CS251 Fall 2021

(cs251.stanford.edu)

Ethereum: mechanics

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Note: HW#2 is posted on the course web site. Due Oct. 18.

Limitations of Bitcoin

Recall: UTXO contains (hash of) ScriptPK

- simple script: indicates conditions when UTXO can be spent

Limitations:

- Difficult to maintain state in multi-stage contracts
- Difficult to enforce global rules on assets

A simple example: rate limiting. My wallet manages 100 UTXOs.

- Desired policy: can only transfer 2BTC per day out of my wallet

An example: NameCoin

Domain name system on the blockchain: [google.com → IP addr]

Need support for three operations:

- **Name.new**(OwnerAddr, DomainName): intent to register
- **Name.update**(DomainName, newVal, newOwner, OwnerSig)
- **Name.lookup**(DomainName)

Note: also need to ensure no front-running on **Name.new**()

A broken implementation

Name.new() and Name.upate() create a UTXO with ScriptPK:

```
DUP  HASH256  <OwnerAddr>  EQVERIFY  CHECKSIG  VERIFY
<NAMECOIN>  <DomainName>  <IPaddr>  <1>
```

verify
sig is valid

ensure top
of stack is 1

only owner can “spend” this UTXO to update domain data

Contract: (should be enforced by miners)

> if domain google.com is registered,
> no one else can register that domain

Problem: this contract cannot be enforced using Bitcoin script

What to do?

NameCoin: fork of Bitcoin that implements this contract

(see also the Handshake, Chia projects)

Can we build a blockchain that natively supports generic contracts like this?

⇒ Ethereum

Ethereum: enables a world of applications

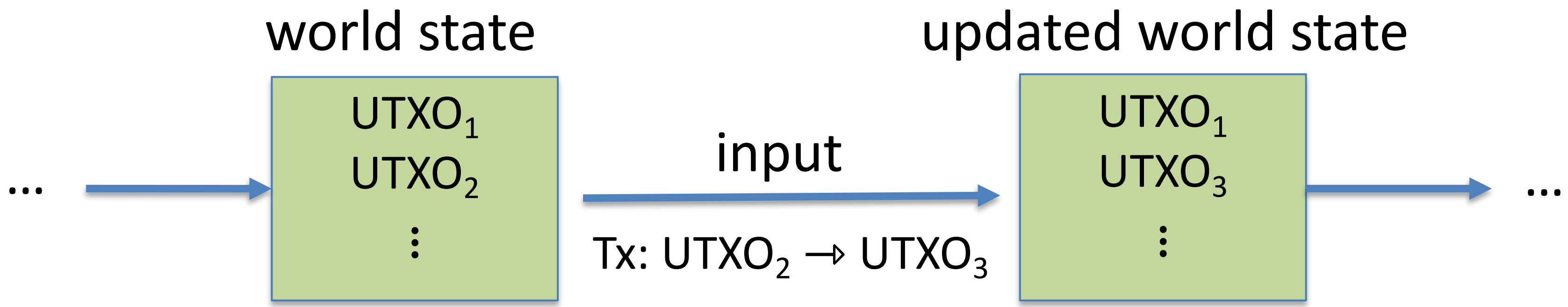
A world of Ethereum Decentralized apps (DAPPs)

- New coins: ERC-20 interface to DAPP
- **DeFi**:   exchanges, lending, stablecoins, derivatives, etc.
- Insurance
- **DAOs**: decentralized organizations
- **NFTs**: Managing distinguished assets (ERC-721 interface)
- **Games, metaverse**: assets managed on chain

