CS251 Fall 2022

(cs251.stanford.edu)

Ethereum: mechanics

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Note: HW#2 posted tonight.   Due Oct. 24.

New topic: 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: DNS

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**
<DNS> <DomainName> <IPaddr> <1>

only owner can "spend" this UTXO to update domain data

verify sig is valid

ensure top of stack is 1

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: a fork of Bitcoin that implements this contract

(see also the Ethereum Name Service -- ENS)

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

⇒ Ethereum

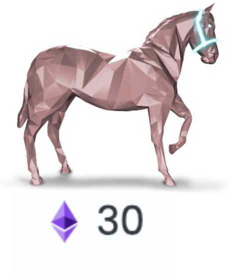
Ethereum: enables a world of applications

A world of Ethereum Decentralized apps (DAPPs)

- New coins: ERC-20 standard interface
- **DeFi**:   exchanges, lending, stablecoins, derivatives, etc.
- **Insurance**
- **DAOs**: decentralized organizations
- **NFTs**: Managing asset ownership (ERC-721 interface)

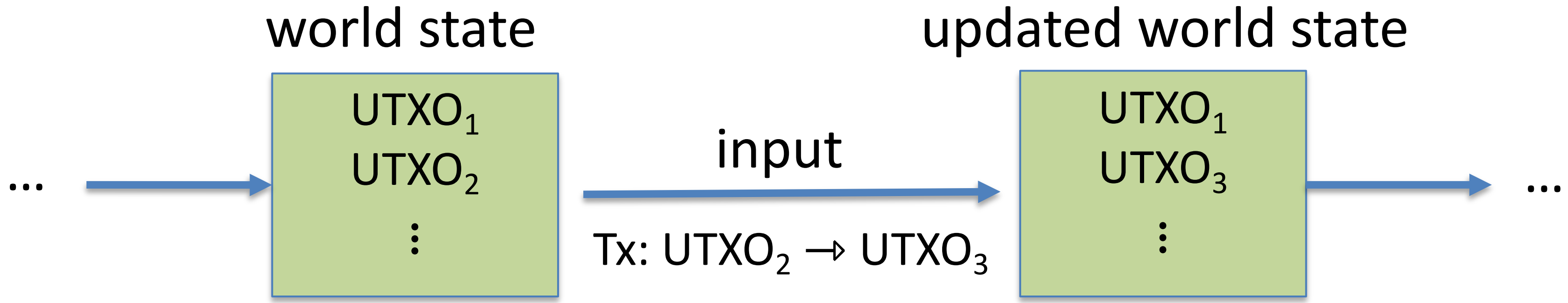
ENS

⋮



stateofthedapps.com,   dapp.review

Bitcoin as a state transition system



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

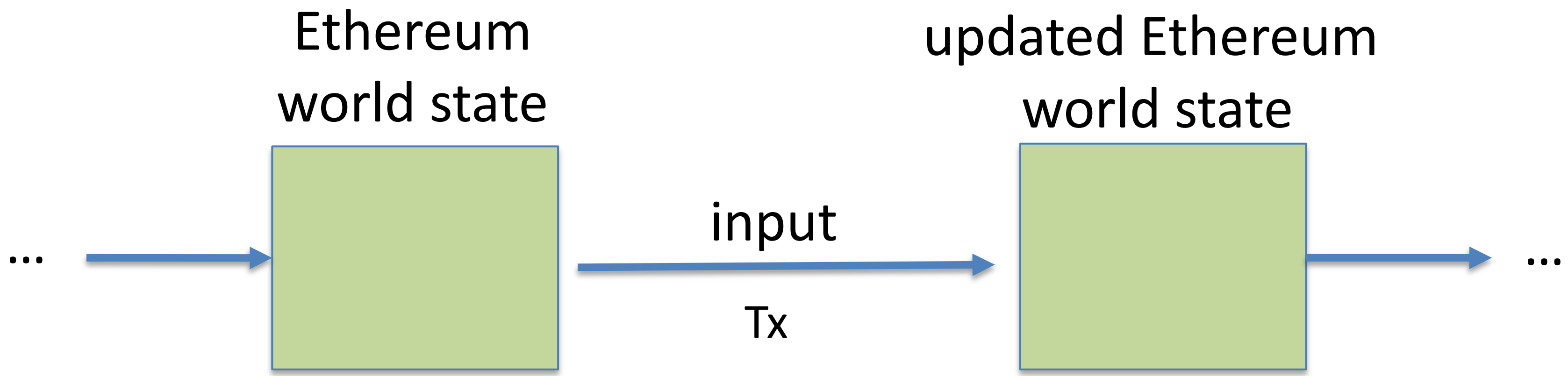
S: set of all possible world states, $s_0 \in S$ genesis state

