Emerging Technologies for the Circular Economy

Lecture 10: Ethereum and Smart Contracts

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- All their slides, exercises and further information are available online: https://github.com/sebischair/bbse

INTRODUCTION TO ETHEREUM

History

- Publicly announced in January 2014 by Vitalik Buterin
- Public crowd sale in July 2014
  - 60 million Ether sold for 31,591 Bitcoin
  - Worth around 18.5 million USD at that time
  - Funds controlled by the Ethereum foundation

History of Ethereum: http://ethdocs.org/en/latest/introduction/history-of-ethereum.html

Ethereum Foundation

*"The Ethereum Foundation's **mission is** to **promote and support Ethereum platform** and **base layer research, development** and **education** to bring decentralized protocols and tools to the world that empower developers **to produce next generation decentralized applications** (dApps), and together build a more globally accessible, more free and more trustworthy Internet."*

Ethereum Foundation

- Founded in June 2014 in Zug, Switzerland
- Non-profit organization
- Foundation council consists of Vitalik Buterin and Patrick Storchenegger (legal affairs)
- Owns (or owned) at least 31,591 Bitcoins funding capital from the initial crowd sale

Ethereum White Paper

- First draft was written by Vitalik Buterin himself (2013)
- Contains high-level descriptions of Ethereum’s core functionalities
- Living document and regularly updated by Ethereum core developers
- Extensive summary of the Ethereum platform and technology
- Most current version is available via the public Git-repository: Link

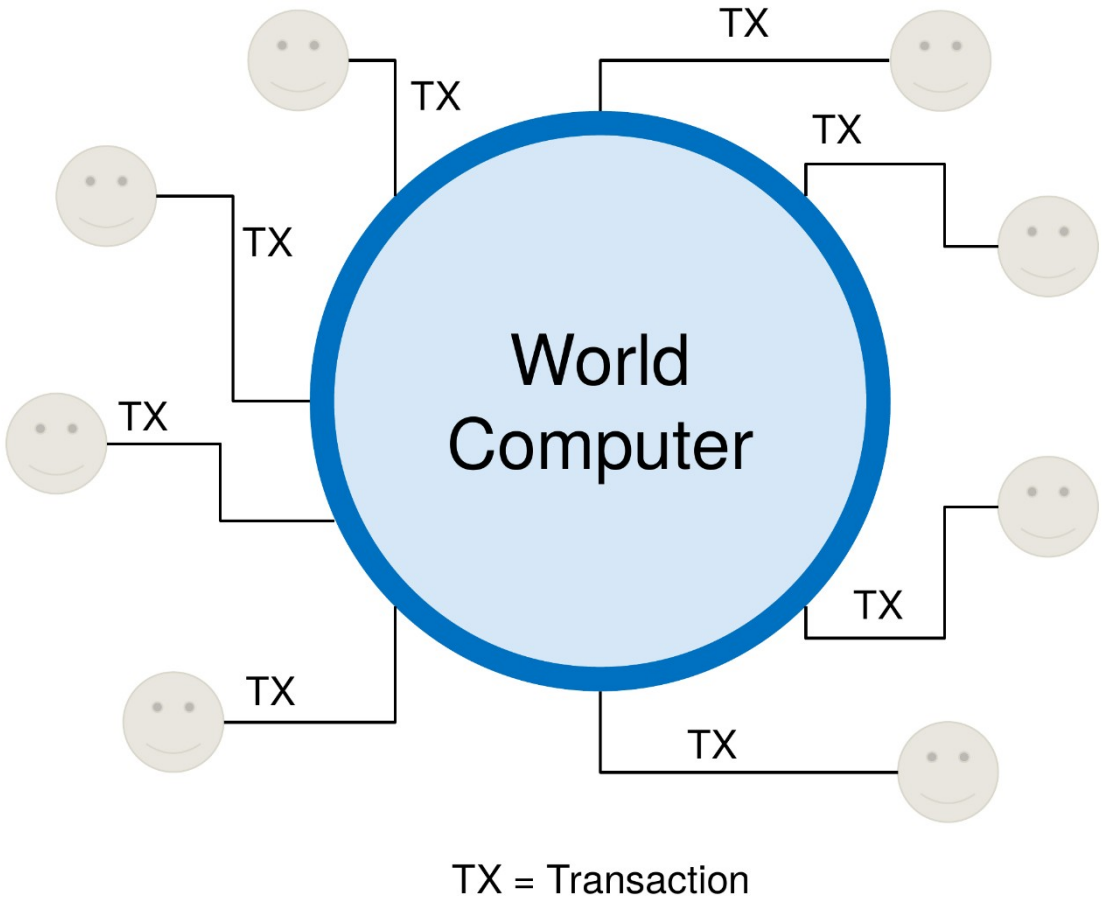
Ethereum Yellow Paper

- Published in April 2014 by Dr. Gavin Wood
- Dr. Gavin Wood is still listed as the only author
- Defines the technical specification of Ethereum
- Very detailed, contains mathematical function definitions and byte code mappings
- Required to implement a full node
- Only updated when errors are found or the specification changes
- Yellow Paper

ETHEREUM SYSTEM ARCHITECTURE

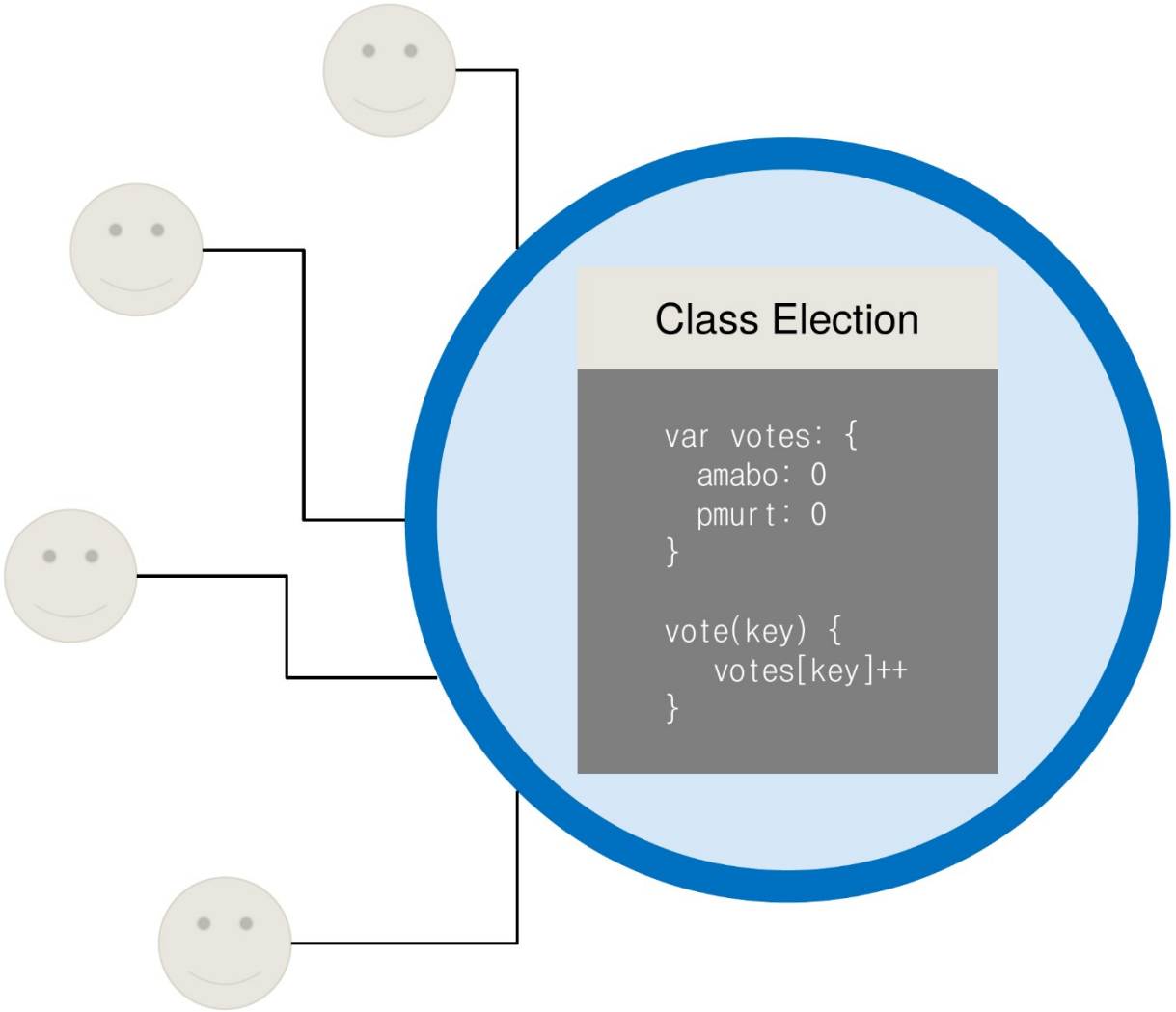
The Concept of a World Computer

- All participants are using the same computer
- Users issue transactions to call programs on the computer
- Everyone shares the same resources and storage
- The computer has no explicit, single owner
- Using the computer's resources costs money



U. Gallersdörfer, P. Holl, and F. Matthes, "Blockchain-based Systems Engineering – Lecture Slides," Oct 2019. [Online]. Available: https://github.com/sebischair/bbse

Elections using a World Computer



State of the world

State 0 (initial)
(nothing happened yet)

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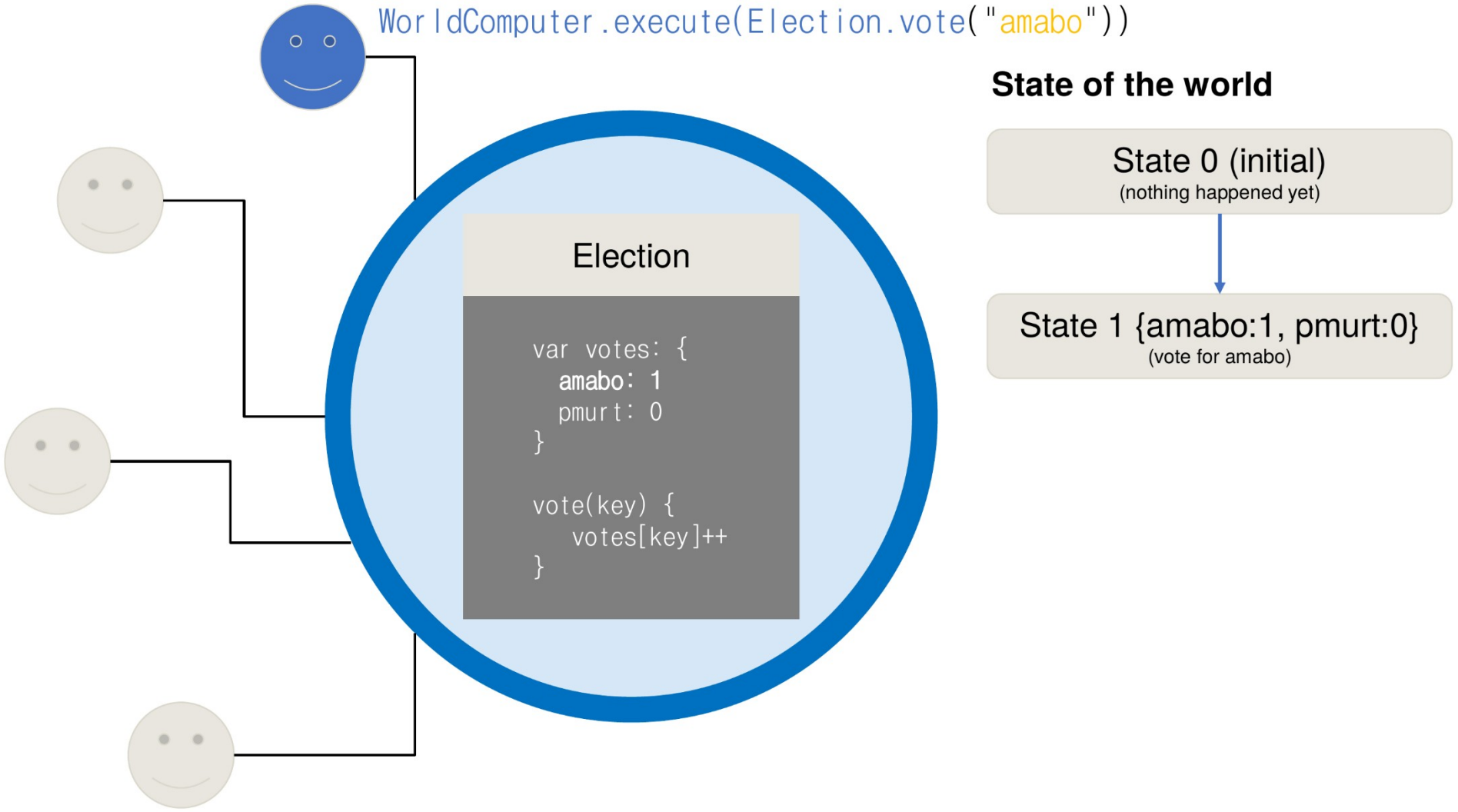
Elections using a World Computer