CryptoPunk #2890

stateofthedapps.com,   dapp.review

Bitcoin as a state transition system



world state

$UTXO_1$
$UTXO_2$
⋮

input

Tx: $UTXO_2 \to UTXO_3$

updated world state

$UTXO_1$
$UTXO_3$
⋮

…

…

Bitcoin rules: $\boxed{F_{bitcoin} : S \times I \to S}$

S: set of all possible world states, $s_0 \in S$ genesis state

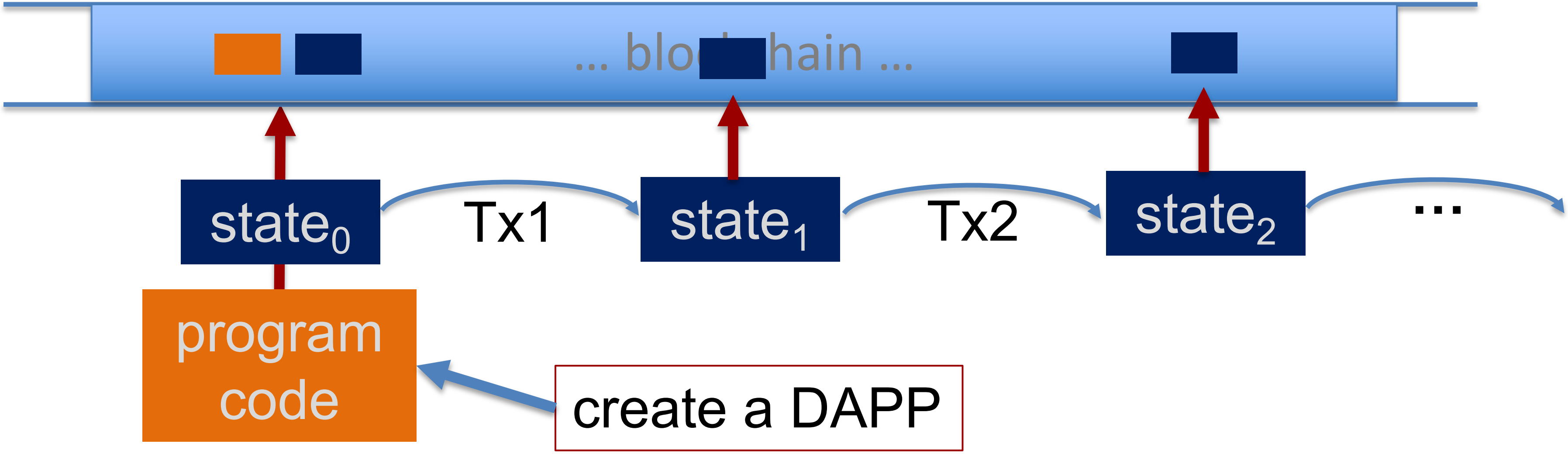
I: set of all possible inputs

Ethereum as a state transition system

Much richer state transition functions

⇒ one transition executes an entire program

Running a program on a blockchain (DAPP)

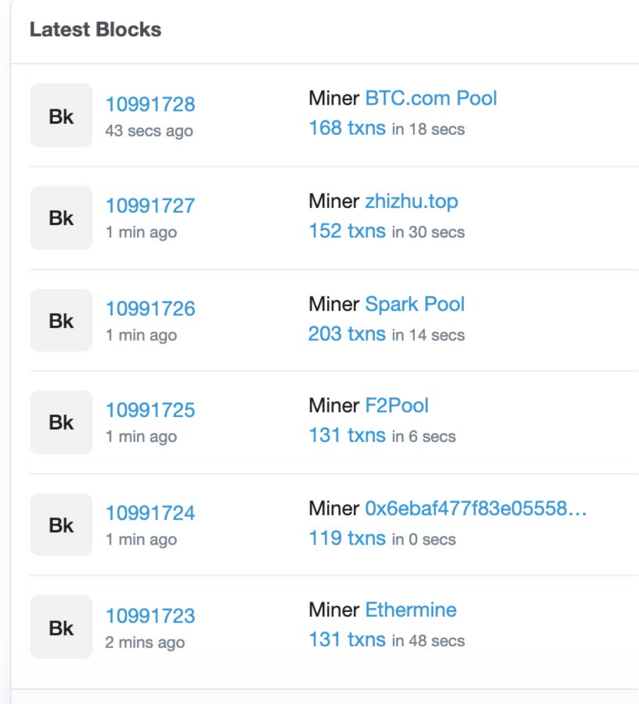


compute layer (executed by miners): The EVM

consensus layer

The Ethereum system

Layer 1 (ETHv1): PoW consensus. Block reward = 2 ETH + Tx fees (gas)



Latest Blocks

Bk	10991728 43 secs ago	Miner BTC.com Pool 168 txns in 18 secs
Bk	10991727 1 min ago	Miner zhizhu.top 152 txns in 30 secs
Bk	10991726 1 min ago	Miner Spark Pool 203 txns in 14 secs
Bk	10991725 1 min ago	Miner F2Pool 131 txns in 6 secs
Bk	10991724 1 min ago	Miner 0x6ebaf477f83e05558… 119 txns in 0 secs
Bk	10991723 2 mins ago	Miner Ethermine 131 txns in 48 secs

avg. block rate = 15 seconds.

ETHv1: variant of Nakamoto PoW

ETHv2: proof of stake consensus

about 150 Tx per block.

Ethereum compute layer: the EVM

World state: set of accounts identified by 32-byte address.

Two types of accounts:

(1) owned accounts: controlled by ECDSA signing key pair (PK,SK).

SK signing key known only to account owner

(2) **contracts**: controlled by code.

code set at account creation time, does not change

Data associated with an account

Account data	Owned	Contracts
address (computed):	H(PK)	H(CreatorAddr, CreatorNonce)
code:	⊥	CodeHash
storage root (state):	⊥	StorageRoot
balance (in Wei):	balance	balance (10^{18} Wei = 1 ETH)
nonce:	nonce	nonce

(#Tx sent) + (#accounts created): anti-replay mechanism

Account state: persistent storage

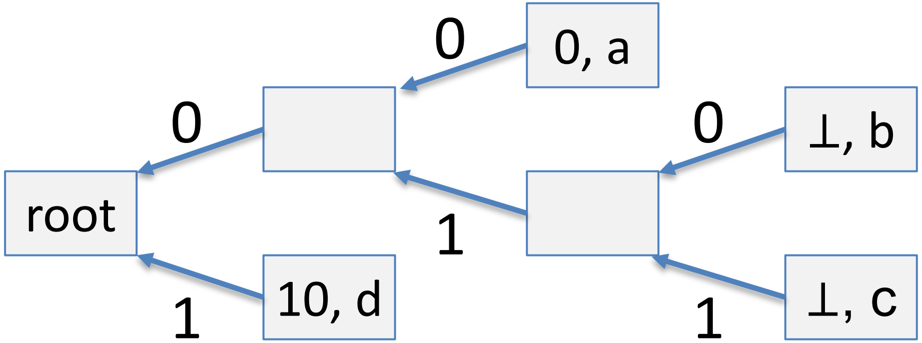
Every contract has an associated **storage array S**[]:

S[0], S[1], … , S[2^{256}-1]: each cell holds 32 bytes, init to 0.