I: set of all possible inputs

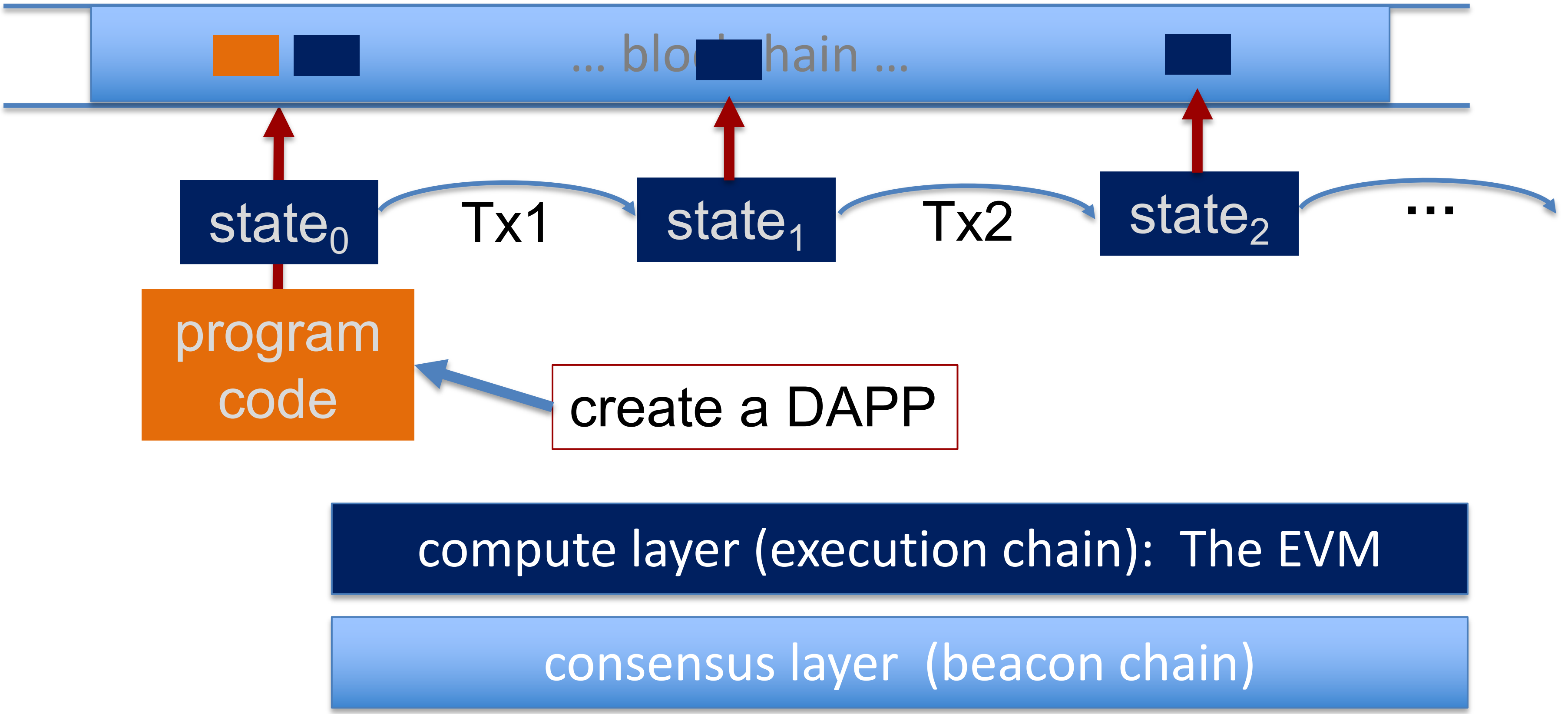
Ethereum as a state transition system

Much richer state transition functions

⇒ one transition executes an entire program



Running a program on a blockchain (DAPP)



The Ethereum system

Proof-of-Stake consensus

Block	Age	Txn	Fee Recipient
15764027	4 secs ago	91	Fee Recipient: 0x467...263
15764026	16 secs ago	26	0xedc7ec654e305a38ffff…
15764025	28 secs ago	165	bloXroute: Max Profit Bui…
15764024	40 secs ago	188	Lido: Execution Layer Re…
15764023	52 secs ago	18	Fee Recipient: 0xeBe...Acf
15764022	1 min ago	282	0xd4e96ef8eee8678dbff…
15764021	1 min ago	295	0xbb3afde35eb9f5feb53…
15764020	1 min ago	71	Fee Recipient: 0x6d2...766