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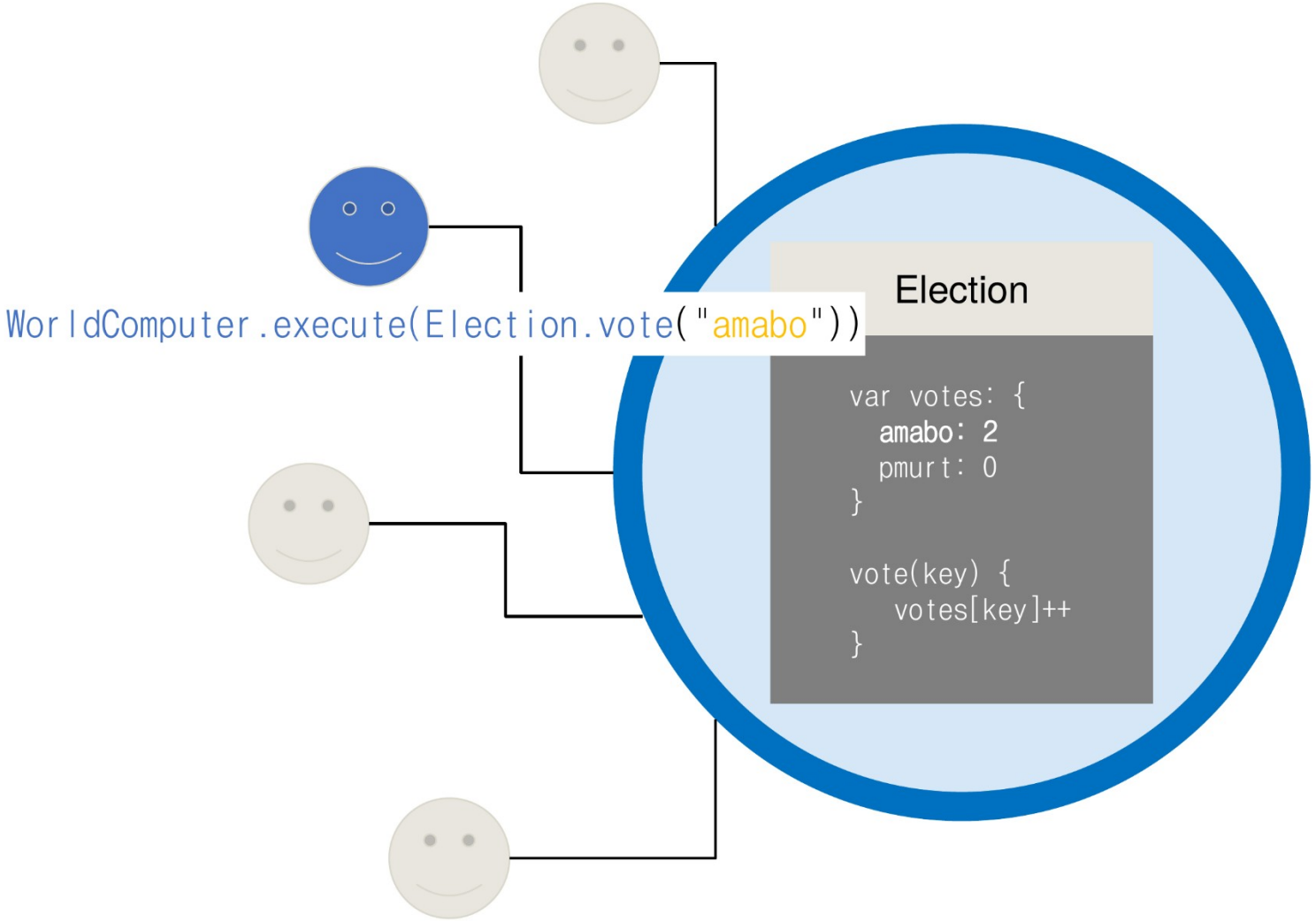
Elections using a World Computer



State of the world

State 0 (initial)
(nothing happened yet)

↓

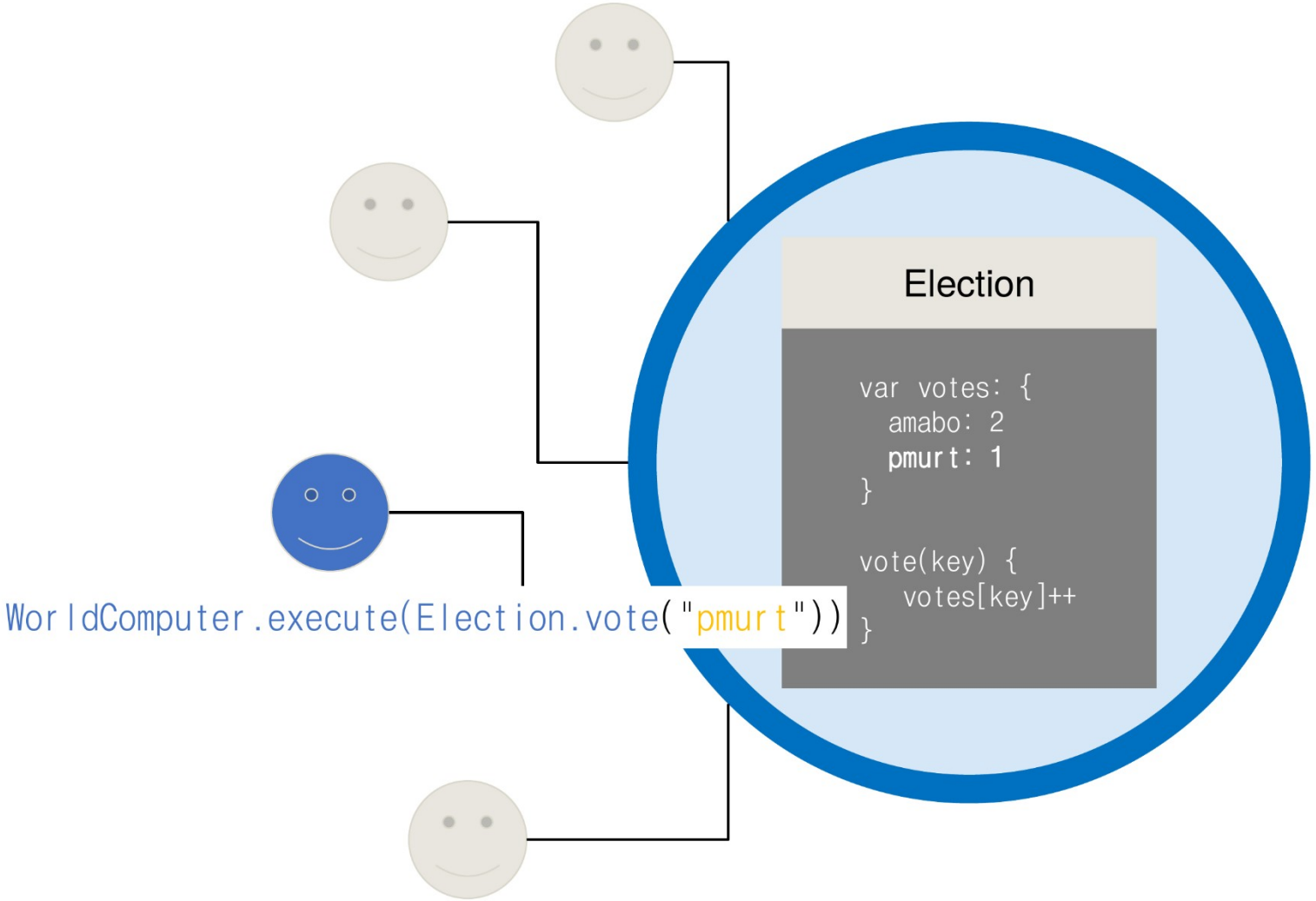
State 1 {amabo:1, pmurt:0}
(vote for amabo)

↓

State 2 {amabo:2, pmurt:0}
(vote for amabo)

U. Gallersdörfer, P. Holl, and F. Matthes, “Blockchain-based Systems Engineering – Lecture Slides,” Oct 2019. [Online]. Available: https://github.com/sebischair/bbse

Elections using a World Computer



State of the world

State 0 (initial)
(nothing happened yet)

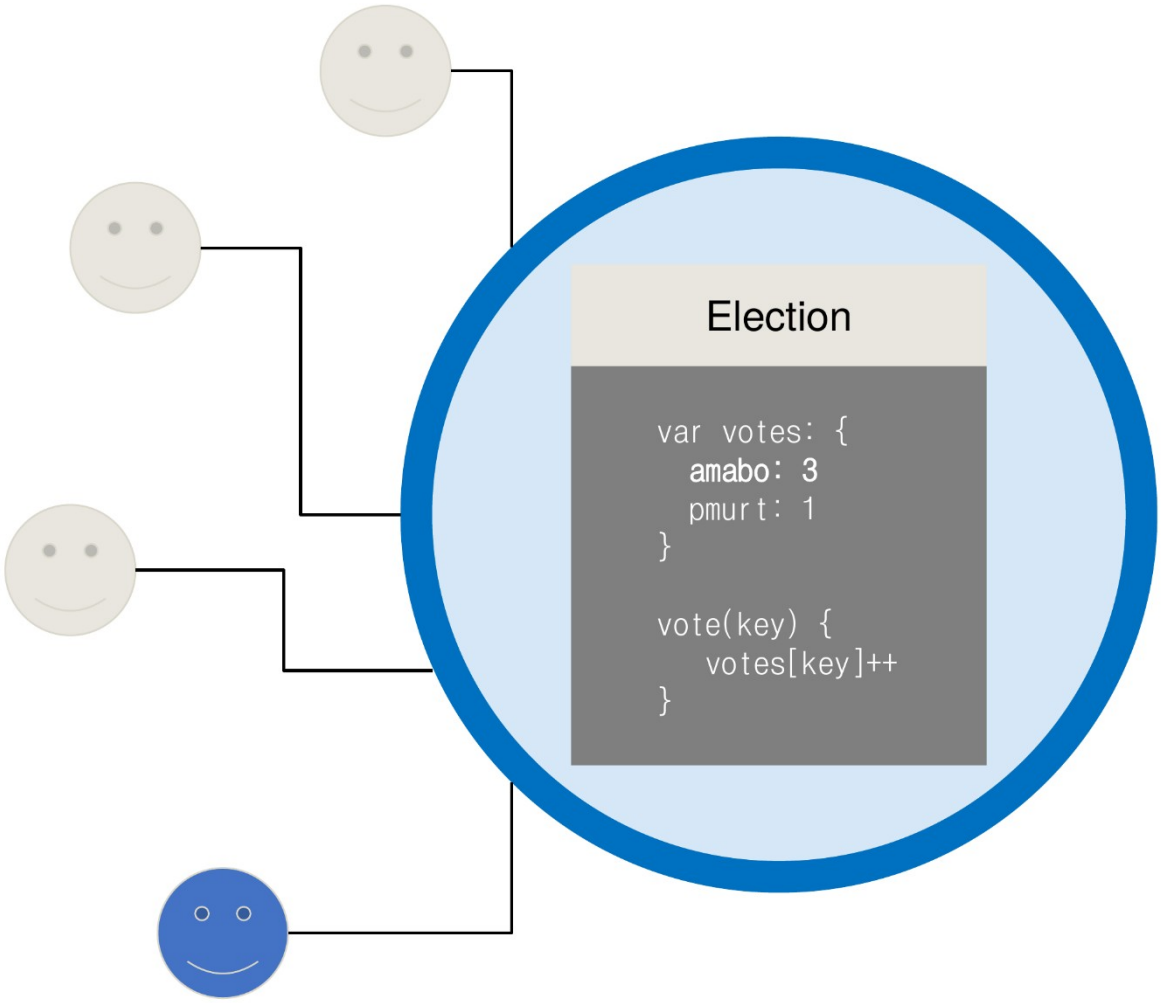
State 1 {amabo:1, pmurt:0}
(vote for amabo)

State 2 {amabo:2, pmurt:0}
(vote for amabo)

State 3 {amabo:2, pmurt:1}
(vote for pmurt)

U. Gallersdörfer, P. Holl, and F. Matthes, “Blockchain-based Systems Engineering – Lecture Slides,” Oct 2019. [Online]. Available: https://github.com/sebischair/bbse

Elections using a World Computer



State of the world

State 0 (initial)
(nothing happened yet)

State 1 {amabo:1, pmurt:0}
(vote for amabo)

State 2 {amabo:2, pmurt:0}
(vote for amabo)

