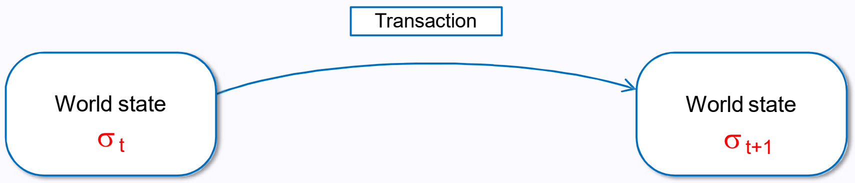
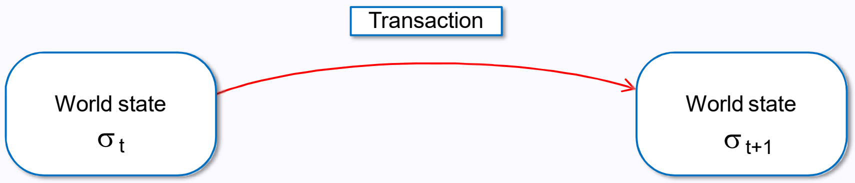
Ethereum-EVM

A transaction-based state machine



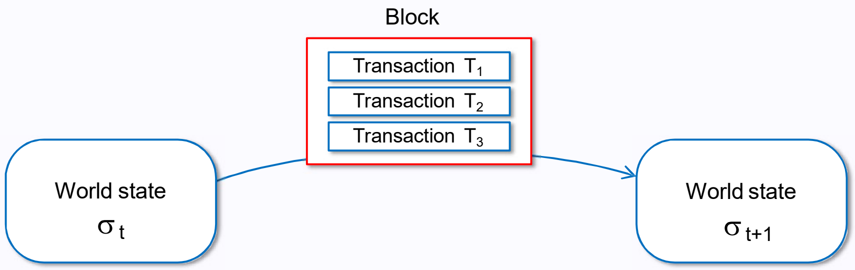
Ethereum can be viewed as a transaction-based state machine.

A transaction-based state machine



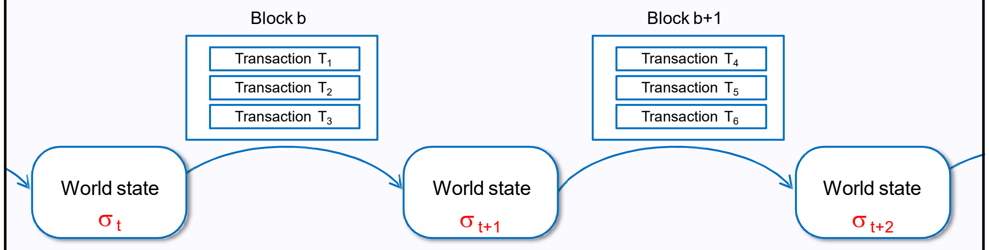
A transaction represents a valid arc between two states.

Block and transactions



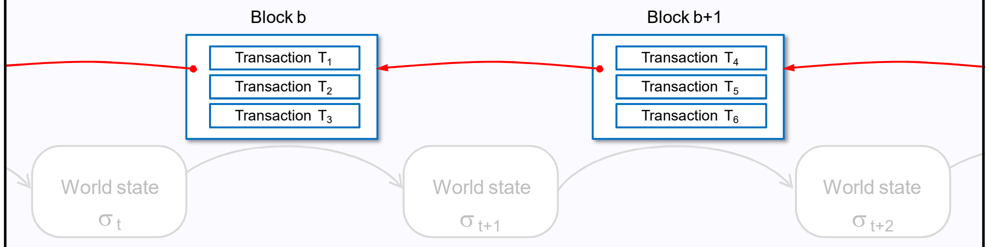
Transactions are collated into blocks.
A block is a package of data.

Chain of states



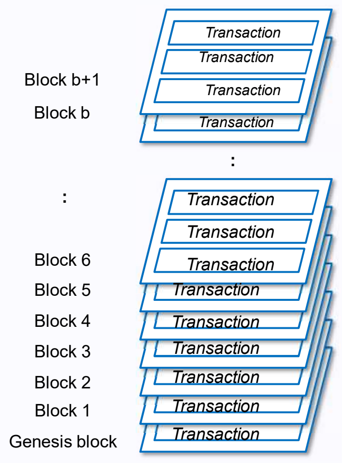
From the viewpoint of the states,
Ethereum can be seen as a state chain.

Chain of blocks: Blockchain



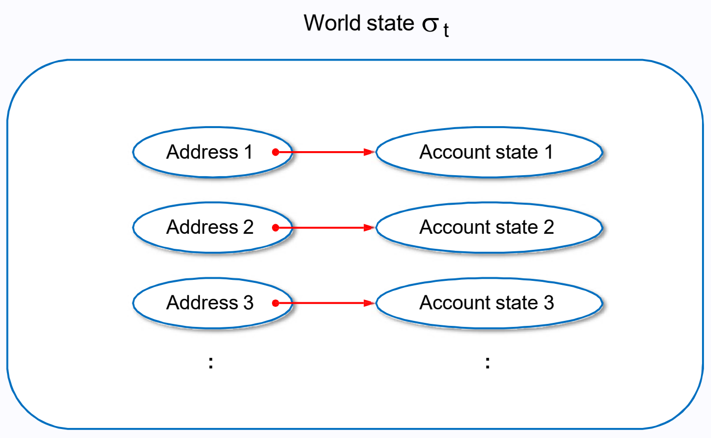
From the viewpoint of the implementation,
Ethereum can also be seen as a chain of blocks, so it is `BLOCKCHAIN`.

Stack of transactions : Ledger



From the viewpoint of the ledger,
Ethereum can also be seen as a stack of transactions.

World state



The world state is a mapping between address and account state.

Several views of world state

Mapping view

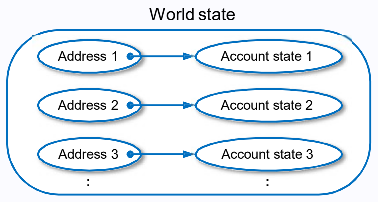
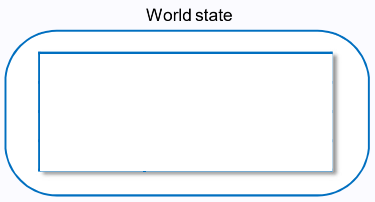
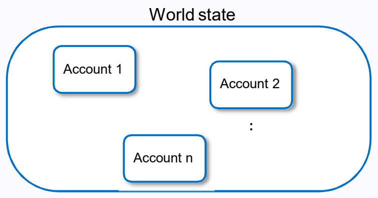


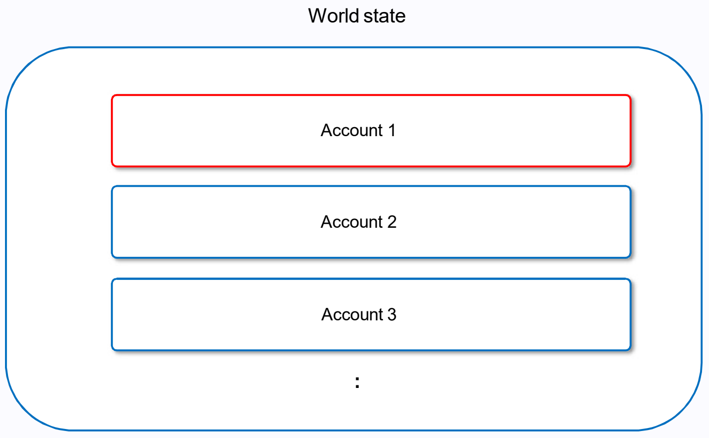
Table view



Object view

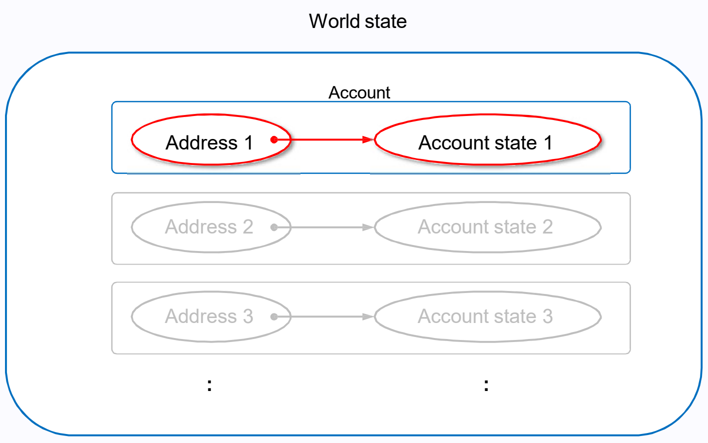


Account



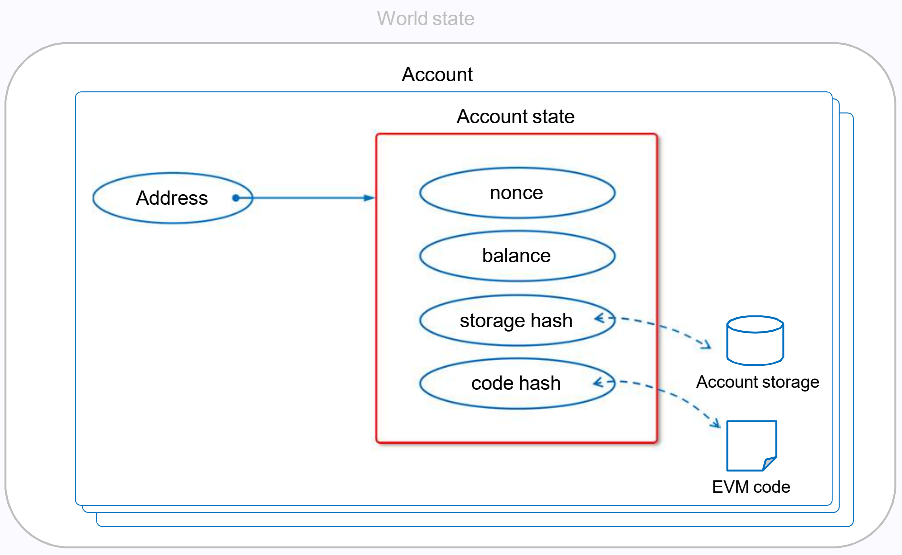
An account is an object in the world state.

Account



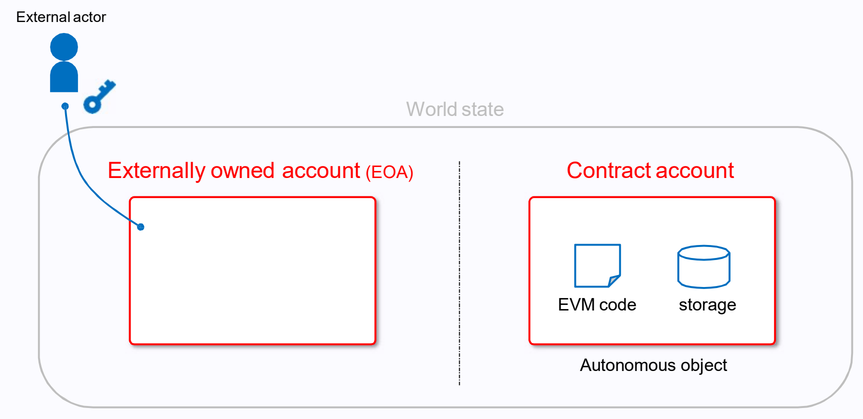
An account is a mapping between address and account state.

Account state



An account state could contain EVM code and storage.

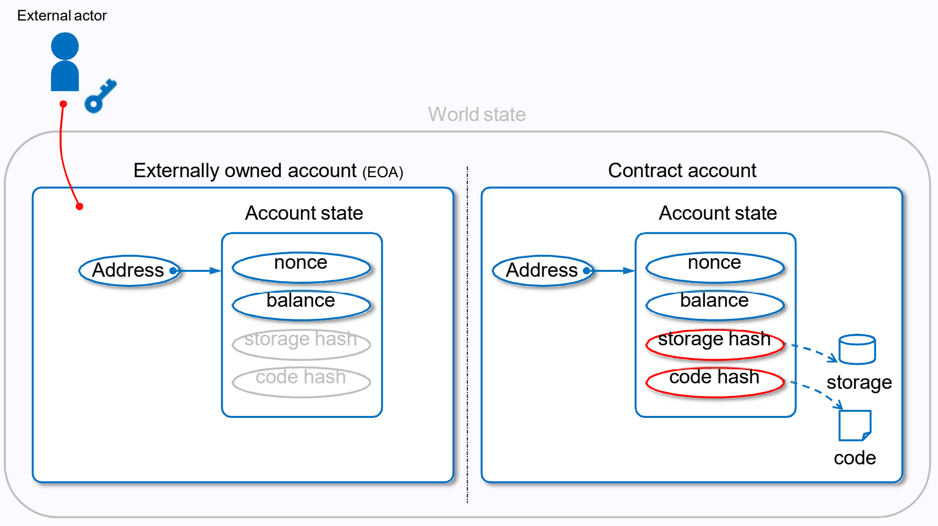
Two practical types of account



EOA is controlled by a private key.

