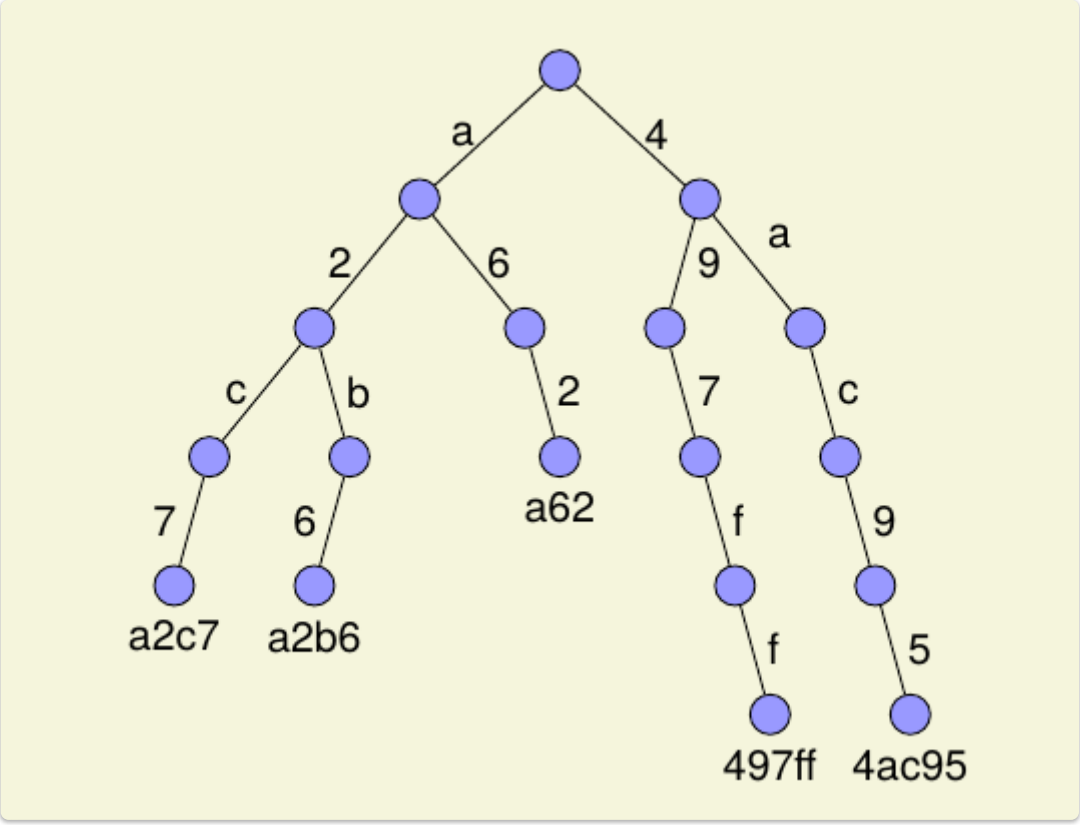
EVM Deep Dive

Topics

- Ethereum data structures
- Ethereum state
- Transaction and Block details
- The EVM
  Memory
  Storage
- EVM Languages

Ethereum Data Structures

Ethereum uses Merkle Patricia Tries / Radix Tries for their searching performance and low memory footprint.



More recent data structure is the Verkle tree which we will cover in a later lesson.

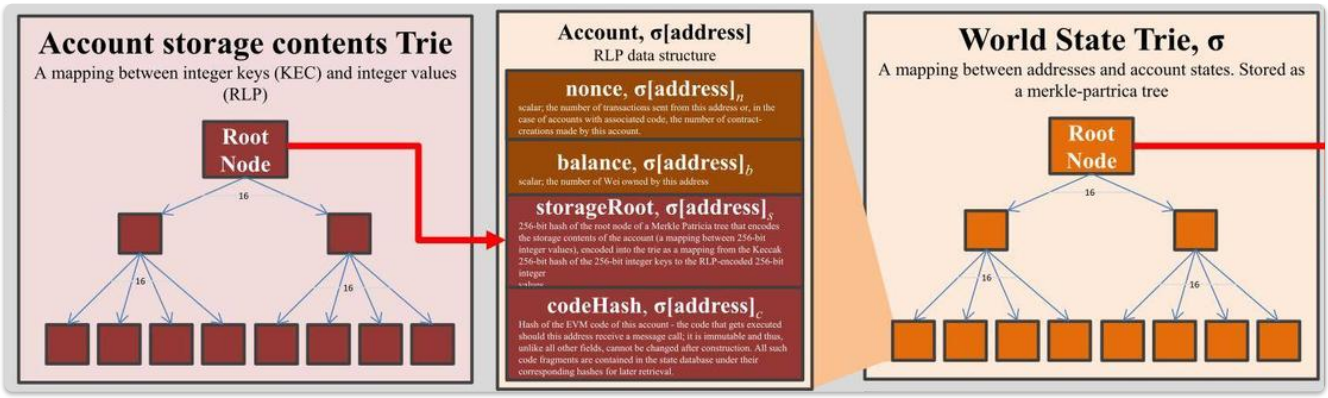
Ethereum State

There are 3 Tries

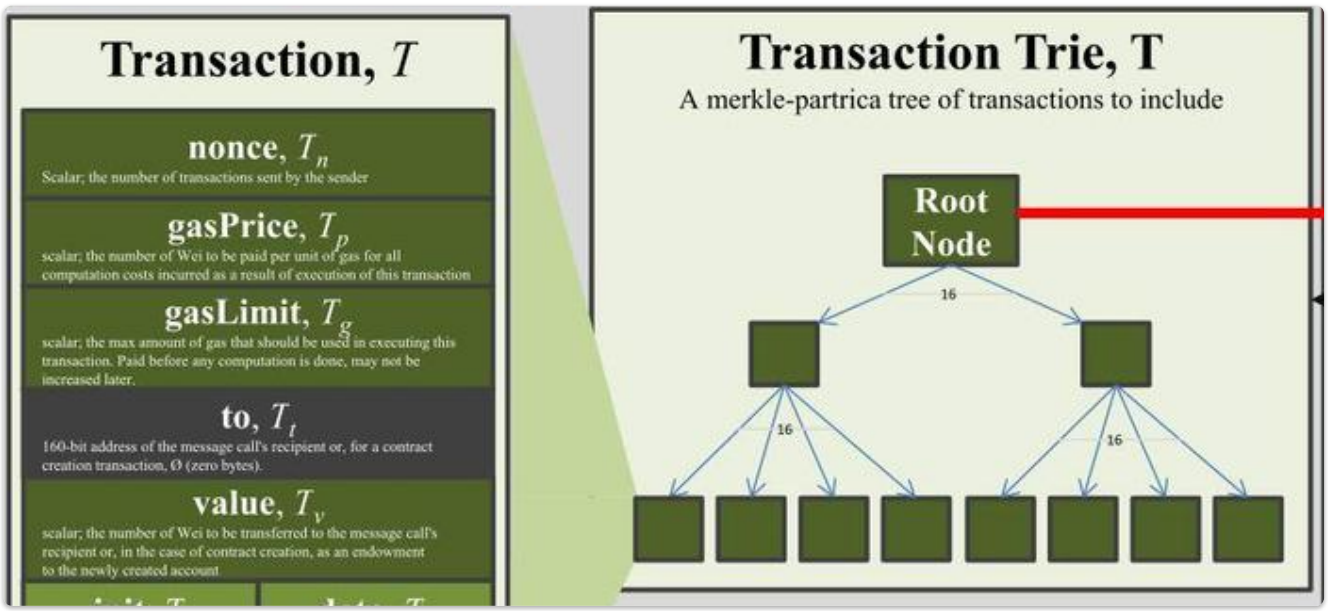
- World State
- Transaction
- Transaction Receipt