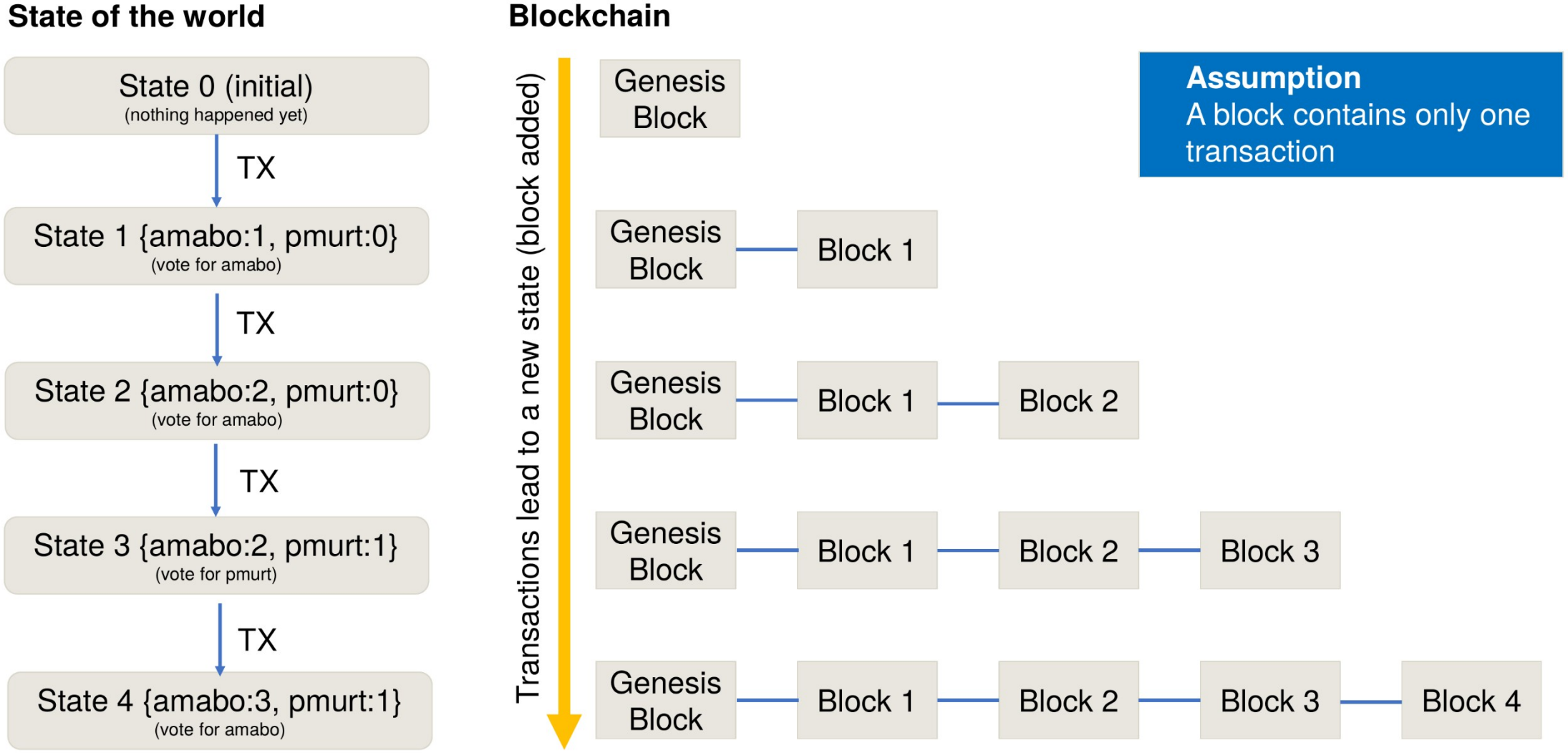
State 3 {amabo:2, pmurt:1}
(vote for pmurt)

State 4 {amabo:3, pmurt:1}
(vote for amabo)

```
WorldComputer.execute(Election.vote( "amabo"))
```

U. Gallersdörfer, P. Holl, and F. Matthes, "Blockchain-based Systems Engineering – Lecture Slides," Oct 2019. [Online]. Available: https://github.com/sebischair/bbse

The Blockchain State Machine



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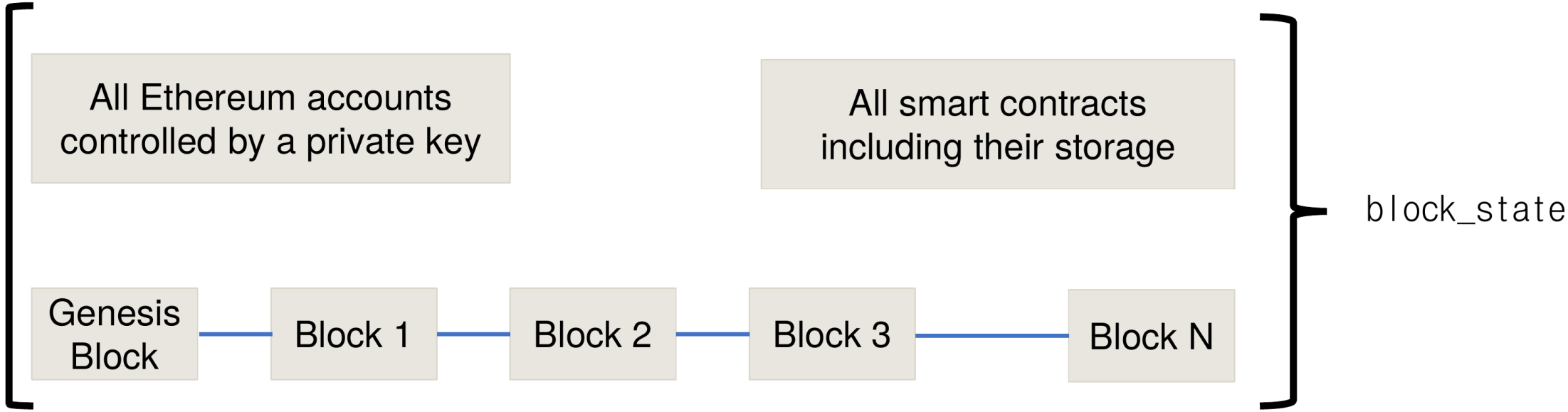
The Concept of a State Machine

- The EVM specifies an execution model for state changes of the blockchain
- Formally, the EVM can be specified by the following tuple: (block state, transaction, message, code, memory, stack, pc, gas)
- The block state represents the global state of the whole blockchain including all accounts, contracts and storage



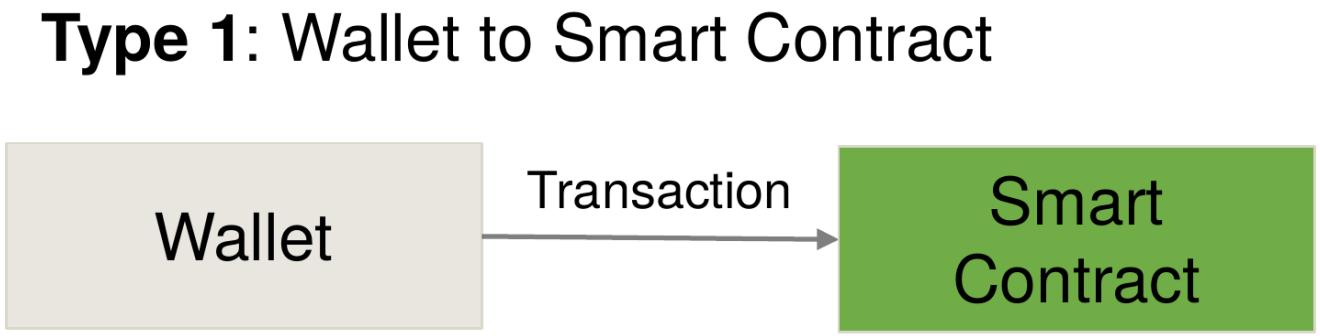
Transaction

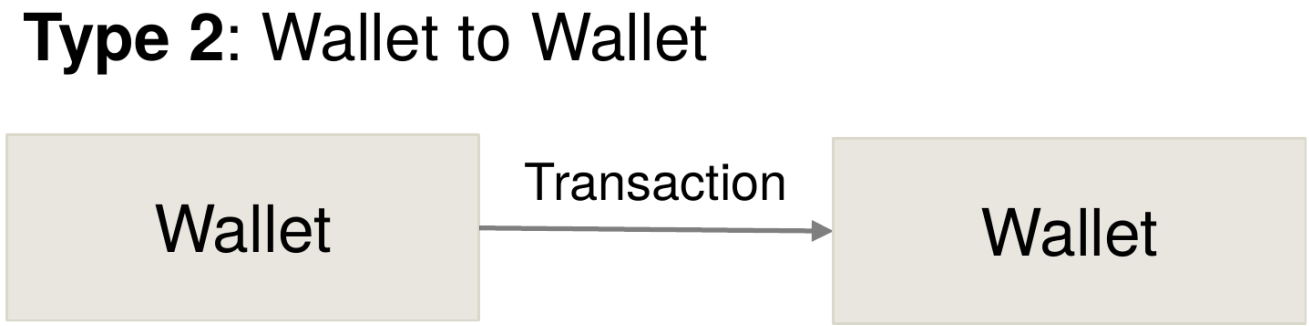
A transaction is a signed data package that is always sent by a wallet and contains the following data:

- Recipient
- Sender’s signature
- Amount of ETH to transfer
- Optional data field
- A *STARTGAS* value, representing the maximum number of computational steps the transaction execution is allowed to take
- A *GASPRICE* value, representing the fee the sender pays per computational step

Transactions

- There are two types of transactions:





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Messages

- Similar to a transaction, but only sent by contracts and exist only virtually, i.e. they are not mined into a block like transactions
- Message contains:
  - Sender of the message (implicit)
  - Recipient
  - Amount of ETH to be transferred
  - Optional data field
  - *STARTGAS* value

Messages

- Whenever a contract calls a method on another contract, a virtual message is sent.
- Whenever a wallet calls a method on a contract, a transaction is sent.

Code and Memory

- Code:
  - Bytecode representation of a smart contract. EVM interprets smart contracts as a sequence of opcodes similar to assembly code.

Example:

```
PUSH1 0x60
PUSH1 0x40
MSTORE
PUSH1 0x04
CALLDATASIZE
LT
PUSH2 0x00b6
JUMPI
PUSH4 0xffffffff
```

U. Gallersdörfer, P. Holl, and F. Matthes, “Blockchain-based Systems Engineering – Lecture Slides,” Oct 2019. [Online]. Available: https://github.com/sebischair/bbse

Code and Memory

- Code:
  - Bytecode representation of a smart contract. EVM interprets smart contracts as a sequence of opcodes similar to assembly code.
- Memory:
  - An infinitely expandable byte array that is non-persistent and used as temporal storage during execution.

Example:

```
PUSH1 0x60
PUSH1 0x40
MSTORE
PUSH1 0x04
CALLDATASIZE
LT
PUSH2 0x00b6
JUMPI
PUSH4 0xffffffff
```

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Stack and Program Counter

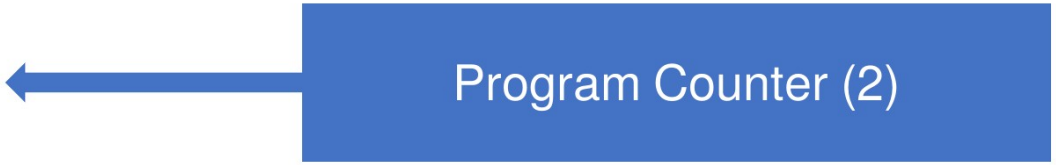
- Stack:
  - The stack is also used as a fast, non-persistent buffer to which 32 byte values can be pushed and popped during execution.

- PC:
  - Stands for “program counter”.
  - The program counter is always initialized with 0 and points to the position of the current opcode instruction.

Stack and Program Counter

Simple Opcode Execution Example:

```
0    PUSH1 0x60
1    PUSH1 0x40
2    MSTORE
3    PUSH1 0x04
4    CALLDATASIZE
5    LT
6    PUSH2 0x00b6
7    JUMPI
8    PUSH4 0xffffffff
```



Gas

- Executed opcode instruction use miner’s computational resources → requires a fee (called gas)
- Each opcode uses a certain amount of gas which may depend on the arguments of the operation
- Opcode for self-destruct(address) uses negative gas because it frees up space from the blockchain
- Sender must specify maximum amount of gas that he/she/it is willing to pay for the transaction
- Sender can set an arbitrary amount of Ether to be spent → called gas price
- Final costs for transaction → gas × gasprice
- If a transaction requires more gas as the maximum specified gas, the transaction fails
- If it takes less, the sender only pays the gas that was used

Account Types

Ethereum uses an account-based ledger → Each distinct address represents a separate, unique account.