Contract account contains EVM code.

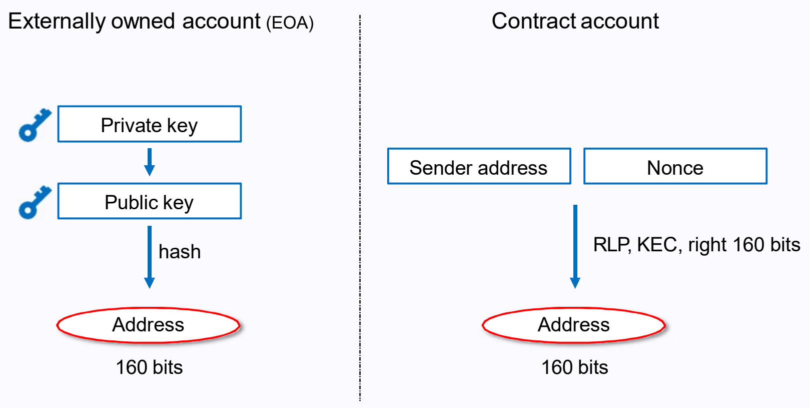
Two practical types of account



EOA is controlled by a private key.
EOA cannot contain EVM code.

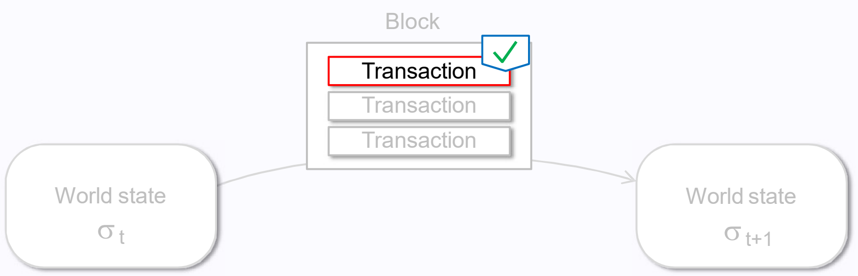
Contract contains EVM code.
Contract is controlled by EVM code.

Address of account



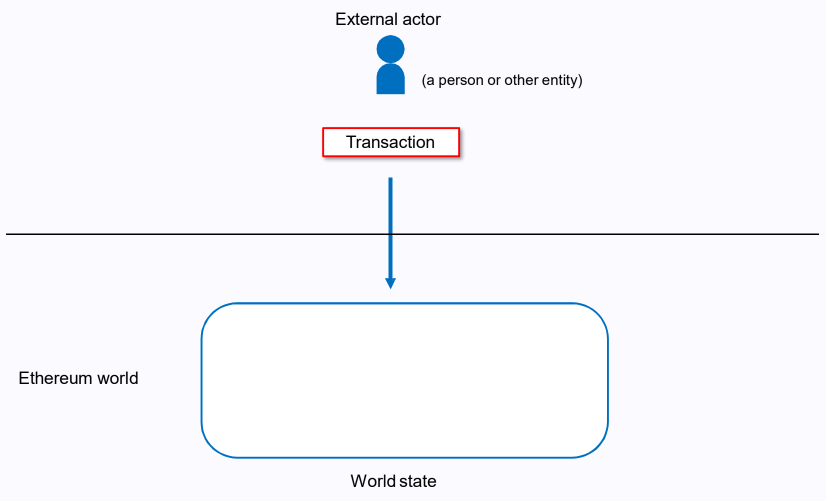
A 160-bit code used for identifying accounts.

A transaction



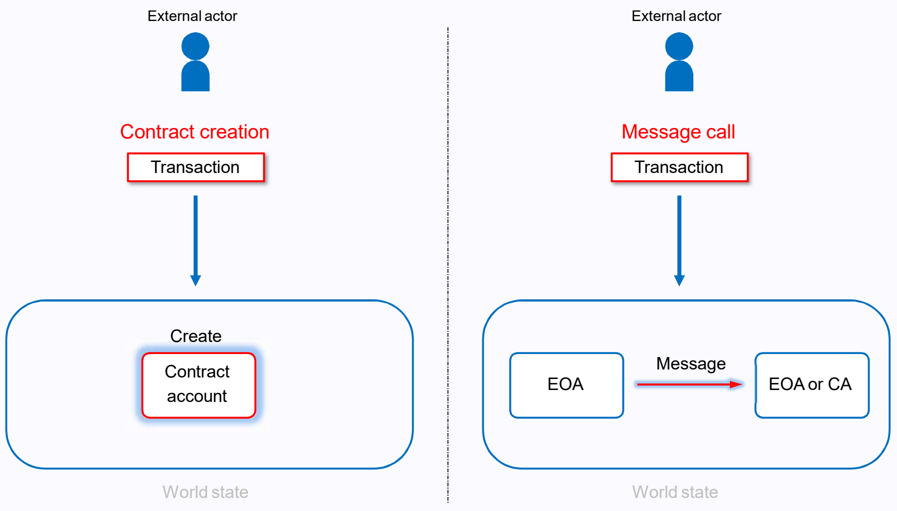
A transaction is a single cryptographically-signed instruction.

A transaction to world state



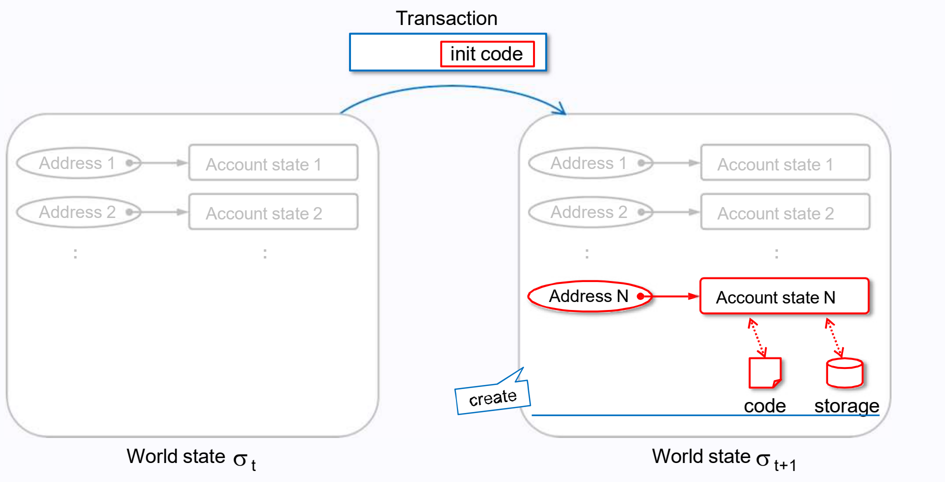
A transaction is submitted by external actor.

Two practical types of transaction

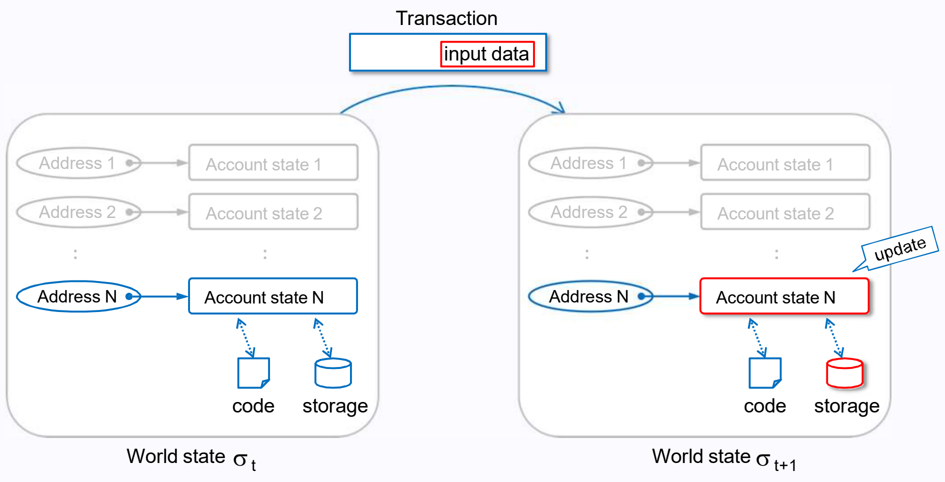


There are two practical types of transaction, contract creation and message call.

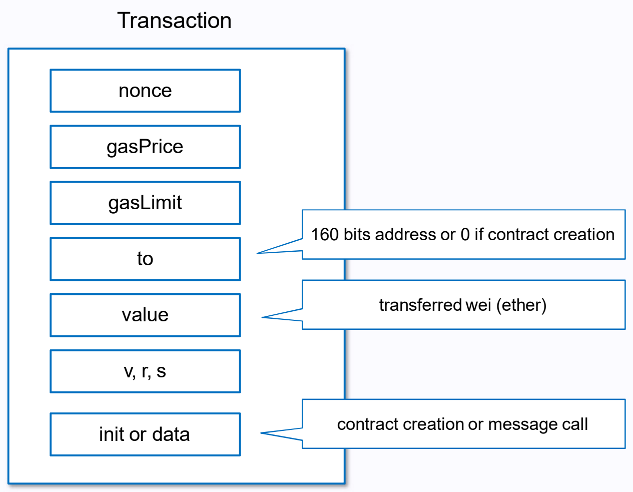
Contract creation



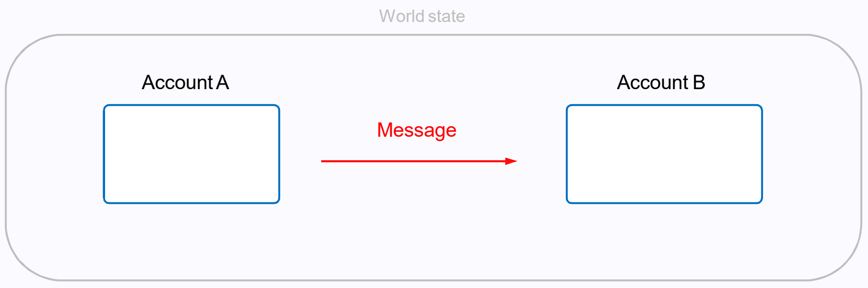
Message call



Field of a transaction



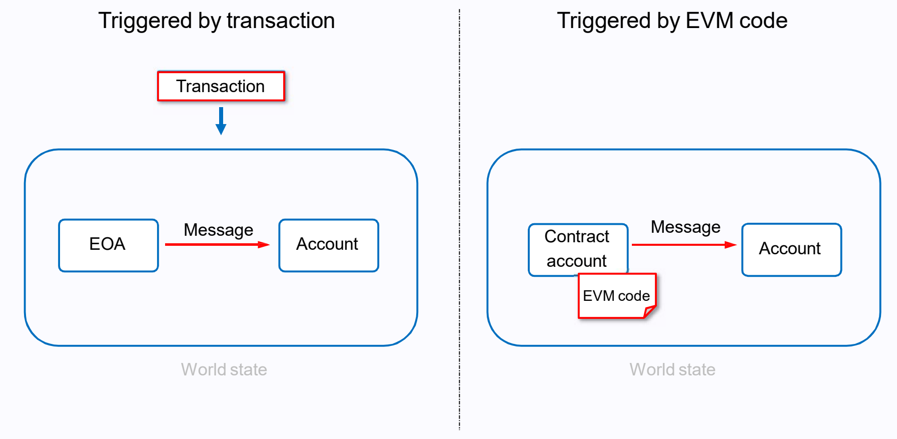
Message



Message is passed between two Accounts.

Message is Data (as a set of bytes) and Value (specified as Ether) .

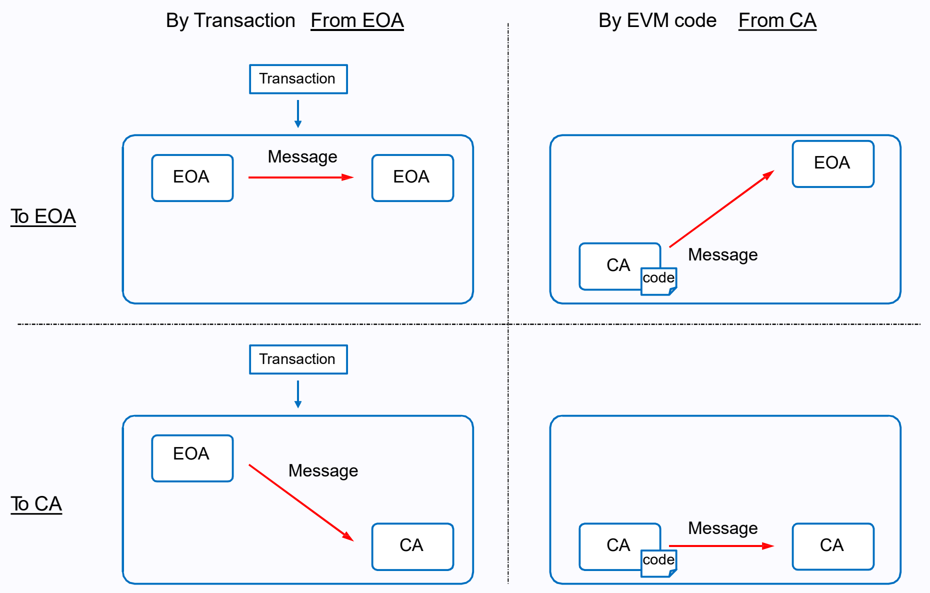
Message



Transaction triggers an associated message.

