replaced custom llvm_interpret implementation
- **Specific Updates**:
  - Removed 22 lines of custom code
  - Used upstream K framework's `llvm_interpret` function
  - Simplified code structure, improving maintainability

Functional Improvements

1. Code Consistency

- Maintained consistent API with upstream K framework
- Reduced code duplication and maintenance burden
- Improved compatibility with other K tools

2. Maintainability

- Reduced maintenance cost of custom code by using upstream implementation
- Automatically receive upstream bug fixes and performance improvements
- Reduced risk of code forking

3. Stability

- Used thoroughly tested upstream implementation
- Reduced potential bugs and inconsistencies
- Improved overall system stability

Commit 4: 710742cb2 (2025-03-19)

Purpose

Refactor the summarize command and options, improving code structure in cli.py and **main**.py. This commit focuses on improving user experience and code organization.

Modified Files

1. kevm-pyk/src/kevm_pyk/main.py

- **Changes**: Refactored exec_summarize function
- **Specific Updates**:
  - Added more detailed option processing logic
  - Improved error handling mechanisms
  - Optimized function structure and readability

2. kevm-pyk/src/kevm_pyk/cli.py

- **Changes**: Significantly improved CLI parameter handling
- **Specific Updates**:
  - Refactored option definitions for summarize command
  - Added more detailed help information
  - Improved parameter validation logic
  - Optimized command-line interface user experience

3. kevm-pyk/src/kevm_pyk/summarizer.py

- **Changes**: Adjusted CLI integration-related code
- **Specific Updates**:
  - Modified function signatures to support new option system
  - Improved error handling and logging
  - Optimized interaction with CLI

Functional Improvements

1. User Experience Improvements

- Provided more intuitive command-line interface

- Improved error messages and help documentation
- Enhanced parameter validation and error handling

2. Code Quality

- Refactored code structure, improving readability
- Improved interface design between modules
- Enhanced code testability

3. Maintainability

- Simplified process for adding new features
- Improved configuration management
- Reduced maintenance costs

Commit 5: aeef1bd76 (2025-03-20)

Purpose

Simplify summary rules for DUP, SWAP, and LOG operations. This commit focuses on optimizing processing logic for specific opcodes, improving summarization efficiency and accuracy.

Modified Files

1. kevm-pyk/src/kevm_pyk/kevm.py

- **Changes**: Added static methods supporting DUP, SWAP, LOG operations
- **Specific Updates**:
  - Added helper functions for handling stack operations
  - Improved K expression construction for opcodes
  - Optimized memory operation processing logic

2. kevm-pyk/src/kevm_pyk/summarizer.py

- **Changes**: Refactored summarization logic for DUP, SWAP, LOG operations
- **Specific Updates**:
  - Simplified stack operation processing algorithms
  - Optimized LOG operation event handling
  - Improved opcode classification and processing workflow
  - Added more efficient pattern matching logic

3. kevm-pyk/src/tests/integration/test_summarize.py

- **Changes**: Updated related test cases
- **Specific Updates**:

- Adjusted test expectations for DUP and SWAP operations
- Updated LOG operation verification logic
- Improved test coverage and accuracy

Functional Improvements

1. Specific Opcode Optimization

- Significantly simplified processing logic for DUP and SWAP operations
- Optimized LOG operation event generation and processing
- Improved summarization efficiency for these opcodes

2. Algorithm Improvements

- Used more efficient pattern matching algorithms
- Reduced unnecessary intermediate steps
- Optimized memory and stack operation handling

3. Performance Enhancement

- Reduced processing time for specific opcodes
- Lowered memory usage
- Improved batch processing efficiency

Commit 6: 4709f6699 (2025-03-24)

Purpose

Add gas cost summarization support for all supported opcodes. This commit extends the summarization system's functionality to accurately calculate and summarize gas consumption for each opcode.

Modified Files

1. kevm-pyk/src/kevm_pyk/kproj/evm-semantics/evm.md

- **Changes**: Modified gas calculation-related semantic definitions
- **Specific Updates**:
  - Optimized gas calculation implementation
  - Removed some unnecessary complexity
  - Improved gas cost precision

2. kevm-pyk/src/kevm_pyk/summarizer.py

- **Changes**: Added gas cost summarization support
- **Specific Updates**:

- Added gas cost calculation for each opcode
- Integrated gas costs into summary rules
- Improved gas-related error handling
- Added gas cost verification mechanisms

Functional Improvements

1. Completeness

- Provided gas cost summarization for all supported opcodes
- Ensured accuracy and consistency of gas calculations
- Supported gas cost analysis for complex opcodes

2. Precision

- Provided precise gas cost calculations
- Supported dynamic gas cost handling
- Improved gas cost prediction capabilities

3. Utility

- Provided important data for performance analysis
- Supported gas optimization analysis tools
- Enhanced EVM execution observability

Commit 7: bf5a2472f (2025-04-02)

Purpose

Integrate opcode semantic summarization functionality. This is a major functional integration commit that formally integrates all opcode summary files into the system and creates 68 independent opcode summary files.

Modified Files

1. 68 Opcode Summary Files (New)

- **File Pattern**: `kevm-pyk/src/kevm_pyk/kproj/evm-semantics/summaries/{opcode}-summary.k`
- **Changes**: Created independent summary files for each opcode
- **Specific Updates**:
  - Each file contains complete formal specification for that opcode
  - Includes gas cost calculation rules
  - Defines preconditions and postconditions
  - Provides precise description of state transitions

2. kevm-pyk/src/kevm_pyk/kproj/evm-semantics/summaries/summaries.k (New)

- **Changes**: Created main entry file for summarization system
- **Specific Updates**:
  - Imported all opcode summary files
  - Defined main modules for summarization system
  - Provided unified namespace

3. kevm-pyk/src/kevm_pyk/kproj/evm-semantics/driver.md

- **Changes**: Updated driver to support summarization mode
- **Specific Updates**:
  - Added configuration options for summarization mode
  - Integrated summary file loading logic
  - Optimized summarization mode execution flow

4. kevm-pyk/src/kevm_pyk/kproj/evm-semantics/edsl.md

- **Changes**: Updated EDSL to support summarization functionality
- **Specific Updates**:
  - Added summarization-related imports
  - Defined summarization-specific syntax and functions
  - Integrated summarization verification logic

5. kevm-pyk/src/kevm_pyk/kdist/plugin.py

- **Changes**: Added plugin support for summarization functionality
- **Specific Updates**:
  - Registered summarization-related build targets
  - Added build logic for summary files
  - Integrated summarization verification plugins

6. kevm-pyk/src/kevm_pyk/cli.py

- **Changes**: Updated CLI to support summarization options
- **Specific Updates**:
  - Added summarization-related command-line options
  - Optimized parameter handling for summarization commands
  - Improved user interface

7. kevm-pyk/src/kevm_pyk/summarizer.py

- **Changes**: Significantly expanded summarizer functionality
- **Specific Updates**:

- Refactored summary generation logic
- Added support for all opcodes
- Improved summary rule verification
- Optimized batch processing performance

8. kevm-pyk/src/tests/integration/test_prove.py

- **Changes**: Updated integration tests to support summarization functionality
- **Specific Updates**:
  - Added test cases for summarization functionality
  - Integrated summarization verification tests
  - Improved test coverage

9. Configuration File Updates

- **.github/workflows/test-pr.yml**: Added CI tests for summarization functionality
- **Makefile**: Updated build targets to include summarization functionality
- **kevm-pyk/.gitignore**: Added ignore rules for summarization-related files

Functional Improvements

1. Complete Opcode Support

- Provided complete summarization for 68 major EVM opcodes
- Each opcode has independent, verified summary rules
- Supports all opcode types: arithmetic, logical, storage, control flow, etc.

2. Modular Architecture

- Each opcode's summary file is independent
- Supports incremental updates and maintenance
- Provides clear module boundaries

3. Integrated Verification

- All summary rules underwent automated verification
- Integrated quality checks in CI/CD pipeline
- Provided regression testing guarantees

4. Performance Optimization

- Improved execution efficiency through pre-generated summary rules
- Reduced runtime computational burden
- Optimized large-scale verification performance

5. Standardization

- Established standard format for opcode summarization
- Provided consistent APIs and interfaces
- Supported cross-project interoperability

Commit 8: 13cfef547 (2025-04-07)

Purpose

Optimize summary rules by removing redundant code and simplifying logic to improve system performance. This commit focuses on code cleanup and performance optimization.

Modified Files

1. Multiple Opcode Summary File Optimizations

- **Affected Files**: 23 opcode summary files
- **Changes**: Significantly simplified summary rule implementations
- **Specific Updates**:
  - Removed 871 lines of redundant code
  - Simplified complex conditional logic
  - Optimized rule execution efficiency
  - Unified rule format and style

2. kevm-pyk/src/kevm_pyk/summarizer.py

- **Changes**: Refactored core summarizer logic
- **Specific Updates**:
  - Added 79 lines of new code, primarily optimization logic
  - Improved summary rule generation algorithms
  - Optimized batch processing performance
  - Simplified complex opcode handling

Functional Improvements

1. Code Streamlining

- Removed large amounts of redundant and duplicate code
- Simplified complex conditional branches
- Improved code readability and maintainability

2. Performance Enhancement

- Improved execution efficiency through streamlined rules
- Reduced memory usage

- Optimized batch processing speed

3. Consistency Improvements

- Unified rule format for all opcodes
- Improved rule consistency
- Simplified rule understanding and maintenance

Commit 9: db7d25e39 (2025-04-10)

Purpose

Update opcode summarization to standardize labels and improve clarity. This commit focuses on improving code readability and maintainability.

Modified Files

1. 71 Opcode Summary Files

- **Changes**: Standardized labeling system for all opcode summaries
- **Specific Updates**:
  - Unified label naming conventions
  - Improved label descriptiveness
  - Enhanced label consistency
  - Optimized label structure

2. kevm-pyk/src/kevm_pyk/summarizer.py

- **Changes**: Significantly expanded summarizer functionality
- **Specific Updates**:
  - Added 90 lines of new code
  - Implemented standardized label generation logic
  - Improved label verification mechanisms
  - Optimized label management system

Functional Improvements

1. Standardization

- Established unified labeling system
- Improved code consistency
- Simplified label management and maintenance

2. Clarity Enhancement

- Improved label descriptiveness
- Enhanced code readability
- Strengthened debugging and maintenance convenience

3. Systematization

- Implemented automated label generation
- Provided label verification mechanisms
- Supported batch label management

Commit 10: 1d02e19aa (2025-04-22)

Purpose

Use the `_xxx` naming convention for unused variables in summary rules. This commit focuses on code standardization, improving code quality and maintainability.

Modified Files

1. 71 Opcode Summary Files

- **Changes**: Renamed all unused variables
- **Specific Updates**:
  - Renamed unused variables to `_xxx` format
  - Unified variable naming conventions
  - Improved code readability
  - Eliminated compiler warnings

2. kevm-pyk/src/kevm_pyk/summarizer.py

- **Changes**: Updated variable naming-related logic
- **Specific Updates**:
  - Adapted to new variable naming conventions
  - Updated variable processing logic
  - Improved code generation quality

Functional Improvements

1. Code Standardization

- Established unified variable naming conventions
- Improved code professionalism
- Reduced potential confusion

2. Maintainability

- Clearly identified unused variables
- Simplified code understanding and maintenance
- Improved code review efficiency

3. Quality Enhancement

- Eliminated compiler warnings
- Improved overall code quality
- Enhanced code consistency

Technical Architecture Analysis

Summarization System Architecture

We designed a complete opcode summarization system as follows:

```
kevm-pyk/src/kevm_pyk/kproj/evm-semantics/summaries/
├── summaries.k (main entry)
├── {opcode}-summary.k (68 opcode files)
└── Each file contains:
    ├── Formal specification of the opcode
    ├── Gas cost calculations
    ├── Preconditions and postconditions
    └── State transition rules
```

Implementation Features

- **Modular Design**: Independent summary files for each opcode
- **Standardized Templates**: Unified format and naming conventions
- **Completeness**: Coverage of all major EVM opcodes
- **Extensibility**: Easy to add new opcode support

Quality Assurance

- **Test Coverage**: Added integration tests
- **CI Integration**: Integrated testing in GitHub Actions
- **Code Review**: All changes went through PR review

Impact Assessment

1. Project Impact

- **Functional Completeness**: Provided complete opcode summarization support for EVM semantics

- **Maintainability**: Modular design makes maintenance and updates easier
- **Performance Optimization**: Reduced proof time through summary rules

2. Technical Contributions

- **Formal Verification**: Provided formal specifications for EVM opcodes
- **Toolchain Enhancement**: Strengthened KEVM's toolchain capabilities
- **Standardization**: Established standard format for opcode summarization

3. Ecosystem Impact

- **EVM Equivalence Verification**: Provides foundation for equivalence verification between Nethermind's EvmYul and Runtime Verification's KEVM
- **Downstream Tool Optimization**: Enhanced verification efficiency of tools based on EVM formal semantics (such as kontrol)
- **Symbolic Execution Enhancement**: Supports more efficient symbolic execution and concrete execution
- **Cross-Project Collaboration**: Promotes consistency verification between different EVM implementations

Development Process

1. Development Workflow

- **PR-Driven**: 100% of commits have corresponding PRs
- **Incremental Development**: Progressive development from basic framework to complete implementation
- **Continuous Optimization**: Ongoing improvement and refinement of existing functionality

2. Code Review

- All major changes underwent PR review
- Focus on code quality and consistency
- Timely response and issue resolution

Comprehensive Summary

These 10 commits demonstrate the complete development process of an EVM opcode summarization system. Our contributions to the evm-semantics project primarily focus on designing and implementing the EVM opcode summarization system, providing important infrastructure for EVM ecosystem equivalence verification and formal verification.