1. Accounts controlled by private keys and owned externally
   - Can sign transactions, issue smart contract functions calls and send Ether from one account to another
   - Origin of any transaction is always an account controlled by a private key
2. Smart contract accounts controlled by their code
   - Smart Contracts are treated as account entities with their own, unique address
   - Can send messages to other accounts, both externally controlled and smart contracts
   - Can’t issue a transaction themselves.
   - Have a persistent internal storage to write and read data from

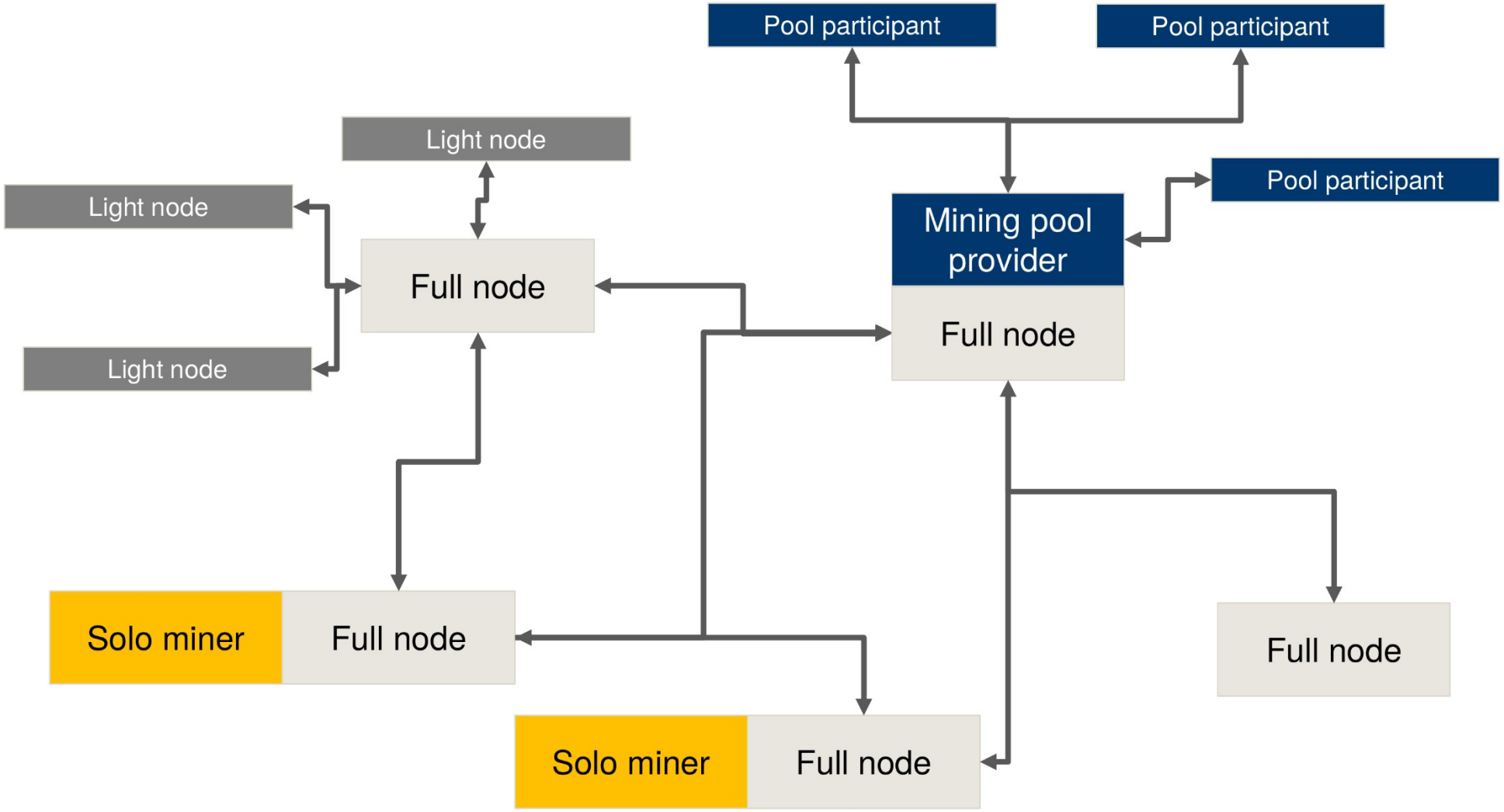
Account Properties

Ethereum account is a 4-tuple containing: (nonce, balance, contract code, storage)

- Nonce:
  - Increasing number that is attached to any transaction to prevent replay attacks and double spending.
- Balance:
  - Current account balance in ETH.
- Contract code:
  - Bytecode representation of the account. If no contract code is present, then the account is externally controlled.
- Storage:
  - Data storage used by the account – empty by default.
  - Only contract accounts can have their own storage.

ETHEREUM NETWORK ARCHITECTURE

Network Architecture Overview



U. Gallersdörfer, P. Holl, and F. Matthes, “Blockchain-based Systems Engineering – Lecture Slides,” Oct 2019. [Online]. Available: https://github.com/sebischair/bbse

Node Types

- Full nodes:
  - Holds complete copy of the entire blockchain
  - P2P synchronization with other full nodes
  - Transactions must be sent to a full node to join the transaction pool
- Light nodes:
  - Clients connected to full nodes → instead of downloading the full blockchain on its own
  - Most commonly used by private users
- Solo miner:
  - An entity that tries to mine a block on its own
- Staking/Mining pools:
  - Coalition of entities combining their hash power / staking power
  - Revenue/Reward is shared among participants

ETHEREUM SMART CONTRACTS

What is a *Smart* Contract?

- A contract is a legal document
  - that binds two or more parties
  - who agree to execute a transaction immediately or in the future
- Smart contracts are digitization of legal contracts
- In Ethereum,
  - smart contracts are deployed, stored and executed within the Ethereum Virtual machine (EVM)

https://medium.com/coinmonks/https-medium-com-ritesh-modi-solidity-chapter1-63dfaff08a11

What is a *Smart* Contract?

- Also known as self executing contract or digital contracts
- It is like a vending machine, i.e. the ledger → You put money/data and you expect a finite item (e.g. your license, ..)
- Vitalik Buterin's explanation:
  - An asset or currency is transferred into a program,
  - the program runs this code and at some point it automatically validates a condition
  - and it automatically determines whether the asset should go to one person or back to the other person,
  - or whether it should be immediately refunded to the person who sent it or some combination thereof.
  - In the meantime, the decentralized ledger also stores and replicates the document which gives it a certain security and immutability.

https://blockgeeks.com/guides/smart-contracts/

Smart Contract – Rent an Apartment

- You get a receipt which is held in our virtual contract;
- I give you the digital entry key which comes to you by a specified date
- If the key does not come on time, the blockchain releases a refund.
- If I send the key before the rental date, the function holds it releasing both the fee to me and key to you respectively when the date arrives.
- If I give you the key, I’m sure to be paid. If you send a certain amount in ETH, you receive the key.
- The document is automatically canceled after the time, and the code cannot be interfered with by either of us.

https://blockgeeks.com/guides/smart-contracts/

What is a *Smart* Contract?

- Smart contracts can also store data
- The data stored can be used to record
  - information, fact, associations, balances
  - or any other information needed to implement logic for real world contracts

https://medium.com/coinmonks/https-medium-com-ritesh-modi-solidity-chapter1-63dfaff08a11

What is a *Smart* Contract?

- Smart contracts can also store data
- The data stored can be used to record
  - information, fact, associations, balances
  - or any other information needed to implement logic for real world contracts
- Smart contracts are similar to Object-oriented classes
  - A smart contract can call another smart contract just like an Object-oriented object to create and use objects of another class.
  - Think of smart contract as a small program consisting of functions.
  - You can create an instance of the contract and invoke functions to view and update contract data along with execution of some logic

https://medium.com/coinmonks/https-medium-com-ritesh-modi-solidity-chapter1-63dfaff08a11

Smart Contracts in a Nutshell

- Is a set of functions that can be called by other users or contracts
- Used to execute functions, send ETH, or store data.
- Each smart contract is an account holding object, i.e. has its own address.
- Smart contracts have some peculiarities compared to traditional software.

Smart Contracts in a Nutshell

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- Smart contracts have some peculiarities compared to traditional software.

All contracts deployed on the Ethereum blockchain are publicly accessible and can’t be patched.

Ethereum Smart Contract Coding

- Solidity is a high-level language to write smart contracts for Ethereum
- Contracts can be defined as encapsulated units, similar to classes in traditional object-oriented programming languages like Java.
- A contract has its own, persistent state on the blockchain which is defined by state variables in the contract.
- Functions are used to change the state of the smart contract or to perform other computations.
- Solidity is compiled to bytecode which is persistent and immutable once deployed to the blockchain → Not patchable.

Brief Insight: Solidity

Solidity is a high-level language with a JavaScript-like syntax for writing Ethereum smart contracts.

- Language properties:
  - Statically typed
  - Object-oriented
  - Supports inheritance
  - Public & private methods
  - Dynamic binding
  - Compiles to EVM opcode instructions

```
pragma solidity ^0.4.24;
contract helloWorld {

    constructor () {}

    function renderHelloWorld () returns (string) {
        return 'helloWorld';
    }
}
```

U. Gallersdörfer, P. Holl, and F. Matthes, “Blockchain-based Systems Engineering – Lecture Slides,” Oct 2019. [Online]. Available: https://github.com/sebischair/bbse

Solidity to Smart Contract

- Solidity code is stored in files with the special file extension .sol
- A good practice is to have one separate .sol file per contract
- The Solidity compiler takes a .sol file as input and generates the corresponding sequence of EVM opcode instructions
- The opcode instructions are then encoded as hex bytecode
- The contract is deployed via a special transaction containing the bytecode as payload
- Once the transaction is mined, a new contract account on the Ethereum network is created
- The contract is now usable

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ETHEREUM DECENTRALIZED APPLICATIONS

Motivation

- Direct interaction with smart contracts is complicated
- Smart contracts do not provide a graphical user interface on their own
- Programming knowledge or special tools are required to make function calls

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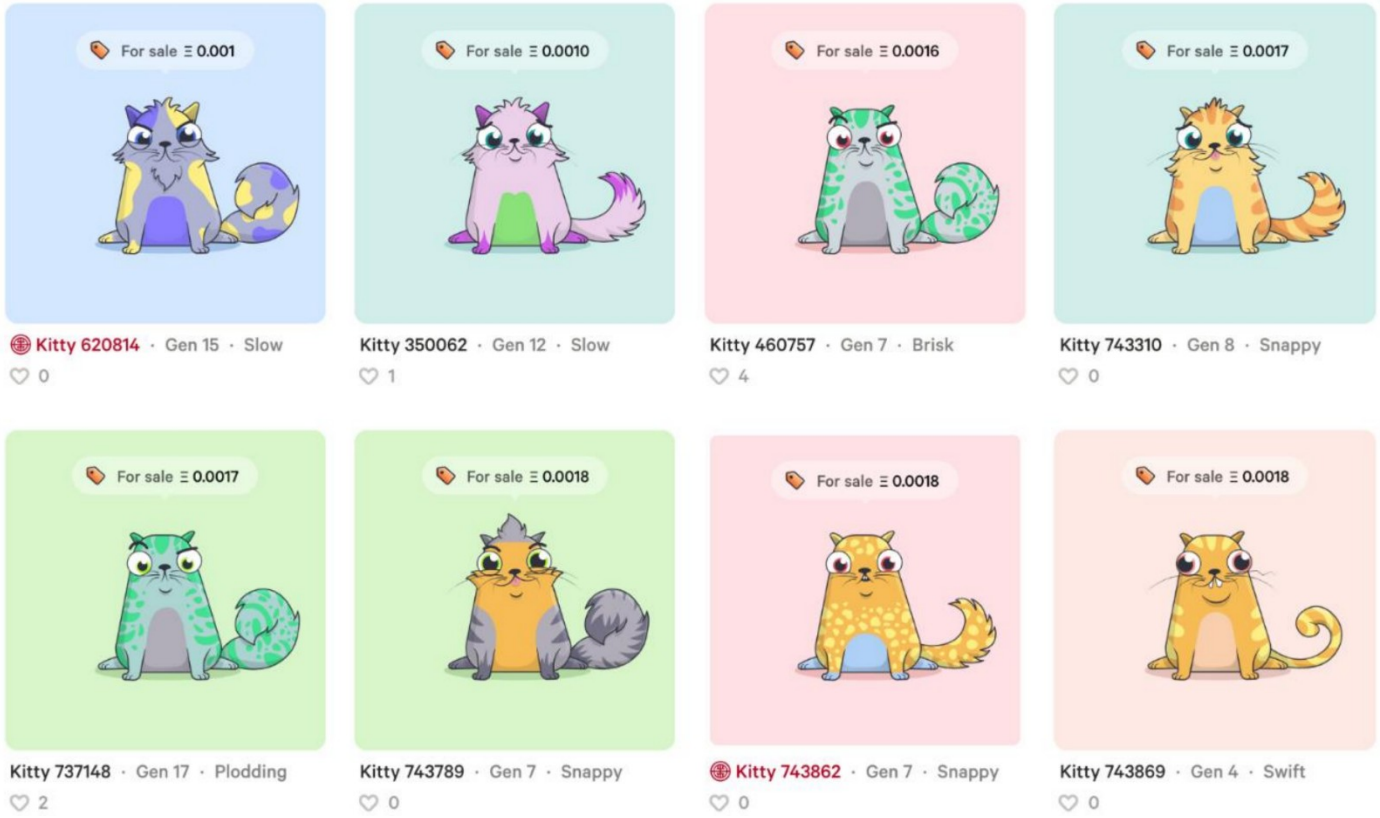
Motivation

- Building UIs on top of smart contracts to make them accessible to average users
- The UI abstracts the complicated function calls and allows a user to interact with them just like with a regular (web) application



U. Gallersdörfer, P. Holl, and F. Matthes, “Blockchain-based Systems Engineering – Lecture Slides,” Oct 2019. [Online]. Available: https://github.com/sebischair/bbse

Definition

- In the community, multiple definitions for dApps exist
- In general, a dApp is not necessarily based on a Blockchain, e.g., BitTorrent is a decentralized P2P application without any blockchain involved
- In this lecture, we consider a dApp as a decentralized application (in the terms of blockchain) based on one or more smart contracts and accessible via a dedicated user interface
- In particular, the following properties must hold:
  - The core data records of the application must be stored on the blockchain
  - The functions that change the core data records must be executed on the blockchain, i.e. via a smart contract

Benefits

The meaningfulness of implementing a distributed application is dependent on the concrete use case and / or the problem that is being solved.