Account storage root: **Merkle Patricia Tree hash** of S[]

- Cannot compute full Merkle tree hash: 2^{256} leaves

S[000] = a
S[010] = b
S[011] = c
S[110] = d



time to compute root hash:
≤ 2 × |S|

|S| = # non-zero cells

State transitions: Tx and messages

Transactions: signed data by initiator

- **To:** 32-byte address of target (0 → create new account)
- **From**, [**Signature**]:   initiator address and signature on Tx (if owned)
- **Value**: # Wei being sent with Tx
- Tx fees (EIP 1559)**:** **gasLimit, maxFee, maxPriorityFee**   (later)
- if To = 0:   create new contract   **code = (init, body)**
- if To ≠ 0:   **data** (what function to call & arguments)
- **nonce**: must match current nonce of sender (prevents Tx replay)

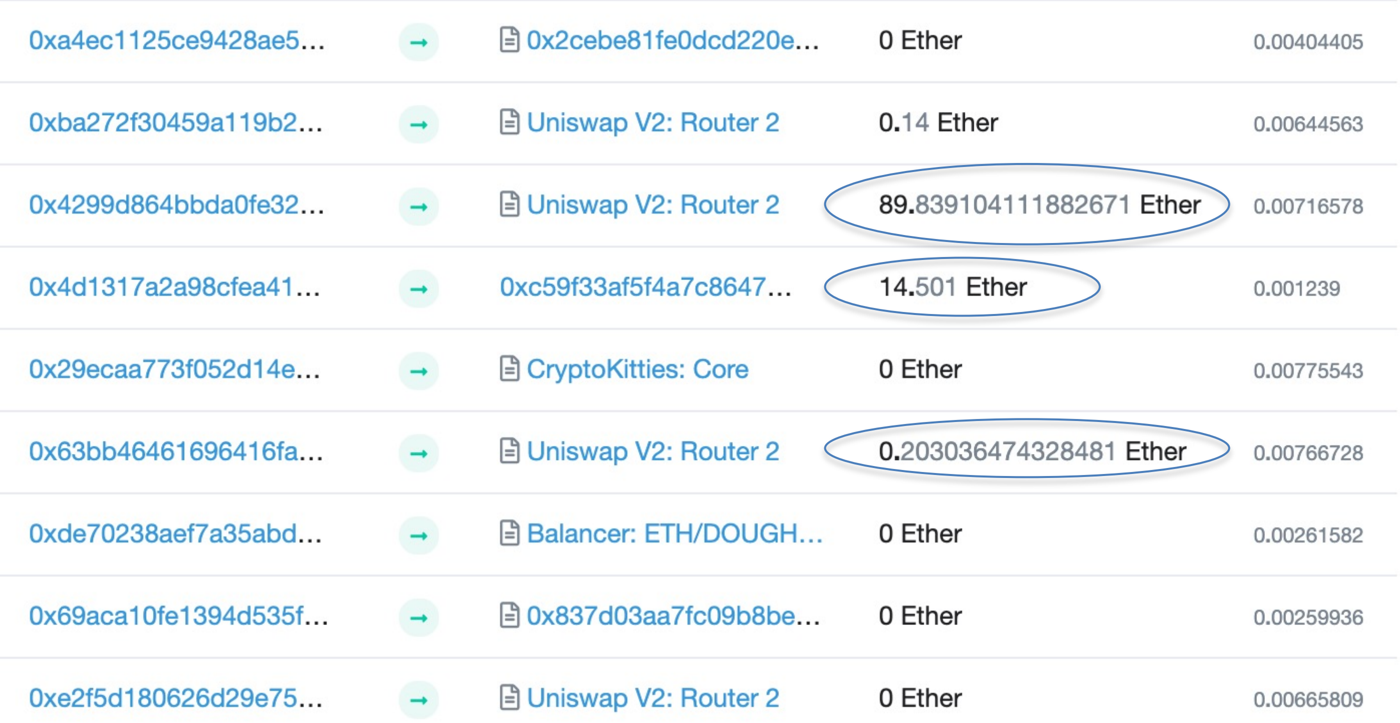
State transitions: Tx and messages

Transaction types:

owned → owned: transfer ETH between users

owned → contract: call contract with ETH & data

Example (block #10993504)



From		To	msg.value	Tx fee (ETH)
0xa4ec1125ce9428ae5…	→	0x2cebe81fe0dcd220e…	0 Ether	0.00404405
0xba272f30459a119b2…	→	Uniswap V2: Router 2	0.14 Ether	0.00644563
0x4299d864bbda0fe32…	→	Uniswap V2: Router 2	89.839104111882671 Ether	0.00716578
0x4d1317a2a98cfea41…	→	0xc59f33af5f4a7c8647…	14.501 Ether	0.001239
0x29ecaa773f052d14e…	→	CryptoKitties: Core	0 Ether	0.00775543
0x63bb46461696416fa…	→	Uniswap V2: Router 2	0.203036474328481 Ether	0.00766728
0xde70238aef7a35abd…	→	Balancer: ETH/DOUGH…	0 Ether	0.00261582
0x69aca10fe1394d535f…	→	0x837d03aa7fc09b8be…	0 Ether	0.00259936
0xe2f5d180626d29e75…	→	Uniswap V2: Router 2	0 Ether	0.00665809