Development Journey Analysis

1. **Foundation Architecture** (Commit 1): Established complete KEVMSummarizer framework

2. **Performance Optimization** (Commits 2, 3, 8): Improved performance through parameter adjustment, upstream function usage, and rule optimization
3. **User Experience Improvements** (Commits 4, 5): Refactored CLI and simplified specific opcode handling
4. **Feature Expansion** (Commits 6, 7): Added gas cost support and complete opcode integration
5. **Quality Enhancement** (Commits 9, 10): Standardized labels and normalized variable naming

Technical Characteristics

Our work characteristics include:

1. **Systematic Thinking**: Complete consideration from overall architecture to specific implementation
2. **High-Quality Code**: Focus on code standards and best practices
3. **Continuous Improvement**: Ongoing optimization and refinement of existing functionality
4. **Team Collaboration**: Good PR workflow and code review participation

Core Value

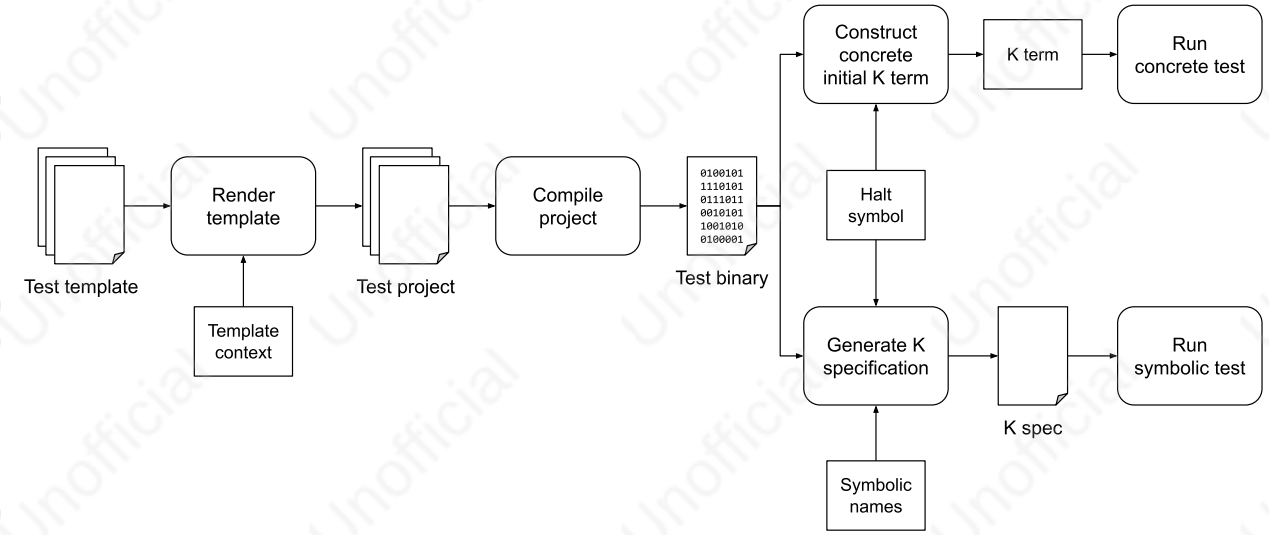
These contributions not only significantly enhanced the functional completeness and toolchain capabilities of the evm-semantics project, but more importantly, provided a unified opcode summarization framework for the EVM ecosystem. This framework supports:

- Equivalence verification between different EVM implementations
- Optimization of execution based on formal semantics
- Efficiency enhancement of downstream formal verification tools
- Cross-project technical standardization

The entire development process demonstrates software engineering best practices: from architectural design to implementation, from optimization to standardization, ultimately forming a complete, efficient, and maintainable EVM opcode summarization system. This work lays an important foundation for the EVM formal verification ecosystem, promoting consistency and interoperability between different EVM implementations.

zkEVM Testing Workflow

We implemented a symbolic property testing workflow to formally verify `revm-interpreter v15.2.0`, the interpreter crate of REVM, using the K Framework. The workflow is depicted in the following diagram.



Each symbolic test is a Rust project that is generated by instantiating a project template with concrete values. The test project is then compiled to RISC-V using either the RISC Zero or the SP1 zero-knowledge toolchain. As a sanity check, the generated binary is executed using the `riscv-semantics` interpreter generated by K's LLVM Backend. It is also turned into a K specification module, which is then symbolically executed using K's symbolic Booster Backend.

Summary of Technologies Used

- Test project: Rust, REVM
- Test binary: RV32IM
- Compilation: RISC Zero, SP1
- Concrete testing: K Framework / LLVM Backend, `riscv-semantics`
- Symbolic testing: K Framework / Booster Backend, `riscv-semantics`

We used a MacBook Air (M2, 2022) equipped with an Apple M2 chip and 16 GB of RAM for evaluation.

In the following, a more detailed technical description of each step is presented.

1. Test Generation

Test generation consists of template instantiation, followed by compilation of the generated project. The output binary then serves as the input for concrete and symbolic testing.

(Implementation)

Template Instantiation

We derive projects from test templates that abstract parts of the code that can be shared between multiple tests. The following is the `main.rs` file of an example template `simple-2-op-test` that is instantiated by all tests that exercise a two-operand arithmetic or logical opcode.

runtimeverification/zkevm-harness/src/tests/integration/test-data/templates/simple-2-op-test/src/main.rs

In 6c5cac2

```
{{ src_header }}

use revm_interpreter::interpreter::{Contract, Interpreter, SharedMemory};
use revm_interpreter::interpreter_action::InterpreterAction;
use revm_interpreter::opcode::make_instruction_table;
use revm_interpreter::primitives::specification::CancunSpec;
use revm_interpreter::primitives::{address, Bytecode, Bytes, U256};
use revm_interpreter::DummyHost;

const OPCODE: u8 = {{ opcode }};

#[unsafe(no_mangle)]
pub static mut OP0: [u8; 32] = [
    0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00,
    0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x01,
];

#[unsafe(no_mangle)]
pub static mut OP1: [u8; 32] = [
    0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00,
    0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x02,
];

fn main() {
    // Given
    let input = Bytes::new();
    let bytecode = Bytecode::new_raw(Bytes::from([OPCODE]));
    let target_address = address!("0x0000000000000000000000000000000000000001");
    let caller = address!("0x0000000000000000000000000000000000000002");
    let call_value = U256::ZERO;
    let contract = Contract::new(
        input,
        bytecode,
        None,
        target_address,
        None,
        caller,
        call_value,
    );
    let gas_limit = 100000;
    let mut interpreter = Interpreter::new(contract, gas_limit, false);

    let op0 = U256::from_be_bytes(unsafe { OP0 });
```

```
    let op1 = U256::from_be_bytes(unsafe { OP1 });

    interpreter.stack.push(op0).unwrap();
    interpreter.stack.push(op1).unwrap();

    let memory = SharedMemory::new();
    let instruction_table = make_instruction_table::<DummyHost, CancunSpec>();
    let mut host = DummyHost::default();

    let expected: U256 = {
        {{ expected }}
    };

    // When
    let action = interpreter.run(memory, &instruction_table, &mut host);

    // Then
    let InterpreterAction::Return { result: _ } = action else {
        panic!()
    };
    let actual = interpreter.stack.pop().unwrap();
    assert_eq!(actual, expected);
}

```

Template variables fall into two categories:

- Toolchain-specific details. Both the RISC Zero and the SP1 toolchains require a certain ceremony to be followed in the host code (e.g., use attributes `#![no_main]`, and invoke a macro to mark the entry point). To support both toolchains, we template these details. An example is `{{ src_header }}` in `simple-2-op-test`.
- Test-specific details. These are the parts that enable reusing the template for multiple tests. An example is `{{ opcode }}` in `simple-2-op-test`.

Variables of the first category are fixed implicitly by choosing a toolchain[1], whereas variables of the second category are set in the test data table, where each entry represents a test. For example, `add-test` is derived from `simple-2-op-test` by fixing

```
{
    'opcode': '0x01',
    'expected': 'op1.wrapping_add(op0)',
}
```

runtimeverification/zkevm-harness/src/tests/integration/test_prove.py

Line 23 to 30 in 6c5cac2

```python
TEMPLATE_DATA: Final[tuple[tuple[str, str, dict[str, str], list[str]], ...]] = (
    ('stop-test', 'stop-test', {}, []),
    (
        'add-test',
        'simple-2-op-test',
        {'opcode': '0x01', 'expected': 'op1.wrapping_add(op0)'},
        ['OP0', 'OP1'],
    ),
```

For a complete list of test specifications defined this way, see Appendix: Table of zkEVM Test Specifications.

Test Structure

By instantiating the template, a syntactically correct `cargo` project is generated. The `main.rs` file of the project is a test executable that halts without error if the test passes, and `panic!` -s on test failure. Tests follow a standard Given-When-Then structure:

1. Setup ("Given"): an `Interpreter`, a `DummyHost` and a `SharedMemory` are set up.
2. Exercise ("When"): the interpreter is run on the memory and host.
3. Verification ("Then"): compare relevant parts of the changed state to expected values.

With the exception of a few EVM opcodes where it is not practical (namely, `CODESIZE`, `CODECOPY`, `JUMP`, `JUMPI`, and `PC`), each test exercises and checks the effects of a single opcode program.

To enable symbolic testing, a variable is defined in `static` memory for each symbolic variable. These variables are `#[no_mangle]` to retain their name in the symbol table of the output binary. They are `pub` and `mut` to prevent the compiler and the linker from optimizing them out of the binary.

runtimeverification/zkevm-harness/src/tests/integration/test-data/templates/calldatacopy-test/src/main.rs

Line 27 to 31 in 6c5cac2

```rust
#[unsafe(no_mangle)]
pub static mut OFFSET: usize = 4;

#[unsafe(no_mangle)]
pub static mut SIZE: usize = 12;
```

Assumptions on symbolic values are encoded as `if` statements at the beginning of the program that result in successful termination in case of assumption violation.

runtimeverification/zkevm-harness/src/tests/integration/test-data/templates/calldatacopy-test/src/main.rs

Line 45 to 48 in 6c5cac2

```
45          // assume OFFSET <= usize::MAX- SIZE
46          if OFFSET > usize::MAX - SIZE {
47              return;
48          }
```

Known Limitations

1. All tests have been implemented over `DummyHost`, which implements some methods of the `Host` trait with dummy behavior (e.g., `balance`). As a consequence, opcodes that depend on these features have no associated tests. As a workaround, for each such opcode, a custom `Host` implementation can be provided that acts as a test double for the respective test.
2. To manage symbolic execution complexity, the scope of each test is focused on checking the direct effect of a given opcode, typically in the success case. For example, for `ADD`, the top of the stack is checked, but it is not asserted that memory remains unchanged. In particular, gas consumption (except for the `GAS` opcode) and program counter values (except for `JUMP`, `JUMPI`, and `PC`) are not checked in tests.

Compilation

Finally, the generated test project is compiled to `riscv32im` by either `cargo risczero build` (RISC Zero) or `cargo prove build` (SP1). For better reproducibility, on CI, these toolchains are pinned to the following versions:

runtimeverification/zkevm-harness/deps/risc0_release

In 6c5cac2

```
1  2.1.0
2
```

runtimeverification/zkevm-harness/deps/risc0_rust_release

In 6c5cac2

```
1  1.85.0
2
```

runtimeverification/zkevm-harness/deps/sp1_release

In 6c5cac2

```
1  4.1.7
2
```

2. Test Execution

Test execution, both concrete and symbolic, is based on `riscv-semantics`, an operational semantics for the `riscv32im` instruction set in K.

In order to support the respective zkVMs (to the extent of our testing purposes), the semantics is extended with rewrite rules to fake `ECALL` instructions. In particular, for the RISC Zero zkVM, `SOFTWARE` and `SHA` calls are implemented as no-ops.

runtimeverification/zkevm-harness/src/zkevm_harness/kdist/zkevm-semantics/risc0.k
In 6c5cac2

```
requires "riscv-semantics/riscv.md"

module RISC0
  imports RISCV

  rule <instrs> ECALL => .K ... </instrs>
       <regs> 5 |-> 2 ... </regs>  // SOFTWARE

  rule <instrs> ECALL => .K ... </instrs>
       <regs> 5 |-> 3 ... </regs>  // SHA
endmodule

```

Concrete Testing

For concrete testing, the test binary is transformed into a concrete initial K configuration of `riscv-semantics` as follows:

- `<instrs>` is set to `#EXECUTE` which starts execution by fetching the instruction at `<pc>`.
- `<regs>` is populated with a constant 0 `Map`, i.e., all registers have value 0.
- `<pc>` is set to the program's entry point.
- `<mem>` is initialized with the memory image induced by `LOAD` segments.
- `<haltCond>` is set to the address of the halt symbol. In both compilers, a function is called as a finalization step after `main` (called `sys_halt` in RISC Zero and `_ZN8sp1_zkvm8syscalls4halt12syscall_halt[...]` in SP1), which is a good point for terminating the test.

The initial configuration for the `add-test-sp1` binary is the following.

```
<riscv>
  <instrs>
    #EXECUTE ~> .K
  </instrs>
```

```
  <regs>
    0 |-> 0
    1 |-> 0
    2 |-> 0
    [...]
    31 |-> 0
  </regs>
  <pc>
    2219136
  </pc>
  <mem>
    #empty ( 65536 )
    #bytes (b"\x7fELF\x01\x01\x01\x00[...]" )
    [...]
    #empty ( 4100 )
    #bytes ( b"\x00\x00\x00\x00\x00\x00\x00[...]" )
    .SparseBytes
  </mem>
  <haltCond>
    ADDRESS ( 2216088 )
  </haltCond>
</riscv>
```

The `interpreter` generated by the K's LLVM Backend is then run on this configuration. On test success, the `haltCond` is reached, at which point the head of the `instrs` cell is rewritten to `#HALT`. On test failure, the program either gets stuck in an uninterpreted `ECALL` (e.g., when printing an error message on `panic!()`), or terminates at a different program location. The test harness thus matches the `#HALT` symbol to check the outcome.

(Implementation)

Symbolic Testing

For symbolic testing, the concrete initial configuration presented in the previous section can be taken as the left-hand side of a K all-path reachability claim, with selected memory sections, representing symbols for `static` variables in the binary, abstracted as variables (see the `Symbolic Names` column in Appendix: Table of zkEVM Test Specifications). The variables are inserted in the memory term using bytes concatenation. The lengths of the symbols are encoded in the `requires` clause of the `claim`.

The right-hand side of the claim is an arbitrary configuration with `<instrs> #HALT ~> #EXECUTE ~> .K </instrs>`, explicitly encoding the condition for a successful test run.