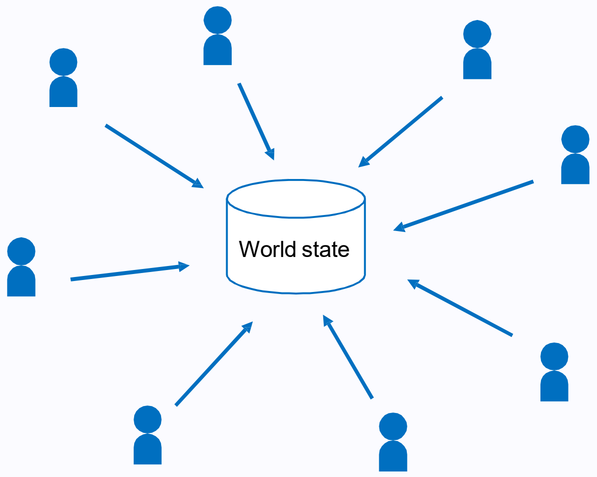
EVM can also send a message.

Four cases of message



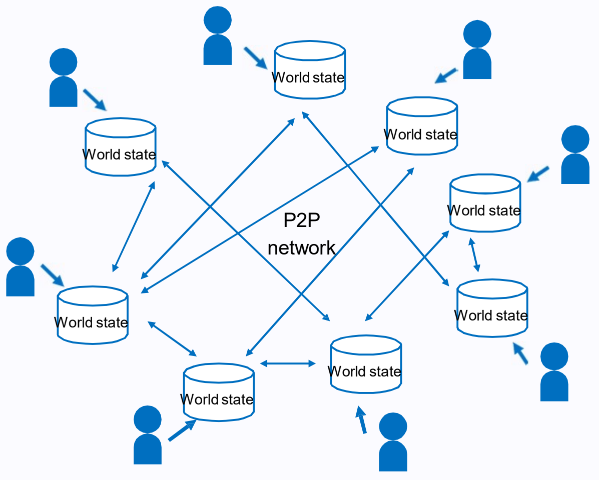
Decentralised database

Globally shared, transactional database



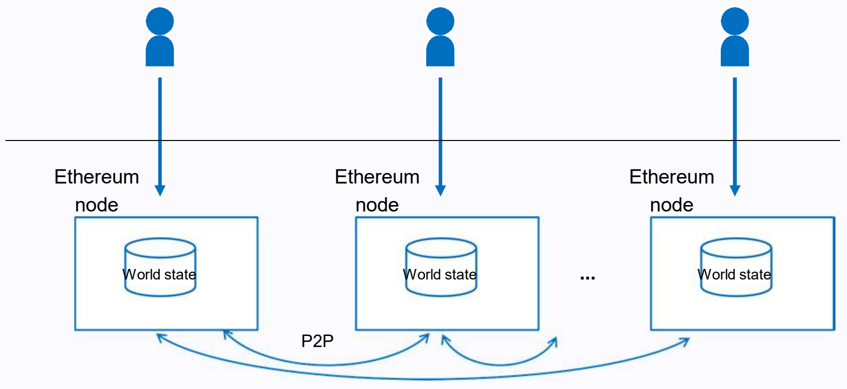
A blockchain is a globally shared, transactional database.

Decentralised database



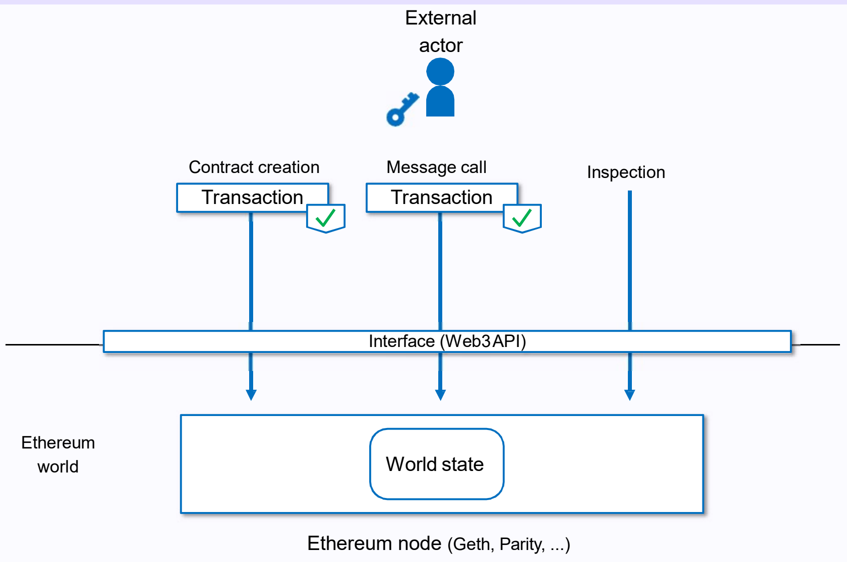
A blockchain is a globally shared, decentralised, transactional database.

P2P network inter nodes



Decentralised nodes constitute Ethereum P2P network.

Interface to a node

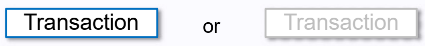


External actors access the Ethereum world through Ethereum nodes.

Atomicity of transaction

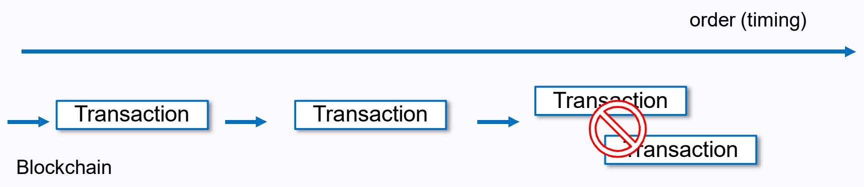
Transaction

A transaction is an atomic operation. Can't divide or interrupt.



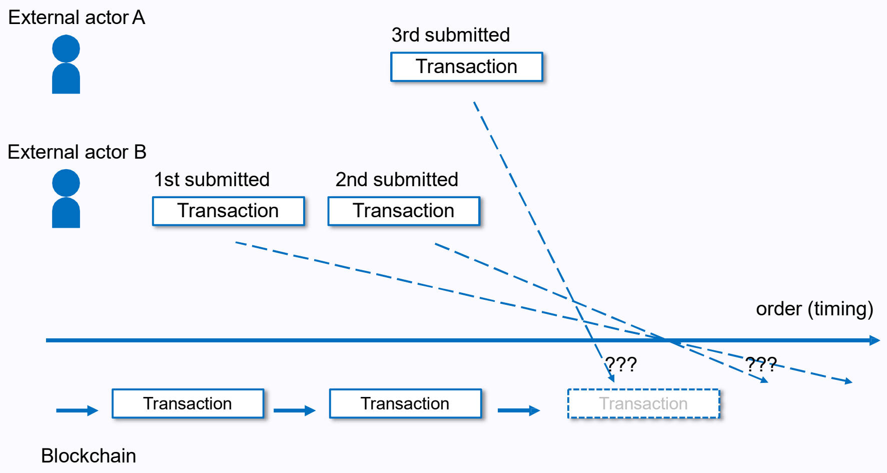
That is, All (complete done) or Nothing (zero effect).

Order of transactions



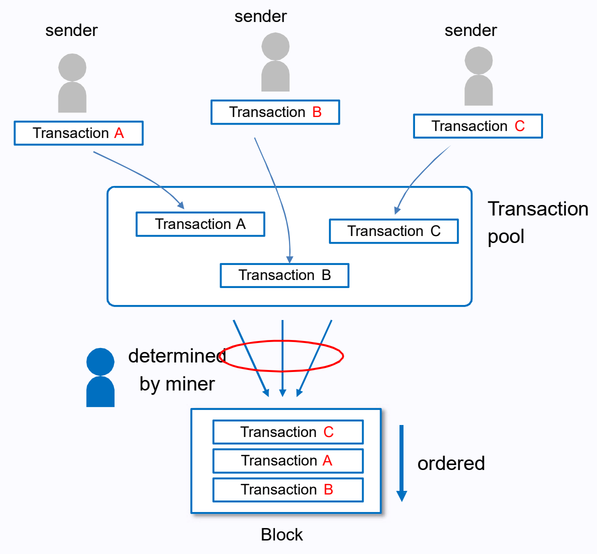
Transactions cannot be overlapped.
Transactions must be executed sequentially.

Order of transactions



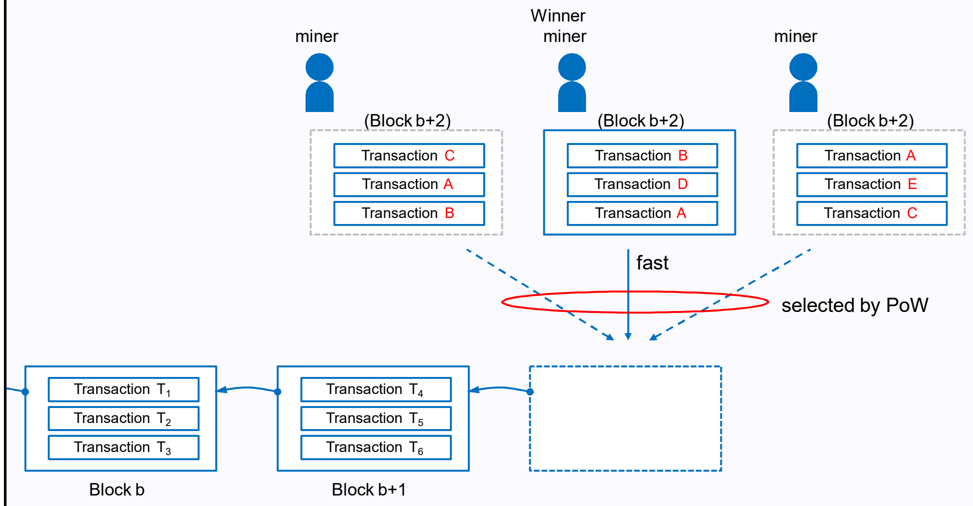
Transaction order is not guaranteed.

Ordering inner block



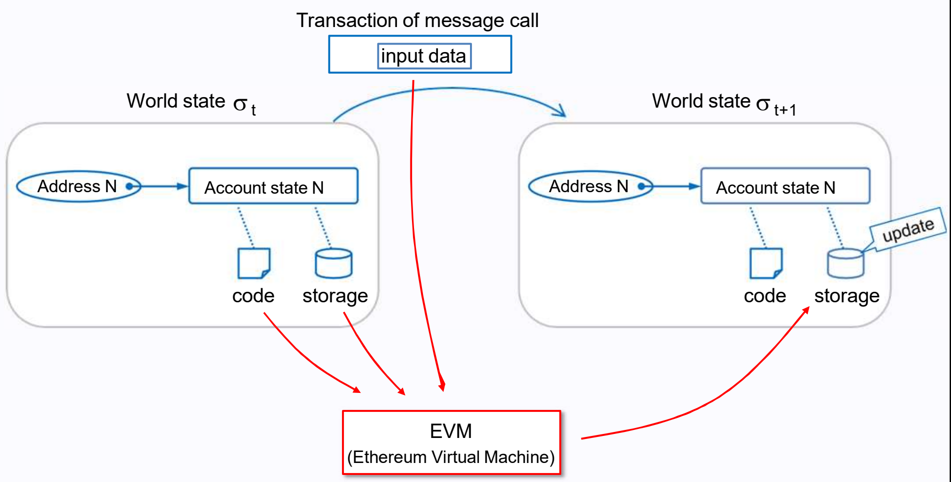
Miner can determine the order of transactions in a block.

Ordering inter blocks



The order between blocks is determined by a consensus algorithm such as PoW.

Ethereum virtual machine



EVM code is executed on Ethereum Virtual Machine (EVM).