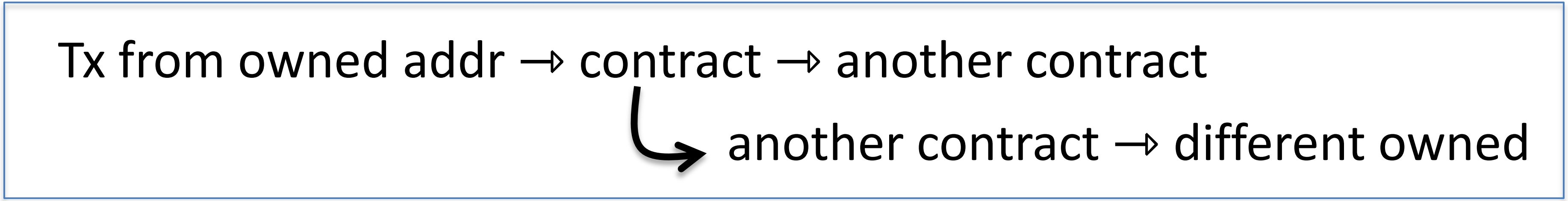
Messages: virtual Tx initiated by a contract

Same as Tx, but no signature (contract has no signing key)

contract → owned: contract sends funds to user

contract → contract: one program calls another (and sends funds)

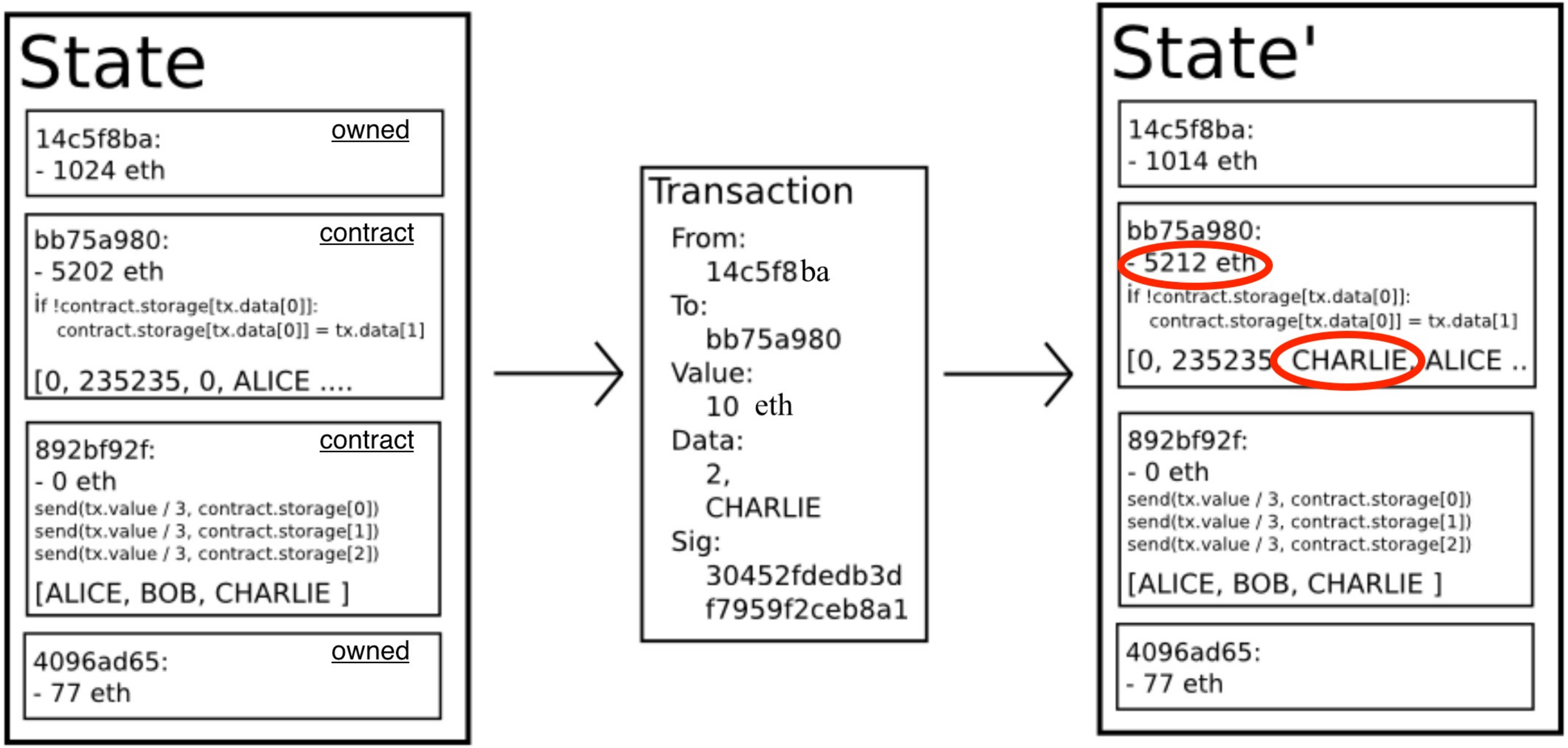
One Tx from user: can lead to many Tx processed. Composability!