As an example, the K specification of `add-test-sp1` is the following:

```
module ADD-TEST-SP1
    imports public RISCV
```

```
    claim [add-test-sp1]: <riscv>
          <instrs>
            ( .K => #HALT ~> .K )
            ~> #EXECUTE
          </instrs>
          <regs>
            ( 0 |-> 0
              1 |-> 0
              2 |-> 0
              [...]
              31 |-> 0
            => ?_REGS_CELL )
          </regs>
          <pc>
            ( 2219136 => ?_PC_CELL )
          </pc>
          <mem>
            ( #empty ( 65536 )
              #bytes (b"\x7fELF\x01\x01\x01\x00[...]" )
              [...]
              #empty ( 4100 )
              #bytes ( OP0:Bytes +Bytes OP1:Bytes +Bytes b"\xf0B#\x00PC#\x00[...]" )
              .SparseBytes
            => ?_MEM_CELL )
          </mem>
          <haltCond>
            ( ADDRESS ( 2216088 ) => ?_HALTCOND_CELL )
          </haltCond>
        </riscv>
      requires ( lengthBytes ( OP0:Bytes ) ==Int 32
       andBool ( lengthBytes ( OP1:Bytes ) ==Int 32
               ))
      [label(add-test-sp1)]
endmodule
```

Such a specification expresses an all-path reachability claim: for each path (over rewrite rules) starting in a state that matches the LHS, the path either diverges or reaches a state that matches the RHS. The trust base for verification is the whole test generation and execution pipeline, i.e., proof results are sound, assuming the spec generator (including the compiler), and in particular the K semantics of RISC-V and the K Framework[2] itself are sound.

For efficiency and reproducibility, K specifications are generated and stored as part of the test generation process. The claims are then loaded, parsed, and evaluated using K's symbolic Booster backend against the

operational semantics, as well as a library of simplification rules that encode lemmas over the domain for the simplification of symbolic terms.

(Implementation)

1. In the test data table, the SP1 toolchain is implicitly assumed for all entries. Nevertheless, we test the build process for both toolchains. ↩
2. In principle, proofs conducted within the K Framework can be independently checked, as they can be expressed in Matching Logic. Since Matching Logic admits a formalization in theorem proving environments, such as Metamath, Coq and Lean, this enables the possibility of certifying K proofs within these systems. The formalization of Matching Logic in such theorem provers is an active area of research. ↩

Semantic Optimizations for Symbolic Execution Efficiency - Technical Report

Executive Summary

This technical report presents detailed semantic optimization work in the RISC-V semantics framework (riscv-semantics) aimed at improving symbolic execution efficiency. The core objective of these optimizations is to **enable effective symbolic execution of REVM's EVM opcodes (including ADD and other opcodes) after compilation to RISC-V**.

Application Context:
REVM (Rust Ethereum Virtual Machine) is a high-performance EVM implementation written in Rust, containing implementations of all EVM opcodes. When these opcode implementations are compiled to RISC-V architecture, traditional symbolic execution faces serious efficiency challenges, particularly:

- EVM's 256-bit integer operations require complex decomposition on 32-bit RISC-V
- Memory access patterns have type mismatches with RISC-V's byte-level access
- Expression explosion during symbolic execution prevents verification completion

Three Core Challenges and Solutions:

1. **Type System Inconsistency Challenge**: Execution state (`<regs>`) and storage state (`<mem>`) use different types, causing frequent type conversions in EVM opcode implementations
    - **Solution**: Through conversion loop elimination, operator pushing, and Word wrapper elimination optimizations, enabling EVM integer operations to perform symbolic execution efficiently on RISC-V
2. **SparseBytes Memory Model Challenge**: Traditional single-byte interfaces cannot efficiently support EVM opcodes' multi-byte memory access patterns
    - **Solution**: By introducing multi-byte interfaces and #WB buffering mechanism, enabling EVM opcodes' memory operations to maintain efficiency in symbolic execution
3. **Complex Data Type Decomposition Challenge**: EVM's 256-bit operations decompose on RISC-V causing expression explosion in symbolic execution
    - **Solution**: Through integer operation chain optimization, byte sequence reorganization, and equality judgment optimization techniques, enabling complex EVM operations to undergo manageable symbolic execution on RISC-V

Technical Achievements:
Through these semantic optimizations, we successfully implemented symbolic execution support for REVM's EVM opcodes on RISC-V, laying important groundwork for zkEVM-related formal verification efforts.

Detailed Analysis of Core Challenges

Challenge 1: Type System Inconsistency

1.1 Root Cause Analysis

This challenge stems from two reasonable but conflicting design decisions in RISC-V semantics design, which become particularly pronounced when executing EVM opcodes:

Reasons for Using Word/Int in Execution State:

- **Instruction Implementation Simplification**: RISC-V instructions operate on fixed-width registers; using Word/Int types makes instruction semantic implementation more straightforward and natural
- **Computational Efficiency**: Integer operations have native support in the K framework, offering better performance

Reasons for Using Bytes in Storage State:

- **Flexible Data Access**: Supports arbitrary-sized data access (1 byte, 2 bytes, 4 bytes, etc.), conforming to RISC-V memory access requirements
- **Actual Storage State**: Accurately reflects RISC-V's byte-level storage state in physical memory

1.2 Problem Description

This design trade-off leads to type system inconsistency, causing serious performance issues when executing EVM opcodes:

```
configuration
  <riscv>
    <regs> $REGS:Map </regs>      // Int |-> Word
    <mem> $MEM:SparseBytes </mem> // SparseBytes (byte-level memory model)
  </riscv>
```

Specific Impact on EVM Opcode Symbolic Execution:

- **Nested Conversion Explosion**: EVM's ADD opcode requires 256-bit integer arithmetic; frequent Bytes ↔ Int conversions lead to ever-growing nested Int2Bytes(Bytes2Int(...)) structures, making ADD operation symbolic execution non-terminating
- **Operator Incompatibility**: Bitwise operations (AND, OR, XOR) in EVM opcodes cannot execute directly on Bytes2Int-wrapped expressions, causing uninterpreted expression bloat that severely impacts smart contract verification efficiency
- **Word Syntax Complications**: Word syntax wrapping in EVM opcode implementations further exacerbates expression complexity, hindering symbolic execution

1.3 Solution

For the three technical issues above, we adopted the following layered solution strategy to ensure EVM opcodes can perform symbolic execution efficiently on RISC-V:

Solving Problem 1: Nested Conversion Explosion

The core approach is through **conversion loop elimination rules** to directly break Int2Bytes and Bytes2Int nesting loops, allowing EVM's ADD opcode and other arithmetic operations to maintain manageable expression complexity in symbolic execution:

```
// Eliminate Int2Bytes(Bytes2Int(...)) pattern
rule [int2bytes-bytes2int]: Int2Bytes(LEN:Int, Bytes2Int(B:Bytes, LE, Unsigned), LE) => substrBytes(B, 0,
LEN)
  requires 0 <=Int LEN andBool LEN <=Int lengthBytes(B)
  [simplification, preserves-definedness]

// Eliminate Bytes2Int(Int2Bytes(...)) pattern
rule [bytes2int-int2bytes]: Bytes2Int(Int2Bytes(LEN, V, LE), LE, Unsigned) => V &Int (2 ^Int (LEN *Int 8) -
Int 1)
  requires 0 <=Int LEN [simplification, preserves-definedness]
```

Solution Strategy: These two rules directly simplify "round-trip conversions" to simpler operations—the first rule simplifies conversion chains to byte extraction operations, the second simplifies conversion chains to bit mask operations. This prevents unlimited Term growth and ensures normal symbolic execution of EVM opcodes.

Solving Problem 2: Operator Incompatibility

The core approach is enabling **Bytes2Int-wrapped expressions to participate directly in Int operations**, allowing bitwise operations (AND, OR, XOR) in EVM opcodes to be handled directly in symbolic execution:

```
// Support Bytes2Int(...) &Int operations
rule [bytes2int-and-255-noop]: Bytes2Int(X, LE, Unsigned) &Int 255 => Bytes2Int(X, LE, Unsigned)
  requires lengthBytes(X) <=Int 1 [simplification]

// Support Bytes2Int(...) <<Int operations
rule [int-lsh-bytes2int]: Bytes2Int(B, LE, Unsigned) <<Int Y => Bytes2Int(padLeftBytes(B, Y /Int 8, 0), LE,
Unsigned)
  requires 0 <=Int Y andBool Y modInt 8 ==Int 0 [simplification, preserves-definedness]

// Support Bytes2Int(...) >>Int operations
rule [int-rsh-substrbytes]: Bytes2Int(substrBytes(B, I, J), LE, Unsigned) >>Int Y => Bytes2Int(substrBytes(B,
I +Int Y /Int 8, J), LE, Unsigned)
  requires 0 <=Int Y andBool Y modInt 8 ==Int 0 andBool I +Int Y /Int 8 <=Int J [simplification, preserves-
definedness]

// Support Bytes2Int(...) |Int operations
rule [int-or-bytes-1]: Bytes2Int(b"\x00" +Bytes X, LE, Unsigned) |Int Bytes2Int(Y, _, Unsigned) =>
```

```
Bytes2Int(Y +Bytes X, LE, Unsigned)
  requires lengthBytes(Y) ==Int 1 [simplification]
```

Solution Strategy: Instead of converting Bytes2Int to Int first then operating, we directly "push" operations into Bytes2Int internally, performing equivalent operations at the byte level. This avoids intermediate conversion steps, ensuring efficient symbolic execution of EVM opcode bitwise operations.

Solving Problem 3: Word Syntax Complications

The core approach is **eliminating Word wrapper layers** to simplify directly to Int operations, thus simplifying expression structure in EVM opcode implementations:

```
// Eliminate unnecessary sign extensions
rule signExtend(Bytes2Int(B, LE, Unsigned), NumBits) => Bytes2Int(B, LE, Unsigned)
  requires NumBits ==Int lengthBytes(B) *Int 8 [simplification(45), preserves-definedness]
// Remove Word wrapper layers
syntax Word ::= "W" "(" Int ")"
```

Solution Strategy: When sign extension bits match the actual bits of byte data, directly eliminate signExtend wrapping to avoid adding extra syntactic layers. This rule, combined with other Word-to-Int simplifications, effectively reduces expression complexity.

Challenge 2: SparseBytes Memory Model Complexity

2.1 Root Cause Analysis

This challenge stems from adaptation difficulties between **SparseBytes memory model and EVM opcode memory operations**, particularly in supporting EVM's complex memory access patterns:

SparseBytes Design Advantages:

- **Compared to simple Bytes representation**: SparseBytes can save significant storage space for uninitialized and sparse memory regions, substantially improving both concrete and symbolic execution efficiency
- **Compared to Map representation**: Map may have memory overlap issues during insertion, requiring complex overlap checking during storage, while SparseBytes avoids this through structural design
- **Compared to Array representation**: Arrays are inconvenient for dynamic, sparse memory access, while SparseBytes is optimized for symbolic execution memory access patterns

Early Design Limitations:

In version 16b2d11, SparseBytes only provided simple single-byte interfaces:

```
// Early design (commit 16b2d11 version)
syntax MaybeByte ::= Int | ".Byte"
```

```
syntax MaybeByte ::= readByte(SparseBytes, Int) [function, total]
syntax SparseBytes ::= writeByte(SparseBytes, Int, Int) [function, total]
```

Core Challenge: Single-byte interfaces cannot effectively support EVM opcode memory operations:

- **EVM memory access complexity**: EVM opcodes (like MLOAD, MSTORE) need to handle 256-bit data memory access; single-byte interfaces make implementation extremely complex
- **Low symbolic execution efficiency**: EVM opcode memory operations generate numerous intermediate expressions in symbolic execution, preventing smart contract verification completion
- **Frequent type conversions**: Frequent conversions between EVM's 256-bit data and RISC-V's 32-bit architecture severely impact symbolic execution efficiency

2.2 Problem Description

SparseBytes Alternating Structure Foundation:

```
syntax SparseBytes ::= SparseBytesEF | SparseBytesBF

// SparseBytesEF: Sparse byte structure starting with #empty (Empty First)
syntax SparseBytesEF ::=
    ".SparseBytes"            // Completely empty memory
  | EmptySBItem SparseBytesBF // #empty followed by SparseBytesBF

// SparseBytesBF: Sparse byte structure starting with #bytes (Bytes First)
syntax SparseBytesBF ::=
    BytesSBItem SparseBytesEF // #bytes followed by SparseBytesEF

syntax BytesSBItem ::= #bytes(Bytes) // Initialized data segment
syntax EmptySBItem ::= #empty(Int)   // Uninitialized data segment
```

Specific Issues with Single-byte Interface:

1. **Complex load/store instruction implementation**:

   ```
   // Complexity of implementing 4-byte load using single-byte interface
   rule <k> LW RD, OFF(RS1) => ... </k>
   // Requires 4 readByte calls, then concatenation to integer
   // Implementation is very complex and inefficient
   ```

2. **Expression explosion in symbolic execution**:
   Each multi-byte operation generates numerous single-byte operation sequences, causing exponential expression growth in symbolic execution

3. **Fundamental difficulty with symbolic index writes**:
   Single-byte interfaces cannot effectively handle symbolic index write operations; when write address is a

symbolic value, the specific write location and impact range cannot be determined, preventing symbolic execution continuation

2.3 Solution

For **single-byte interface limitations**, we designed a completely new multi-byte interface and intelligent buffering mechanism:

Solution Strategy 1: Introducing Multi-byte Interfaces

To support RISC-V's multi-byte load/store operations, we introduced new multi-byte interfaces:

```
// New multi-byte interface design
syntax Int ::= readBytes(Int, Int, SparseBytes) [function, total]
syntax SparseBytes ::= writeBytes(Int, Int, Int, SparseBytes) [function, total]
```

Multi-byte Interface Advantages:

- **Atomic Operations**: Multi-byte load/store can be handled as single atomic operations, avoiding complex decomposition
- **Simplified Instruction Semantics**: Load/store instruction semantic implementation is greatly simplified
- **Symbolic Execution Efficiency**: Reduces generation of numerous intermediate expressions

Solution Strategy 2: Efficient Implementation through Three-layer Function Composition

`readBytes` is implemented through three-layer function composition:
`Bytes2Int(pickFront(NUM, dropFront(I, SBS)), LE, Unsigned)`

To avoid expression explosion in symbolic execution, we designed **composite operation pattern recognition** optimization:

```
// Most common pattern: direct extraction from #bytes segment
rule pickFront(I, #bytes(B +Bytes _) _) => substrBytes(B, 0, I)
  requires I >Int 0 andBool I <=Int lengthBytes(B) [simplification(45), preserves-definedness]

// Intelligent simplification for cross-segment reads: avoid full recursive expansion
rule pickFront(I, #bytes(B +Bytes BS) EF) => B +Bytes pickFront(I -Int lengthBytes(B), #bytes(BS) EF)
  requires I >Int lengthBytes(B) [simplification(45), preserves-definedness]

// dropFront intra-segment optimization: avoid recursion to next layer
rule dropFront(I, #bytes(B +Bytes BS) EF) => dropFront(0, #bytes(substrBytes(B, I, lengthBytes(B)) +Bytes BS)
EF)
  requires I >Int 0 andBool I <Int lengthBytes(B) [simplification(45), preserves-definedness]
```

Solution Strategy: Identify the most common access patterns and provide "shortcut" rules for these patterns to avoid full three-layer function expansion. For example, when reads fall exactly within a #bytes segment,

convert directly to `substrBytes` operations.