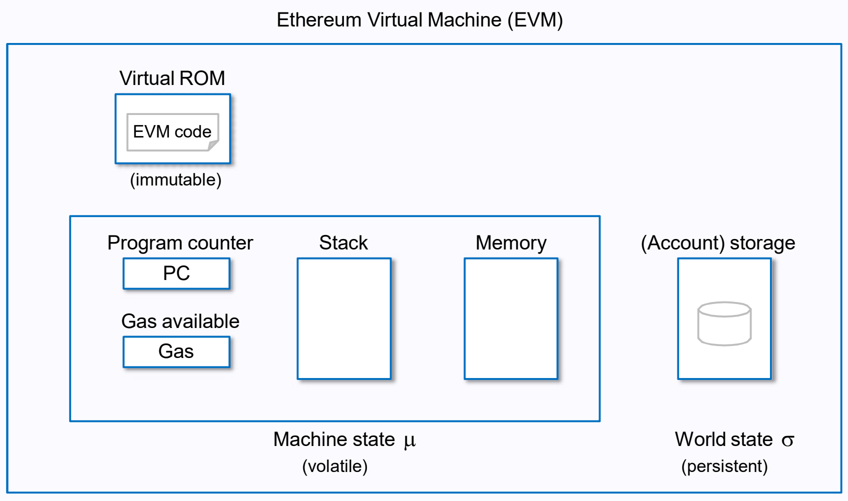
Ethereum virtual machine

Code — EVM code

Virtual machine — EVM (Ethereum Virtual Machine)

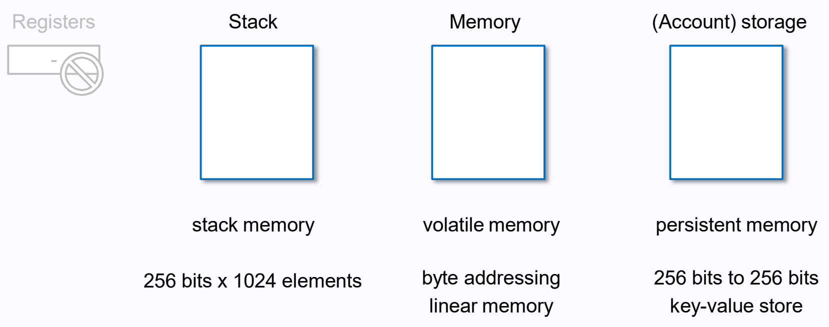
The Ethereum Virtual Machine is the runtime environment for smart contracts in Ethreum.

EVM architecture



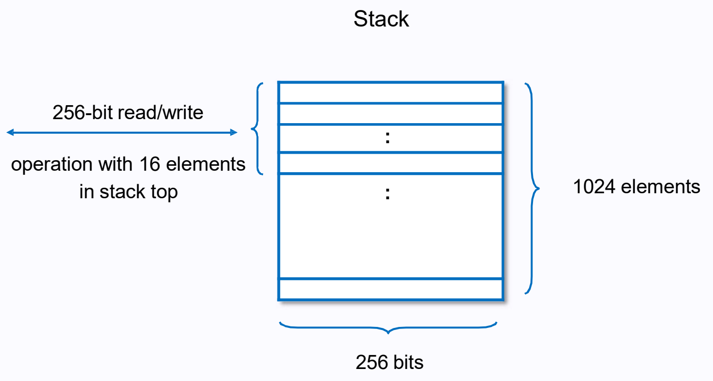
The EVM is a simple stack-based architecture.

Machine space of EVM



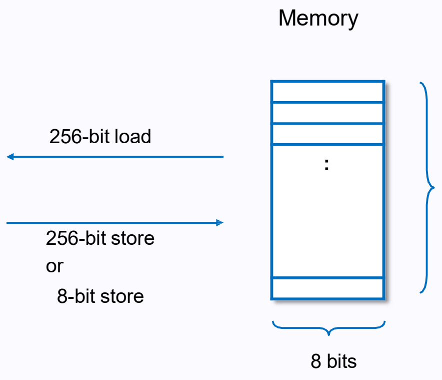
There are several resources as space.

Stack



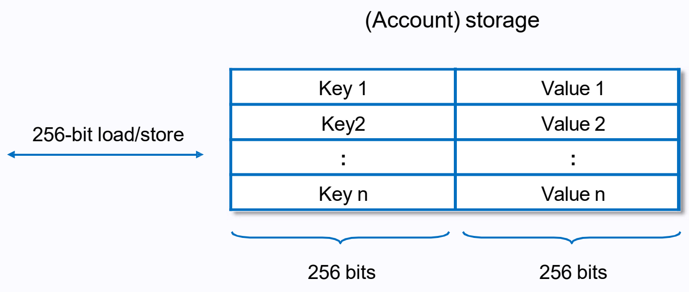
All operation are performed on the stack.
Access with many instructions such as PUSH/POP/COPY/SWAP, ...

Memory



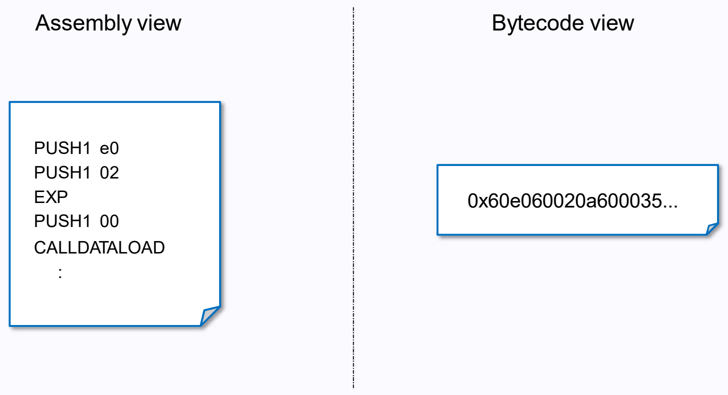
Memory is linear and can be addressed at byte level.
Access with MSTORE/MSTORE8/MLOAD instructions.
All locations in memory are well-defined initially as zero.

Account storage



Storage is a key-value store that maps 256-bit words to 256-bit words.
Access with SSTORE/SLOAD instructions.
All locations in storage are well-defined initially as zero.

EVM code

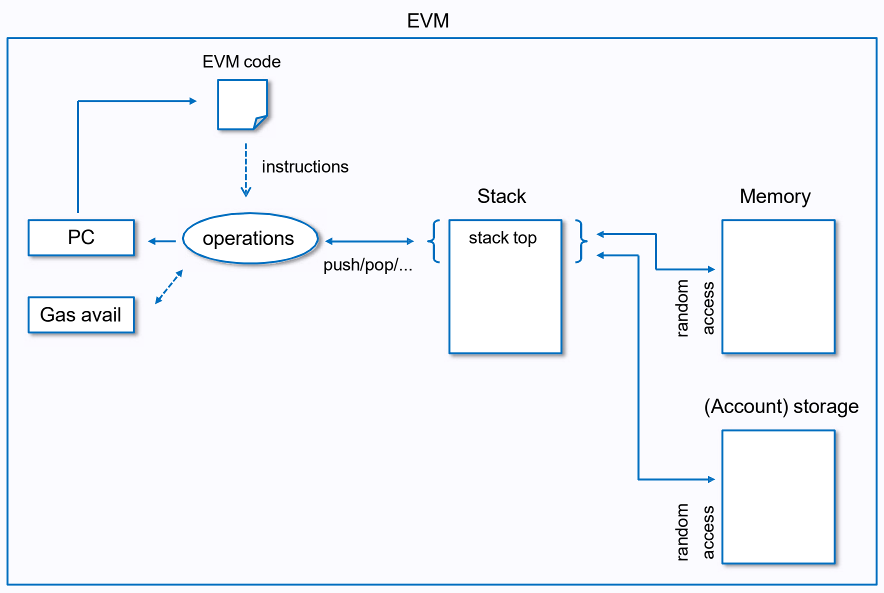


```
PUSH1  e0
PUSH1  02
EXP
PUSH1  00
CALLDATALOAD
    :
```

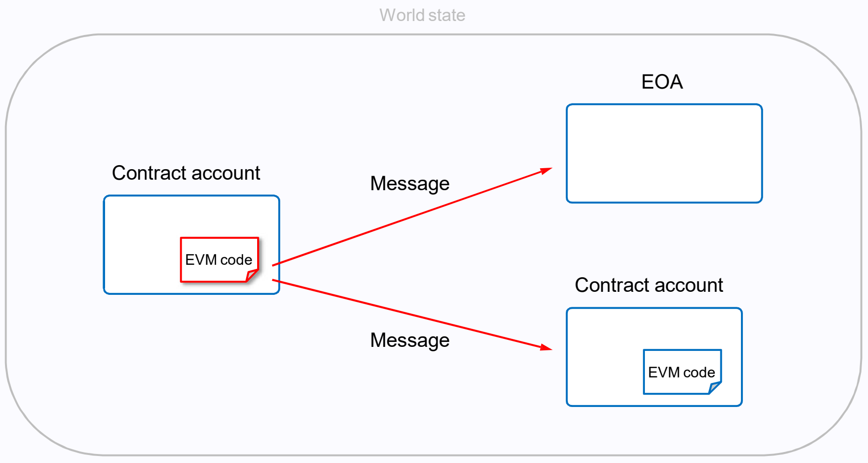
```
0x60e060020a600035...
```

EVM Code is the bytecode that the EVM can natively execute.

Execution model

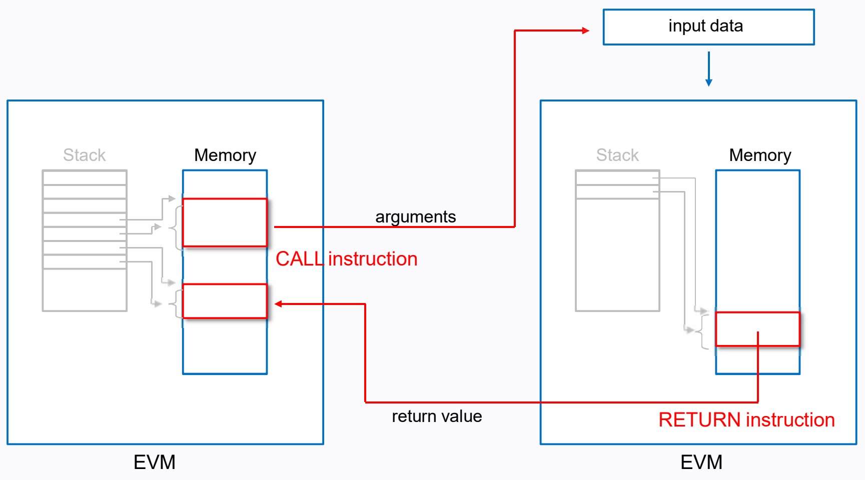


Message call



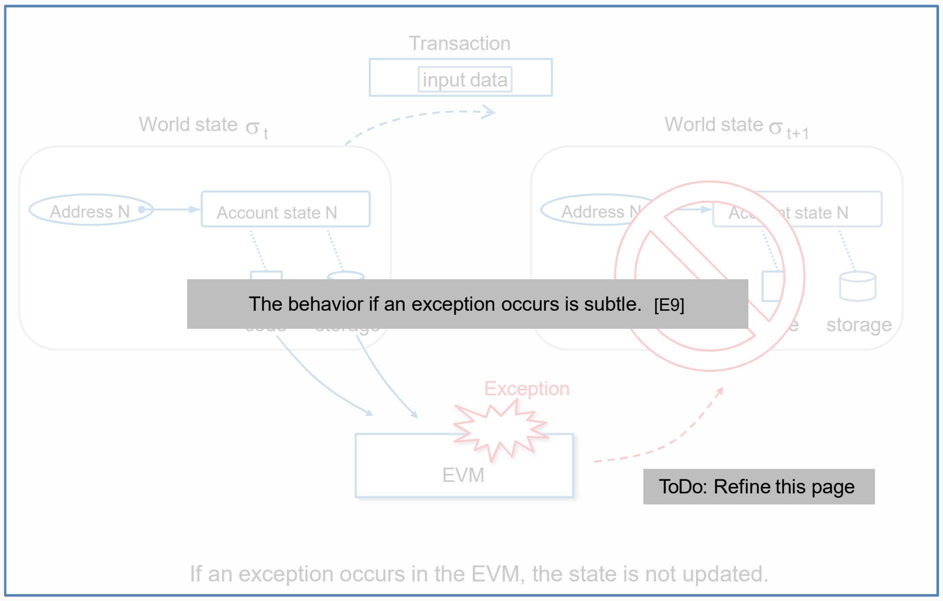
EVM can send a message to other account.
The depth of message call is limited to less than 1024 levels.

Instructions for Message call



Message call is triggered by CALL instruction.
Arguments and return values are passed using memory.