Tx from owned addr → contract → another contract

another contract → different owned

Example Tx



State

14c5f8ba: owned
- 1024 eth

bb75a980: contract
- 5202 eth

```
if !contract.storage[tx.data[0]]:
    contract.storage[tx.data[0]] = tx.data[1]
```

[0, 235235, 0, ALICE ....

892bf92f: contract
- 0 eth

```
send(tx.value / 3, contract.storage[0])
send(tx.value / 3, contract.storage[1])
send(tx.value / 3, contract.storage[2])
```

[ALICE, BOB, CHARLIE]

4096ad65: owned
- 77 eth

Transaction
From:
14c5f8ba
To:
bb75a980
Value:
10 eth
Data:
2,
CHARLIE
Sig:
30452fdedb3d
f7959f2ceb8a1

State'

14c5f8ba:
- 1014 eth

bb75a980:
- 5212 eth

```
if !contract.storage[tx.data[0]]:
    contract.storage[tx.data[0]] = tx.data[1]
```

[0, 235235, CHARLIE, ALICE ..

892bf92f:
- 0 eth

```
send(tx.value / 3, contract.storage[0])
send(tx.value / 3, contract.storage[1])
send(tx.value / 3, contract.storage[2])
```

[ALICE, BOB, CHARLIE]

4096ad65:
- 77 eth

world state (four accounts)

updated world state

An Ethereum Block

Miners collect Txs from users ⇒ leader creates a block of n Tx

- Miner does:
  - for i=1,…,n: execute state change of Tx_i sequentially

    (can change state of >n accounts)
  - record updated world state in block

Other miners re-execute all Tx to verify block

- Miners should only build on a valid block
- Miners are not paid for verifying block (note: verifier’s dilemma)

Block header data (simplified)

(1) consensus data: parent hash, difficulty, PoW solution, etc.

(2) address of gas beneficiary: where Tx fees will go

(3) world state root: updated world state

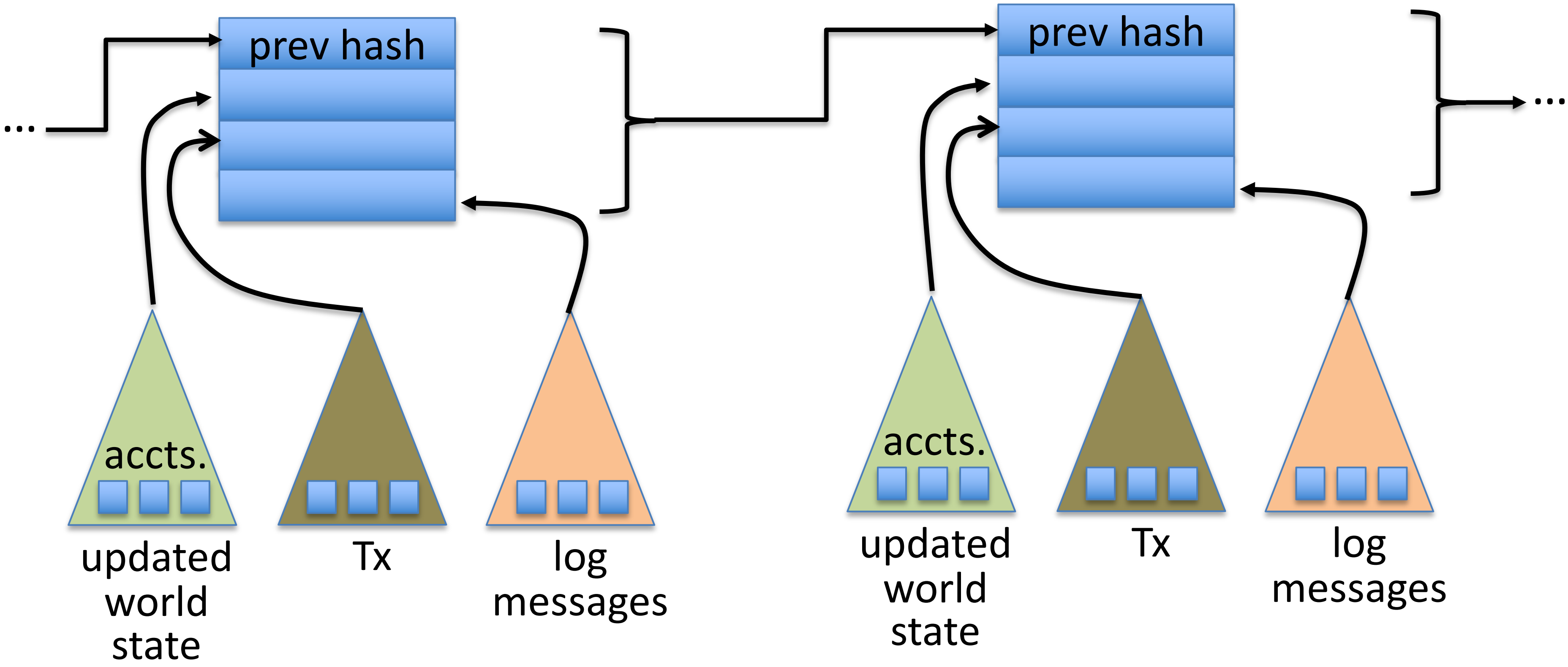
Merkle Patricia Tree hash of all accounts in the system