Solution Strategy 3: Write Buffer (#WB) Buffering Mechanism

To address **the inability to determine symbolic index byte writes**, we introduced the **Write Buffer (#WB) buffering mechanism**:

```
// Unified entry point for symbolic index writes
syntax SparseBytes ::= #WB(Bool, Int, Int, Int, SparseBytes) [function, total]
rule writeBytes(I, V, NUM, B:SparseBytes) => #WB(false, I, V, NUM, B) [simplification]

// Direct dispatch for concrete addresses
rule writeBytes(I, V, NUM, BF:SparseBytesBF) => writeBytesBF(I, V, NUM, BF) [simplification(45), concrete(I)]
rule writeBytes(I, V, NUM, EF:SparseBytesEF) => writeBytesEF(I, V, NUM, EF) [simplification(45), concrete(I)]
```

Core Design Philosophy of #WB Mechanism:

- **Uninterpreted delayed writes**: When index is symbolic, write location cannot be directly determined; #WB provides delayed write mechanism, maintaining symbolic write operations in uninterpreted form
- **Avoid term bloat**: Through a series of simplification rules, avoid term bloat caused by repeated writes
- **Symbolic index handling**: Buffering solution specifically designed for symbolic index write scenarios

#WB simplification rules preventing term bloat:

```
// Write overwrite optimization: when new write completely covers old write, eliminate old write to avoid
redundant #WB layer accumulation
rule #WB(false, I0, V0, NUM0, #WB(_, I1, _, NUM1, B:SparseBytes)) => #WB(false, I0, V0, NUM0, B)
  requires I0 <=Int I1 andBool I1 +Int NUM1 <=Int I0 +Int NUM0 [simplification(45)]

// Write reordering: order optimization for non-intersecting writes, maintaining compact term structure
rule #WB(false, I0, V0, NUM0, #WB(true, I1, V1, NUM1, B:SparseBytes)) => #WB(true, I1, V1, NUM1, #WB(false,
I0, V0, NUM0, B))
  requires I0 +Int NUM0 <=Int I1 orBool I1 +Int NUM1 <=Int I0 [simplification]
```

Core Strategy for Preventing Term Bloat:

- **Write elimination**: When new write completely covers old write, directly eliminate old write to avoid meaningless #WB layer accumulation
- **Write merging**: Through reordering rules, optimize combination of mutually independent write operations
- **Delayed concretization**: Only concretize symbolic writes to actual memory modifications when necessary

Solution Strategy 4: #WB-aware Read System

We designed **#WB-aware read rules** and **>>SparseBytes operator** to handle symbolic read-write interactions:

```
// Dedicated right-shift operator for offset calculation in #WB
syntax SparseBytes ::= SparseBytes ">>SparseBytes" Int [function, total]
rule SBS >>SparseBytes SHIFT => dropFront(SHIFT, SBS) [concrete]
rule #WB(FLAG, I, V, NUM, B:SparseBytes) >>SparseBytes SHIFT => #WB(FLAG, maxInt(0, I -Int SHIFT), V >>Int
(SHIFT *Int 8), NUM, B >>SparseBytes SHIFT)
  requires SHIFT >=Int 0 [simplification(45), preserves-definedness]

// #WB-aware reads: directly extract data from Write Buffer
rule pickFront(PICK, #WB(_, I, V, NUM, B:SparseBytes)) => Int2Bytes(minInt(PICK, NUM), V, LE) +Bytes
pickFront(maxInt(0, PICK -Int NUM), B >>SparseBytes NUM)
  requires 0 ==Int I [simplification(40)]

// Read position before write: bypass Write Buffer
rule pickFront(PICK, #WB(_, I, _, _, B:SparseBytes)) => pickFront(PICK, B)
  requires PICK <=Int I [simplification(45)]
```

Solution Strategy: Enable read operations to "see through" #WB structure, directly extract required content from buffered write data, or intelligently bypass unrelated write operations. This avoids fully expanding every `readBytes` into complex three-layer nested expressions.

Challenge 3: Complex Data Type Decomposition

3.1 Root Cause Analysis

This challenge stems from the enormous abstraction level gap between EVM's 256-bit data types and RISC-V instruction set architecture:

Root Cause Analysis:

- **Architecture bit-width limitations**: RISC-V is 32-bit architecture; single instructions can only process 32-bit data, while EVM opcodes need to handle 256-bit data types
- **Abstraction level differences**: The gap between EVM's high-level data operations and RISC-V ISA is enormous, involving not just bit length but also data abstraction, type systems, memory management, and other aspects
- **Compilation transformation complexity**: From EVM opcode Rust implementations to RISC-V assembly code involves many compilation steps, each potentially introducing additional complexity

Specific Impact on EVM Opcodes:

- **Data decomposition**: EVM's 256-bit data types must decompose into 8 32-bit RISC-V operations
- **Operation decomposition**: Single EVM operations (like ADD opcode's 256-bit addition) need expansion into multiple 32-bit operations with carry
- **Control flow complications**: EVM opcodes' complex logic needs implementation using basic branch instructions

3.2 Problem Description

When executing Rust programs on RISC-V, this abstraction gap causes complex instruction expansion:

```
// uint256 variable in Rust code
let a: u256 = 0x123456789abcdef0123456789abcdef0123456789abcdef0123456789abcdef0;
```

On RISC-V, this decomposes into:

- **Storage decomposition**: Multiple 4-byte, 2-byte, 1-byte load/store instructions
- **Operation decomposition**: Complex arithmetic instruction sequences including carry handling
- **State management**: Numerous intermediate states and conversion operations
- **Expression explosion**: In symbolic execution, these decomposition operations cause exponential symbolic expression growth

Issues not resolved by Challenges 1 and 2:

- While Challenge 1 solved core type conversion issues, complex integer operations (like shift operations, bit mask operations) still need further optimization
- While Challenge 2 solved core memory access issues, byte sequence reorganization, concatenation, indexing operations remain complex
- Other type operations like boolean-to-word conversion, complex byte equality judgments still need handling

3.3 Solution

This challenge spawned all semantic optimization work beyond Challenges 1 and 2, mainly including:

Solution Strategy 1: Integer Operation Chain Optimization

For complex integer operation decomposition, we designed **operation chain simplification rules**:

```
// Shift operation chain optimization
rule [int-lsh-lsh]: (W0 <<Int N0) <<Int N1 => W0 <<Int (N0 +Int N1)
  requires 0 <=Int N0 andBool 0 <=Int N1 [simplification, preserves-definedness]

// Bit mask optimization
rule [chop-32bits]: X &Int 4294967295 => X
  requires 0 <=Int X andBool X <Int 4294967296 [simplification]
rule [chop-16bits]: X &Int 65535 => X
  requires 0 <=Int X andBool X <Int 65536 [simplification]

// Bitwise operation associativity optimization
rule [int-and-assoc]: (X &Int Y) &Int Z => X &Int (Y &Int Z)
  [simplification, symbolic(X), concrete(Y,Z)]

// Addition and bit mask combination optimization
```

```
rule [int-and-add-assoc-32]: ((X &Int 4294967295) +Int Y) &Int 4294967295 => (X +Int Y) &Int 4294967295
  [simplification]
```

Solution Strategy: By identifying common integer operation patterns, simplify complex operation chains to more direct forms, avoiding lengthy intermediate expressions in symbolic execution.

Solution Strategy 2: Byte Sequence Reorganization Optimization

For complex byte sequence operations, we designed **byte reorganization rules**:

```
// Consecutive byte concatenation optimization
rule [bytes-concat-substr]: substrBytes(A, I0, J0) +Bytes substrBytes(A, I1, J1) => substrBytes(A, I0, J1)
  requires I0 <=Int J0 andBool I1 <=Int J1 andBool J0 ==Int I1 andBool J1 <=Int lengthBytes(A)
  [simplification, preserves-definedness]

// Byte length calculation optimization
rule [bytes-length-concat]: lengthBytes(A +Bytes B) => lengthBytes(A) +Int lengthBytes(B)
  [simplification]
rule [bytes-length-substr]: lengthBytes(substrBytes(B, I, J)) => J -Int I
  requires 0 <=Int I andBool I <=Int J andBool J <=Int lengthBytes(B) [simplification, preserves-definedness]

// Nested substr optimization
rule [substr-substr]: substrBytes(substrBytes(B, I, J), I0, J0) => substrBytes(B, I +Int I0, I +Int J0)
  requires 0 <=Int I andBool I <=Int J andBool J <=Int lengthBytes(B)
   andBool 0 <=Int I0 andBool I0 <=Int J0 andBool J0 <=Int J -Int I [simplification, preserves-definedness]
```

Solution Strategy: By identifying repetitive patterns in byte sequences, merge multi-step byte operations into single-step operations, reducing intermediate states in symbolic execution.

Solution Strategy 3: Data Equality Judgment Optimization

For complex data equality judgments, we designed **equality simplification rules**:

```
// Byte equality optimization by length
rule [bytes-not-equal-length]: BA1:Bytes ==K BA2:Bytes => false
  requires lengthBytes(BA1) =/=Int lengthBytes(BA2) [simplification]

// Byte concatenation equality decomposition
rule [bytes-equal-concat-split-k]: A:Bytes +Bytes B:Bytes ==K C:Bytes +Bytes D:Bytes => A ==K C andBool B ==K
D
  requires lengthBytes(A) ==Int lengthBytes(C) orBool lengthBytes(B) ==Int lengthBytes(D) [simplification]

// Integer equality relationship with byte concatenation
rule [int-eq-bytes-concat-split]: X ==Int Bytes2Int(B0 +Bytes B1, LE, Unsigned) =>
  (X &Int ((1 <<Int (lengthBytes(B0) *Int 8)) -Int 1)) ==Int Bytes2Int(B0, LE, Unsigned) andBool
  (X >>Int (lengthBytes(B0) *Int 8)) ==Int Bytes2Int(B1, LE, Unsigned)
  [simplification, concrete(B0), preserves-definedness]
```

Solution Strategy: By early judgment of obvious inequality cases, avoid complex equality calculations, and decompose complex equality judgments into simpler sub-problems.

Solution Strategy 4: Bool2Word Conversion Optimization

For boolean-to-word conversion, we designed **Bool2Word simplification rules**:

```
// Bool2Word basic properties
rule [bool2word-non-neg]: 0 <=Int Bool2Word(_) => true [simplification]
rule [bool2word-eq-0]: Bool2Word(B) ==Int 0 => notBool B [simplification]
rule [bool2word-eq-1]: Bool2Word(B) ==Int 1 => B [simplification]

// Bool2Word combination with bitwise operations
rule [int-bool2word-or-ineq]: 0 <Int (0 -Int Bool2Word(4294967295 <Int X)) &Int 4294967295 |Int X &Int
4294967295 => true
  requires 0 <Int X [simplification(45)]
```

Solution Strategy: By identifying common usage patterns of Bool2Word, directly convert boolean conditions to simpler expression forms.

Solution Strategy 5: Inequality Relationship Optimization

For complex inequality judgments, we designed **inequality simplification rules**:

```
// Non-negativity of bitwise operation results
rule [int-and-ineq]: 0 <=Int A &Int B => true requires 0 <=Int A andBool 0 <=Int B [simplification]
rule [int-rhs-ineq]: 0 <=Int A >>Int B => true requires 0 <=Int A andBool 0 <=Int B [simplification]

// Monotonicity of addition
rule [int-add-ineq]: A <=Int A +Int B => true requires 0 <=Int B [simplification]
rule [int-add-ineq-0]: 0 <=Int A +Int B => true requires 0 <=Int A andBool 0 <=Int B [simplification]

// Range judgment for byte integers
rule [bytes2int-upperbound]: Bytes2Int(B, _, Unsigned) <Int X => true
  requires 2 ^Int (lengthBytes(B) *Int 8) <=Int X [simplification]
rule [bytes2int-lowerbound]: 0 <=Int Bytes2Int(_, _, Unsigned) => true [simplification]
```

Solution Strategy: By identifying natural range constraints of data types, determine inequality relationships early to avoid complex numerical calculations.

System Architecture

Optimization rules are organized through layered modular structure, with each module targeting specific EVM opcode requirements:

```
module LEMMAS
  imports SPARSE-BYTES-SIMPLIFICATIONS  // Memory operation optimizations supporting EVM opcodes
```

```
  imports BYTES-SIMPLIFICATIONS          // Byte sequence processing optimizations supporting EVM opcodes
  imports INT-SIMPLIFICATIONS            // Integer operation optimizations supporting EVM opcodes
  imports WORD-SIMPLIFICATIONS           // Type conversion optimizations supporting EVM opcodes
endmodule
```

Detailed Module Functionality:

- **SPARSE-BYTES-SIMPLIFICATIONS**: Specifically optimizes EVM opcodes' (like MLOAD, MSTORE) memory access patterns, supporting symbolic execution of 256-bit data
- **BYTES-SIMPLIFICATIONS**: Optimizes byte sequence operations in EVM opcodes, ensuring complex data processing can proceed efficiently in symbolic execution
- **INT-SIMPLIFICATIONS**: Optimizes integer operations in EVM opcodes (like ADD, MUL, AND, OR, etc.), supporting symbolic execution of 256-bit arithmetic and logical operations
- **WORD-SIMPLIFICATIONS**: Optimizes type conversions in EVM opcode implementations, simplifying expression structures to improve symbolic execution efficiency

Optimization Effects

Through implementing these semantic optimizations:

1. **EVM Arithmetic Operation Support**: Successfully implemented symbolic execution of EVM's ADD, MUL, SUB and other arithmetic opcodes on RISC-V, solving type conversion and expression explosion issues in 256-bit integer operations
2. **EVM Memory Operation Support**: Successfully implemented symbolic execution of EVM's MLOAD, MSTORE and other memory opcodes on RISC-V, effectively handling symbolic index access through #WB mechanism
3. **EVM Logical Operation Support**: Successfully implemented symbolic execution of EVM's AND, OR, XOR and other logical opcodes on RISC-V, optimizing complex bitwise operations and byte sequence operations

Real-world Application Verification:

- **REVM Compatibility**: All optimizations were verified against REVM's actual implementations, ensuring semantic correctness of EVM opcodes
- **Symbolic Execution Efficiency**: Dramatically improved smart contract symbolic execution efficiency, making formal verification of complex contracts feasible
- **Expression Management**: Effectively controlled expression complexity in symbolic execution, avoiding symbolic execution timeouts or memory overflow issues

Technical Significance

1. **Filling Technical Gaps**: First complete implementation of EVM opcode symbolic execution support on RISC-V architecture, laying foundation for blockchain formal verification

2. **Modular Design**: Implemented extensible optimization solutions through layered architecture, facilitating future support for more EVM opcodes and new optimization requirements
3. **Practical Application Value**: Provides crucial technical support for Ethereum smart contract security analysis and formal verification, with significant practical application value

Conclusion

The semantic optimization work presented in this report systematically addresses three core challenges in RISC-V symbolic execution, **successfully implementing symbolic execution support for REVM's EVM opcodes (including ADD opcode and others) after compilation to RISC-V**. These optimizations not only solve technical challenges but also provide important technical foundation for Ethereum smart contract formal verification and blockchain security analysis.