Exception

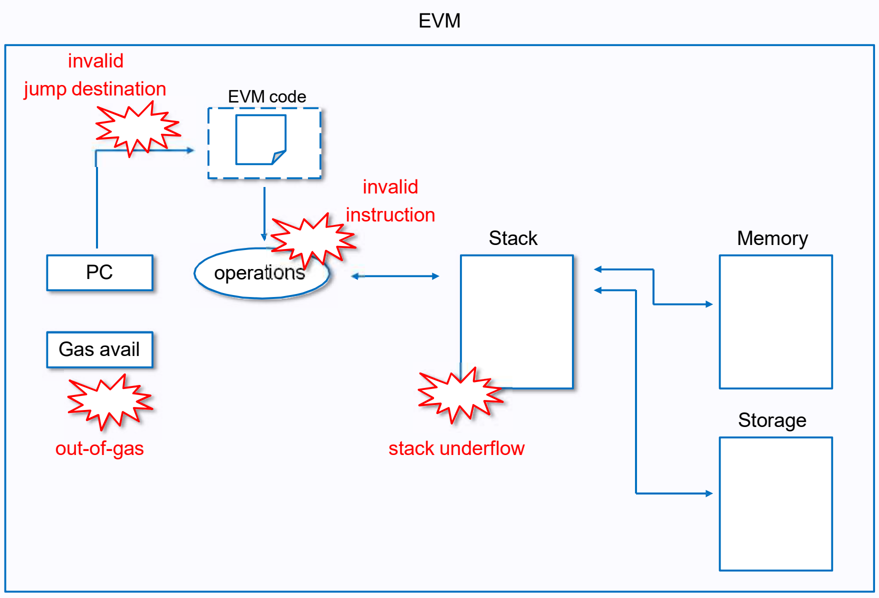


The behavior if an exception occurs is subtle. [E9]

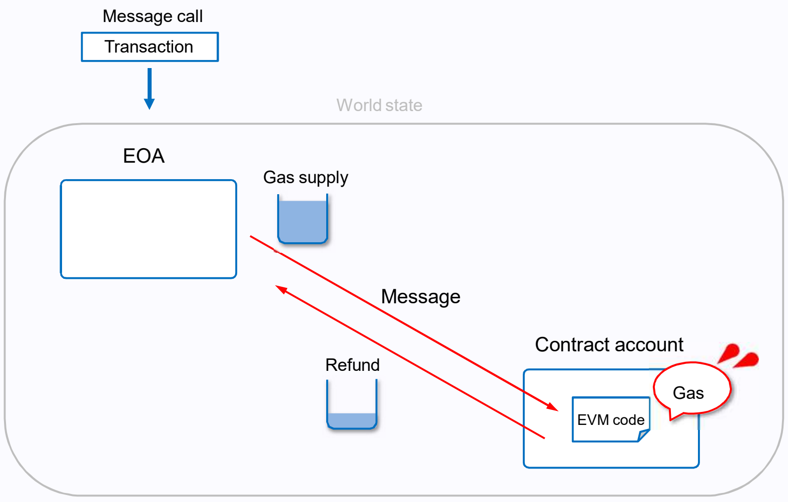
ToDo: Refine this page

If an exception occurs in the EVM, the state is not updated.

Exception

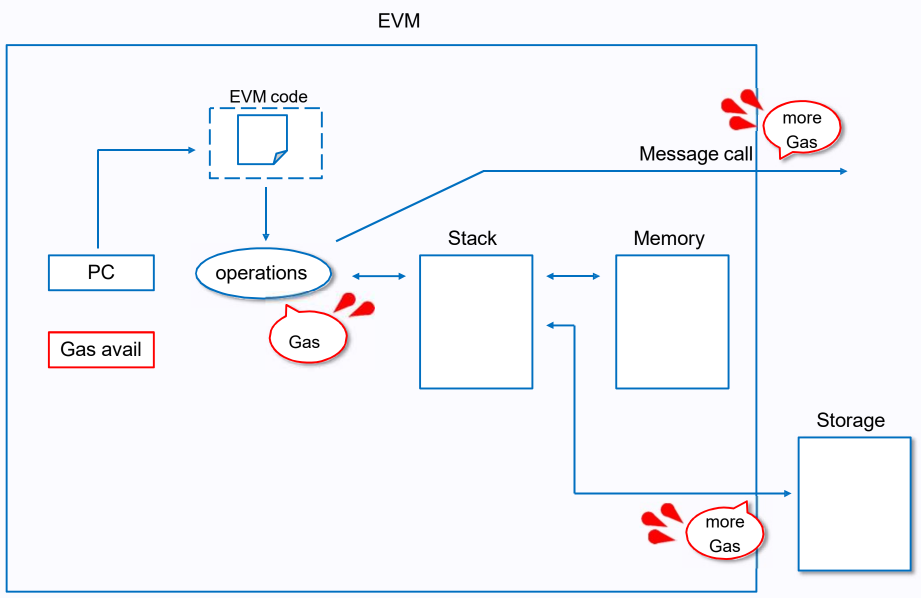


Gas and fee

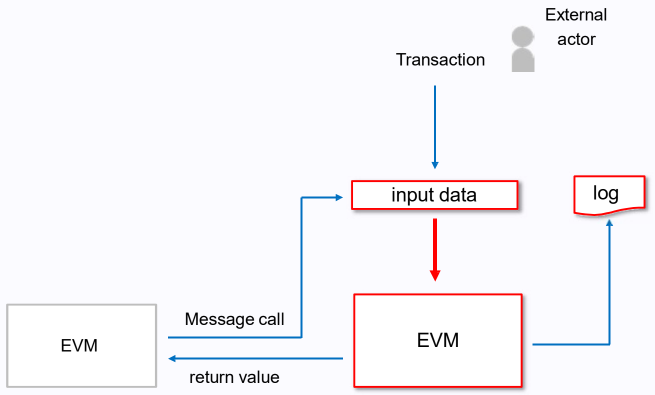


All programmable computation in Ethereum is subject to fees (denominated in gas).

Gas

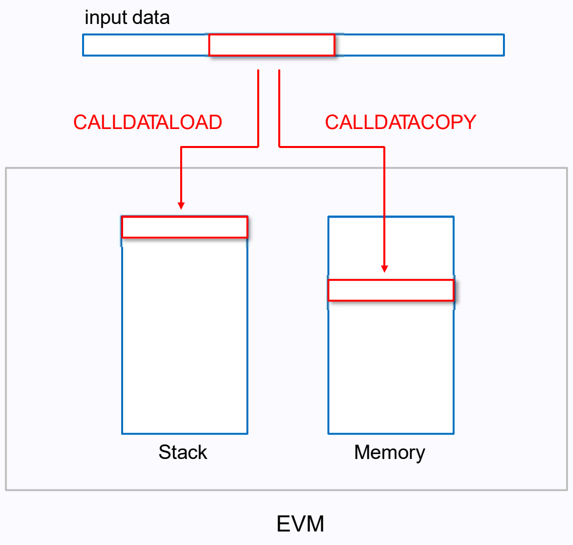


Input and Output of EVM

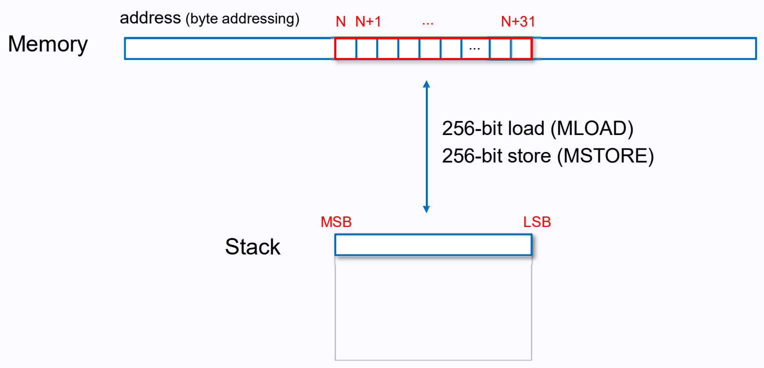


EVM can input external data from a message call.
EVM can output log. EVM can also return values to Caller EVM.

Instructions for input data

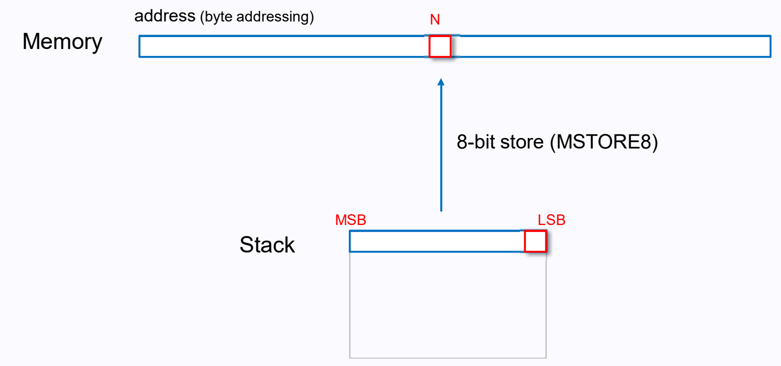


Endian for Memory



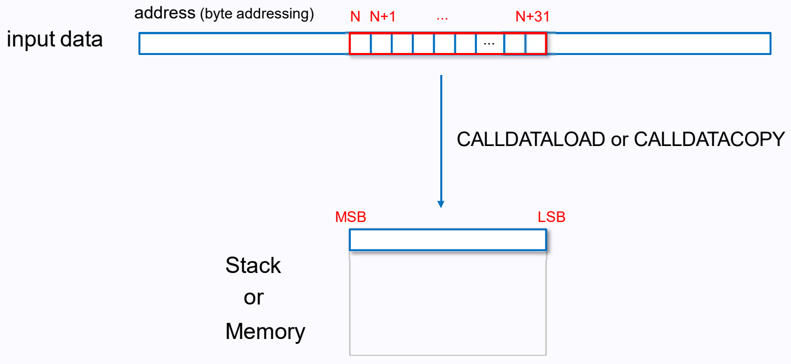
EVM is big endian order (network byte order).

Endian for Memory



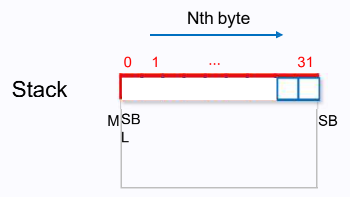
EVM is big endian order (network byte order).

Endian for input data

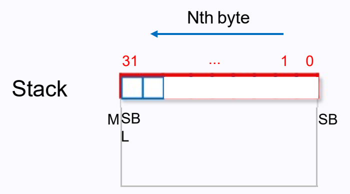


EVM is big endian order (network byte order).

Byte order of BYTE and SIGNEXTEND instruction



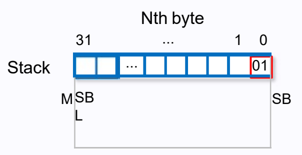
BYTE instruction counts from MSB.



SIGNEXTEND instruction counts from LSB.

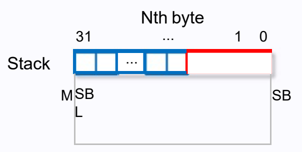
Byte order of PUSH instructions

PUSH1 0x01



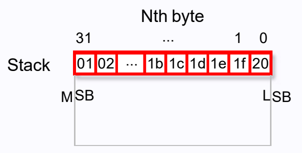
right-aligned, big endian

PUSH4 0x01020304



right-aligned, big endian

PUSH32 0x0102...1f20



right-aligned, big endian

Instruction set

* Basically, 256-bit operation.

* Contract creation and destruct
    * CREATE, DELEGATECALL

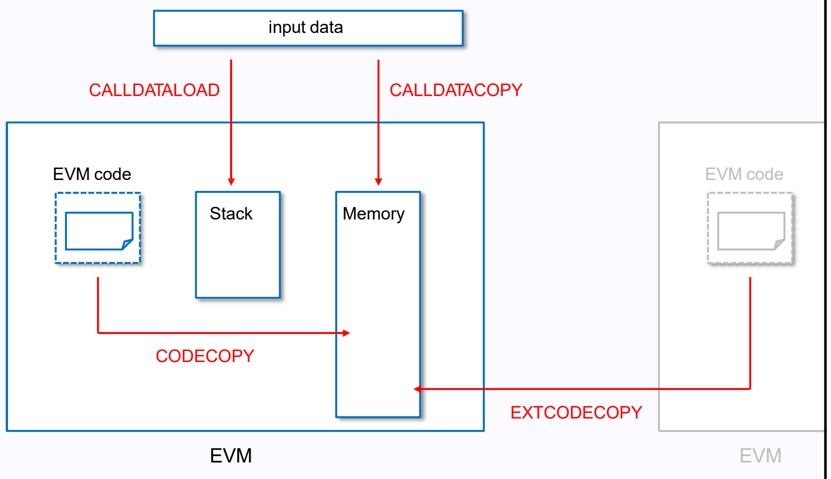
* Hash
    * SHA3

* Shift operation
    * using MUL or DIV, SDIV

* Div operation
    * without zero divisional exception

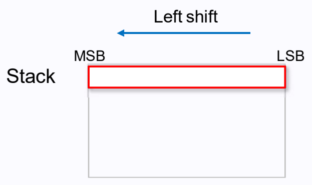
* ...

Copy of code and input data



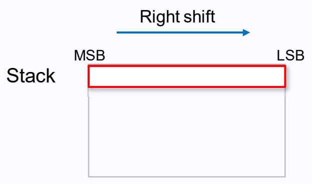
There are several copy instructions for inter spaces.

Shift by MUL, DIV and SDIV



MUL m (2^n) == m << n

Left shift is represented by MUL instruction.