(4) **Tx root**: Merkle hash of all Tx processed in block

(5) **Tx receipt root**: Merkle hash of log messages generated in block

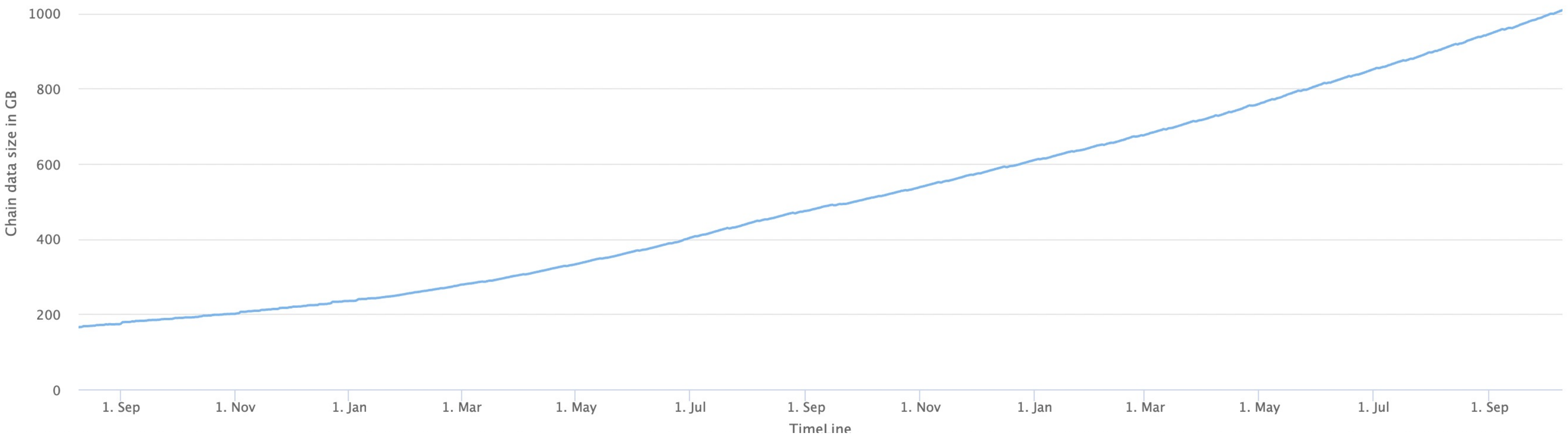
(5) Gas used: tells verifier how much work to verify block

The Ethereum blockchain: abstractly



Amount of memory to run a node (in GB)

≈1 TB



ETH total blockchain size: 8.6 TB (Oct. 2021)

An example contract: NameCoin

```
contract nameCoin {          // Solidity code   (next lecture)

    struct nameEntry {
        address owner;       // address of domain owner
        bytes32 value;       // IP address
    }

    // array of all registered domains
    mapping (bytes32 => nameEntry)  data;
```

An example contract: NameCoin

```
function nameNew(bytes32 name) {

    // registration costs is 100 Wei

    if (data[name] == 0   &&   msg.value >= 100) {
        data[name].owner = msg.sender    // record domain owner
        emit Register(msg.sender, name)   // log event
}}
```

Code ensures that no one can take over a registered name

Serious bug in this code!   Front running. Solved using commitments.

An example contract: NameCoin

```
function nameUpdate(
                    bytes32 name, bytes32 newValue, address newOwner) {

   // check if message is from domain owner,
   //              and update cost of 10 Wei is paid

   if (data[name].owner == msg.sender   &&   msg.value >= 10) {

          data[name].value = newValue;          // record new value

          data[name].owner = newOwner;       // record new owner
 }}}
```

An example contract: NameCoin

```
    function nameLookup(bytes32 name) {
        return data[name];
    }

}  // end of contract
```

EVM mechanics: execution environment

Write code in Solidity (or another front-end language)

⇒ compile to EVM bytecode

(some projects use WASM or BPF bytecode)

⇒ miners use the EVM to execute contract bytecode
in response to a Tx

The EVM

Stack machine (like Bitcoin) but with JUMP

- max stack depth = 1024
- program aborts if stack size exceeded; miner keeps gas
- contract can create or call another contract

In addition: two types of zero initialized memory

- Persistent storage (on blockchain): SLOAD, SSTORE (expensive)
- Volatile memory (for single Tx): MLOAD, MSTORE (cheap)
- LOG0(data): write data to log

see https://ethervm.io/

Every instruction costs gas, examples:

SSTORE addr (32 bytes), **value** (32 bytes)

- zero → non-zero: 20,000 gas
- non-zero → non-zero: 5,000 gas
- non-zero → zero: 15,000 gas refund

Refund is given for reducing size of blockchain state

SELFDESTRUCT addr: kill current contract. 24,000 gas refund

CREATE : 32,000 gas CALL **gas**, addr, **value**, args

Gas calculation

Why charge gas?