RISC-V Semantics Commit Change Analysis

This section provides a detailed analysis of **62 commits** in the RISC-V Semantics project, spanning **4 months (March-June 2025)** from version **v0.1.51 to v0.1.112** (specifically, from commit 082c5f9fe394524ebb0a8e4ddd55d048a696745e to 42176ce). Among these 62 commits, **36 commits (58%) were authored by JianHong Zhao**, with the remaining 26 commits contributed by team members Tamás Tóth, Julian Kuners, and automated dependency updates. This analysis is crucial because REVM verification relies on compiling REVM to RISC-V, which in turn requires formal verification-ready RISC-V semantics.

These commits collectively enable formal verification of **real-world REVM code compiled to RISC-V**, addressing the significant challenge that even simple Rust programs become complex when compiled through ZK toolchains to RISC-V, let alone production REVM implementations with their intricate state management and cryptographic operations.

Major Improvement Directions for Formal Verification

These 62 commits systematically transform RISC-V Semantics into a production-ready formal verification platform through four key improvement directions:

1. Architecture Foundations for Verification

Core Infrastructure for Reliable Formal Verification

- **Migration from Poetry to UV package manager** (faster, more reliable builds)
  - v0.1.96: [Commit 711f12b] - "Migrate from `poetry` to `uv`"
  - v0.1.100: [Commit fb931c8] - "fix version of `uv` in CI"
  - v0.1.99: [Commit c77e2a5] - "Fix version in `uv.lock`"
  - v0.1.102: [Commit 0d09047] - "Update dependency: deps/k_release"
- **Extensible prover architecture** enabling pluggable verification backends
  - v0.1.101: [Commit fca8f9f] - "Add extensible prover implementation"
- **ELF file handling consolidation** for better program analysis
  - v0.1.86: [Commit 25b7057] - "Consolidate ELF file handling under class `ELF`"
- **Build system and infrastructure improvements**
  - v0.1.95: [Commit 07180df] - "Remove attribute `source_dir` from `SymTools`"
  - v0.1.89: [Commit d411af1] - "Write temporary test data into separate folders by default"
  - v0.1.88: [Commit 759923e] - "Inline the `<test>` cell"

2. Python Toolchain Enhancements

Enhanced Development and Verification Tools

- **kriscv-asm command** for test case generation and debugging
  - v0.1.57: [Commit 76f893a] - "Add command `kriscv-asm <instruction>`"

- **Enhanced symbolic execution tools** with configuration management
  - v0.1.90: [Commit cba2d2b] - "Enable instantiating symbolic config"
  - v0.1.104: [Commit db011d7] - "Add `optimize_kcfg` parameter in `SymTool`"
  - v0.1.93: [Commit c2d312e] - "Add property `proof_show` to `SymTools`"
  - v0.1.68: [Commit 85e3216] - "Add option `--depth` to `kriscv run`"
  - v0.1.59: [Commit 74dc542] - "Allow `--temp-dir` option for `test-prove`"

- **Enhanced debugging capabilities** with bug report integration
  - v0.1.58: [Commit 1e43e19] - "Enhance SymTools with bug report integration"

- **CI/CD improvements** for reliable verification workflows
  - v0.1.55: [Commit 0526095] - "Add job for notifying dependents"

- **Runtime and tool organization**
  - v0.1.53: [Commit 344cc7e] - "Factor out `runtime` from `Tools`"
  - v0.1.51: [Commit 79552f6] - "Add option `--zero-init`"

3. RISC-V Semantics Completeness & Optimization for Formal Verification

Complete RISC-V Instruction Set Coverage & Semantic Optimizations

- **Division operation implementation** (DIV/DIVU) for complete arithmetic support
  - v0.1.111: [Commit efe1f78] - "Add division operations for RISC-V semantics"

- *MUL instruction family implementation** for M-extension coverage
  - v0.1.52: [Commit b8bf5d2] - "Implement `MUL*` instructions"

- **Type system refactoring (Word → Int)** for simplified formal reasoning
  - v0.1.91: [Commit f680218] - "Refactor RISC-V semantics to replace `Word` with `Int`"
  - v0.1.71: [Commit 883fd6e] - "Remove the `format` attribute from `Word`"
  - v0.1.73: [Commit 0c40c65] - "Make `Word` shift operations `total`"
  - v0.1.74: [Commit 8090120] - "Avoid ambiguity for Word expressions"

- **Sparse bytes support** for efficient memory modeling in verification
  - v0.1.62: [Commit c6b16ef] - "Support symbolic sparse bytes generation via `SparseBytes`"

- **Symbolic execution foundation** for formal property checking
  - v0.1.54: [Commit ae15f5d] - "Add symbolic execution support"

- **Memory operation improvements** (loadBytes/storeBytes) for precise modeling
  - v0.1.70: [Commit ec95dd6] - "Better `loadBytes` for symbolic execution"
  - v0.1.69: [Commit 3a2bbc0] - "Better `storeBytes` for symbolic execution"
  - v0.1.60: [Commit 98eea27] - "Add symbolic execution rules for `readByteBF` in `sparse-bytes.md` "
  - v0.1.61: [Commit 2755c4c] - "Add `writeByteBF` simplification rules"

- **Branch handling refactoring** for cleaner control flow semantics
  - v0.1.87: [Commit 202c19a] - "Transform function `branchPC` to effect function `#PC_BRANCH` "

- **Function interface improvements**
  - v0.1.112: [Commit 42176ce] - "Move the `memory` to the end in functions"

4. Simplification Rules for Symbolic Execution Acceleration

40+ Optimization Rules for Faster Constraint Solving

- **Byte operation simplifications** (comprehensive rule set)
  - v0.1.110: [Commit ddf2811] - "Simp rule 4 `int2bytes o bytes2int` "
  - v0.1.109: [Commit 940f257] - "Remove redundant requirement for `substr o int2bytes` "
  - v0.1.106: [Commit 471d05f] - "Refine simp rule for `Bytes2Int o Int2Byes` "
  - v0.1.105: [Commit 3804716] - "Add simplification rule for `Bytes2Int &Int 4294967295` "
  - v0.1.98: [Commit 570e0f4] - "Add simp rules for revsersed `substrBytes` concat"
  - v0.1.97: [Commit 2fc0603] - "Add simp rules 4 `Bytes2Int o Int2Bytes` and `substrBytes o Int2Bytes` "
  - v0.1.85: [Commit bb2934c] - "Add simp rules for `Int2Bytes o Bytes2Int` "
  - v0.1.84: [Commit 4c53805] - "Add simp rules for `Bytes2Int o |Int o Bytes2Int` "
  - v0.1.83: [Commit 803850d] - "simplify patterns `Bytes2Int o <<Int` & `Bytes2Int o >>Int` & chop"
  - v0.1.82: [Commit c157326] - "Add simp rules for `replaceAtBytes` "
  - v0.1.81: [Commit e2369f6] - "Add simp rules for `substrBytes(A +Bytes B, I, J)` "
  - v0.1.78: [Commit 66ddeca] - "Simplify pattern `Bytes2Int o substrBytes &Int 65280` "
  - v0.1.63: [Commit 8f5e5b7] - "Add Byte simplification rules from evm semantics"

- **Integer arithmetic optimizations** for faster constraint solving
  - v0.1.108: [Commit f5738c0] - "Simp rulle 4 `>> 0` "
  - v0.1.107: [Commit 123a234] - "Simp rule 4 complex `(X + Y & 4294967295) + Z & 4294967295` "
  - v0.1.103: [Commit c72b80f] - "Simp rule 4 `(A +Int B) &Int 4294967295 <Int A` "
  - v0.1.94: [Commit cf4108d] - "Add simp rules 4 `&Int` assoc"
  - v0.1.77: [Commit 79bf2fd] - "Add simp rule to eliminate `SignExtend` "
  - v0.1.75: [Commit 72ad19b] - "Add simp rule for `<<Int o <<Int` "

- **Sparse bytes and memory optimizations**

- v0.1.76: [Commit 4dcaa6f] - "Tackle unexpected pattern for `pickfront` and `dropfront`"
- v0.1.72: [Commit 58d1958] - "Add new lemmas for `substrBytes` and update `pickFront` rule"
- v0.1.67: [Commit 60f10e1] - "Add simplification rule for storing symbolic bytes"

- **Dependency updates** for latest optimizations
  - v0.1.92: [Commit 0949ca5] - "Update dependency: deps/k_release"
  - v0.1.80, v0.1.79: [Commits a5b98f5, 81d5723] - "Update dependency: deps/k_release"
  - v0.1.66, v0.1.65, v0.1.64: [Commits 778e705, 53567c0, 951e6e7] - "Update dependency: deps/k_release"
  - v0.1.56: [Commit 9f4184e] - "Update dependency: deps/k_release"

Detailed Commit Analysis

Latest Commits (June 2025)

1. Commit 42176ce (v0.1.112) - "Move the `memory` to the end in functions"

- **Purpose**: Adjust function parameter order, moving memory parameter to the end
- **Modified Files**:
  - `src/kriscv/kdist/riscv-semantics/riscv.md` - Updated instruction semantics to use new parameter order for memory operations, affecting load/store instructions and their interaction with memory
  - `src/kriscv/kdist/riscv-semantics/sparse-bytes.md` - Refactored sparse bytes operations to consistently place memory parameter at the end, improving API consistency across all memory manipulation functions
  - `src/kriscv/kdist/riscv-semantics/lemmas/sparse-bytes-simplifications.md` - Updated simplification rules to match new parameter ordering for functions like `pickFront`, `dropFront`, `writeBytesBF`, ensuring all lemmas work with the new function signatures
  - `src/kriscv/term_builder.py` - Modified Python term builder to generate function calls with correct parameter order, updating all memory-related function call constructions
  - Test files and specification files - Updated all test cases and specifications to use new parameter ordering, ensuring compatibility with the refactored function signatures

- **Functional Improvements**:
  - Unified function interface by moving memory parameter to the end
  - Changed parameter order for `loadBytes` and `storeBytes` functions
  - Updated all related sparse bytes operation functions

2. Commit efe1f78 (v0.1.111) - "Add division operations for RISC-V semantics"

- **Purpose**: Add division operation support to RISC-V semantics

- **Modified Files**:
  - `src/kriscv/kdist/riscv-semantics/riscv.md` - Added complete implementation of `DIV` and `DIVU` instructions with proper handling of division by zero (returning -1 for signed, all 1s for unsigned) and overflow cases (signed division of most negative number by -1)
  - `src/kriscv/kdist/riscv-semantics/word.md` - Added `/Word` and `/uWord` syntax definitions for signed and unsigned word division operations, including proper type annotations and operator precedence
  - `src/tests/integration/test_functions.py` - Added comprehensive test suite with 83 lines covering all division scenarios: normal division, division by zero, overflow conditions, and edge cases for both signed and unsigned operations

- **Functional Improvements**:
  - Implemented signed division `DIV` and unsigned division `DIVU` instructions
  - Properly handled special cases for division by zero and overflow
  - Added 83 lines of comprehensive test code

3. Commit ddf2811 (v0.1.110) - "Simp rule 4 `int2bytes o bytes2int` "

- **Purpose**: Add simplification rules for byte and integer conversion
- **Modified Files**:
  - `src/kriscv/kdist/riscv-semantics/lemmas/bytes-simplifications.md` - Added `substr-reverse-bytes` rule to simplify substring operations on reversed bytes and `int2bytes-bytes2int-pad-zeros` rule to optimize conversion chains that involve padding with zeros
  - `src/tests/integration/test-data/specs/int2bytes-bytes2int.k` - Added test specifications to verify the new simplification rules work correctly in various scenarios involving byte-to-integer and integer-to-byte conversions

- **Functional Improvements**:
  - Added `substr-reverse-bytes` and `int2bytes-bytes2int-pad-zeros` simplification rules
  - Optimized byte operation performance in symbolic execution

4. Commit 940f257 (v0.1.109) - "Remove redundant requirement for `substr o int2bytes` "

- **Purpose**: Remove redundant requirements for `substr o int2bytes`
- **Modified Files**:
  - `src/kriscv/kdist/riscv-semantics/lemmas/bytes-simplifications.md` - Removed unnecessary condition `0 <=Int Start` from `substr-int2bytes` rule, making the rule more broadly applicable by eliminating overly restrictive constraints
  - `src/tests/integration/test-data/specs/bytes-int.k` - Updated test specifications to reflect the more general rule and added test cases that verify the rule works correctly without the redundant

constraint

- **Functional Improvements**:
  - Removed redundant conditions in `substr-int2bytes` rule
  - Made simplification rules more general

5. Commit f5738c0 (v0.1.108) - "Simp rulle 4 `>> 0`"

- **Purpose**: Simplify right shift by 0 operations
- **Modified Files**:
  - `src/kriscv/kdist/riscv-semantics/lemmas/int-simplifications.md` - Added `rule [rsh-0]: X >>Int 0 => X` to eliminate unnecessary right shift by zero operations and removed some non-negative number constraints that were overly restrictive
- **Functional Improvements**:
  - Added `rule [rsh-0]: X >>Int 0 => X` simplification rule
  - Removed some unnecessary non-negative constraints

6. Commit 123a234 (v0.1.107) - "Simp rule 4 complex `(X + Y & 4294967295) + Z & 4294967295`"

- **Purpose**: Simplify complex 32-bit addition and bitwise operation expressions
- **Modified Files**:
  - `src/kriscv/kdist/riscv-semantics/lemmas/int-simplifications.md` - Added sophisticated simplification rules to handle complex arithmetic expressions involving 32-bit masking, particularly for nested addition and bitwise AND operations
  - `src/kriscv/kdist/riscv-semantics/lemmas/word-simplifications.md` - Added non-negativity rules for `Bool2Word` conversions and other word-level operations to enable more aggressive optimization
  - `.gitignore` - Updated to exclude additional build artifacts and temporary files generated during development
- **Functional Improvements**:
  - Added simplification rules for complex addition and bitwise operation combinations
  - Added non-negativity rules for `Bool2Word`
  - Improved `.gitignore` file