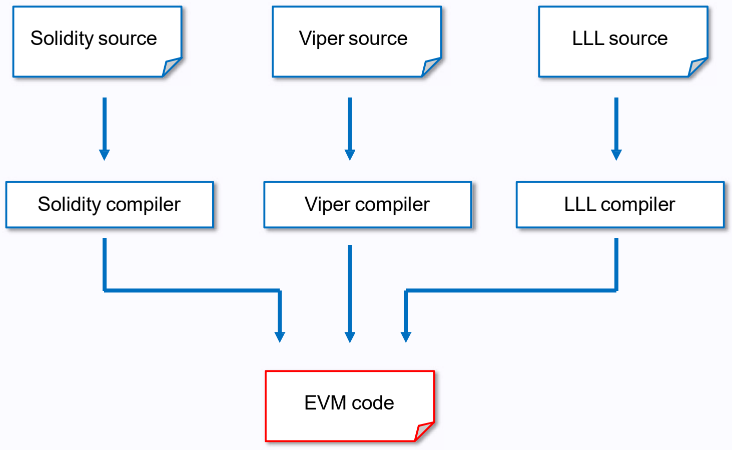


DIV m (2^n) == m >> n

DIV for logical right shift
SDIV for arithmetic right shift

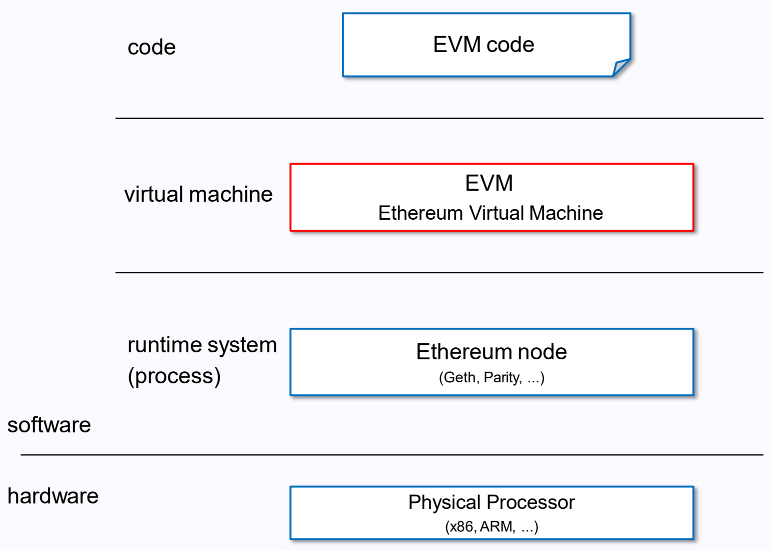
Right shift is represented by DIV and SDIV instruction.

EVM code generation



Ethereum virtual machine code

Ethereum virtual machine layer



Block header

(go-ethereum version 1.8)

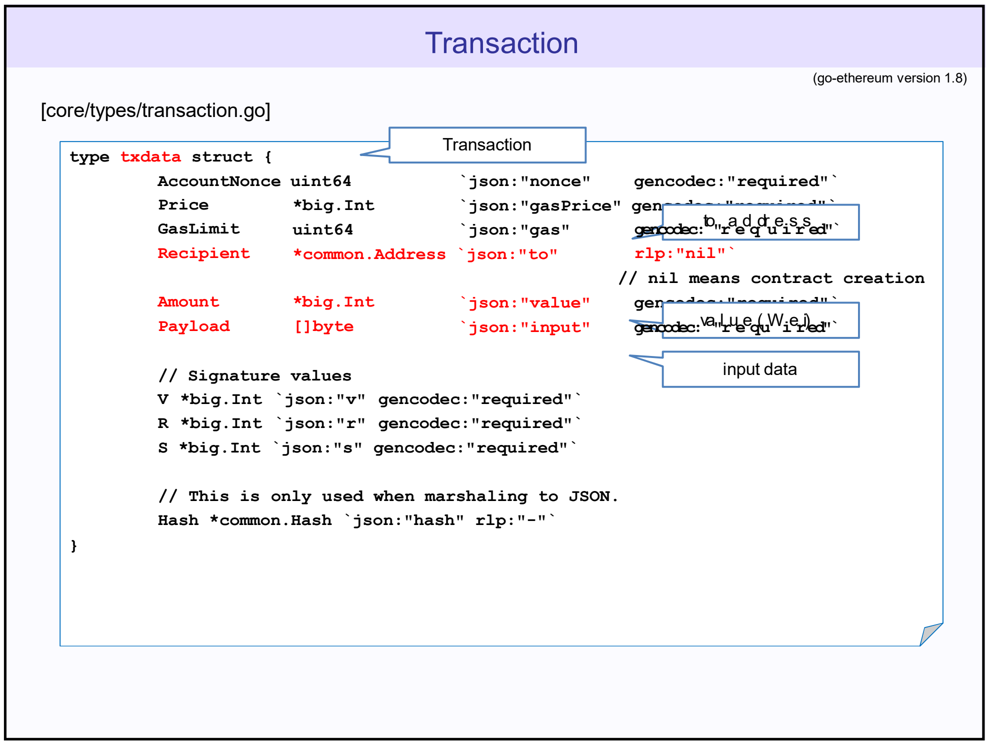
[core/types/block.go]

Block header

```
type Header struct {
        ParentHash  common.Hash    `json:"parentHash"       gencodec:"required"`
        UncleHash   common.Hash    `json:"sha3Uncles"       gencodec:"required"`
        Coinbase    common.Address `json:"miner"            gencodec:"required"`
        Root        common.Hash    `json:"stateRoot"        gencodec:"required"`
        TxHash      common.Hash    `json:"transactionsRoot" gencodec:"required"`
        ReceiptHash common.Hash    `json:"receiptsRoot"     gencodec:"required"`
        Bloom       Bloom          `json:"logsBloom"        gencodec:"required"`
        Difficulty  *big.Int       `json:"difficulty"       gencodec:"required"`
        Number      *big.Int       `json:"number"           gencodec:"required"`
        GasLimit    uint64         `json:"gasLimit"         gencodec:"required"`
        GasUsed     uint64         `json:"gasUsed"          gencodec:"required"`
        Time        *big.Int       `json:"timestamp"        gencodec:"required"`
        Extra       []byte         `json:"extraData"        gencodec:"required"`
        MixDigest   common.Hash    `json:"mixHash"          gencodec:"required"`
        Nonce       BlockNonce     `json:"nonce"            gencodec:"required"`
}
```

Root of State

Root of Transaction



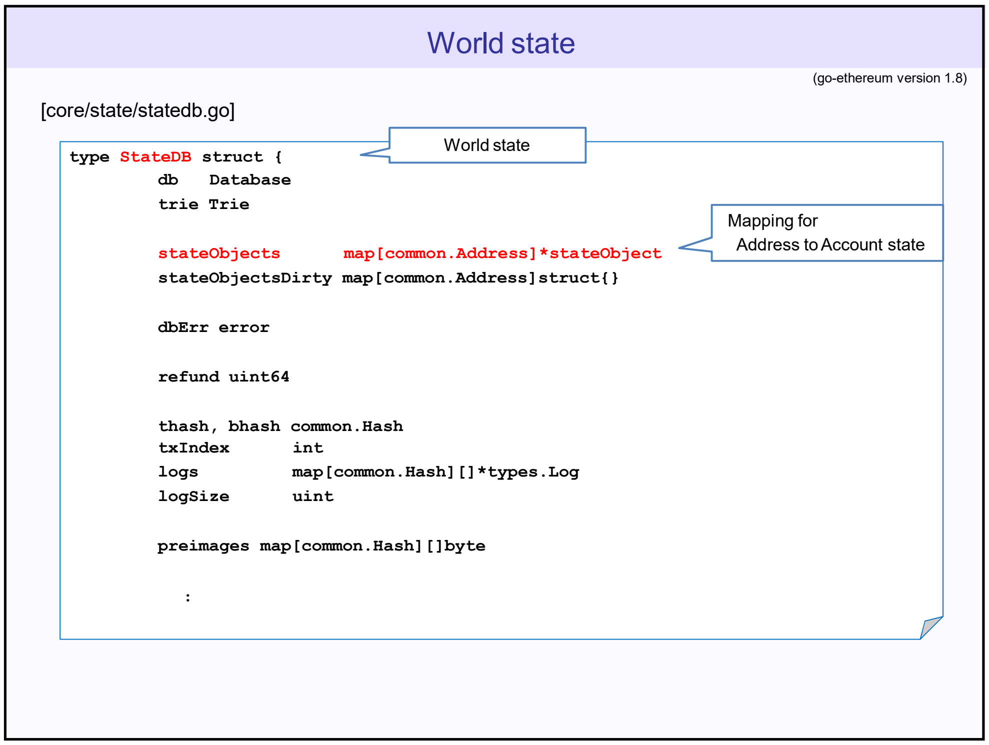
Transaction

(go-ethereum version 1.8)

[core/types/transaction.go]

```
type txdata struct {
        AccountNonce uint64          `json:"nonce"    gencodec:"required"`
        Price        *big.Int        `json:"gasPrice" gencodec:"required"`
        GasLimit     uint64          `json:"gas"      gencodec:"required"`
        Recipient    *common.Address `json:"to"       rlp:"nil"`
                                                     // nil means contract creation

        Amount       *big.Int        `json:"value"    gencodec:"required"`
        Payload      []byte          `json:"input"    gencodec:"required"`

        // Signature values
        V *big.Int `json:"v" gencodec:"required"`
        R *big.Int `json:"r" gencodec:"required"`
        S *big.Int `json:"s" gencodec:"required"`

        // This is only used when marshaling to JSON.
        Hash *common.Hash `json:"hash" rlp:"-"`
}
```

Transaction
to address
value (Wei)
input data



World state

(go-ethereum version 1.8)

[core/state/statedb.go]

```
type StateDB struct {
        db   Database
        trie Trie

        stateObjects      map[common.Address]*stateObject
        stateObjectsDirty map[common.Address]struct{}

        dbErr error

        refund uint64

        thash, bhash common.Hash
        txIndex      int
        logs         map[common.Hash][]*types.Log
        logSize      uint

        preimages map[common.Hash][]byte

           :
```

World state
Mapping for
Address to Account state

Account object (state object)

(go-ethereum version 1.8)

[core/state/state_object.go]

```
type stateObject struct {
        address  common.Address
        addrHash common.Hash
        data     Account
        db       *StateDB

        dbErr error

        trie Trie // storage trie, which becomes non-nil on first access
        code Code // contract bytecode, which gets set when code is loaded

        cachedStorage Storage // Storage entry cache to avoid duplicate reads
        dirtyStorage  Storage // Storage entries that need to be flushed to disk

        dirtyCode bool // true if the code was updated
        suicided  bool
        touched   bool
        deleted   bool
        onDirty   func(addr common.Address)
}
```

Address

Account state

Account state, Code and Storage

(go-ethereum version 1.8)

[core/state/state_object.go]

```
type Account struct {
        Nonce    uint64
        Balance  *big.Int
        Root     common.Hash // merkle root of the storage trie
        CodeHash []byte
}


type Code []byte


type Storage map[common.Hash]common.Hash
```

Account state

EVM code

Account storage

Stack and Memory

(go-ethereum version 1.8)

[core/vm/stack.go]

```
type Stack struct {
        data []*big.Int
}

func newstack() *Stack {
        return &Stack{data: make([]*big.Int, 0, 1024)}
}
```

Stack

[core/vm/memory.go]

```
type Memory struct {
        store       []byte
        lastGasCost uint64
}

func NewMemory() *Memory {
        return &Memory{}
}
```

Memory

Instruction operation (arithmetic and stack)

(go-ethereum version 1.8)