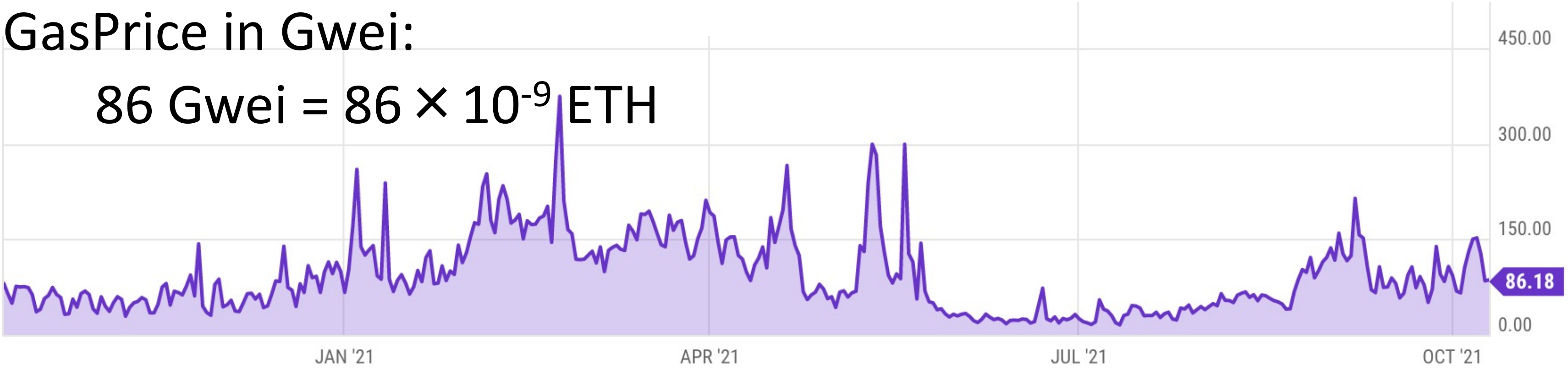
- Tx fees (gas) prevents submitting Tx that runs for many steps.
- During high load: miners choose Tx from the mempool that maximize their income.

Old EVM: (prior to EIP1559, live on 8/2021)

- Every Tx contains a gasPrice ``bid'' (gas → Wei conversion price)
- Miners choose Tx with highest gasPrice (max sum(gasPrice × gasLimit))

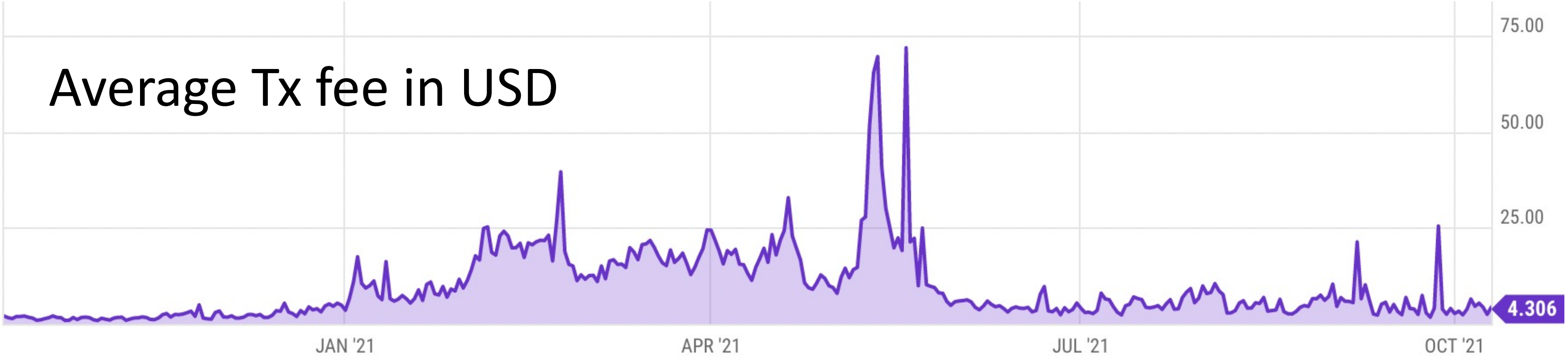
$\Longrightarrow$ not an efficient auction mechanism (first price auction)

Gas prices spike during congestion



GasPrice in Gwei:

86 Gwei = 86 × 10^{-9} ETH



Average Tx fee in USD

Gas calculation: EIP1559

Every block has a “baseFee”:

the **minimum** gasPrice for all Tx in the block

baseFee is computed from <u>total gas</u> in earlier blocks:

- earlier blocks at gas limit (30M gas) ⟹ base fee goes up 12.5%
- earlier blocks empty ⟹ base fee decreases by 12.5%

interpolate in between

If earlier blocks at “target size” (15M gas) ⟹ base fee does not change

Gas calculation

EIP1559 Tx specifies three parameters:

- **gasLimit**: max total gas allowed for Tx
- **maxFee:**   maximum allowed gas price (max gas → Wei conversion)
- **maxPriorityFee**: additional “tip” to be paid to miner

Computed **gasPrice** bid:

gasPrice ← min(**maxFee**,   **baseFee** + **maxPriorityFee)**

Max Tx fee: **gasLimit** × **gasPrice**

Gas calculation

(1) if **gasPrice** < **baseFee**: abort

(2) If **gasLimit × gasPrice** < msg.sender.balance: abort

(3) deduct **gasLimit × gasPrice** from msg.sender.balance

---

(4) set **Gas** ← **gasLimit**

(5) execute Tx: deduct gas from **Gas** for each instruction

if at end (**Gas** < 0): abort, Tx is invalid (miner keeps **gasLimit × gasPrice)**