See ：Ethereum State Trie Architecture Explained**

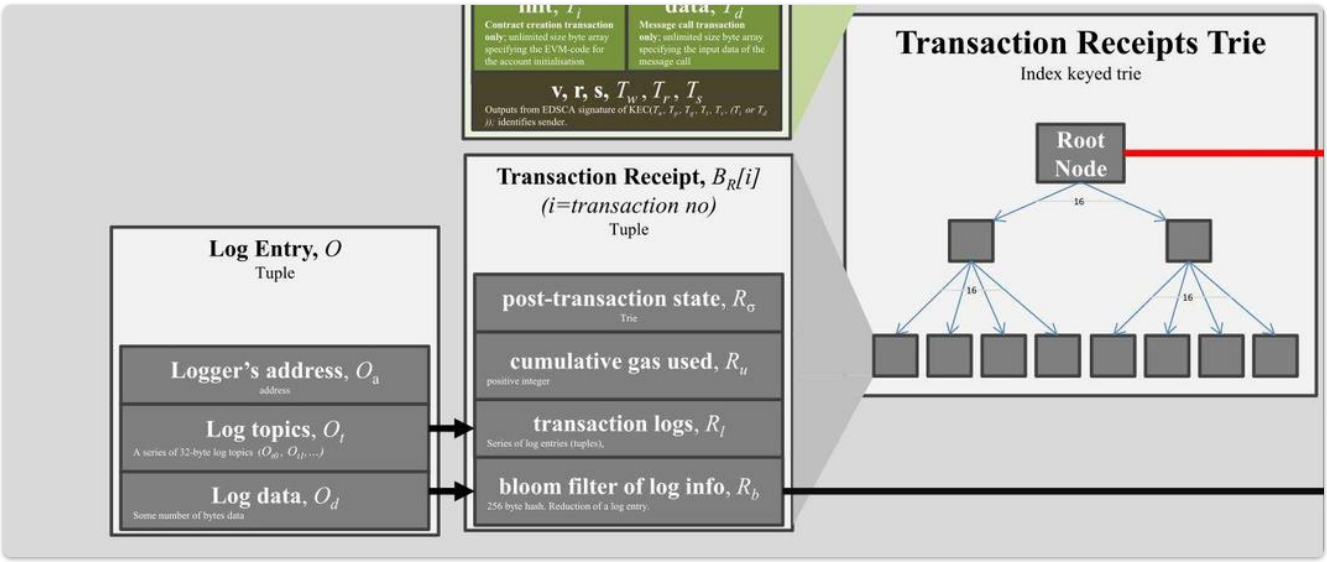
World and Account State


Account storage contents Trie
A mapping between integer keys (KEC) and integer values (RLP)
Root Node
16
16
16
Account, σ[address]
RLP data structure
nonce, σ[address]n
scalar; the number of transactions sent from this address or, in the case of accounts with associated code, the number of contract-creations made by this account.
balance, σ[address]b
scalar; the number of Wei owned by this address
storageRoot, σ[address]s
256-bit hash of the root node of a Merkle Patricia tree that encodes the storage contents of the account (a mapping between 256-bit integer values), encoded into the trie as a mapping from the Keccak 256-bit hash of the 256-bit integer keys to the RLP-encoded 256-bit integer
codeHash, σ[address]c
Hash of the EVM code of this account - the code that gets executed should this address receive a message call; it is immutable and thus, unlike all other fields, cannot be changed after construction. All such code fragments are contained in the state database under their corresponding hashes for later retrieval.
World State Trie, σ
A mapping between addresses and account states. Stored as a merkle-partrica tree
Root Node
16
16
16

Transactions



Transaction Receipts and Logs



Transaction and Transaction Receipt Tries

Purpose:

- Transaction Tries: records transaction request
- Transaction Receipt Tries: records the transaction outcome

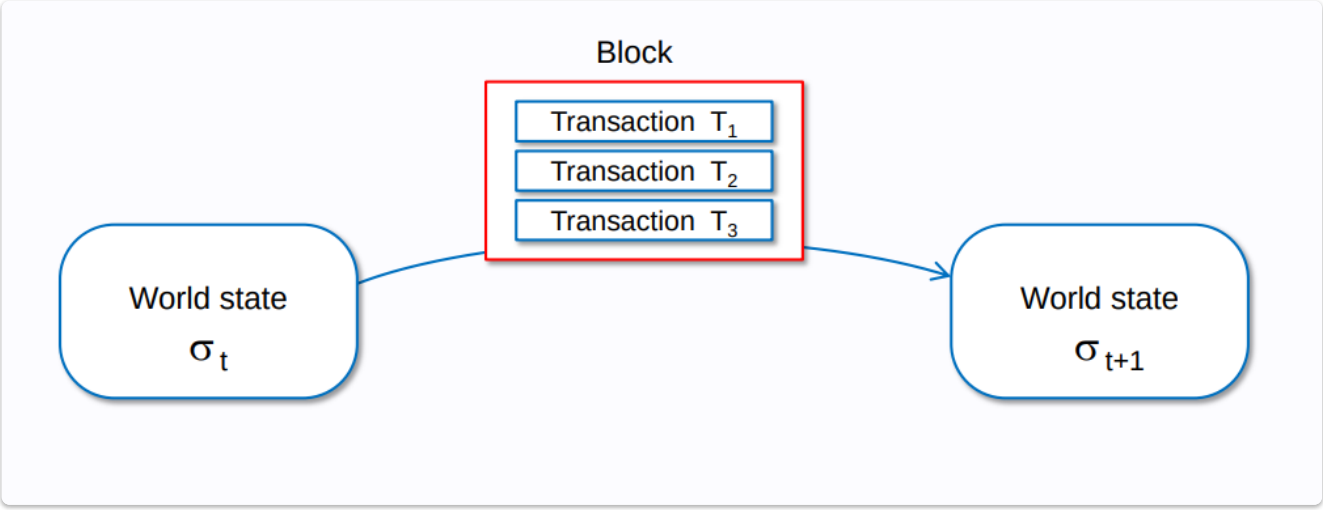
Parameters used in composing a Transaction Trie details in section 4.3 of the [yellow paper]