Some general properties of Ethereum-based dApps:

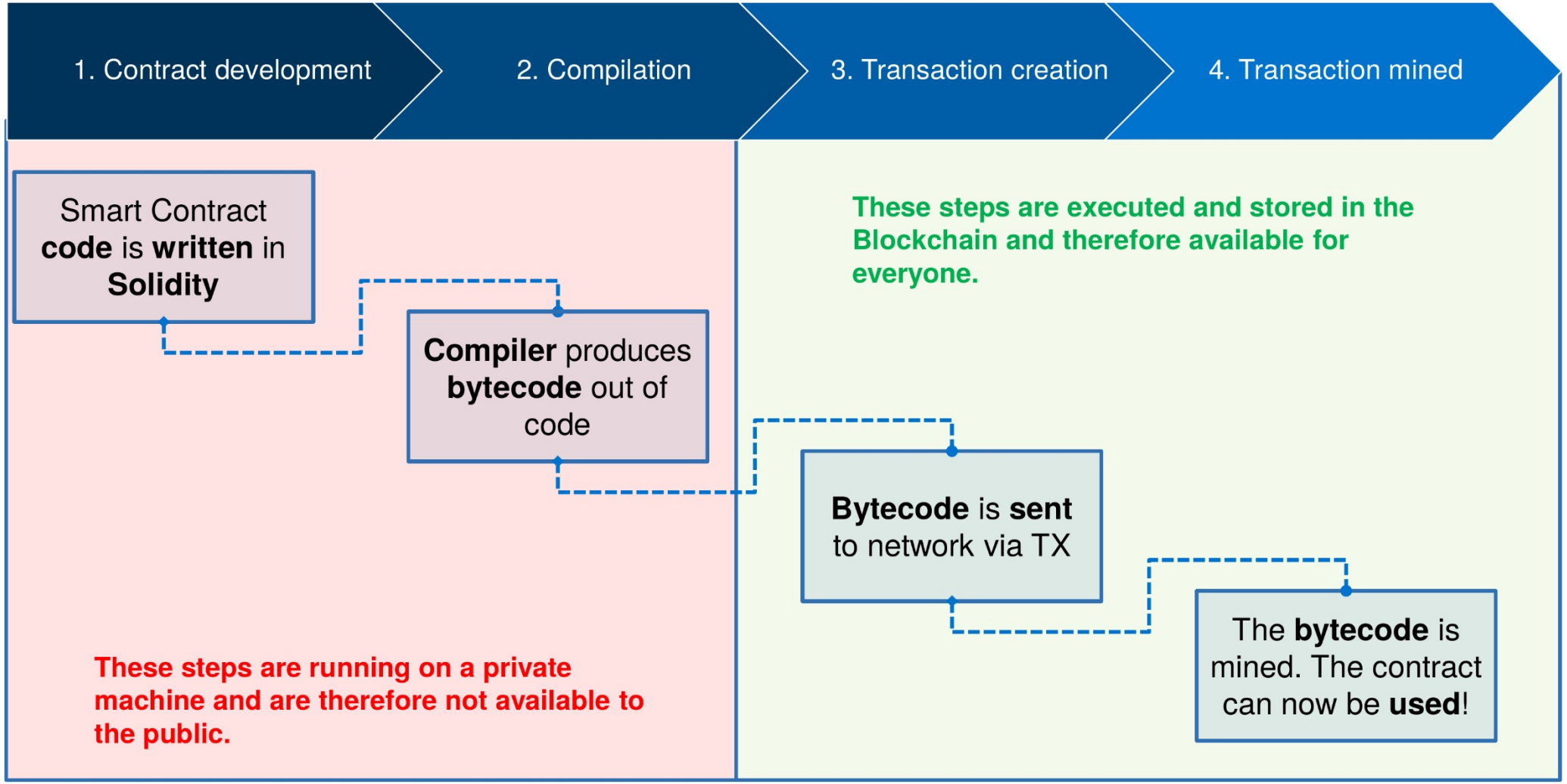
- **Trust**
  - The source code of any verified smart contract can be checked by anyone.
- **Payment**
  - Payment is implemented by default since anyone can send / receive Ether.
- **Accounts**
  - dApps can be build on top of Ethereum’s account system, so there is no need to implement an additional user account management system.
- **Storage**
  - dApps can leverage the Blockchain as common (expensive) data storage.

Drawbacks

Decentralized applications have also some intrinsic disadvantages:

- **Costs**
  - Any state change and computation costs money. For that reason, only mission-critical data and functionality should leverage the blockchain.
- **Time**
  - The current block time of Ethereum is around 14 seconds, i.e., it takes at least 14 seconds from the function call to the definite result of it.
- **Availability**
  - In theory, availability is one of the key advantages of dApps. However, in high transaction scenarios (e.g. the release of crypto kitties) it is possible that the network throttles and is not able to process function calls anymore.
- **Transparency**
  - Without third party services, it is impossible to access and verify a Smart Contract source code.

Recap – Deploy Smart Contract on Chain



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Bytecode Source Code on Chain

Switch To Opcodes View | Find Similiar Contracts

0x6080604052600436106100995760003357c0100000000000000000000000000000000000000000000000000000000900463ffffffff16806306fdde031461009e578063095ea7b31461012e57806318160ddd1461019357806323b872dd146101be578063313ce567146102435780636370a082311461027457806395d89b41146102cb578063a9059cbb1461035b578063dd62ed3e146103c0575b600080fd5b3480156100aa57600080fd5b506100b3610437565b6040518080602001828103825283818151815260200191508051906020019080838360005b838110156100f357808201518184015260208101905061...

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Publicly Available Source Code

Etherscan.io is a service which also verifies source codes and the respective byte code.

Contract Source Code Verified (Exact Match)

Contract Name:	SparkleCrowdsale	Optimization Enabled:	No
Compiler Text:	v0.4.25+commit.59dbf8f1	Runs (Optimiser):	200

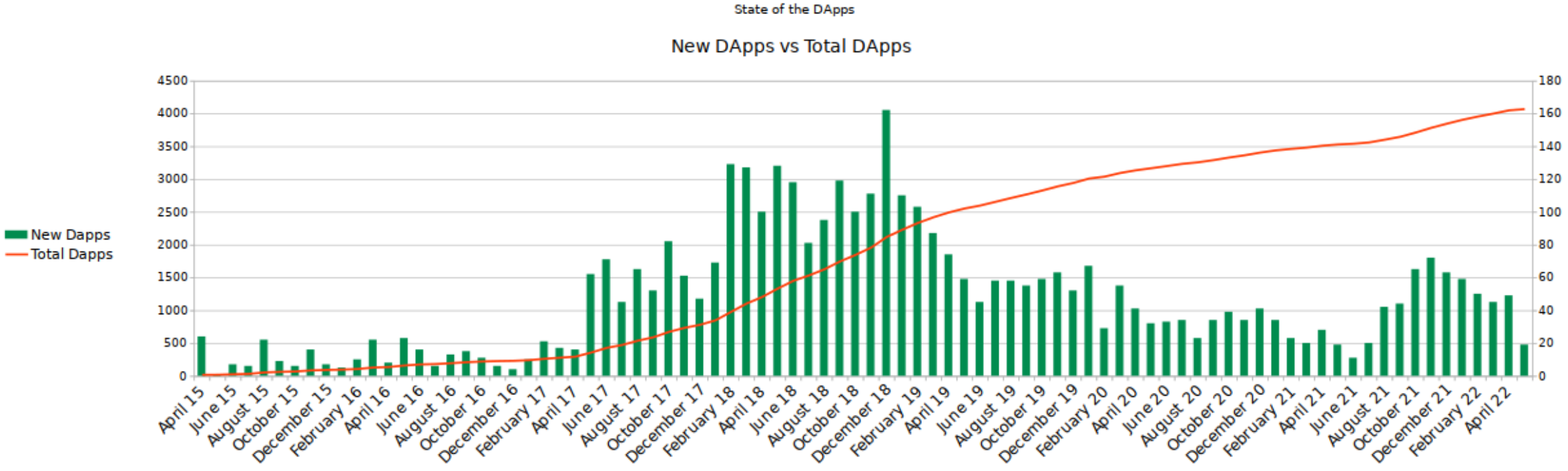
Contract Source Code </> Copy Find Similiar Contracts

```
1  pragma solidity 0.4.25;
2
3  // File: openzeppelin-solidity/contracts/ownership/Ownable.sol
4
5  /**
6   * @title Ownable
7   * @dev The Ownable contract has an owner address, and provides basic authorization control
8   * functions, this simplifies the implementation of "user permissions".
9   */
10 contract Ownable {
11   address private _owner;
12
13   event OwnershipTransferred(
14     address indexed previousOwner,
15     address indexed newOwner
16   );
17
18   /**
19    * @dev The Ownable constructor sets the original `owner` of the contract to the sender
20    * account.
21    */
22   constructor() internal {
23     _owner = msg.sender;
24     emit OwnershipTransferred(address(0), _owner);
25   }
```

U. Gallersdörfer, P. Holl, and F. Matthes, “Blockchain-based Systems Engineering – Lecture Slides,” Oct 2019. [Online]. Available: https://github.com/sebischair/bbse

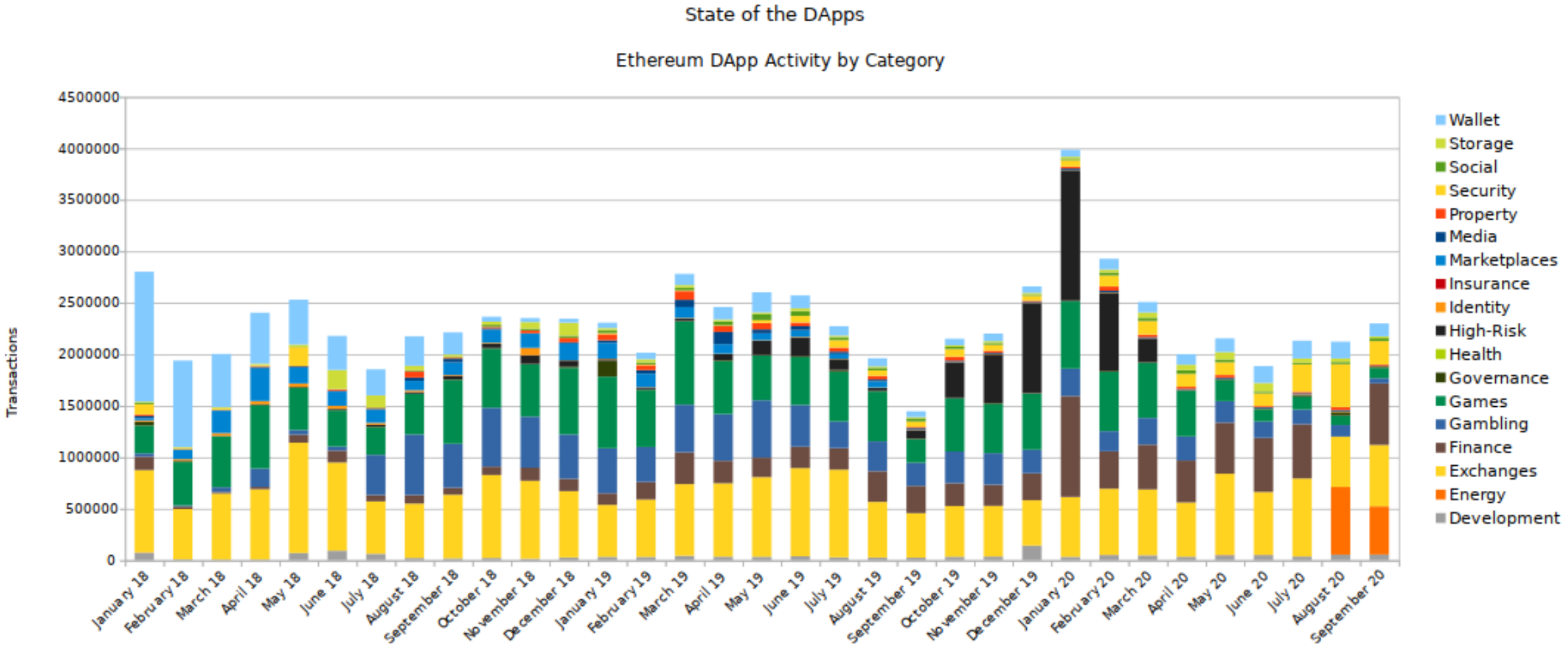
Web-based Ethereum dApps

- State of the Dapps (Link) is a curated and community-driven directory of decentralized applications.
- As of May 2022, the directory lists 4073 DApps (2970 Ethereum DApps).