(6) Refund **Gas** × **gasPrice** to msg.sender.balance

---

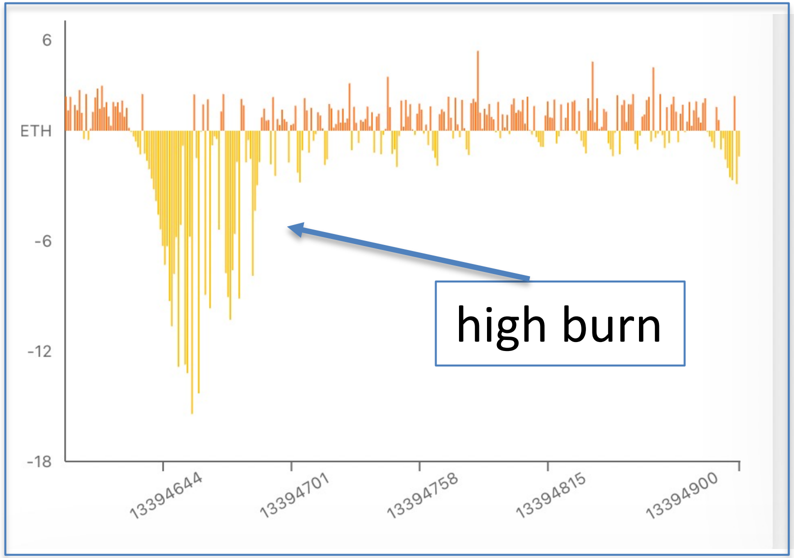
(7) **gasUsed** ← **gasLimit – Gas**

(7a) BURN **gasUsed × baseFee**

(7b) Send **gasUsed × (gasPrice – baseFee)** to miner

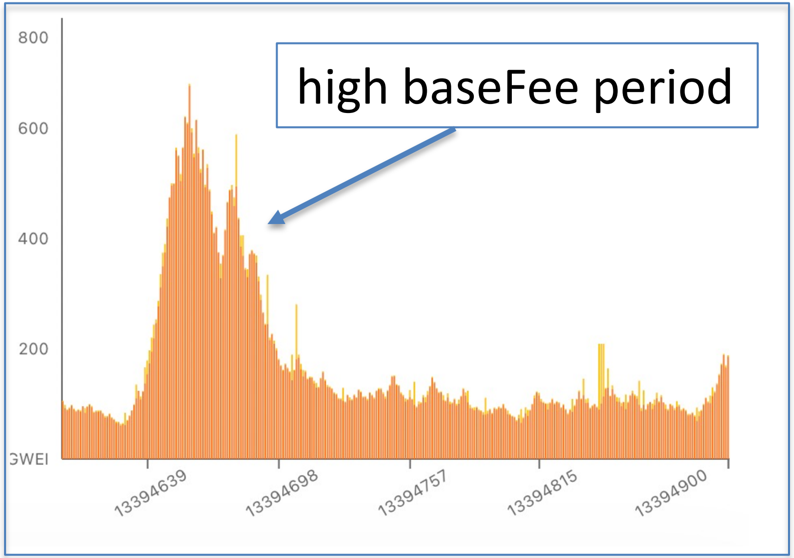
Burn results in practice

block reward (2ETH) –
Total baseFee burned in block



high burn

baseFee for block (Wei)



high baseFee period

… sometimes burn exceeds block rewards ⟹ ETH deflation

watchtheburn.com

Why burn ETH ???

EIP1559 goals (informal):

- users incentivized to bid their true utility for posting Tx,
- miners incentivized to not create fake Tx, and
- disincentivize off chain agreements.

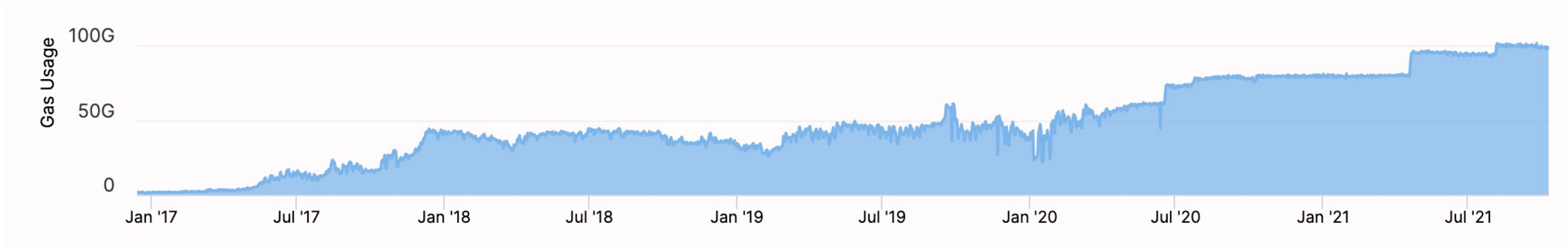
Suppose no burn (i.e., baseFee given to miners):

$\Longrightarrow$ in periods of low Tx volume miners would try to increase volume by offering to refund the baseFee *off chain* to users.

Note: transactions are becoming more complex

Total Gas Usage

Evolution of the total gas used by the Ethereum network per day



Gas usage is increasing ⇒ each Tx takes more instructions to execute

END OF LECTURE

Next lecture: writing Solidity contracts