7. Commit 471d05f (v0.1.106) - "Refine simp rule for `Bytes2Int o Int2Byes`"

- **Purpose**: Improve byte to integer conversion simplification rules
- **Modified Files**:

- `src/kriscv/kdist/riscv-semantics/lemmas/bytes-simplifications.md` - Removed the overly restrictive `0 <=Int V` constraint from `bytes2int-int2bytes` rule, allowing the rule to apply to negative values as well, which is safe for byte conversion operations

- **Functional Improvements**:
  - Removed `0 <=Int V` constraint from `bytes2int-int2bytes` rule
  - Resolved issue #137

8. Commit 3804716 (v0.1.105) - "Add simplification rule for `Bytes2Int &Int 4294967295`"

- **Purpose**: Add simplification rules for byte to integer with 32-bit mask operations
- **Modified Files**:
  - `src/kriscv/kdist/riscv-semantics/lemmas/bytes-simplifications.md` - Added `bytes2int-ffffffff` rule that simplifies `Bytes2Int(B, LE, Unsigned) &Int 4294967295` to `Bytes2Int(substrBytes(B, 0, 4), LE, Unsigned)` when byte array length is greater than 4, effectively extracting only the first 4 bytes for 32-bit operations

- **Functional Improvements**:
  - Added `bytes2int-ffffffff` simplification rule
  - Optimized 32-bit mask operations

9. Commit db011d7 (v0.1.104) - "Add `optimize_kcfg` parameter in `SymTool`"

- **Purpose**: Add configuration graph optimization parameter to symbolic tools
- **Modified Files**:
  - `src/kriscv/symtools.py` - Added `optimize_kcfg` parameter to the `SymTools` class constructor and passed it to the underlying prover, allowing users to enable/disable control flow graph optimization based on their specific verification needs

- **Functional Improvements**:
  - Added `optimize_kcfg` parameter
  - Improved control flow graph optimization strategy for symbolic execution

10. Commit c72b80f (v0.1.103) - "Simp rule 4 `(A +Int B) &Int 4294967295 <Int A`"

- **Purpose**: Simplify inequality comparisons for addition operations with 32-bit mask
- **Modified Files**:
  - `src/kriscv/kdist/riscv-semantics/lemmas/int-simplifications.md` - Added new inequality simplification rules for expressions involving addition and 32-bit masking, particularly for overflow detection patterns

- `src/kriscv/kdist/riscv-semantics/lemmas/bytes-simplifications.md` - Fixed bug in `bytes2int-upperbound` rule where the condition was incorrectly specified, correcting the upper bound calculation for byte-to-integer conversions

- **Functional Improvements**:
  - Added new inequality simplification rules
  - Fixed bug in `bytes2int-upperbound` rule

11. Commit 0d09047 (v0.1.102) - "Update dependency: deps/k_release"

- **Purpose**: Update K dependency version
- **Modified Files**:
  - `deps/k_release` - Updated to newer version of K framework to get latest bug fixes and performance improvements
  - `deps/uv_release` - Updated UV package manager dependency to maintain compatibility with latest version
  - `uv.lock` - Refreshed lock file to reflect new dependency versions and their transitive dependencies

- **Functional Improvements**:
  - Updated dependency versions to get latest features

12. Commit fca8f9f (v0.1.101) - "Add extensible prover implementation"

- **Purpose**: Add extensible prover implementation
- **Modified Files**:
  - `src/kriscv/kprovex/` - Added complete new module with extensible prover implementation including `__init__.py` for module initialization, `api.py` for plugin API definitions, `_default.py` for semantics-agnostic default implementations, `_loader.py` for dynamic plugin loading, and `_kprovex.py` for main prover logic based on APRProver
  - `src/kriscv/symtools.py` - Integrated the new extensible prover into the symbolic tools framework, allowing users to choose between different prover implementations

- **Functional Improvements**:
  - Added new `kprovex` module implementing extensible prover based on `APRProver`
  - Includes plugin API definition, semantics-agnostic defaults, plugin loader, etc.
  - Architecture designed for upstream contribution

13. Commit fb931c8 (v0.1.100) - "fix version of `uv` in CI"

- **Purpose**: Fix UV version in CI
- **Modified Files**:
  - `.github/actions/with-docker/Dockerfile` - Fixed UV version specification in Docker build to ensure consistent package manager version across all CI environments

- `.github/workflows/test.yml` - Updated GitHub Actions workflow to use pinned UV version, preventing CI failures due to version mismatches
- `deps/uv2nix` - Added new dependency for UV to Nix conversion, enabling better integration with Nix-based builds
- `deps/uv_release` - Added versioning file for UV package manager to track and manage UV updates systematically

- **Functional Improvements**:
  - Fixed UV version, improving CI stability

14. Commit c77e2a5 (v0.1.99) - "Fix version in `uv.lock`"

- **Purpose**: Fix lock file version
- **Modified Files**:
  - `uv.lock` - Massive update with 500+ lines changed, fixing version inconsistencies across all dependencies, resolving conflicts between direct and transitive dependencies, and ensuring reproducible builds

- **Functional Improvements**:
  - Fixed dependency version inconsistency issues

15. Commit 570e0f4 (v0.1.98) - "Add simp rules for reversed `substrBytes` concat"

- **Purpose**: Add simplification rules for reversed byte string concatenation
- **Modified Files**:
  - `src/kriscv/kdist/riscv-semantics/lemmas/bytes-simplifications.md` - Added 29 lines of sophisticated simplification rules for handling reversed byte string concatenation patterns, particularly for operations like `substrBytes(A +Bytes B, I, J)` where the result can be optimized based on the relationship between indices and byte string lengths

- **Functional Improvements**:
  - Added 29 lines of new simplification rules
  - Optimized reversed byte string concatenation operations

16. Commit 2fc0603 (v0.1.97) - "Add simp rules 4 `Bytes2Int o Int2Bytes` and `substrBytes o Int2Bytes`"

- **Purpose**: Add simplification rules for byte-integer conversion
- **Modified Files**:
  - `src/kriscv/kdist/riscv-semantics/lemmas/bytes-simplifications.md` - Added rules to simplify `Bytes2Int(Int2Bytes(...))` patterns where the conversion chain can be eliminated or simplified, particularly for cases where the byte representation is immediately converted back to integer

- `src/kriscv/kdist/riscv-semantics/lemmas/int-simplifications.md` - Added complementary integer simplification rules to handle the mathematical aspects of byte-integer conversion chains
- **Functional Improvements**:
  - Optimized conversion operations between bytes and integers

Major Architecture Changes

17. Commit 711f12b (v0.1.96) - "Migrate from `poetry` to `uv`"

- **Purpose**: Migrate from Poetry to UV package manager
- **Modified Files**:
  - Removed `poetry.lock` (2166 lines) - Deleted old Poetry lock file with all its dependency specifications and version constraints
  - Added `uv.lock` (1555 lines) - New UV lock file with streamlined dependency management, faster resolution, and better conflict handling
  - `pyproject.toml` - Updated build configuration to use UV instead of Poetry, including new tool configuration sections and dependency specifications
  - `Makefile` - Updated build targets to use UV commands instead of Poetry, including installation, development setup, and testing commands
  - `flake.nix` - Updated Nix configuration to integrate with UV, providing better reproducibility and cross-platform compatibility
  - `nix/` directory structure - Added complete Nix overlay system with kriscv-specific configurations and build system integrations
- **Functional Improvements**:
  - Adopted more modern package management tool
  - Improved build system and CI configuration
  - Added Nix build system support

18. Commit 07180df (v0.1.95) - "Remove attribute `source_dir` from `SymTools`"

- **Purpose**: Remove source directory attribute from symbolic tools
- **Modified Files**:
  - `src/kriscv/symtools.py` - Removed `source_dir` attribute from `SymTools` class, simplifying the API by eliminating the need for users to specify source directories explicitly
  - Multiple test specification files - Updated all test cases that previously relied on explicit source directory specification to use the new simplified API
- **Functional Improvements**:
  - Simplified symbolic tools API
  - Removed unnecessary source directory dependency

19. Commit cf4108d (v0.1.94) - "Add simp rules 4 `&Int` assoc"

- **Purpose**: Add associativity simplification rules for bitwise operations
- **Modified Files**:
  - `src/kriscv/kdist/riscv-semantics/lemmas/int-simplifications.md` - Added 12 lines of new simplification rules implementing associativity and commutativity for bitwise AND operations, enabling more aggressive optimization of complex bitwise expressions
- **Functional Improvements**:
  - Added 12 lines of new simplification rules
  - Optimized bitwise operation performance

20. Commit c2d312e (v0.1.93) - "Add property `proof_show` to `SymTools`"

- **Purpose**: Add proof display property to symbolic tools
- **Modified Files**:
  - `src/kriscv/symtools.py` - Added `proof_show` property to control proof output display, allowing users to enable/disable detailed proof information during symbolic execution
  - `src/kriscv/tools.py` - Updated tool integration to respect proof display settings and route proof output appropriately
  - `src/kriscv/utils.py` - Added utility functions for proof formatting and display, including proper handling of proof trees and step-by-step execution traces
- **Functional Improvements**:
  - Added 69 lines of new code
  - Enhanced proof display functionality
  - Added symbolic configuration tests

21. Commit 0949ca5 (v0.1.92) - "Update dependency: deps/k_release"

- **Purpose**: Update K dependency version
- **Modified Files**:
  - `deps/k_release` - Updated to newer K framework version to get latest bug fixes, performance improvements, and new features for better semantic analysis
- **Functional Improvements**:
  - Obtained latest K framework features

22. Commit f680218 (v0.1.91) - "Refactor RISC-V semantics to replace `Word` with `Int`"

- **Purpose**: Refactor RISC-V semantics to replace Word with Int

- **Modified Files**:
  - `src/kriscv/kdist/riscv-semantics/riscv.md` - Comprehensive refactoring of all instruction semantics to use Int instead of Word for program counter, memory addresses, and register values, simplifying type management
  - `src/kriscv/kdist/riscv-semantics/word.md` - Updated Word module to work with Int-based system while maintaining backward compatibility for existing Word operations
  - `src/kriscv/term_builder.py` - Modified Python term builder to generate Int-based terms instead of Word-based terms, updating all term construction logic
  - `src/kriscv/tools.py` - Updated tools to use Int-based semantics, including configuration parsing and result formatting
  - Multiple test files - Updated all test cases to use Int-based expectations and assertions instead of Word-based ones

- **Functional Improvements**:
  - Changed program counter, memory addresses, register values to use Int
  - Simplified type handling
  - Affected 17 files, optimized code structure

23. Commit cba2d2b (v0.1.90) - "Enable instantiating symbolic config"

- **Purpose**: Enable symbolic configuration instantiation
- **Modified Files**:
  - `src/kriscv/__main__.py` - Added command-line interface for symbolic configuration instantiation, allowing users to create symbolic configurations from ELF files
  - `src/kriscv/sparse_bytes.py` - Enhanced sparse bytes implementation to support symbolic byte generation and manipulation
  - `src/kriscv/symtools.py` - Added symbolic configuration instantiation methods to symbolic tools, enabling creation of symbolic initial states
  - `src/kriscv/term_builder.py` - Updated term builder to handle symbolic configuration construction with proper variable binding and constraint generation
  - `src/kriscv/tools.py` - Added tools for symbolic configuration management, including validation and serialization
  - Added `src/tests/integration/test_config_from_elf.py` - New test suite with 104 lines testing symbolic configuration instantiation from ELF files, including various scenarios and edge cases

- **Functional Improvements**:
  - Added symbolic configuration instantiation capability
  - Refactored toolchain to support symbolic execution
  - Added 104 lines of configuration test cases

24. Commit d411af1 (v0.1.89) - "Write temporary test data into separate folders by default"

- **Purpose**: Write temporary test data into separate folders by default
- **Modified Files**:
  - `src/tests/conftest.py` - Modified test configuration to create separate temporary directories for each test worker, preventing race conditions and test interference by ensuring each test has its own isolated workspace
- **Functional Improvements**:
  - Resolved race conditions between test workers
  - Improved test reliability

25. Commit 759923e (v0.1.88) - "Inline the `<test>` cell"

- **Purpose**: Inline the test cell
- **Modified Files**:
  - `src/kriscv/kdist/riscv-semantics/riscv.md` - Inlined test cell configurations directly into the main semantics file, ensuring user-specified configuration parts have a single root node for better parsing
  - Multiple test specification files - Updated all test specifications to work with the inlined test cell structure, maintaining compatibility while improving organization
- **Functional Improvements**:
  - Ensured user-specified configuration part has single root node
  - Optimized serialization of parseable claims

26. Commit 202c19a (v0.1.87) - "Transform function `branchPC` to effect function `#PC_BRANCH`"

- **Purpose**: Transform branch PC function to effect function
- **Modified Files**:
  - `src/kriscv/kdist/riscv-semantics/riscv.md` - Refactored branch PC handling from a pure function `branchPC` to an effect function `#PC_BRANCH`, improving semantic consistency and enabling better optimization of branch instructions
- **Functional Improvements**:
  - Refactored branch handling logic
  - Improved semantic consistency

27. Commit 25b7057 (v0.1.86) - "Consolidate ELF file handling under class `ELF`"

- **Purpose**: Consolidate ELF file handling under ELF class
- **Modified Files**:
  - `src/kriscv/elf_parser.py` - Added 124 lines of new ELF class implementation, consolidating all ELF file operations including parsing, symbol resolution, and section handling into a single cohesive interface
  - `src/kriscv/__main__.py` - Updated command-line interface to use the new ELF class for file operations
  - `src/kriscv/term_builder.py` - Modified term builder to use consolidated ELF interface for symbol resolution and address mapping
  - `src/kriscv/tools.py` - Updated tools to use the new ELF class for file handling and configuration generation
- **Functional Improvements**:
  - Added 124 lines of code
  - Consolidated ELF file handling logic
  - Improved code organization structure

Optimization and Simplification Rules

28. Commit bb2934c (v0.1.85) - "Add simp rules for `Int2Bytes o Bytes2Int`"

- **Purpose**: Add simplification rules for integer-byte conversion
- **Modified Files**:
  - `src/kriscv/kdist/riscv-semantics/lemmas/bytes-simplifications.md` - Added 9 lines of new simplification rules for `Int2Bytes(Bytes2Int(...))` patterns, optimizing round-trip conversions that can be eliminated or simplified
- **Functional Improvements**:
  - Added 9 lines of new simplification rules