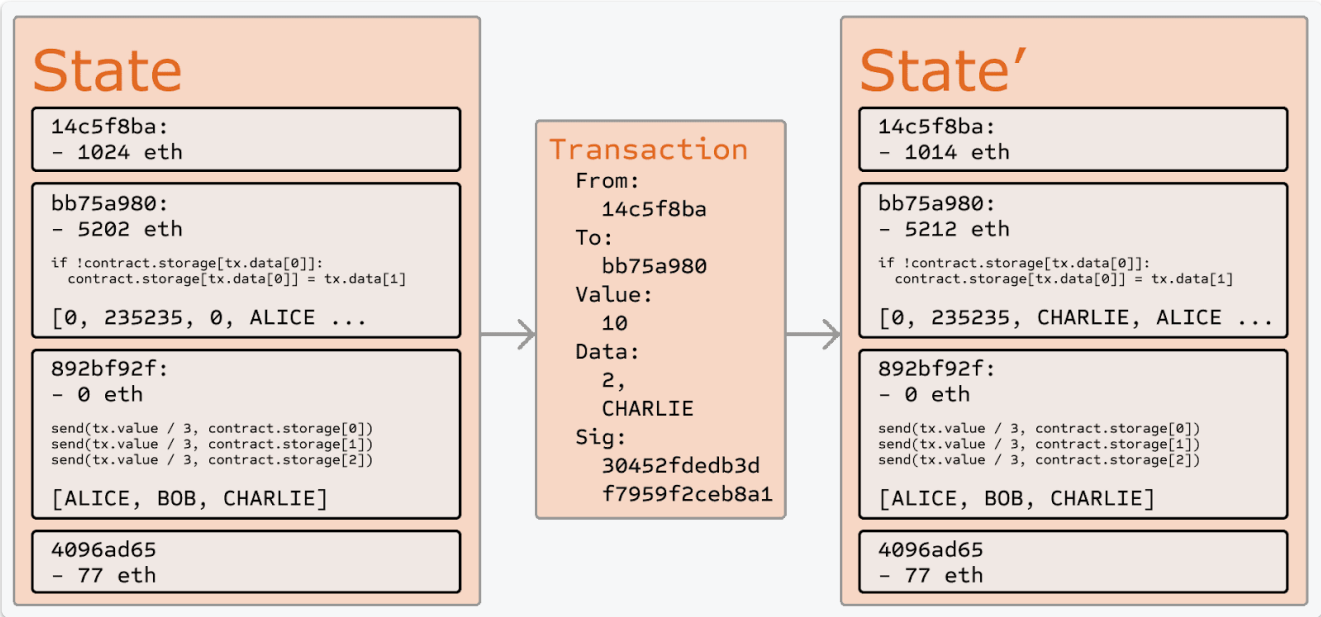
- nonce,
- gas price,
- gas limit,
- recipient,
- transfer value,
- transaction signature values, and
- account initialization (if transaction is of contract creation type), or transaction data (if transaction is a message call)

Parameters used in composing a Transaction Receipt Trie details in section 4.4.1 of the [yellow paper]:

- post-transaction state,
- the cumulative gas used,
- the set of logs created through execution of the transaction, and
- the Bloom filter composed from information in those logs

Ethereum Transactions





Some practical points about transaction selection

- Miners choose which transactions to include in a block
- Miners can add their own transactions to a block
- Miners choose the order of transactions in a block
- Your transaction is in competition with other transactions for inclusion in the block

We will talk about the consequences of these points in our MEV lesson.

Transaction Processing

Before the transaction executes it needs to pass some validity tests

- The transaction follows the rules for the encoding scheme (now Simple Serialize SSZ, previous RLP)
- The signature on the transaction is valid.
- The nonce on the transaction is valid, i.e. it is equivalent to the sender account's current nonce.
- The gas_limit is greater than or equal to the intrinsic_gas used by the transaction.
- The sender's account balance contains the cost required in up-front payment.

(For details of SSZ see docs)

View Functions and modifying state

From documentation

If the compiler's EVM target is Byzantium or newer (default) the opcode `STATICCALL` is used when `view` functions are called, which enforces the state to stay unmodified as part of the EVM execution.
For library `view` functions `DELEGATECALL` is used, because there is no combined `DELEGATECALL` and `STATICCALL`.
This means library `view` functions do not have run-time checks that prevent state modifications.

The following statements are considered modifying the state:

1. Writing to state variables.
2. Emitting events
3. Creating other contracts
4. Using `selfdestruct`.
5. Sending Ether via calls.
6. Calling any function not marked `view` or `pure`.
7. Using low-level calls.
8. Using inline assembly that contains certain opcodes.

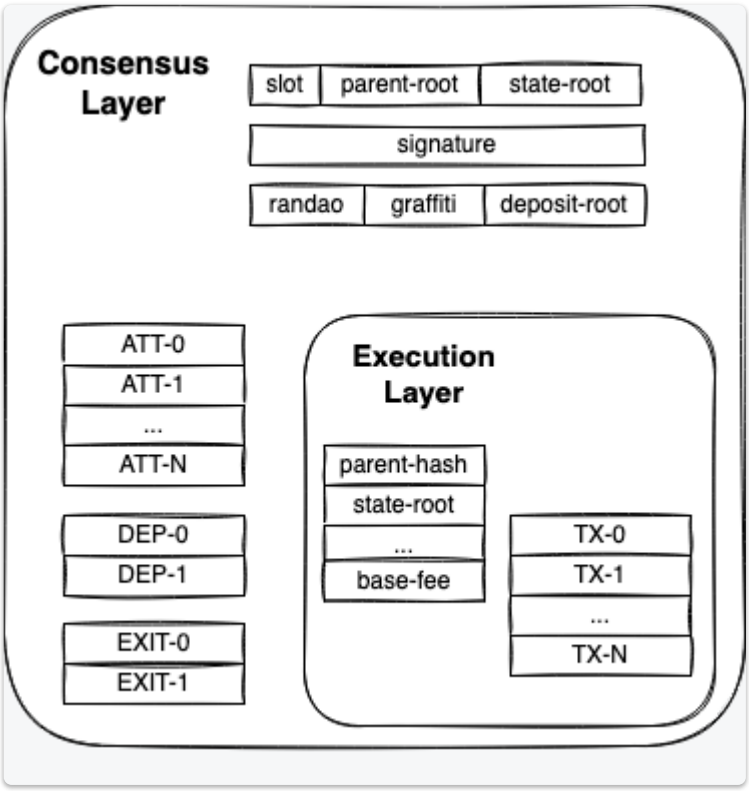
Note : Getter methods are automatically marked `view`.