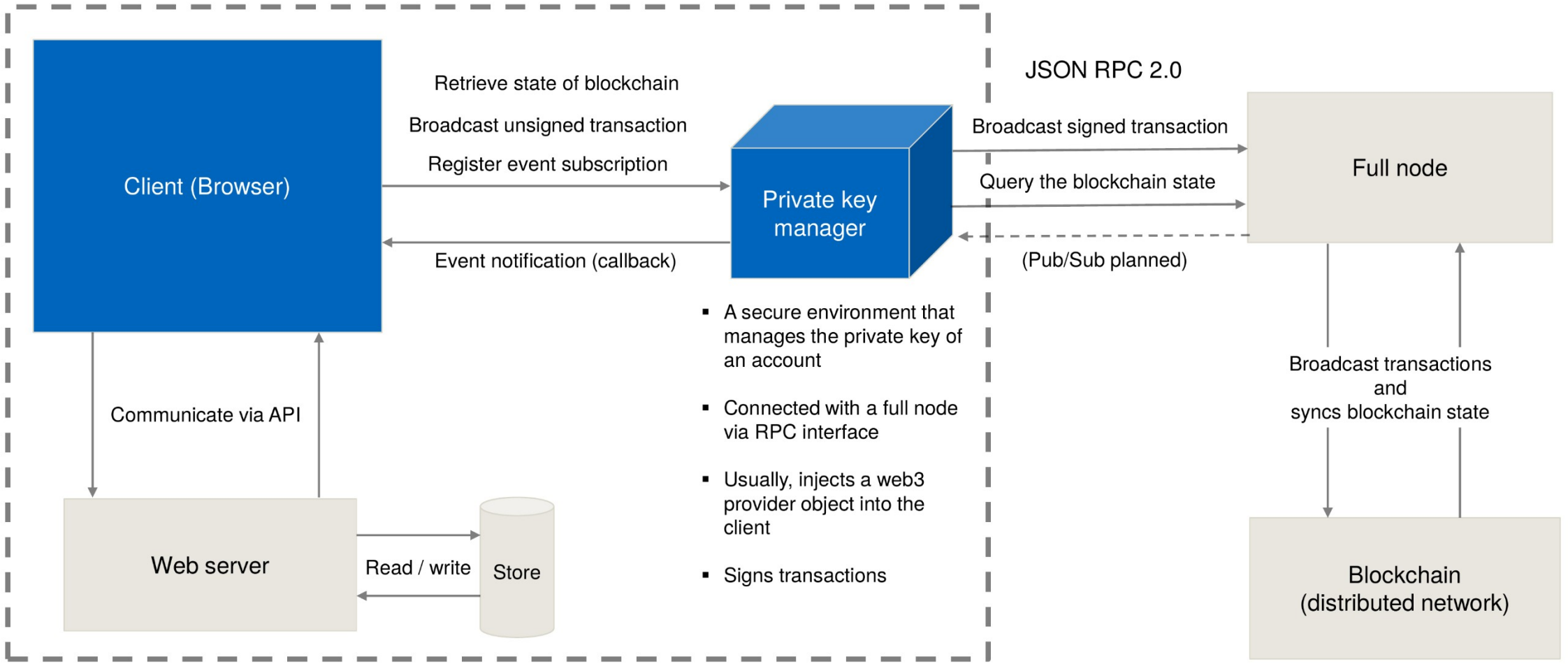
Graph recreated based on data from https://www.stateofthedapps.com/stats

dApps Statistics – Transactions per dApp



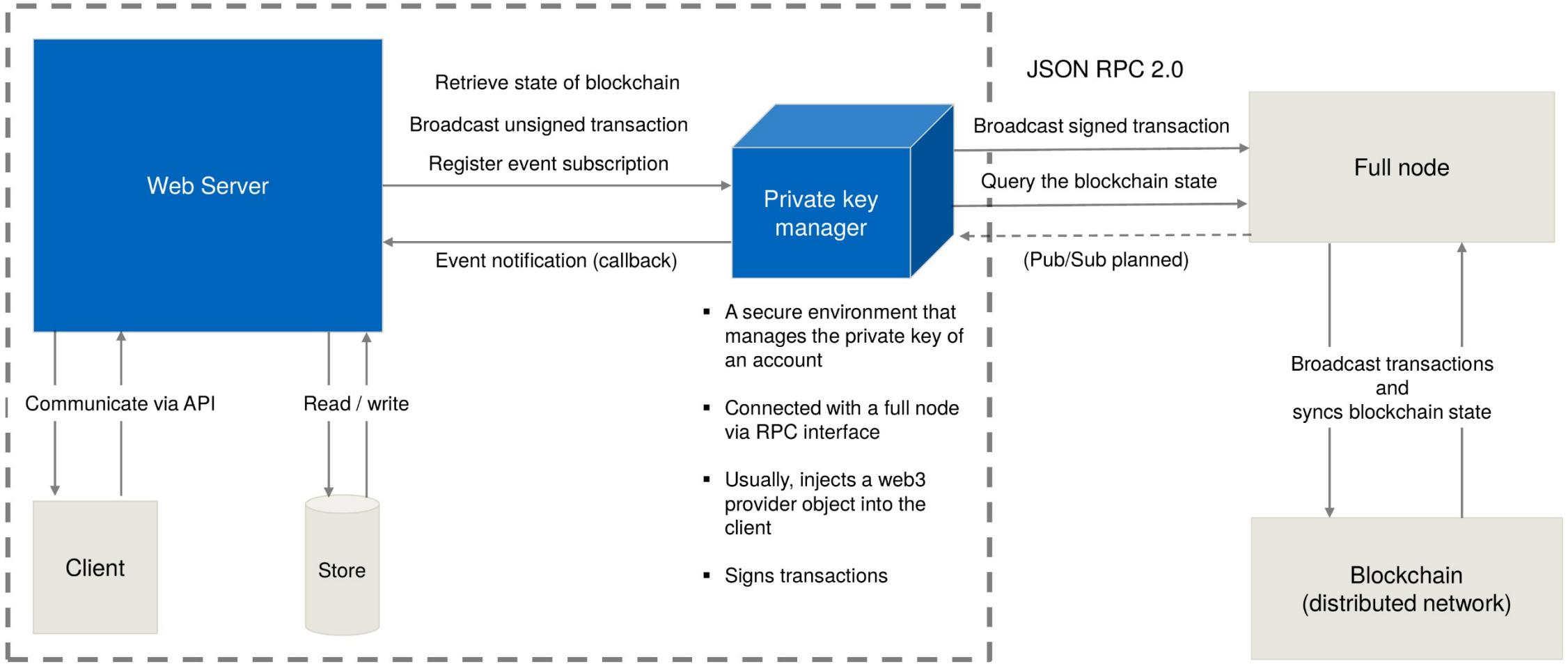
Graph recreated based on data from https://www.stateofthedapps.com/stats

Architecture of Web-based dApps



U. Gallersdörfer, P. Holl, and F. Matthes, “Blockchain-based Systems Engineering – Lecture Slides,” Oct 2019. [Online]. Available: https://github.com/sebischair/bbse

Architecture of Web-based dApps



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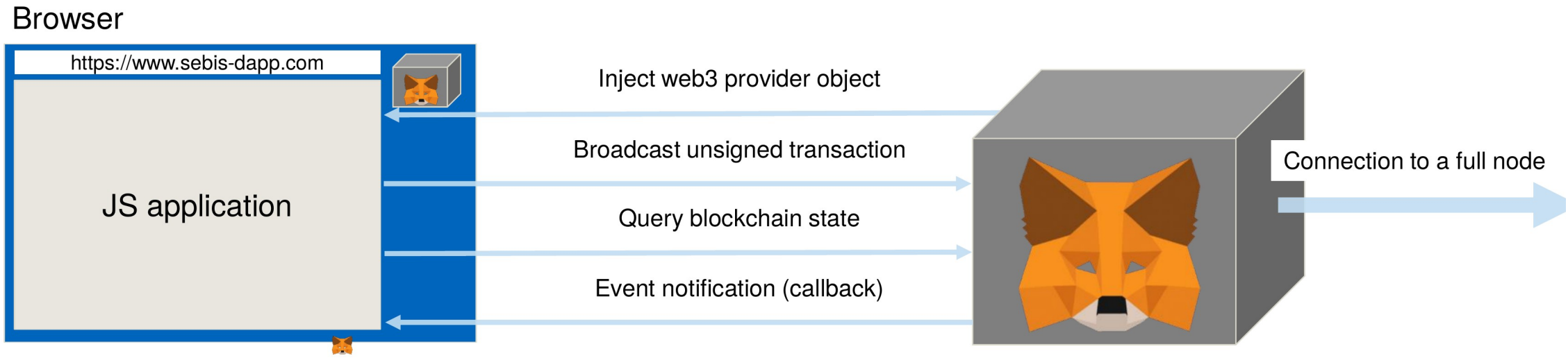
Metamask



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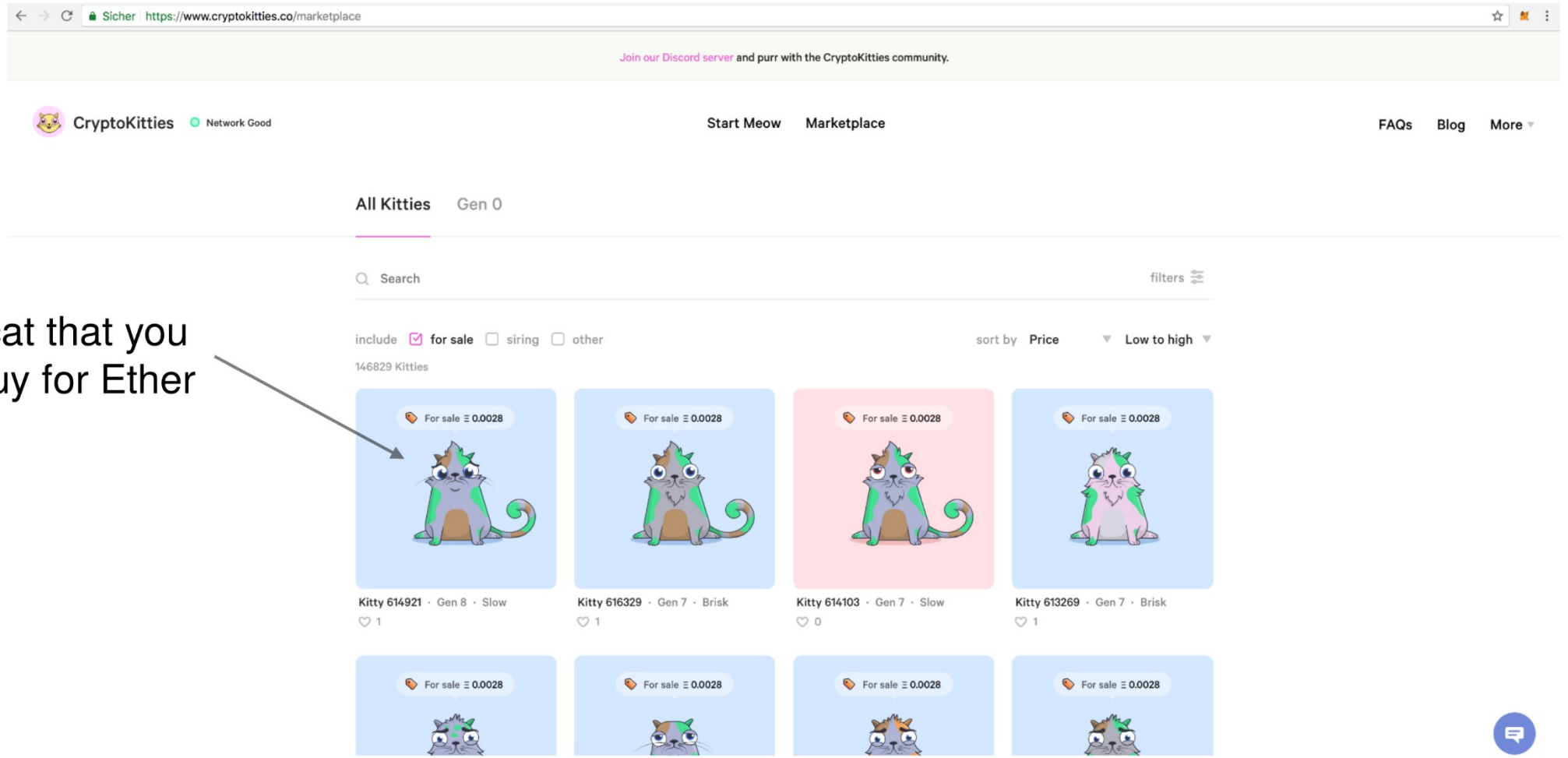
Example: CryptoKitties