29. Commit 4c53805 (v0.1.84) - "Add simp rules for `Bytes2Int o |Int o Bytes2Int`"

- **Purpose**: Add simplification rules for byte-integer bitwise OR operations
- **Modified Files**:
  - `src/kriscv/kdist/riscv-semantics/lemmas/bytes-simplifications.md` - Added sophisticated simplification rules for complex expressions involving byte-to-integer conversion, bitwise OR operations, and conversion back to bytes
- **Functional Improvements**:
  - Optimized complex byte bitwise operations

30. Commit 803850d (v0.1.83) - "simplify patterns `Bytes2Int o <<Int` & `Bytes2Int o >>Int` & chop"

- **Purpose**: Simplify byte-integer shift operation patterns
- **Modified Files**:
  - `src/kriscv/kdist/riscv-semantics/lemmas/bytes-simplifications.md` - Added rules to simplify `Bytes2Int(B) << N` and `Bytes2Int(B) >> N` patterns, along with chop operations that can be optimized when combined with byte operations
- **Functional Improvements**:
  - Optimized shift operation handling

31. Commit c157326 (v0.1.82) - "Add simp rules for `replaceAtBytes`"

- **Purpose**: Add simplification rules for byte replacement
- **Modified Files**:
  - `src/kriscv/kdist/riscv-semantics/lemmas/bytes-simplifications.md` - Added rules to optimize `replaceAtBytes` operations, particularly for cases where the replacement can be simplified or combined with other byte operations
- **Functional Improvements**:
  - Optimized byte replacement operations

32. Commit e2369f6 (v0.1.81) - "Add simp rules for `substrBytes(A +Bytes B, I, J)`"

- **Purpose**: Add simplification rules for substring of byte concatenation
- **Modified Files**:
  - `src/kriscv/kdist/riscv-semantics/lemmas/bytes-simplifications.md` - Added rules to simplify substring operations on concatenated byte strings, optimizing cases where the substring can be taken directly from one of the components
- **Functional Improvements**:
  - Optimized substring operations on byte concatenation

33-35. Commits a5b98f5, 81d5723 (v0.1.80, v0.1.79) - "Update dependency: deps/k_release"

- **Purpose**: Update K dependency version
- **Functional Improvements**:
  - Maintained compatibility with latest K framework

36. Commit 66ddeca (v0.1.78) - "Simplify pattern `Bytes2Int o substrBytes &Int 65280`"

- **Purpose**: Simplify byte-integer bitwise AND with 65280
- **Modified Files**:
  - `src/kriscv/kdist/riscv-semantics/lemmas/bytes-simplifications.md` - Added specific optimization for `Bytes2Int(substrBytes(...)) & 65280` patterns, which commonly occur in byte manipulation operations
- **Functional Improvements**:
  - Optimized specific bitwise operation patterns

37. Commit 79bf2fd (v0.1.77) - "Add simp rule to eliminate `SignExtend`"

- **Purpose**: Add simplification rules to eliminate sign extension
- **Modified Files**:
  - `src/kriscv/kdist/riscv-semantics/lemmas/int-simplifications.md` - Added rules to eliminate redundant sign extension operations, particularly when the value is already in the correct format
- **Functional Improvements**:
  - Optimized sign extension handling

38. Commit 4dcaa6f (v0.1.76) - "Tackle unexpected pattern for `pickfront` and `dropfront`"

- **Purpose**: Handle unexpected patterns for pickfront and dropfront
- **Modified Files**:
  - `src/kriscv/kdist/riscv-semantics/lemmas/sparse-bytes-simplifications.md` - Added rules to handle edge cases in `pickfront` and `dropfront` operations that weren't covered by existing simplifications
- **Functional Improvements**:
  - Improved sparse byte front-end operations

39. Commit 72ad19b (v0.1.75) - "Add simp rule for `<<Int o <<Int`"

- **Purpose**: Add simplification rules for consecutive left shifts
- **Modified Files**:
  - `src/kriscv/kdist/riscv-semantics/lemmas/int-simplifications.md` - Added rule to combine consecutive left shifts: `(X << A) << B` becomes `X << (A + B)` when safe
- **Functional Improvements**:

- Optimized consecutive left shift operations

40. Commit 8090120 (v0.1.74) - "Avoid ambiguity for Word expressions"

- **Purpose**: Avoid ambiguity in Word expressions
- **Modified Files**:
  - `src/kriscv/kdist/riscv-semantics/word.md` - Updated Word expression parsing to eliminate ambiguity in operator precedence and associativity rules
- **Functional Improvements**:
  - Improved Word expression parsing

41. Commit 0c40c65 (v0.1.73) - "Make `Word` shift operations `total`"

- **Purpose**: Make Word shift operations total
- **Modified Files**:
  - `src/kriscv/kdist/riscv-semantics/word.md` - Made Word shift operations total functions by defining behavior for all possible shift amounts, including out-of-range values
- **Functional Improvements**:
  - Improved shift operation definitions

42. Commit 58d1958 (v0.1.72) - "Add new lemmas for `substrBytes` and update `pickFront` rule"

- **Purpose**: Add new lemmas for sub-byte strings and update pickFront rule
- **Modified Files**:
  - `src/kriscv/kdist/riscv-semantics/lemmas/sparse-bytes-simplifications.md` - Added new lemmas for `substrBytes` operations and updated `pickFront` rule to handle more cases correctly
- **Functional Improvements**:
  - Added new sparse byte simplification rules

43. Commit 883fd6e (v0.1.71) - "Remove the `format` attribute from `Word`"

- **Purpose**: Remove format attribute from Word
- **Modified Files**:
  - `src/kriscv/kdist/riscv-semantics/word.md` - Removed the `format` attribute from Word definitions, simplifying the Word type and eliminating unnecessary complexity
- **Functional Improvements**:
  - Simplified Word definition

Symbolic Execution Improvements

44. Commit ec95dd6 (v0.1.70) - "Better `loadBytes` for symbolic execution"

- **Purpose**: Improve loadBytes operation for symbolic execution
- **Modified Files**:
  - `src/kriscv/kdist/riscv-semantics/sparse-bytes.md` - Enhanced `loadBytes` implementation for symbolic execution by adding better handling of symbolic addresses and symbolic memory content
- **Functional Improvements**:
  - Optimized memory loading in symbolic execution

45. Commit 3a2bbc0 (v0.1.69) - "Better `storeBytes` for symbolic execution"

- **Purpose**: Improve storeBytes operation for symbolic execution
- **Modified Files**:
  - `src/kriscv/kdist/riscv-semantics/sparse-bytes.md` - Enhanced `storeBytes` implementation for symbolic execution by improving handling of symbolic writes and memory aliasing
- **Functional Improvements**:
  - Optimized memory storing in symbolic execution

46. Commit 85e3216 (v0.1.68) - "Add option `--depth` to `kriscv run`"

- **Purpose**: Add depth option to kriscv run
- **Modified Files**:
  - `src/kriscv/__main__.py` - Added `--depth` command-line option to control execution depth in symbolic execution and simulation modes
  - `src/kriscv/tools.py` - Updated tools to respect depth limits and provide appropriate feedback when limits are reached
- **Functional Improvements**:
  - Enhanced runtime control options

47. Commit 60f10e1 (v0.1.67) - "Add simplification rule for storing symbolic bytes"

- **Purpose**: Add simplification rules for symbolic byte storage
- **Modified Files**:
  - `src/kriscv/kdist/riscv-semantics/lemmas/sparse-bytes-simplifications.md` - Added rules to optimize symbolic byte storage operations, particularly for cases where symbolic values can be reasoned about statically
- **Functional Improvements**:

- Optimized symbolic byte storage operations

48-50. Commits 778e705, 53567c0, 951e6e7 (v0.1.66, v0.1.65, v0.1.64) - "Update dependency: deps/k_release"

- **Purpose**: Update K dependency version
- **Functional Improvements**:
  - Maintained compatibility with latest K framework

51. Commit 8f5e5b7 (v0.1.63) - "Add Byte simplification rules from evm semantics"

- **Purpose**: Add byte simplification rules from EVM semantics
- **Modified Files**:
  - `src/kriscv/kdist/riscv-semantics/lemmas/bytes-simplifications.md` - Ported proven byte simplification rules from EVM semantics, including optimizations for byte array operations that have been battle-tested in Ethereum verification
- **Functional Improvements**:
  - Leveraged optimization experience from EVM semantics

52. Commit c6b16ef (v0.1.62) - "Support symbolic sparse bytes generation via `SparseBytes`"

- **Purpose**: Support symbolic sparse bytes generation via SparseBytes
- **Modified Files**:
  - `src/kriscv/sparse_bytes.py` - Added 190 lines of new code implementing complete sparse bytes support with symbolic generation capabilities, including efficient representation of sparse memory regions
  - `src/kriscv/term_builder.py` - Updated term builder to handle sparse bytes construction and manipulation
  - `src/tests/unit/test_sparse_bytes.py` - Added 152 lines of comprehensive unit tests covering all aspects of sparse bytes functionality
- **Functional Improvements**:
  - Added complete sparse bytes support
  - Significantly enhanced symbolic execution capabilities

53. Commit 2755c4c (v0.1.61) - "Add `writeByteBF` simplification rules"

- **Purpose**: Add writeByteBF simplification rules
- **Modified Files**:

- `src/kriscv/kdist/riscv-semantics/lemmas/sparse-bytes-simplifications.md` - Added simplification rules for `writeByteBF` operations, optimizing byte-level write operations in sparse memory representations
- **Functional Improvements**:
  - Optimized byte write operations

54. Commit 98eea27 (v0.1.60) - "Add symbolic execution rules for `readByteBF` in `sparse-bytes.md` "

- **Purpose**: Add symbolic execution rules for readByteBF in sparse bytes
- **Modified Files**:
  - `src/kriscv/kdist/riscv-semantics/sparse-bytes.md` - Added symbolic execution rules for `readByteBF` operations, enabling better symbolic reasoning about byte-level memory reads
- **Functional Improvements**:
  - Improved byte reading in symbolic execution

55. Commit 74dc542 (v0.1.59) - "Allow `--temp-dir` option for `test-prove` "

- **Purpose**: Allow temporary directory option for test-prove
- **Modified Files**:
  - `src/kriscv/symtools.py` - Added `--temp-dir` option to `test-prove` command, allowing users to specify custom temporary directories for proof artifacts
- **Functional Improvements**:
  - Enhanced test tool flexibility

56. Commit 1e43e19 (v0.1.58) - "Enhance SymTools with bug report integration"

- **Purpose**: Enhance symbolic tools with bug report integration
- **Modified Files**:
  - `src/kriscv/symtools.py` - Added `bug_report` parameter to symbolic tools, enabling automatic bug report generation when verification fails or encounters errors
- **Functional Improvements**:
  - Added bug_report parameter
  - Improved debugging capabilities

57. Commit 76f893a (v0.1.57) - "Add command `kriscv-asm <instruction>` "

- **Purpose**: Add kriscv-asm instruction command
- **Modified Files**:

- `src/kriscv/devtools.py` - Added new development tool for generating assembly instructions, including encoding and decoding capabilities
- `pyproject.toml` - Added new console script entry point for the `kriscv-asm` command

- **Functional Improvements**:
  - Added assembly instruction generation tool
  - Convenient for building test cases

58. Commit 9f4184e (v0.1.56) - "Update dependency: deps/k_release"

- **Purpose**: Update K dependency version
- **Functional Improvements**:
  - Kept dependencies up to date

59. Commit 0526095 (v0.1.55) - "Add job for notifying dependents"

- **Purpose**: Add job for notifying dependents
- **Modified Files**:
  - `.github/workflows/update.yml` - Added GitHub Actions job to automatically notify dependent projects when new versions are released

- **Functional Improvements**:
  - Improved CI/CD workflow

60. Commit ae15f5d (v0.1.54) - "Add symbolic execution support"

- **Purpose**: Add symbolic execution support
- **Modified Files**:
  - `src/kriscv/kdist/plugin.py` - Added plugin support for symbolic execution, enabling extensible symbolic execution capabilities
  - `src/kriscv/kdist/riscv-semantics/riscv.md` - Updated RISC-V semantics to support symbolic execution with proper symbolic state handling
  - `src/kriscv/symtools.py` - Added 101 lines of new symbolic execution tools, including configuration, execution, and result analysis
  - `src/tests/integration/test_prove.py` - Added 58 lines of integration tests for symbolic execution and proof capabilities

- **Functional Improvements**:
  - Added complete symbolic execution support
  - Significantly enhanced verification capabilities

61. Commit 344cc7e (v0.1.53) - "Factor out `runtime` from `Tools`"

- **Purpose**: Factor out runtime from Tools
- **Modified Files**:
  - `src/kriscv/tools.py` - Refactored tools to separate runtime concerns from tool logic, improving code organization and enabling better testing
- **Functional Improvements**:
  - Improved code organization structure

62. Commit b8bf5d2 (v0.1.52) - "Implement `MUL*` instructions"

- **Purpose**: Implement MUL* instructions
- **Modified Files**:
  - `src/kriscv/kdist/riscv-semantics/riscv-disassemble.md` - Added disassembly support for M extension multiply instructions including MUL, MULH, MULHU, and MULHSU
  - `src/kriscv/kdist/riscv-semantics/riscv-instructions.md` - Added instruction definitions and encoding information for all multiply instructions
  - `src/kriscv/kdist/riscv-semantics/riscv.md` - Implemented complete semantics for multiply instructions with proper handling of overflow and signed/unsigned variants
  - `src/kriscv/kdist/riscv-semantics/word.md` - Added word-level multiply operations and helper functions
  - `src/tests/integration/test_functions.py` - Added 126 lines of comprehensive tests covering all multiply instruction variants and edge cases
- **Functional Improvements**:
  - Added M extension disassembler support
  - Implemented MUL, MULH, MULHU, MULHSU instructions
  - Added comprehensive multiplication tests

63. Commit 79552f6 (v0.1.51) - "Add option `--zero-init` "

- **Purpose**: Add zero initialization option
- **Modified Files**:
  - `src/kriscv/tools.py` - Added `--zero-init` option to initialize memory and registers to zero at startup, useful for deterministic testing and debugging
- **Functional Improvements**:
  - Enhanced initialization options