Ethereum Blocks post merge

See documentation
And EIP for changes

Some block fields have been deprecated

- Ommers hash and ommers array
- Difficulty
- Mix Hash
- Nonce



Fields

slot: the slot the block belongs to
proposer_index: the ID of the validator proposing the block
parent_root: the hash of the preceding bloc
state_root: the root hash of the state object
body: an object containing several fields, as defined below

BLOCK BODY

randao_reveal: a value used to select the next block proposer
eth1_data: information about the deposit contract
graffiti: arbitrary data used to tag blocks
proposer_slashings: list of validators to be slashed
attester_slashings: list of validators to be slashed
attestations: list of attestations in favor of the current block

deposits: list of new deposits to the deposit contract
voluntary_exits: list of validators exiting the network
sync_aggregate: subset of validators used to serve light clients
execution_payload: transactions passed from the execution client

ATTESTATIONS FIELD

aggregation_bits: a list of which validators participated in this attestation
data: a container with multiple subfields
signature: aggregate signature of all attesting validators

DATA FIELD

slot: the slot the attestation relates to
index: indices for attesting validators
beacon_block_root: the root hash of the Beacon block containing this object
source: the last justified checkpoint
target: the latest epoch boundary block

EXECUTION PAYLOAD HEADER

parent_hash: hash of the parent block
fee_recipient: account address for paying transaction fees to
state_root: root hash for the global state after applying changes in this block
receipts_root: hash of the transaction receipts trie
logs_bloom: data structure containign event logs
prev_randao: value used in random validator selection
block_number: the number of the current block
gas_limit: maximum gas allowed in this block
gas_used: the actual amount of gas used in this block
timestamp: the block time
extra_data: arbitrary additional data as raw bytes
base_fee_per_gas: the base fee value
block_hash: Hash of execution block
transactions_root: root hash of the transactions in the payload

EXECUTION PAYLOAD

parent_hash: hash of the parent block
account address for paying transaction fees to
state_root: root hash for the global state after applying changes in this block
receipts_root: hash of the transaction receipts trie
logs_bloom: data structure containign event logs
prev_randao: value used in random validator selection
block_number: the number of the current block
gas_limit: maximum gas allowed in this block

gas_used: the actual amount of gas used in this block
timestamp: the block time
extra_data: arbitrary additional data as raw bytes
base_fee_per_gas: the base fee value
block_hash: Hash of execution block
transactions: list of transactions to be executed

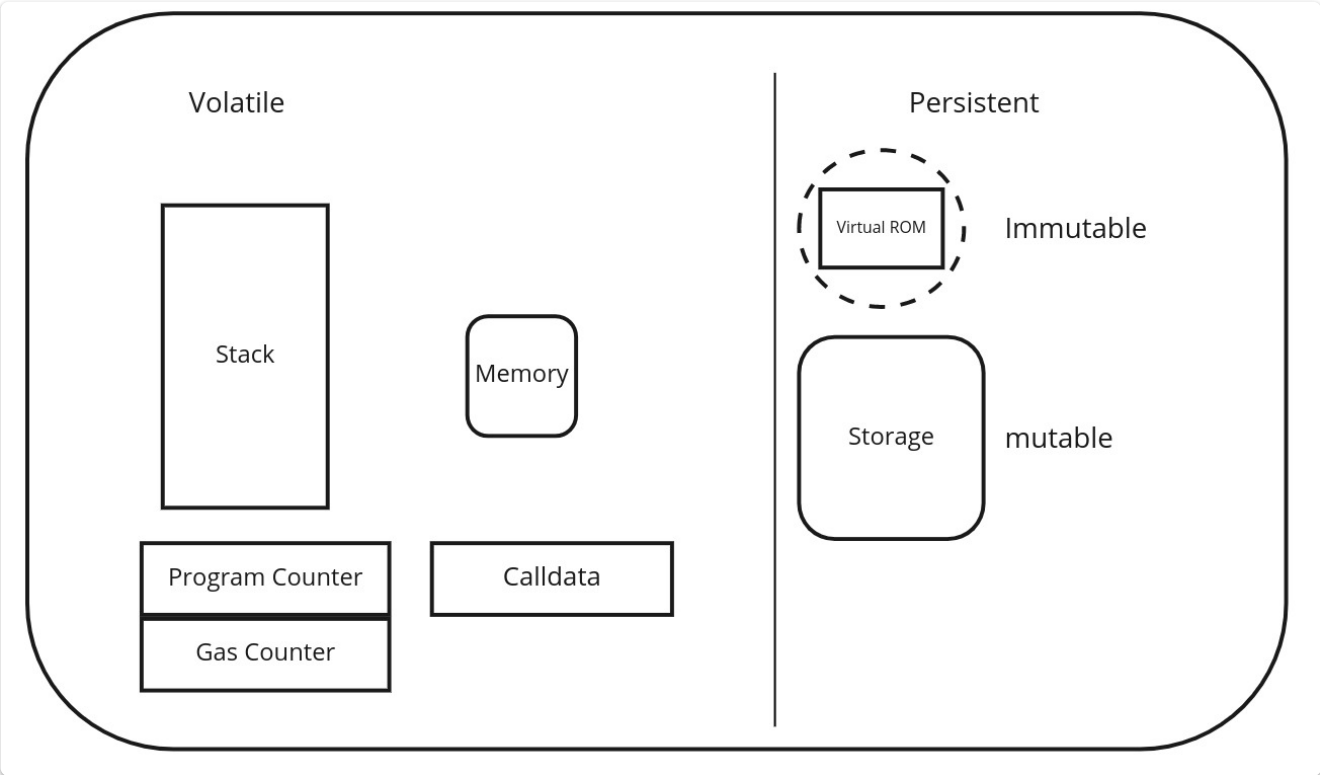
The EVM

The EVM is a stack machine , the stack has a maximum size of 1024.

Stack items have a size of 256 bits; in fact, the EVM is a 256-bit word machine (this facilitates Keccak256 hash scheme and elliptic-curve computations).

During execution 2 areas are available for variables

- memory - a transient memory which does not persist between transactions
- storage - part of a Merkle Patricia storage trie associated with the contract's account, part of the global state