Select a cat that you want to buy for Ether

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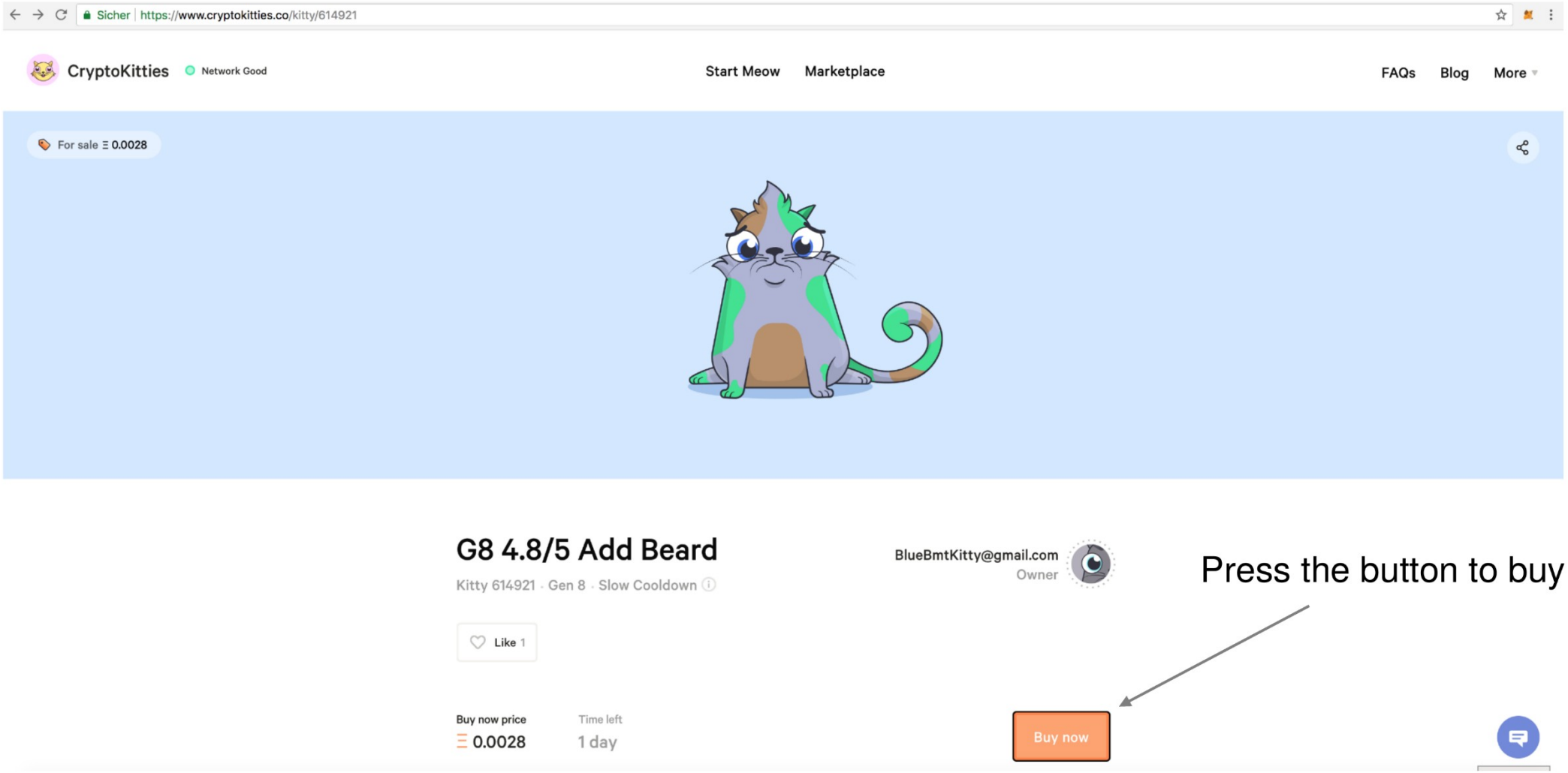
Example: CryptoKitties



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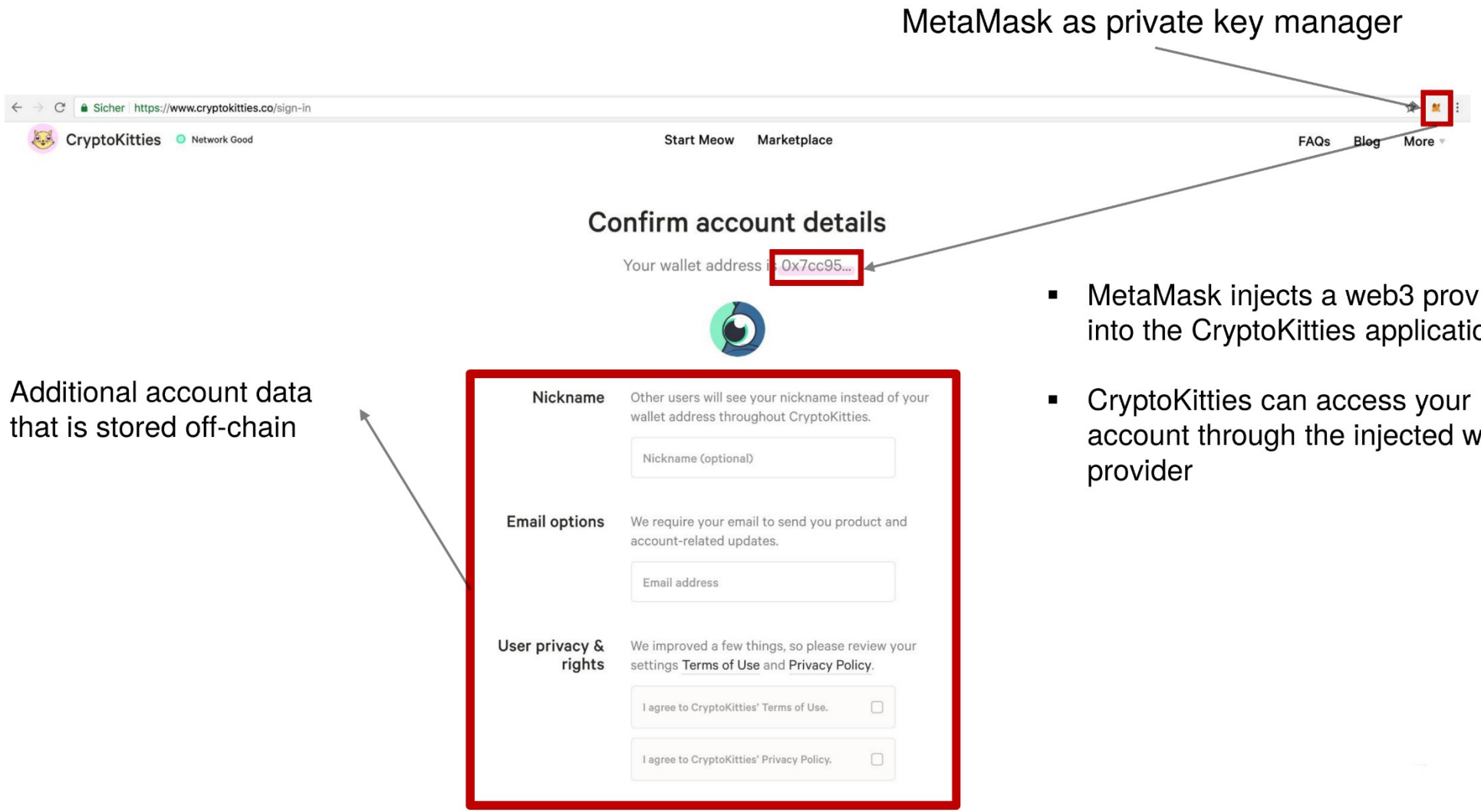
Example: CryptoKitties



- Additional account data that is stored off-chain

- MetaMask injects a web3 provider into the CryptoKitties application
- CryptoKitties can access your account through the injected web3 provider

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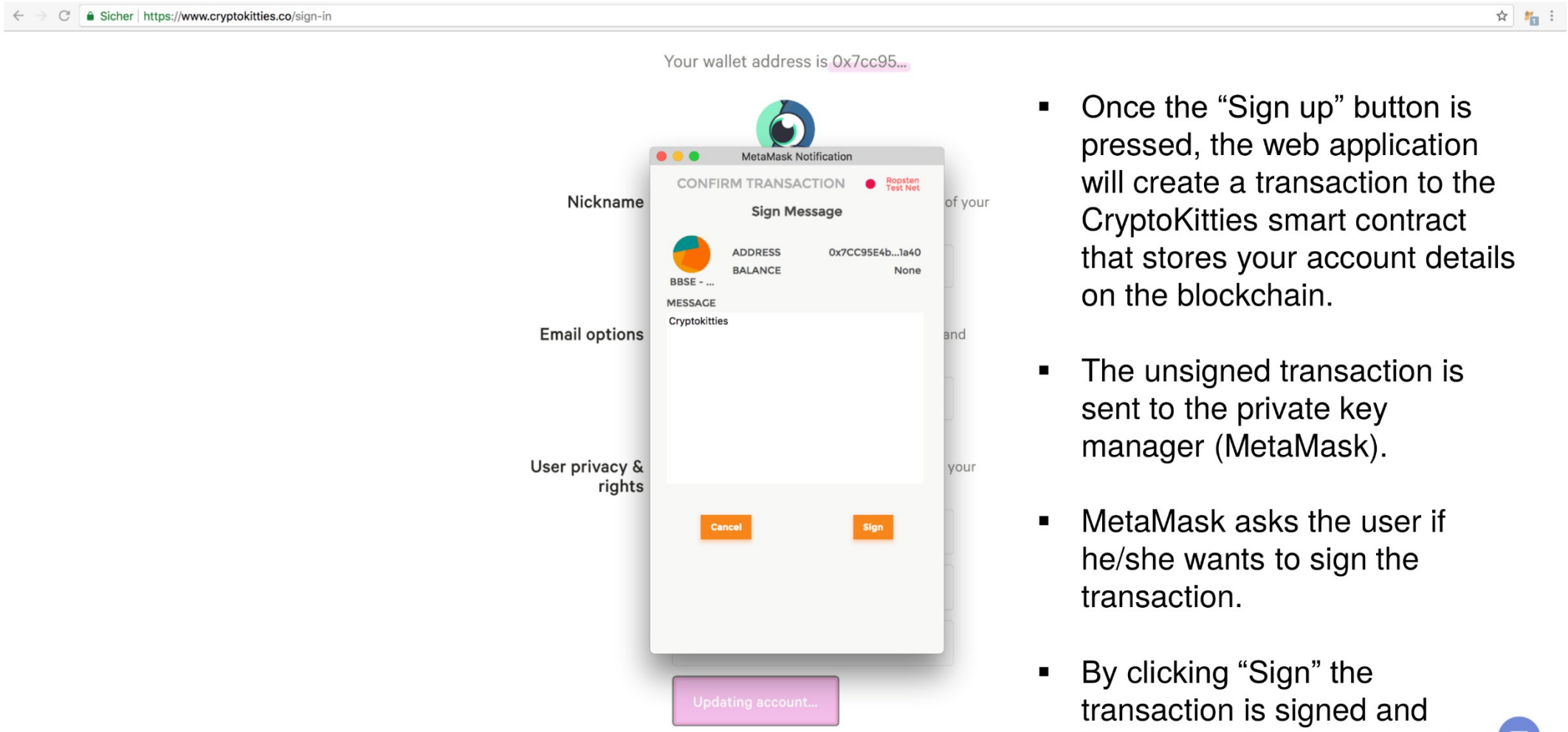
Example: CryptoKitties



- Once the “Sign up” button is pressed, the web application will create a transaction to the CryptoKitties smart contract that stores your account details on the blockchain.
- The unsigned transaction is sent to the private key manager (MetaMask).
- MetaMask asks the user if he/she wants to sign the transaction.
- By clicking “Sign” the transaction is signed and broadcasted to the network

U. Gallersdörfer, P. Holl, and F. Matthes, “Blockchain-based Systems Engineering – Lecture Slides,” Oct 2019. [Online]. Available: https://github.com/sebischair/bbse

Deployment Lifecycle

- Compilation of the Solidity source code
- Generate an **Application Binary Interface** (ABI) in JSON that can be used by other applications to interact with the contract