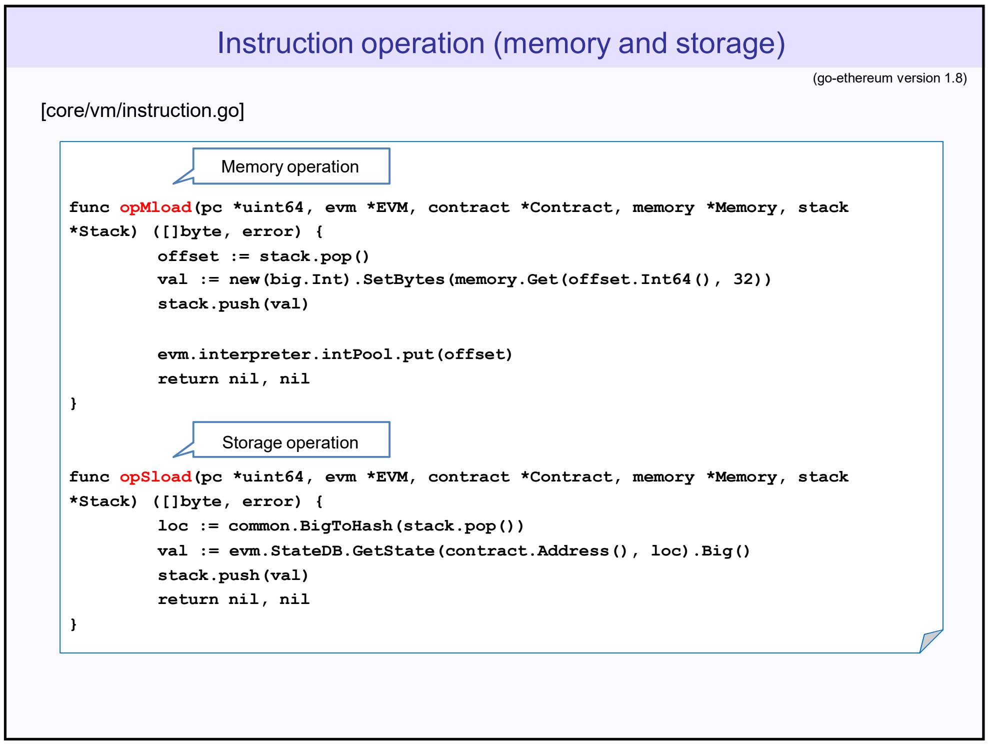
[core/vm/instruction.go]

Arithmetic operation

```
func opAdd(pc *uint64, evm *EVM, contract *Contract, memory *Memory, stack *Stack)
([]byte, error) {
        x, y := stack.pop(), stack.pop()
        stack.push(math.U256(x.Add(x, y)))

        evm.interpreter.intPool.put(y)

        return nil, nil
}
```

Stack operation

```
func opPop(pc *uint64, evm *EVM, contract *Contract, memory *Memory, stack *Stack)
([]byte, error) {
        evm.interpreter.intPool.put(stack.pop())
        return nil, nil
}
```



Instruction operation (memory and storage)

(go-ethereum version 1.8)

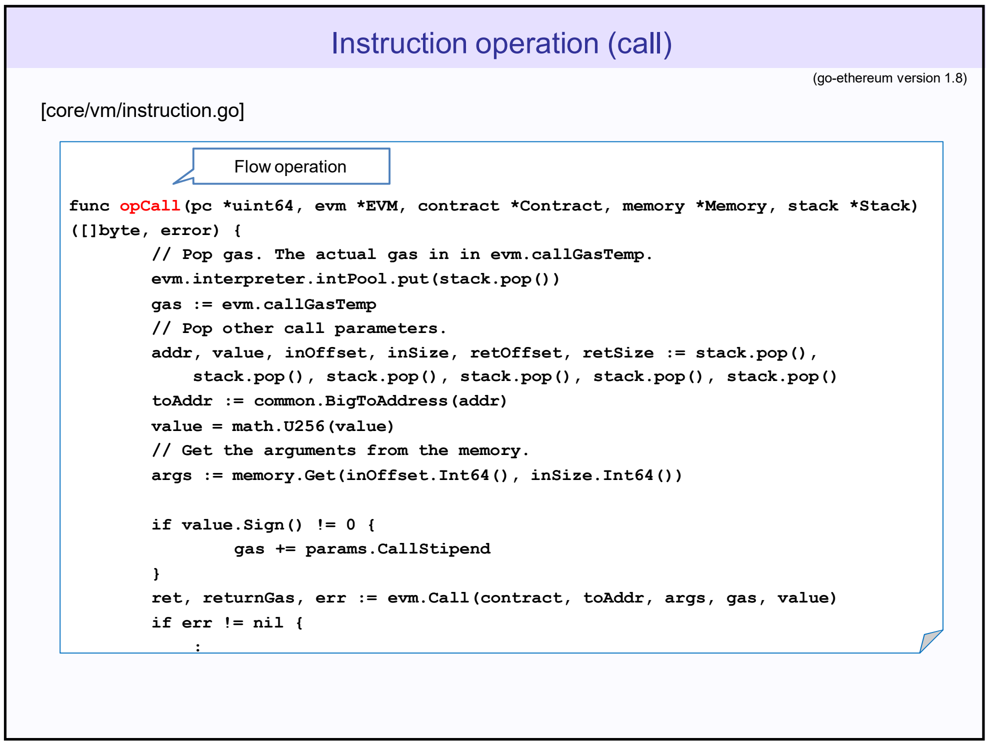
[core/vm/instruction.go]

Memory operation

```
func opMload(pc *uint64, evm *EVM, contract *Contract, memory *Memory, stack
*Stack) ([]byte, error) {
        offset := stack.pop()
        val := new(big.Int).SetBytes(memory.Get(offset.Int64(), 32))
        stack.push(val)

        evm.interpreter.intPool.put(offset)
        return nil, nil
}
```

Storage operation

```
func opSload(pc *uint64, evm *EVM, contract *Contract, memory *Memory, stack
*Stack) ([]byte, error) {
        loc := common.BigToHash(stack.pop())
        val := evm.StateDB.GetState(contract.Address(), loc).Big()
        stack.push(val)
        return nil, nil
}
```



Instruction operation (call)

(go-ethereum version 1.8)

[core/vm/instruction.go]

Flow operation

```
func opCall(pc *uint64, evm *EVM, contract *Contract, memory *Memory, stack *Stack)
([]byte, error) {
        // Pop gas. The actual gas in in evm.callGasTemp.
        evm.interpreter.intPool.put(stack.pop())
        gas := evm.callGasTemp
        // Pop other call parameters.
        addr, value, inOffset, inSize, retOffset, retSize := stack.pop(),
            stack.pop(), stack.pop(), stack.pop(), stack.pop(), stack.pop()
        toAddr := common.BigToAddress(addr)
        value = math.U256(value)
        // Get the arguments from the memory.
        args := memory.Get(inOffset.Int64(), inSize.Int64())

        if value.Sign() != 0 {
                gas += params.CallStipend
        }
        ret, returnGas, err := evm.Call(contract, toAddr, args, gas, value)
        if err != nil {
            :
```

Gas

(go-ethereum version 1.8)

[core/vm/gas.go]

```
const (
        GasQuickStep   uint64 = 2
        GasFastestStep uint64 = 3
        GasFastStep    uint64 = 5
        GasMidStep     uint64 = 8
        GasSlowStep    uint64 = 10
        GasExtStep     uint64 = 20

        GasReturn       uint64 = 0
        GasStop         uint64 = 0
        GasContractByte uint64 = 200
)
```

G_{base}

$G_{verylow}$

[core/vm/gas_table.go]

```
func gasSStore(gt params.GasTable, evm *EVM, contract *Contract, stack *Stack, mem
*Memory, memorySize uint64) (uint64, error) {
        var (
                y, x = stack.Back(1), stack.Back(0)
                val  = evm.StateDB.GetState(contract.Address(),
         :
```

Interpreter

(go-ethereum version 1.8)

[core/vm/interpreter.go]

```
func (in *Interpreter) Run(contract *Contract, input []byte) (ret []byte, err
error) {
        // Increment the call depth which is restricted to 1024
        in.evm.depth++
        defer func() { in.evm.depth-- }()

        in.returnData = nil

        if len(contract.Code) == 0 {
                return nil, nil
        }

        codehash := contract.CodeHash // codehash is used when doing jump dest caching
        if codehash == (common.Hash{}) {
                codehash = crypto.Keccak256Hash(contract.Code)
        }

        var (
                op    OpCode        // current opcode
                mem   = NewMemory() // bound memory
                stack = newstack()  // local stack
         :
```

increment call depth

create Memory

create Stack

ApplyTransaction

(go-ethereum version 1.8)

[core/state_processor.go]

```
func ApplyTransaction(config *params.ChainConfig, bc *BlockChain, author
*common.Address, gp *GasPool, statedb *state.StateDB, header *types.Header, tx
*types.Transaction, usedGas *uint64, cfg vm.Config) (*types.Receipt, uint64, error)
{
        msg, err := tx.AsMessage(types.MakeSigner(config, header.Number))
        if err != nil {
                return nil, 0, err
        }
        // Create a new context to be used in the EVM environment
        context := NewEVMContext(msg, header, bc, author)
        // Create a new environment which holds all relevant information
        // about the transaction and calling mechanisms.
        vmenv := vm.NewEVM(context, statedb, config, cfg)
        // Apply the transaction to the current state (included in the env)
        _, gas, failed, err := ApplyMessage(vmenv, msg, gp)
        if err != nil {
                return nil, 0, err
        }
        // Update the state with pending changes
        var root []byte
        if config.IsByzantium(header.Number) {
            :
```

create EVM

Version of EVM instruction set

(go-ethereum version 1.8)

[core/vm/interpreter.go]

```
func NewInterpreter(evm *EVM, cfg Config) *Interpreter {
if !cfg.JumpTable[STOP].valid {
                switch {
                case evm.ChainConfig().IsByzantium(evm.BlockNumber):
                        cfg.JumpTable = byzantiumInstructionSet
                case evm.ChainConfig().IsHomestead(evm.BlockNumber):
                        cfg.JumpTable = homesteadInstructionSet
                default:
                        cfg.JumpTable = frontierInstructionSet
                  :
```

added instructions:
STATICCALL, RETURNDATASIZE, RETURNDATACOPY and REVERT

added instruction:
DELEGATECALL

[core/config.go]

```
var (
 MainnetChainConfig = &ChainConfig{
                ChainId:        big.NewInt(1),
                HomesteadBlock: big.NewInt(1150000),
                DAOForkBlock:   big.NewInt(1920000),
                DAOForkSupport: true,
                EIP150Block:    big.NewInt(2463000),
                EIP150Hash: common.HexToHash("0x2086799aeebeae135c246c65021c82b4e15a2c451340993a
                EIP155Block:    big.NewInt(2675000),
                EIP158Block:    big.NewInt(2675000),
                ByzantiumBlock: big.NewInt(4370000),
                  :
```

Bootstrap of EVM in Geth

(go-ethereum version 1.8)

:

ApplyTransaction [core/state_processor.go] → create EVM

ApplyMessage [core/state_transaction.go]

TransactionDb [core/state_transaction.go]

Call [core/vm/evm.go]

run [core/vm/evm.go]

Run [core/vm/interpreter.go] → create Memory
create Stack

Example of evm command

(go-ethereum version 1.8)

The go-ethereum project provides evm utility command.

Compile EVM assembly code

```
$ cat sample.asm
push 0x1
push 0x2
add

$ evm compile sample.asm
6001600201
```

Disassemble EVM bytecode

```
$ cat sample.bin
6001600201

$ evm disasm sample.bin
000000: PUSH1 0x01
000002: PUSH1 0x02
000004: ADD
```

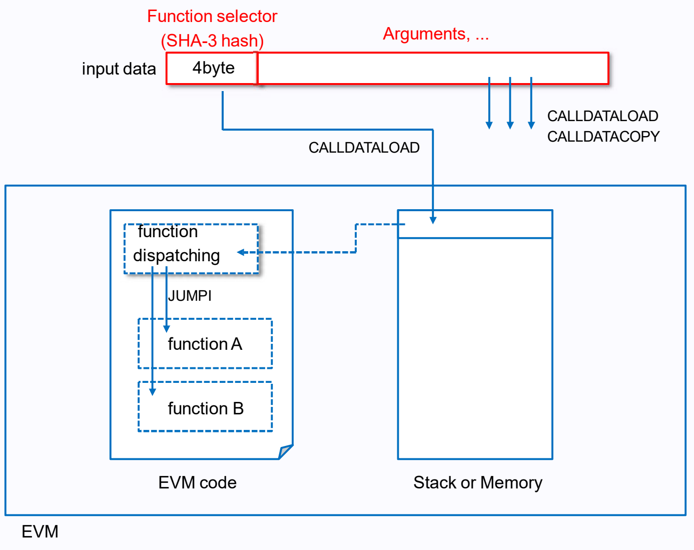
Example of evm command

(go-ethereum version 1.8)

Run EVM assembly code

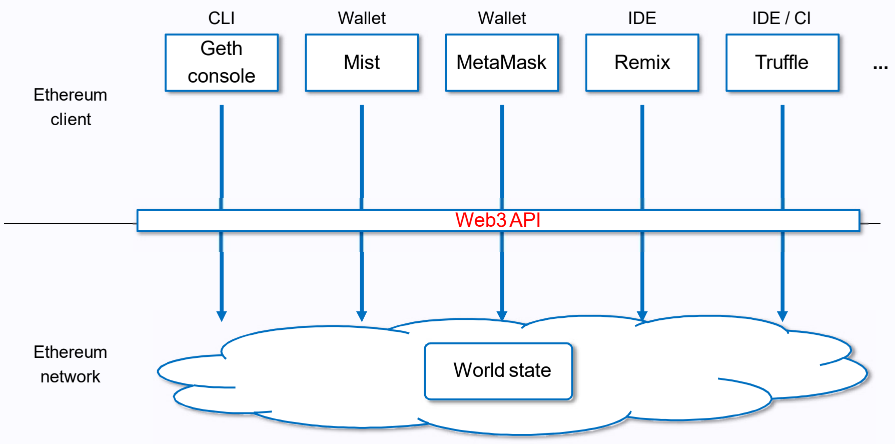
```
$ evm --debug run sample.asm

#### TRACE ####
PUSH1           pc=00000000 gas=10000000000 cost=3

PUSH1           pc=00000002 gas=9999999997 cost=3
Stack:
00000000  0000000000000000000000000000000000000000000000000000000000000001

ADD             pc=00000004 gas=9999999994 cost=3
Stack:
00000000  0000000000000000000000000000000000000000000000000000000000000002
00000001  0000000000000000000000000000000000000000000000000000000000000001

STOP            pc=00000005 gas=9999999991 cost=0
Stack:
00000000  0000000000000000000000000000000000000000000000000000000000000003

#### LOGS ####
```