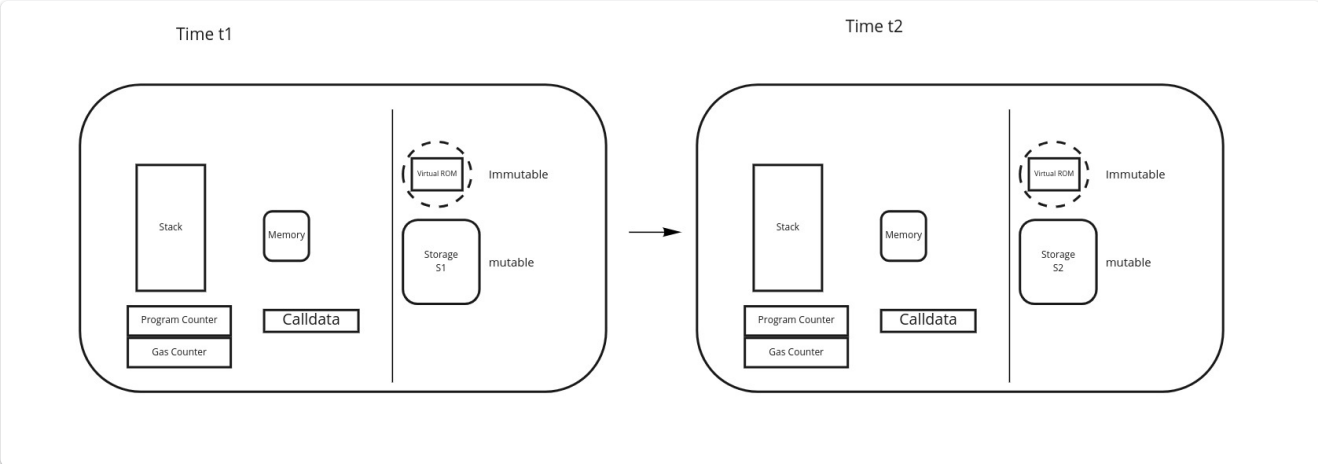


Data areas

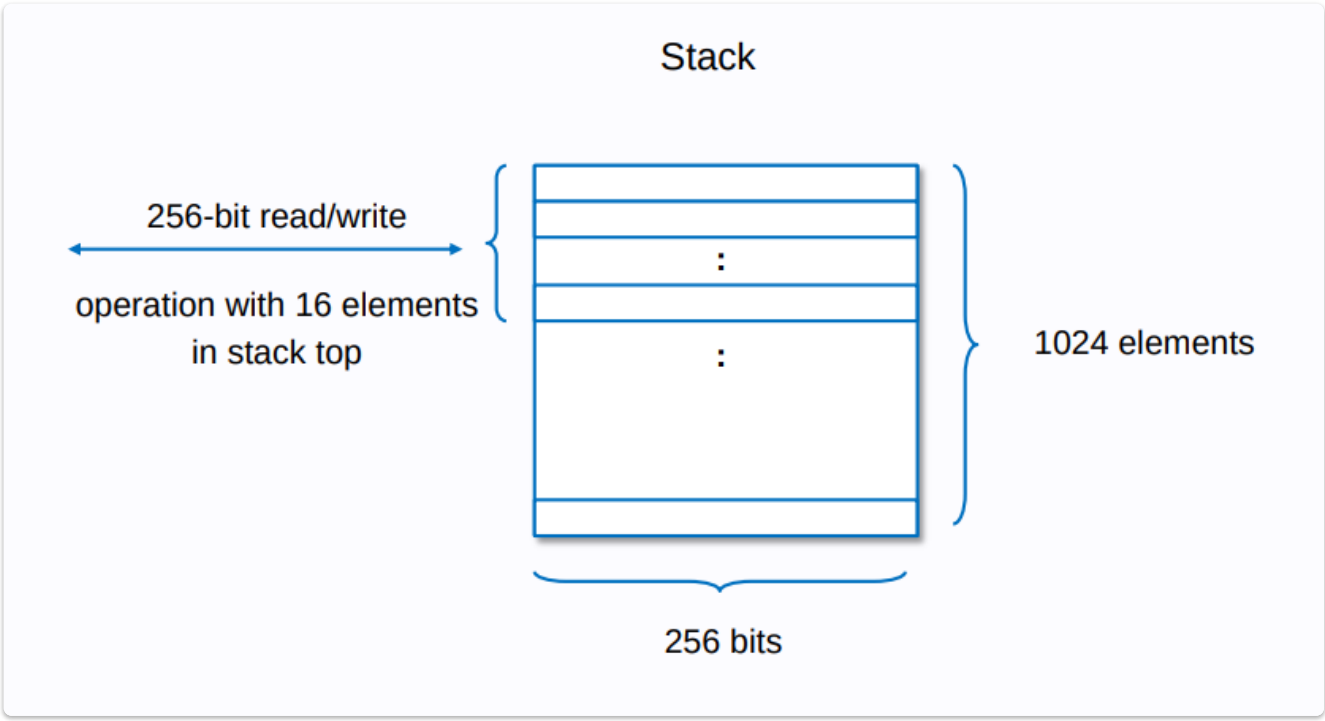
Data can be stored in

- Stack
- Calldata
- Memory
- Storage
- Code
- Logs

EVM State transition

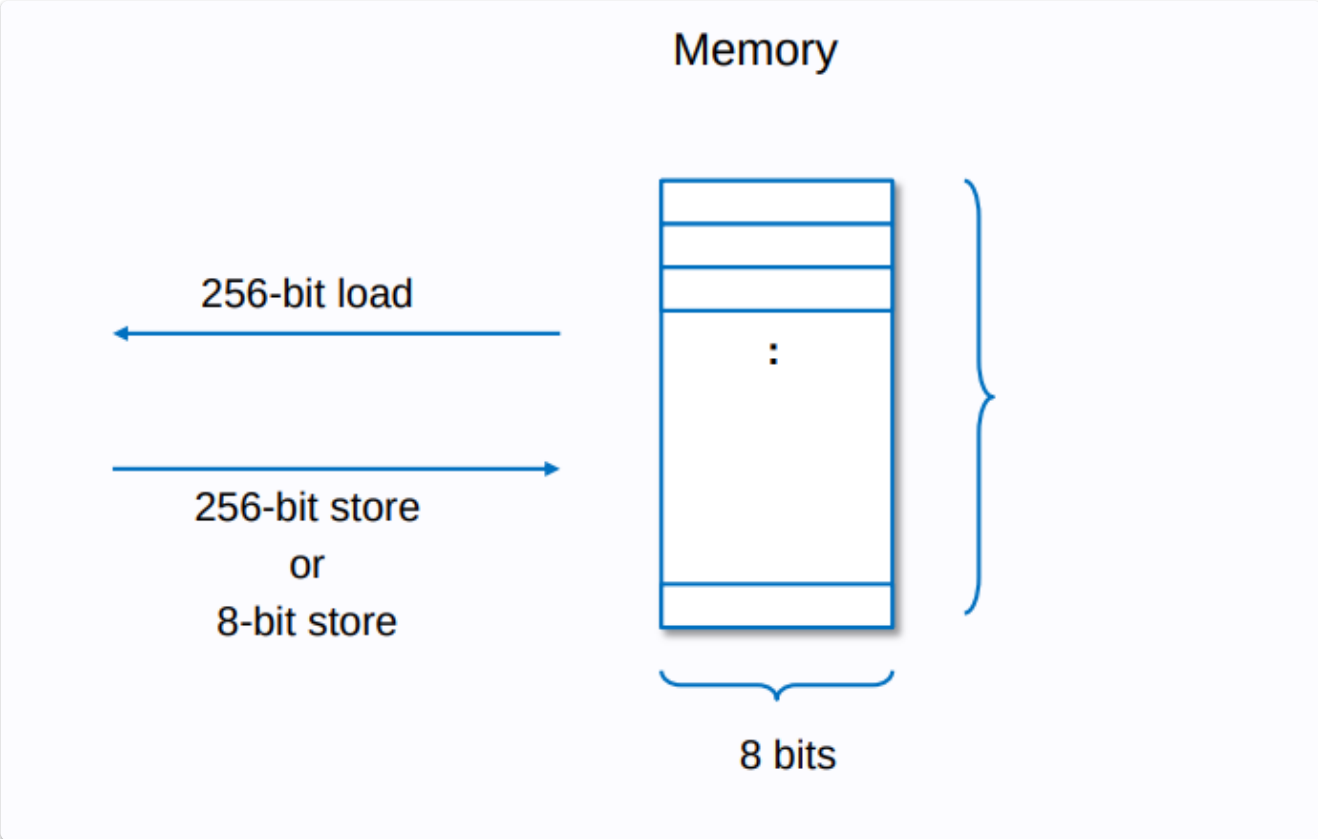


The Stack



The top 16 items can be manipulated or accessed at once (or stack too deep error)

Memory



Memory is a byte-array. Memory starts off zero-size, but can be expanded in 32-byte chunks by simply accessing or storing memory at indices greater than its current size. Since memory is contiguous, it does save gas to keep it packed and shrink its size, instead of having large patches of zeros.