Appendix: Table of zkEVM Test Specifications

Test ID	Template	Context	Symbolic Names
stop-test	stop-test		
add-test	simple-2-op-test	opcode: 0x01 expected: op1.wrapping_add(op0)	OP0, OP1
mul-test	simple-2-op-test	opcode: 0x02 expected: op1.wrapping_mul(op0)	OP0, OP1
sub-test	simple-2-op-test	opcode: 0x03 expected: op1.wrapping_sub(op0)	OP0, OP1
div-test	simple-2-op-test	opcode: 0x04 expected: op1.wrapping_div(op0)	OP0, OP1

sdiv-test	simple-2-op-test	opcode: 0x05
		expected:
		`use revm_interpreter::instructions::i256::i256_div;`
		`i256_div(op1, op0)`
			OP0, OP1

mod-test	simple-2-op-test	opcode: 0x06 expected: op1.wrapping_rem(op1)	OP0, OP1

smod-test	simple-2-op-test	opcode: 0x07
		expected:
		`use revm_interpreter::instructions::i256::i256_mod;`
		`i256_mod(op1, op0)`
			OP0, OP1

addmod-test	simple-3-op-test	opcode: 0x08 expected: op2.add_mod(op1, op0)	OP0, OP1, OP2
mulmod-test	simple-3-op-test	opcode: 0x09 expected: op2.mul_mod(op1, op0)	OP0, OP1, OP2

Test ID	Template	Context	Symbolic Names
exp-test	simple-2-op-test	opcode: 0x0a expected: op1.pow(op0)	OP0, OP1

signextend-test	simple-2-op-test	opcode: 0x0b
		expected:
		`if op1 < U256::from(31) {`
		`  let op1 = op1.as_limbs()[0];`
		`  let bit_index = (8 * op1 + 7) as usize;`
		`  let bit = op0.bit(bit_index);`
		`  let mask = (U256::from(1) << bit_index) - U256::from(1);`
		`  if bit {`
		`  op0 | !mask`
		`  } else {`
		`  op0 & mask`
		`  }`
		`} else {`
		`  op0`
		`}`
			OP0, OP1

lt-test	simple-2-op-test	opcode: 0x10 expected: U256::from(op1 < op0)	OP0, OP1
gt-test	simple-2-op-test	opcode: 0x11 expected: U256::from(op1 > op0)	OP0, OP1

slt-test	simple-2-op-test	opcode: 0x12
		expected:
		`use core::cmp::Ordering;`
		`use revm_interpreter::instructions::i256::i256_cmp;`
		`U256::from(i256_cmp(&op1, &op0) == Ordering::Less)`
			OP0, OP1

Test ID	Template	Context	Symbolic Names

sgt-test	simple-2-op-test	opcode: 0x13
		expected:
		`use core::cmp::Ordering;`
		`use revm_interpreter::instructions::i256::i256_cmp;`
		`U256::from(i256_cmp(&op1, &op0) == Ordering::Greater)`
			OP0 , OP1

eq-test	simple-2-op-test	opcode: 0x14 expected: U256::from(op1 == op0)	OP0 , OP1
iszero-test	simple-1-op-test	opcode: 0x15 expected: U256::from(op0.is_zero())	OP0
and-test	simple-2-op-test	opcode: 0x16 expected: op1 & op0	OP0 , OP1
or-test	simple-2-op-test	opcode: 0x17 expected: op1 | op0	OP0 , OP1
xor-test	simple-2-op-test	opcode: 0x18 expected: op1 ^ op0	OP0 , OP1
not-test	simple-1-op-test	opcode: 0x19 expected: !op0	OP0

byte-test	simple-2-op-test	opcode: 0x1a
		expected:
		`if op1 < U256::from(32) {`
		`  U256::from(op0.byte(31 - usize::try_from(op1).unwrap()))`
		`} else {`
		`  U256::ZERO`
		`}`
			OP0 , OP1

<table>
<tr><th>Test ID</th><th>Template</th><th>Context</th><th>Symbolic Names</th></tr>
<tr><td>shl-test</td><td>simple-2-op-test</td><td><table>
<tr><td>opcode</td><td>0x1b</td></tr>
<tr><td>expected</td><td><pre>
if op1 < U256::from(256) {
    op0 << op1
} else {
    U256::ZERO
}
</pre></td></tr>
</table></td><td>OP0 , OP1</td></tr>
<tr><td>shr-test</td><td>simple-2-op-test</td><td><table>
<tr><td>opcode</td><td>0x1c</td></tr>
<tr><td>expected</td><td><pre>
if op1 < U256::from(256) {
    op0 >> op1
} else {
    U256::ZERO
}
</pre></td></tr>
</table></td><td>OP0 , OP1</td></tr>
<tr><td>sar-test</td><td>simple-2-op-test</td><td><table>
<tr><td>opcode</td><td>0x1d</td></tr>
<tr><td>expected</td><td><pre>
if op1 < U256::from(256) {
op0.arithmetic_shr(usize::try_from(op1).unwrap())
} else if op0.bit(255) {
    U256::MAX
} else {
    U256::ZERO
}
</pre></td></tr>
</table></td><td>OP0 , OP1</td></tr>
<tr><td>keccak256-test</td><td>keccak256-test</td><td></td><td>DATA , OFFSET , SIZE</td></tr>
<tr><td>address-test</td><td>address-test</td><td></td><td>VALUE</td></tr>
<tr><td>origin-test</td><td>host-property-address-test</td><td><table>
<tr><td>opcode</td><td>0x32</td></tr>
<tr><td>property</td><td>env.tx.caller</td></tr>
</table></td><td>VALUE , INDEX</td></tr>
<tr><td>caller-test</td><td>caller-test</td><td></td><td>VALUE , INDEX</td></tr>
<tr><td>callvalue-test</td><td>callvalue-test</td><td></td><td>VALUE</td></tr>
</table>

Test ID	Template	Context	Symbolic Names
calldataload-test	calldataload-test		DATA , DATA_SIZE , LOAD_INDEX , INDEX
calldatasize-test	calldatasize-test		DATA , DATA_SIZE
calldatacopy-test	calldatacopy-test		DATA , DATA_SIZE , DEST_OFFSET , OFFSET , SIZE , INDEX
codesize-test	codesize-test		CODE , CODE_SIZE
codecopy-test	codecopy-test		CODE , CODE_SIZE , DEST_OFFSET , OFFSET , SIZE , INDEX
gasprice-test	host-property-u256-test	opcode: 0x3a property: env.tx.gas_price	VALUE
returndatasize-test	returndatasize-test		DATA , DATA_SIZE
returndatacopy-test	returndatacopy-test		DATA , DATA_SIZE , DEST_OFFSET , OFFSET , SIZE , INDEX
coinbase-test	host-property-address-test	opcode: 0x41 property: env.block.coinbase	VALUE , INDEX
timestamp-test	host-property-u256-test	opcode: 0x42 property: env.block.timestamp	VALUE
number-test	host-property-u256-test	opcode: 0x43 property: env.block.number	VALUE
prevrandao-test	prevrandao-test		VALUE
gaslimit-test	host-property-u256-test	opcode: 0x45 property: env.block.gas_limit	VALUE
chainid-test	chainid-test		VALUE
basefee-test	host-property-u256-test	opcode: 0x48 property: env.block.basefee	VALUE
blobhash-test	blobhash-test		INDEX , VALUE
blobbasefee-test	blobbasefee-test		VALUE
pop-test	pop-test		VALUE
mload-test	mload-test		DATA , OFFSET , INDEX

Test ID	Template	Context	Symbolic Names
mload-concrete-offset-test	mload-test		DATA
mstore-test	mstore-test		OFFSET , VALUE
mstore-concrete-offset-test	mstore-test		VALUE
mstore8-test	mstore8-test		OFFSET , VALUE
sload-test	sload-test		KEY , VALUE
sload-concrete-key-test	sload-test		VALUE
sload-concrete-value-test	sload-test		KEY
sstore-test	sstore-test		KEY , VALUE
sstore-concrete-key-test	sstore-test		VALUE
sstore-concrete-value-test	sstore-test		KEY
jump-test	jump-test		CODE , CODE_SIZE
jumpi-test	jumpi-test		CODE , CODE_SIZE , COND
pc-test	pc-test		CODE , PC
msize-test	msize-test		SIZE
gas-test	gas-test		GAS_LIMIT
tload-test	tload-test		KEY , VALUE
tload-concrete-key-test	tload-test		VALUE
tload-concrete-value-test	tload-test		KEY
tstore-test	tstore-test		KEY , VALUE
tstore-concrete-key-test	tstore-test		VALUE
tstore-concrete-value-test	tstore-test		KEY
mcopy-test	mcopy-test		DATA , DEST_OFFSET , SRC_OFFSET , SIZE , INDEX
push0-test	push-test	opcode: 0x5f n: 0	
push1-test	push-test	opcode: 0x60 n: 1	OP0
push2-test	push-test	opcode: 0x61 n: 2	OP0
push3-test	push-test	opcode: 0x62 n: 3	OP0
push4-test	push-test	opcode: 0x63 n: 4	OP0

Test ID	Template	Context	Symbolic Names
push5-test	push-test	opcode: 0x64 n: 5	OP0
push6-test	push-test	opcode: 0x65 n: 5	OP0
push7-test	push-test	opcode: 0x66 n: 7	OP0
push8-test	push-test	opcode: 0x67 n: 8	OP0
push9-test	push-test	opcode: 0x68 n: 9	OP0
push10-test	push-test	opcode: 0x69 n: 10	OP0
push11-test	push-test	opcode: 0x6a n: 11	OP0
push12-test	push-test	opcode: 0x6b n: 12	OP0
push13-test	push-test	opcode: 0x6c n: 13	OP0
push14-test	push-test	opcode: 0x6d n: 14	OP0
push15-test	push-test	opcode: 0x6e n: 15	OP0
push16-test	push-test	opcode: 0x6f n: 16	OP0
push17-test	push-test	opcode: 0x70 n: 17	OP0

Test ID	Template	Context	Symbolic Names
push18-test	push-test	opcode: 0x71 n: 18	OP0
push19-test	push-test	opcode: 0x72 n: 19	OP0
push20-test	push-test	opcode: 0x73 n: 20	OP0
push21-test	push-test	opcode: 0x74 n: 21	OP0
push22-test	push-test	opcode: 0x75 n: 22	OP0
push23-test	push-test	opcode: 0x76 n: 23	OP0
push24-test	push-test	opcode: 0x77 n: 24	OP0
push25-test	push-test	opcode: 0x78 n: 25	OP0
push26-test	push-test	opcode: 0x79 n: 26	OP0
push27-test	push-test	opcode: 0x7a n: 27	OP0
push28-test	push-test	opcode: 0x7b n: 28	OP0
push29-test	push-test	opcode: 0x7c n: 29	OP0
push30-test	push-test	opcode: 0x7d n: 30	OP0

Test ID	Template	Context	Symbolic Names
push31-test	push-test	opcode: 0x7e n: 31	OP0
push32-test	push-test	opcode: 0x7f n: 32	OP0
dup1-test	dup-test	opcode: 0x80 n: 1	OP0
dup2-test	dup-test	opcode: 0x81 n: 2	OP0
dup3-test	dup-test	opcode: 0x82 n: 3	OP0
dup4-test	dup-test	opcode: 0x83 n: 4	OP0
dup5-test	dup-test	opcode: 0x84 n: 5	OP0
dup6-test	dup-test	opcode: 0x85 n: 6	OP0
dup7-test	dup-test	opcode: 0x86 n: 7	OP0
dup8-test	dup-test	opcode: 0x87 n: 8	OP0
dup9-test	dup-test	opcode: 0x88 n: 9	OP0
dup10-test	dup-test	opcode: 0x89 n: 10	OP0
dup11-test	dup-test	opcode: 0x8a n: 11	OP0

Test ID	Template	Context	Symbolic Names
dup12-test	dup-test	opcode: 0x8b n: 12	OP0
dup13-test	dup-test	opcode: 0x8c n: 13	OP0
dup14-test	dup-test	opcode: 0x8d n: 14	OP0
dup15-test	dup-test	opcode: 0x8e n: 15	OP0
dup16-test	dup-test	opcode: 0x8f n: 16	OP0
swap1-test	swap-test	opcode: 0x90 n: 1	OP0, OP1
swap2-test	swap-test	opcode: 0x91 n: 2	OP0, OP1
swap3-test	swap-test	opcode: 0x92 n: 3	OP0, OP1
swap4-test	swap-test	opcode: 0x93 n: 4	OP0, OP1
swap5-test	swap-test	opcode: 0x94 n: 5	OP0, OP1
swap6-test	swap-test	opcode: 0x95 n: 6	OP0, OP1
swap7-test	swap-test	opcode: 0x96 n: 7	OP0, OP1
swap8-test	swap-test	opcode: 0x97 n: 8	OP0, OP1

Test ID	Template	Context	Symbolic Names
swap9-test	swap-test	opcode: 0x98 n: 9	OP0, OP1
swap10-test	swap-test	opcode: 0x99 n: 10	OP0, OP1
swap11-test	swap-test	opcode: 0x9a n: 11	OP0, OP1
swap12-test	swap-test	opcode: 0x9b n: 12	OP0, OP1
swap13-test	swap-test	opcode: 0x9c n: 13	OP0, OP1
swap14-test	swap-test	opcode: 0x9d n: 14	OP0, OP1
swap15-test	swap-test	opcode: 0x9e n: 15	OP0, OP1
swap16-test	swap-test	opcode: 0x9f n: 16	OP0, OP1
log0-test	log-test	opcode: 0xa0 n_topics: 0	DATA, OFFSET, SIZE, INDEX
log1-test	log-test	opcode: 0xa1 n_topics: 1	DATA, OFFSET, SIZE, INDEX, TOPIC_DATA, TOPIC_INDEX
log2-test	log-test	opcode: 0xa2 n_topics: 2	DATA, OFFSET, SIZE, INDEX, TOPIC_DATA, TOPIC_INDEX
log3-test	log-test	opcode: 0xa3 n_topics: 3	DATA, OFFSET, SIZE, INDEX, TOPIC_DATA, TOPIC_INDEX
log4-test	log-test	opcode: 0xa4 n_topics: 4	DATA, OFFSET, SIZE, INDEX, TOPIC_DATA, TOPIC_INDEX

Test ID	Template	Context	Symbolic Names
create-test	create-test		DATA, VALUE, OFFSET, SIZE, INDEX
return-test	return-with-output-test	opcode: 0xf3 instruction_result: Return	DATA, OFFSET, SIZE, INDEX
create2-test	create2-test		DATA, VALUE, OFFSET, SIZE, SALT, INDEX
revert-test	return-with-output-test	opcode: 0xfd instruction_result: Revert	DATA, OFFSET, SIZE, INDEX
invalid-test	invalid-test		