Solidity Application Binary Interface(ABI)



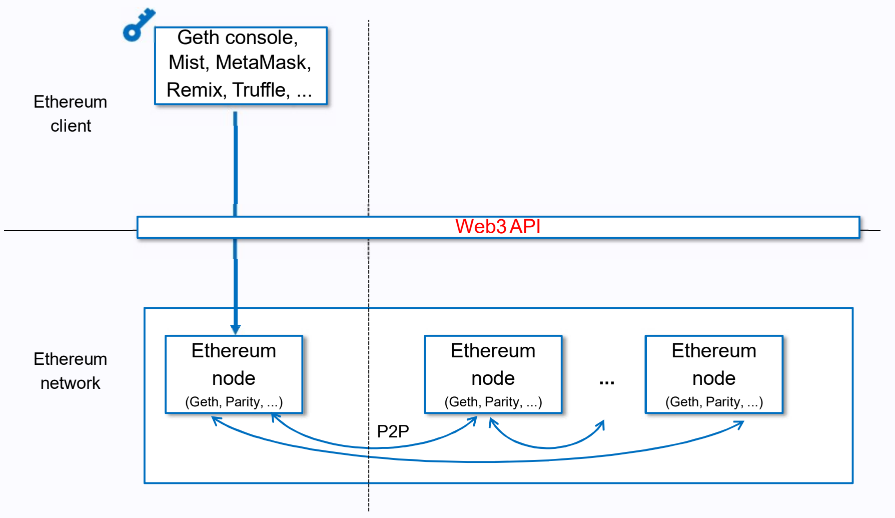
References : [E7]. Ch.7, [E1] Ch.9, Appendix H, [W4], [W2]

Web3 API and client



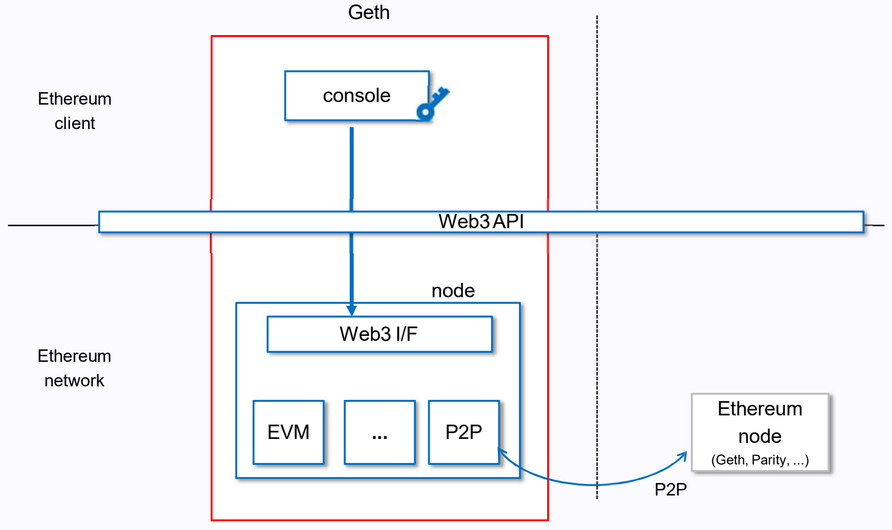
Ethereum clients access to Ethereum network via Web3 API.

Web3 API and client


Geth console, Mist, MetaMask, Remix, Truffle, ...
Ethereum client
Web3 API
Ethereum network
Ethereum node (Geth, Parity, ...)
Ethereum node (Geth, Parity, ...)
...
Ethereum node (Geth, Parity, ...)
P2P

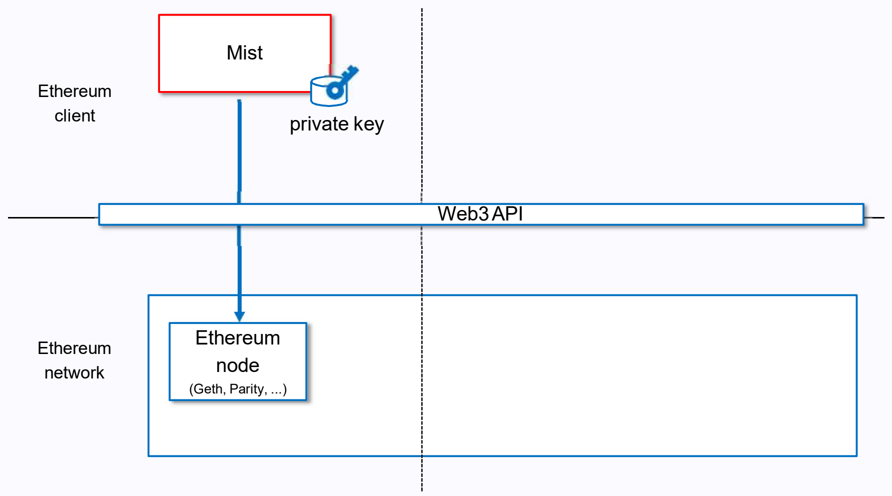
Ethereum clients access to Ethereum network via Web3 API.

Geth



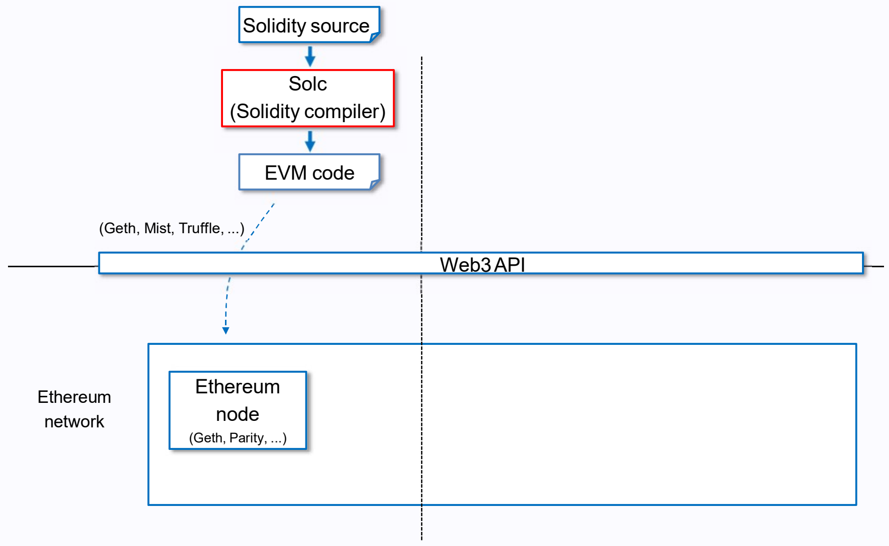
Geth
Ethereum client
console
Web3 API
node
Web3 I/F
Ethereum network
EVM
...
P2P
Ethereum node (Geth, Parity, ...)
P2P

Mist

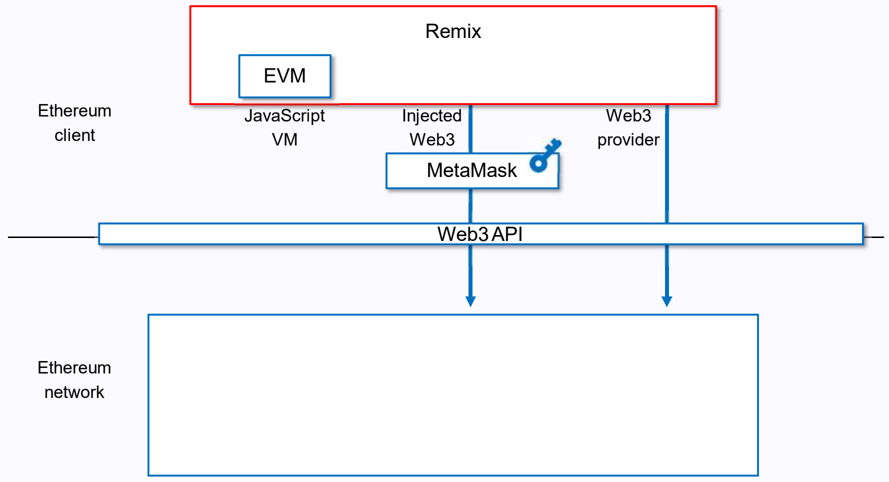


Mist
Ethereum client
private key
Web3 API
Ethereum network
Ethereum node (Geth, Parity, ...)

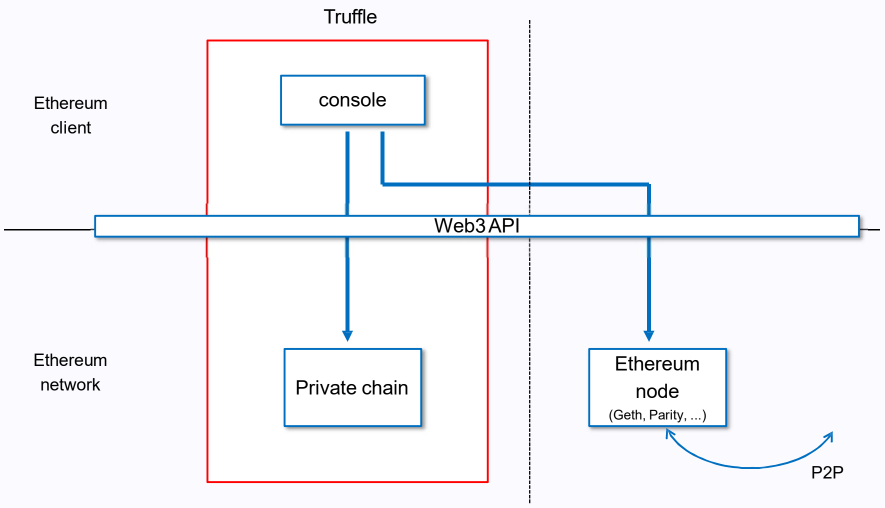
Solc


Solidity source
Solc
(Solidity compiler)
EVM code
(Geth, Mist, Truffle, ...)
Web3 API
Ethereum network
Ethereum node
(Geth, Parity, ...)

Remix


Remix
EVM
Ethereum client
JavaScript VM
Injected Web3
MetaMask
Web3 provider
Web3 API
Ethereum network

Truffle



References

Ethereum Yellow Paper
ETHEREUM: A SECURE DECENTRALISED GENERALISED TRANSACTION LEDGER
https://ethereum.github.io/yellowpaper/paper.pdf

Glossary
https://github.com/ethereum/wiki/wiki/Glossary

White Paper
A Next-Generation Smart Contract and Decentralized Application Platform
https://github.com/ethereum/wiki/wiki/White-Paper

Design Rationale
https://github.com/ethereum/wiki/wiki/Design-Rationale

Ethereum Development Tutorial
https://github.com/ethereum/wiki/wiki/Ethereum-Development-Tutorial

Ethereum Introduction
https://github.com/ethereum/wiki/wiki/Ethereum-introduction

Solidity Documentation
https://media.readthedocs.org/pdf/solidity/develop/solidity.pdf
https://solidity.readthedocs.io/en/develop/

Web3 JavaScript app API for 0.2x.x
https://github.com/ethereum/wiki/wiki/JavaScript-API

ethereum/wiki Subtleties
https://github.com/ethereum/wiki/wiki/Subtleties#exceptional-conditions

References

Awesome Ethereum Virtual Machine
https://github.com/pirapira/awesome-ethereum-virtual-machine

Diving Into The Ethereum VM
https://blog.qtum.org/diving-into-the-ethereum-vm-6e8d5d2f3c30

Stack Exchange: Ethereum block architecture
https://ethereum.stackexchange.com/questions/268/ethereum-block-architecture/6413

Porosity
https://www.comae.io/reports/dc25-msuiche-Porosity-Decompiling-Ethereum-Smart-Contracts.pdf

Go Ethereum
https://github.com/ethereum/go-ethereum

Solc (Solidity compiler)
https://github.com/ethereum/solidity

Mist (Ethereum Wallet)
https://github.com/ethereum/mist

MetaMask
https://github.com/MetaMask/metamask-extension

Remix
https://github.com/ethereum/browser-solidity

Truffle
https://github.com/trufflesuite/truffle