- MLOAD loads a word from memory into the stack.
- MSTORE saves a word to memory.
- MSTORE8 saves a byte to memory.

MEMORY EXPANSION

From Explanation

When your contract writes to memory, you have to pay for the number of bytes written. If you are writing to an area of memory that hasn't been written to before there is an additional memory expansion cost for using it for the first time.
Memory is expanded in 32 bytes (256-bit) increments when writing to previously untouched memory space.

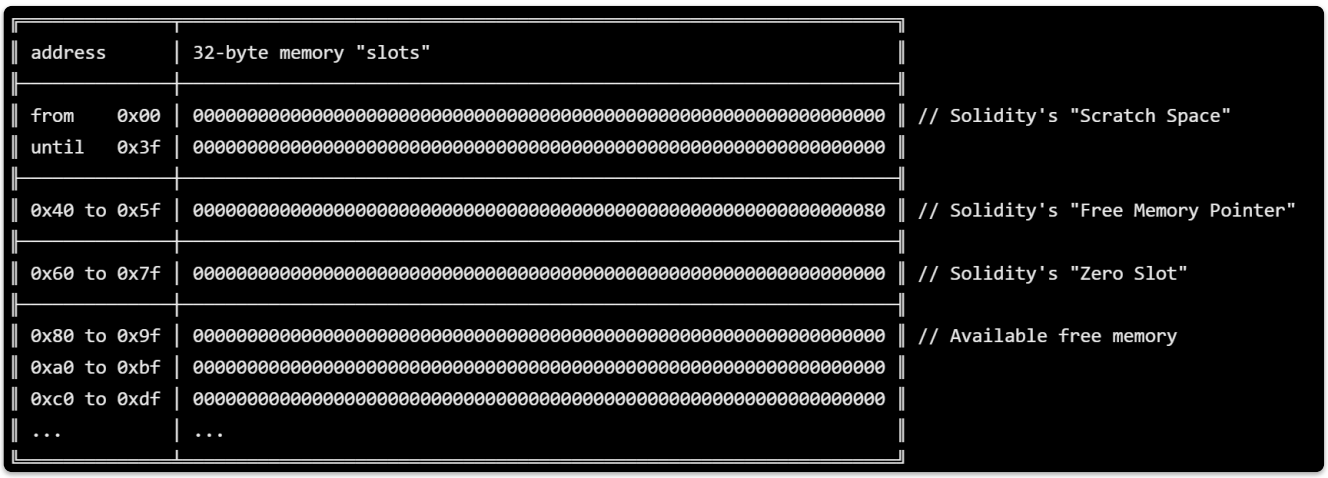
Memory expansion costs scale linearly for the first 724 bytes and quadratically after that. If you use <=724 bytes of memory the second part of the equation is 0

$$C_{\text{mem}}(a) \equiv G_{\text{memory}} \cdot a + \left\lfloor \frac{a^2}{512} \right\rfloor$$

(From the yellow paper)
"Note also that Cmem is the memory cost function (the expansion function being the difference between the cost before and after). It is a polynomial, with the higher-order coefficient divided and floored, and thus linear up to 704B of memory used, after which it costs substantially more"

Memory is a byte array. This means we can start our reads (and our writes) from any memory location. We are not constrained to multiples of 32. Memory is linear and can be addressed at the byte level. Memory can only be newly created in a function.

It can either be newly instantiated complex types like array/struct (e.g. via new int[...]) or copied from a storage referenced variable.



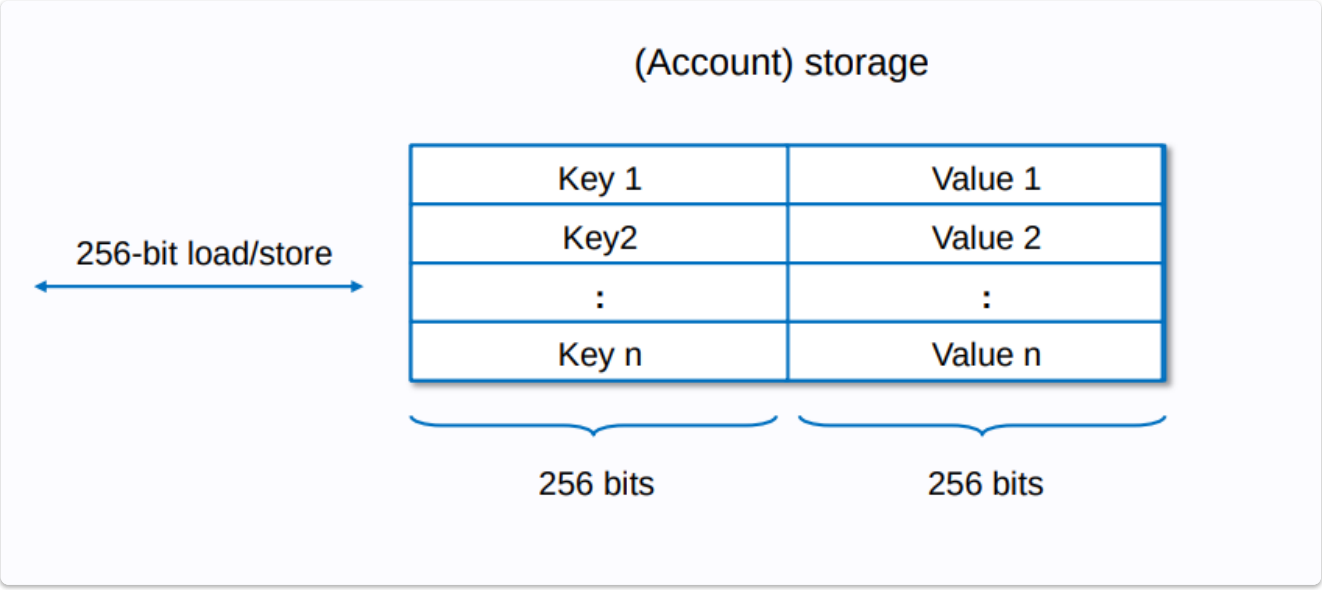
Free Memory Pointer

The free memory pointer is simply a pointer to the location where free memory starts. It ensures smart contracts keep track of which memory locations have been written to and

which haven’t.

This protects against a contract overwriting some memory that has been allocated to another variable.

Storage



See Documentation

It is useful when thinking about the storage to think about fixed size and dynamic sized variables.