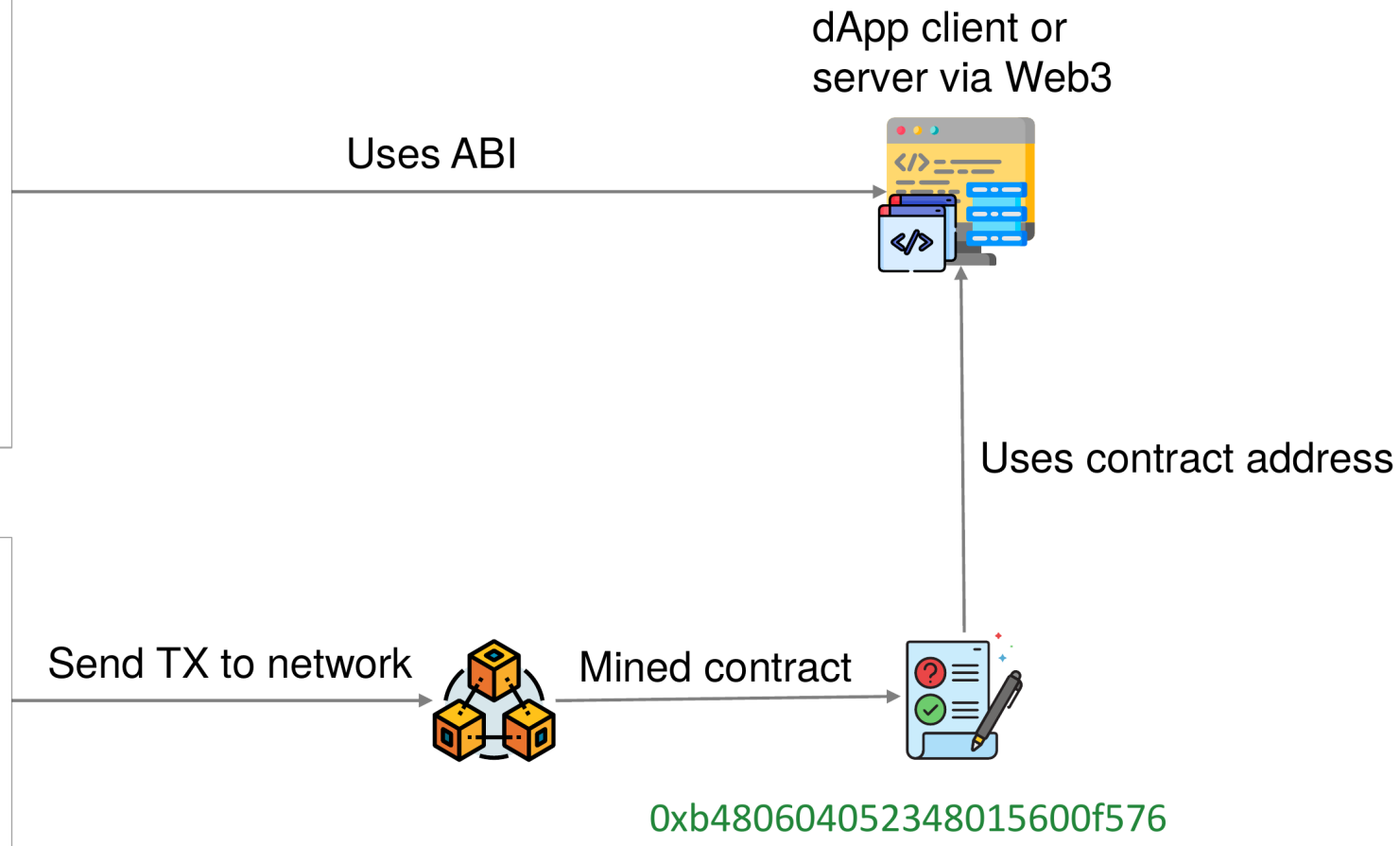
HelloWorld.sol

```
contract HelloWorld {
        function greet() public returns(bytes32) {
                return "Hello World!";
        }
}
```

U. Gallersdörfer, P. Holl, and F. Matthes, “Blockchain-based Systems Engineering – Lecture Slides,” Oct 2019. [Online]. Available: https://github.com/sebischair/bbse

Deployment Lifecycle

```
[
  {
    "constant": false,
    "inputs": [],
    "name": "greet",
    "outputs": [
      {
        "name": "",
        "type": "bytes32"
      }
    ],
    "payable": false,
    "stateMutability": "nonpayable",
    "type": "function"
  }
]
```




```
608060405234801560f57600080fd5b5060ba8061001e6000396
000f3fe608060405260043610603957600035 7c01000000000000
0000000000000000000000000000000000000000000090048063c
fae321714603e575b600080fd5b34801560495760080fd5b50605
06066565b604051808281526020019150506040518091039 0f35b
60007f48656c6c6f20576f726c6421000000000000000000000000
0000000000000000090509056fea165627a7a72305820a4741ad95
e951c73637b4a34111570c749d47ab815d9838dd50c29ed524020
560029
```

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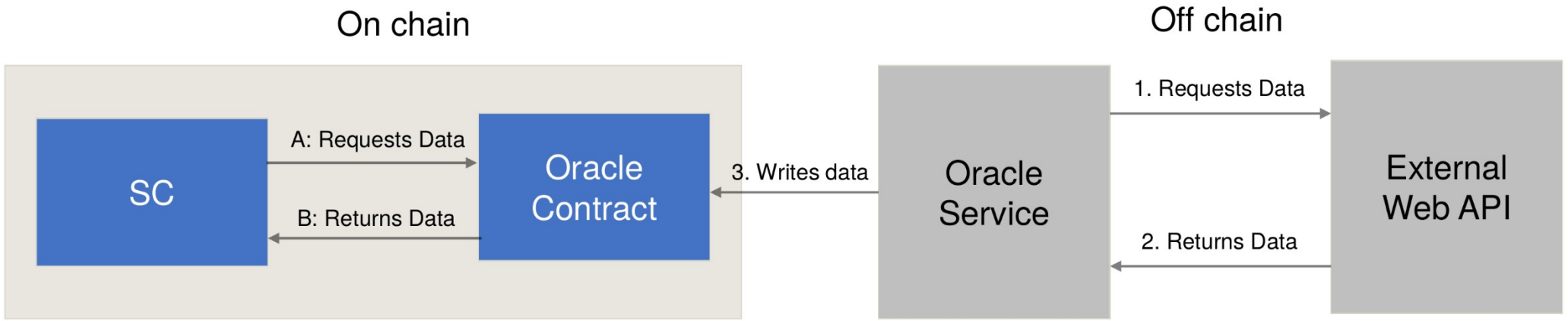
Oracles

- Smart contracts cannot access any data from outside the blockchain on their own → on purpose to prevent non-deterministic behavior
- Also no functions to generate random values

Oracles

- Smart contracts cannot access any data from outside the blockchain on their own → on purpose to prevent non-deterministic behavior
- Also no functions to generate random values
- Solution → Oracles
  - 3rd-party services that verify data from web services and write the data via a smart contract to the chain



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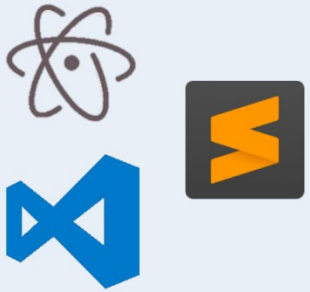
ETHEREUM DEVELOPMENT TOOLS

Development Tools

Local environment

IDE / Code editor



Artifacts

- Solidity source code files
- Test cases

Build management

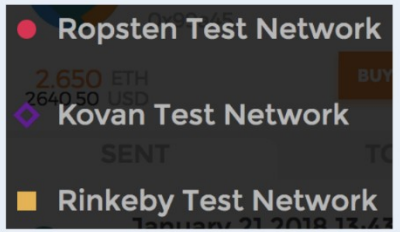
Artifacts

- Compiled .sol files / Bytecode
- Contract ABI / JSON

Network deployment

Local test network

Public test network



Main network

Artifacts

- Transaction for creating the contract
- An address for the contract if the creation was successful

U. Gallersdörfer, P. Holl, and F. Matthes, “Blockchain-based Systems Engineering – Lecture Slides,” Oct 2019. [Online]. Available: https://github.com/sebischair/bbse

Truffle – Development Framework for Smart Contracts

Truffle is a popular framework to facilitate the development of Ethereum smart contracts. It provides tools to compile, test and deploy Solidity contracts.

- Open source – Github
- Built-in network management that allows a developer to deploy a smart contract on various networks, e.g., live and test
- Web-pack like automated re-compilation on code change
- Provides project scaffolding

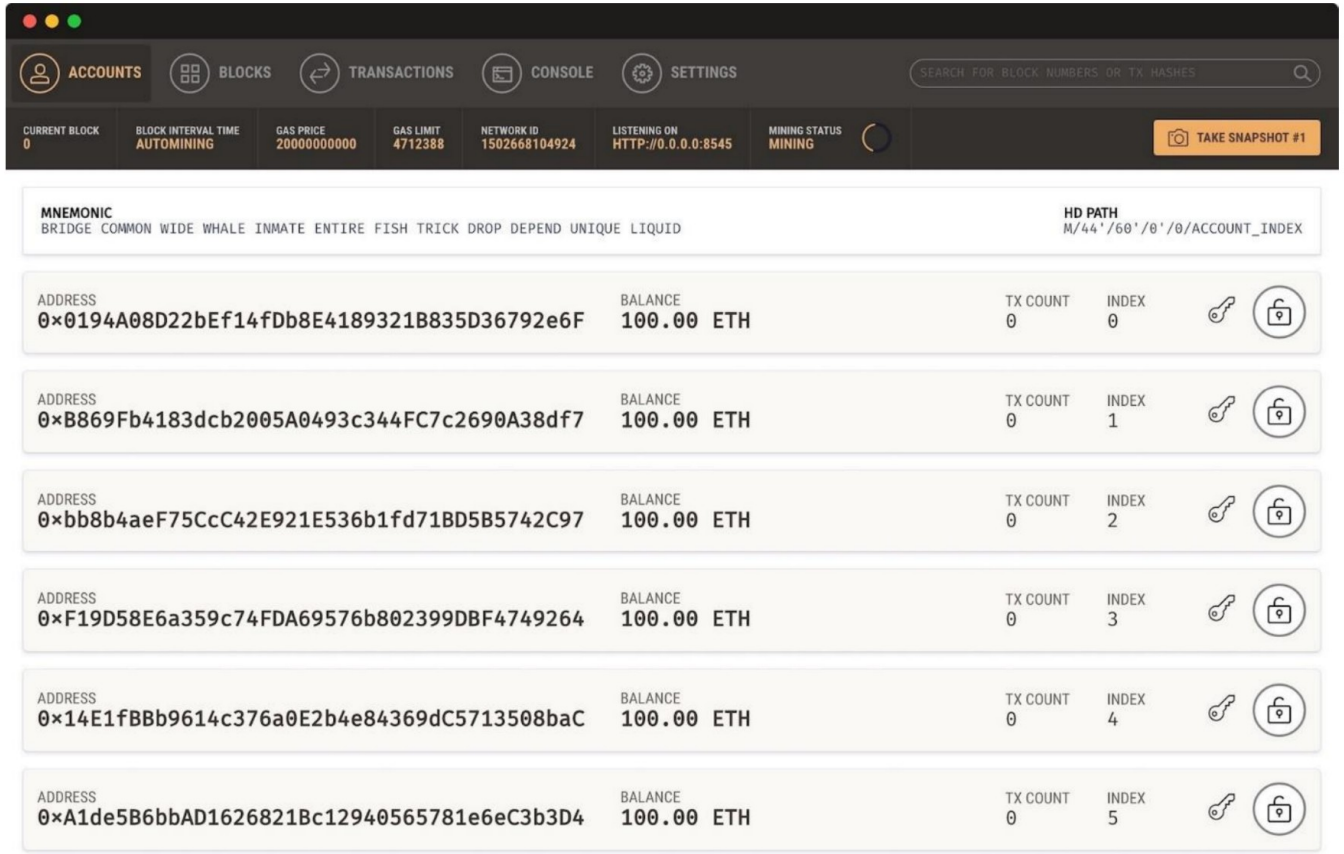
Ganache – Private Ethereum Test Network

Ganache is a local blockchain for Ethereum smart contract development. It can be used to deploy, simulate, and test smart contracts.

- Open source – Github
- Integrates a custom block explorer interface with additional debugging features.
- Uses workspaces to provide multiple Ethereum blockchains with different settings (blocktime etc.)
- Can be linked to Truffle projects to automate tests for smart contracts

Ganache – Private Ethereum Test Network

Ganache ships with a ready-made and developer friendly block explorer:



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Development Tools

Cloud environment

IDE / Code editor + Build management

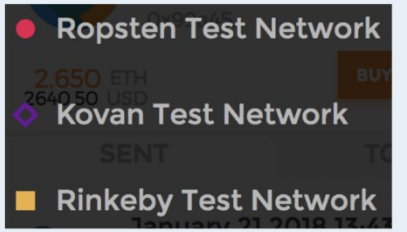
Artifacts

- Solidity source code files
- Compiled contracts bytecode
- Contract ABIs / JSON

Network deployment

Remix emulation

Public test network



Main network

Artifacts

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Test Networks – Ropsten

- Free to use
- Public
- Block time of ca. 30s
- Proof-of-Work consensus
- Geth and Parity compatibility
- Ether distribution via faucet – Link
- Anonymous

Test Networks – Rinkeby

- Free to use
- Public
- Block time of ca. 15s
- Proof-of-Authority consensus, i.e., one central instance decides what transaction will be mined.
- Geth only
- Ether distribution via faucet – Link
- Twitter or Facebook account required (Spam/DoS protection)

Test Networks – Kovan

- Free to use
- Public
- Block time of ca. 4s
- Proof-of-authority consensus, i.e., one central instance decides what transaction will be mined.
- Parity only
- Ether distribution via faucet – Link
- Github account required (Spam/DoS protection)

Questions?