FiatTokenV2_1 <<Contract>> 0xa2327a938febf5fec13bacfb16ae10ecbc4cbdcf			
slot	type: <inherited contract>.variable (bytes)		
0	unallocated (12)	address: Ownable._owner (20)	
1	unallocated (11)	bool: Pausable.paused (1)	address: Pausable.pauser (20)
2	unallocated (12)	address: Blacklistable.blacklister (20)	
3	mapping(address=>bool): Blacklistable.blacklisted (32)		
4	string: FiatTokenV1.name (32)		
5	string: FiatTokenV1.symbol (32)		
6	unallocated (31)	uint8: FiatTokenV1.decimals (1)	
7	string: FiatTokenV1.currency (32)		
8	unallocated (11)	bool: FiatTokenV1.initialized (1)	address: FiatTokenV1.masterMinter (20)
9	mapping(address=>uint256): FiatTokenV1.balances (32)		
10	mapping(address=>mapping(address=>uint256)): FiatTokenV1.allowed (32)		
11	uint256: FiatTokenV1.totalSupply_ (32)		
12	mapping(address=>bool): FiatTokenV1.minters (32)		
13	mapping(address=>uint256): FiatTokenV1.minterAllowed (32)		
14	unallocated (12)	address: Rescuable._rescuer (20)	
15	bytes32: EIP712Domain.DOMAIN_SEPARATOR (32)		
16	mapping(address=>mapping(bytes32=>bool)): EIP3009._authorizationStates (32)		
17	mapping(address=>uint256): EIP2612._permitNonces (32)		
18	unallocated (31)	uint8: FiatTokenV2._initializedVersion (1)	

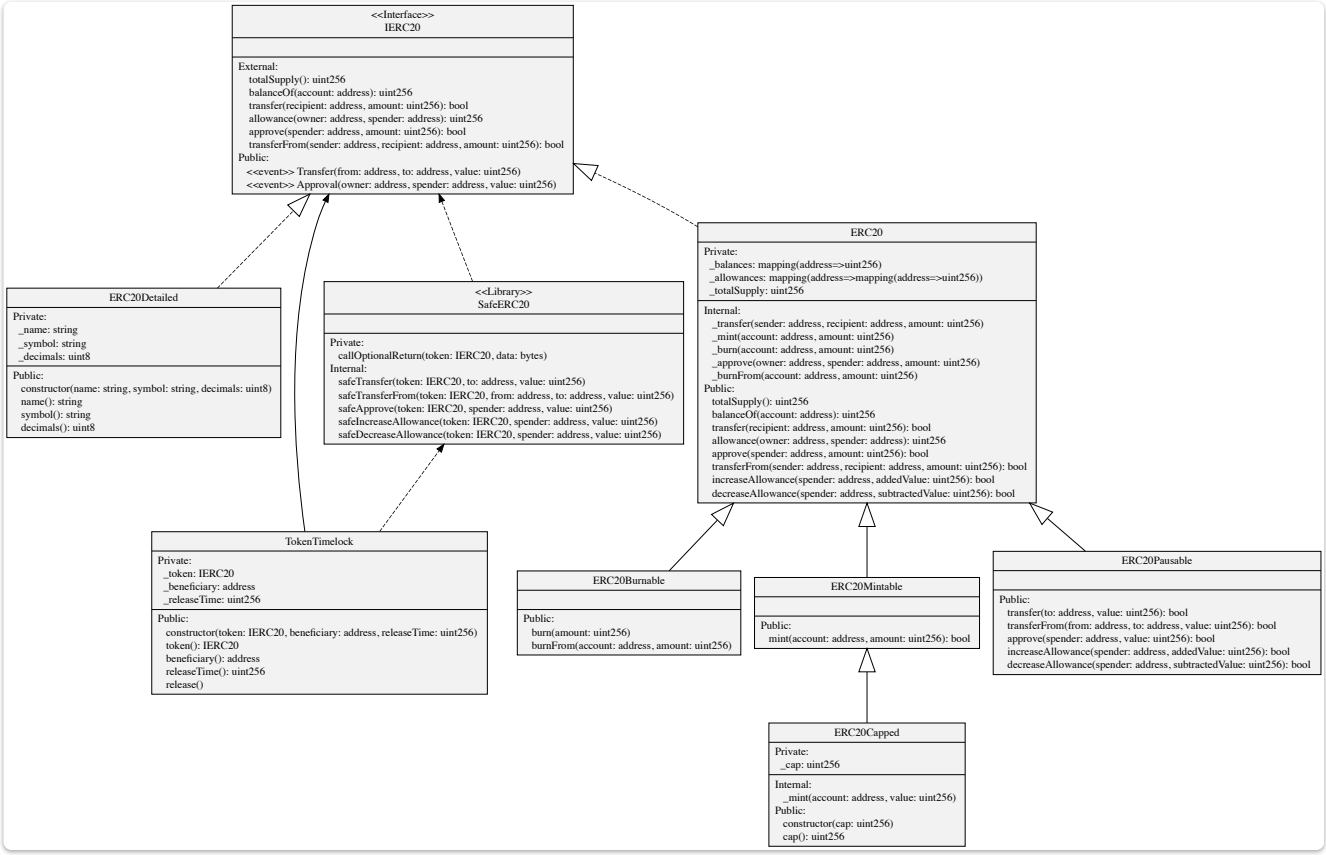
For fixed size variables, data is stored contiguously item after item starting with the first state variable, which is stored in slot 0. For each variable, a size in bytes is determined according to its type.

For variable length items such as arrays and mappings, the storage slot contains a pointer to another area of storage where the variable starts.
For the details see the documentation

Sol2UML Visualisation Tool

See repo

It provides visualisation of storage, plus UML diagrams for the contract.



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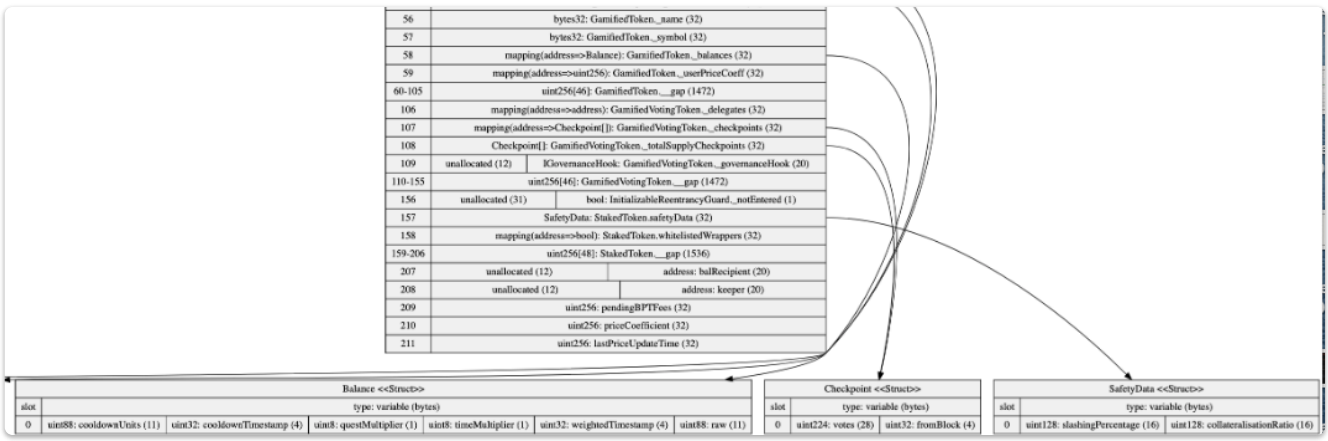
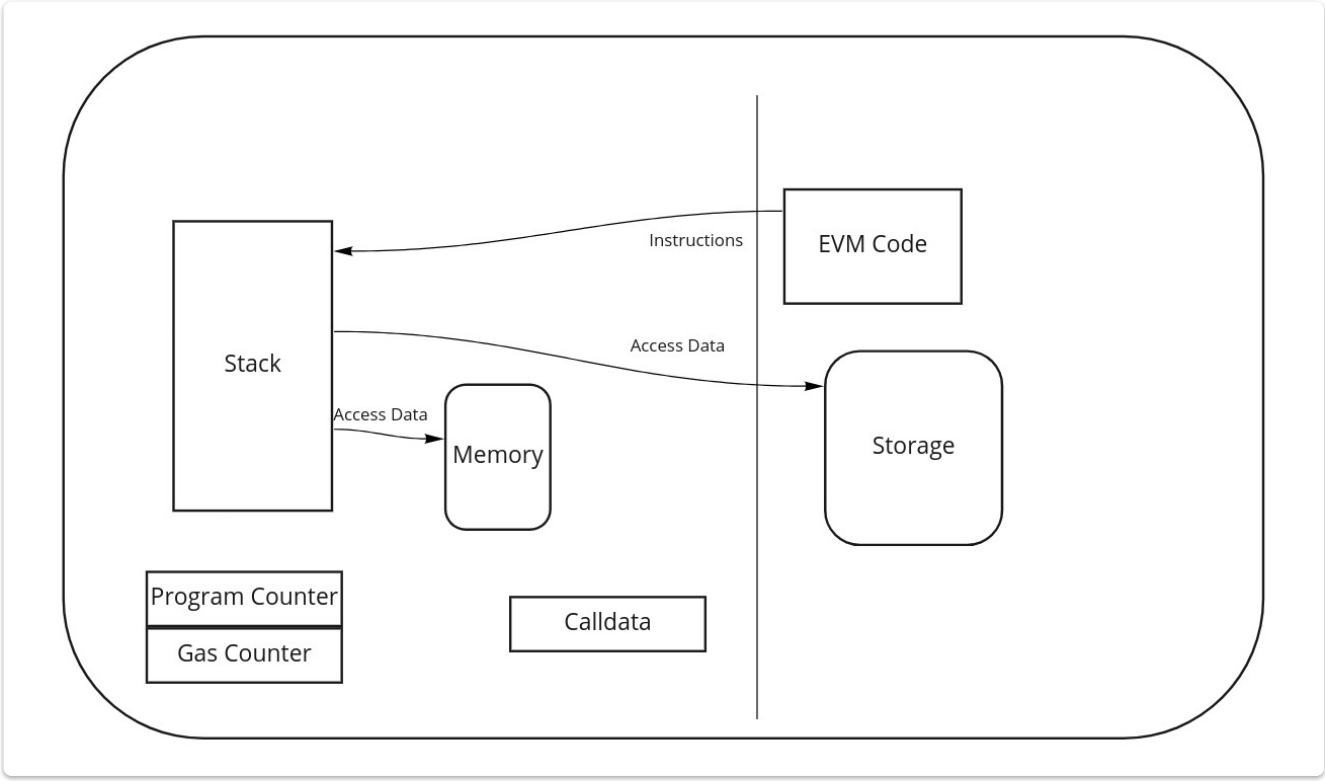


Code Execution



OpCodes

- Stack-manipulating opcodes (POP, PUSH, DUP, SWAP)
- Arithmetic/comparison/bitwise opcodes (ADD, SUB, GT, LT, AND, OR)
- Environmental opcodes (CALLER, CALLVALUE, NUMBER)
- Memory-manipulating opcodes (MLOAD, MSTORE, MSTORE8, MSIZE)
- Storage-manipulating opcodes (SLOAD, SSTORE)
- Program counter related opcodes (JUMP, JUMPI, PC, JUMPDEST)
- Halting opcodes (STOP, RETURN, REVERT, INVALID, SELFDESTRUCT)

https://www.ethervm.io/

Machine State

The machine state is a tuple consisting of five elements:

1. gas_available
2. program_counter
3. memory_contents A series of zeroes of size 2^256
4. memory_words.count
5. stack_contents

There is also the current operation to be executed

EVM Languages

- Solidity
  - The most popular programming language for Ethereum contracts
- LLL
  - Low-level Lisp-like Language
- Vyper
  - A language with overflow-checking, numeric units but without unlimited loops
- Yul / Yul+
  - An intermediate language that can be compiled to bytecode for different backends. Support for EVM 1.0, EVM 1.5 and Ewasm is planned, and it is designed to be a usable common denominator of all three platforms.
- FE
  - Statically typed language Inspired by Rust and Python
- Huff see article
  - Low level language
- Pyramid Scheme (experimental)
  - A Scheme compiler into EVM that follows the SICP compilation approach
- Flint
  - A language with several security features: e.g. asset types with a restricted set of atomic operations
- LLLL
  - An LLL-like compiler being implemented in Isabelle/HOL
- HAseembly-evm
  - An EVM assembly implemented as a Haskell DSL
- Bamboo (experimental)
  - A language without loops

Vyper

- Pythonic programming language
- Strong typing
- Small and understandable compiler code
- Deliberately has less features than Solidity with the aim of making contracts more secure and easier to audit. Vyper does not support
  - Modifiers
  - Inheritance
  - Inline assembly
  - Function overloading
  - Operator overloading
  - Recursive calling
  - Infinite-length loops

FE

See :Repo

- Statically typed language for the Ethereum Virtual Machine (EVM).
- Inspired by Python and Rust.
- Aims to be easy to learn -- even for developers who are new to the Ethereum ecosystem.
- Fe development is still in its early stages, the language had its alpha release in January 2021.

FEATURES

- Bounds and overflow checking
- Decidability by limitation of dynamic program behavior
- More precise gas estimation (as a consequence of decidability)
- Static typing
- Pure function support
- Restrictions on reentrancy
- Static looping
- Module imports
- Standard library
- Usage of YUL IR to target both EVM and eWASM
- WASM compiler binaries for enhanced portability and in-browser compilation of Fe contracts
- Implementation in a powerful, systems-oriented language (Rust) with strong safety guarantees to reduce risk of compiler bugs

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Gas Refunds

Since EIP-3529 gas refunds are not given for self destructing contracts, and the amount of refund for storage has been reduced.

Precompiles Revisited

See medium article about creating precompiles on Avalanche.

References

DEVCON1: Understanding the Ethereum Blockchain Protocol - Vitalik Buterin
Mastering Ethereum by Andreas Antonopoulos
White paper
Beige Paper
Yellow Paper
EVM languages
Noxx Articles about the EVM