One block every 12 seconds.

about 150 Tx per block.

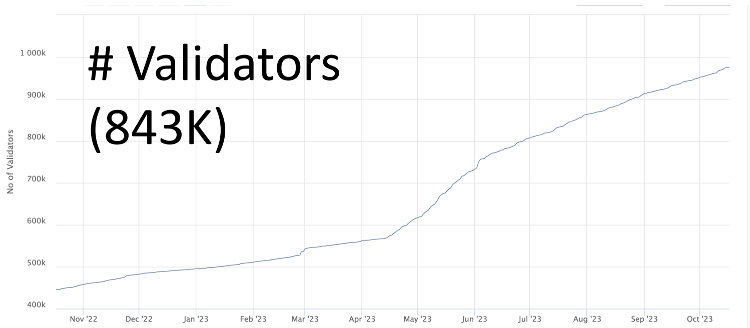
Block proposer receives
Tx fees for block
(along with other rewards)

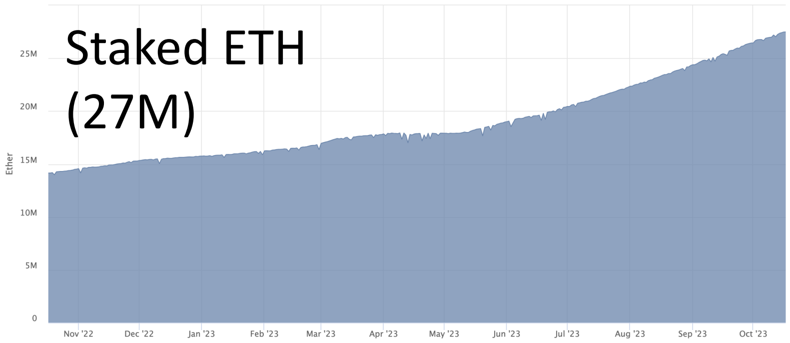
A bit about the beacon chain (Eth2 consensus layer)

To become a validator: stake (lock up) 32 ETH ... or use Lido.

Validators: - sign blocks to express correctness (finalized once enough sigs)

- occasionally act as ***block proposer*** (chosen at random)
- correct behavior ⇒ issued **<u>new ETH</u>** every epoch (32 blocks)
- incorrect behavior ⇒ slashed (lots of details)





The economics of staking

Validator locks up 32 ETH.   Oct 2023:   27M ETH staked (total)

Annual validator income (an example):

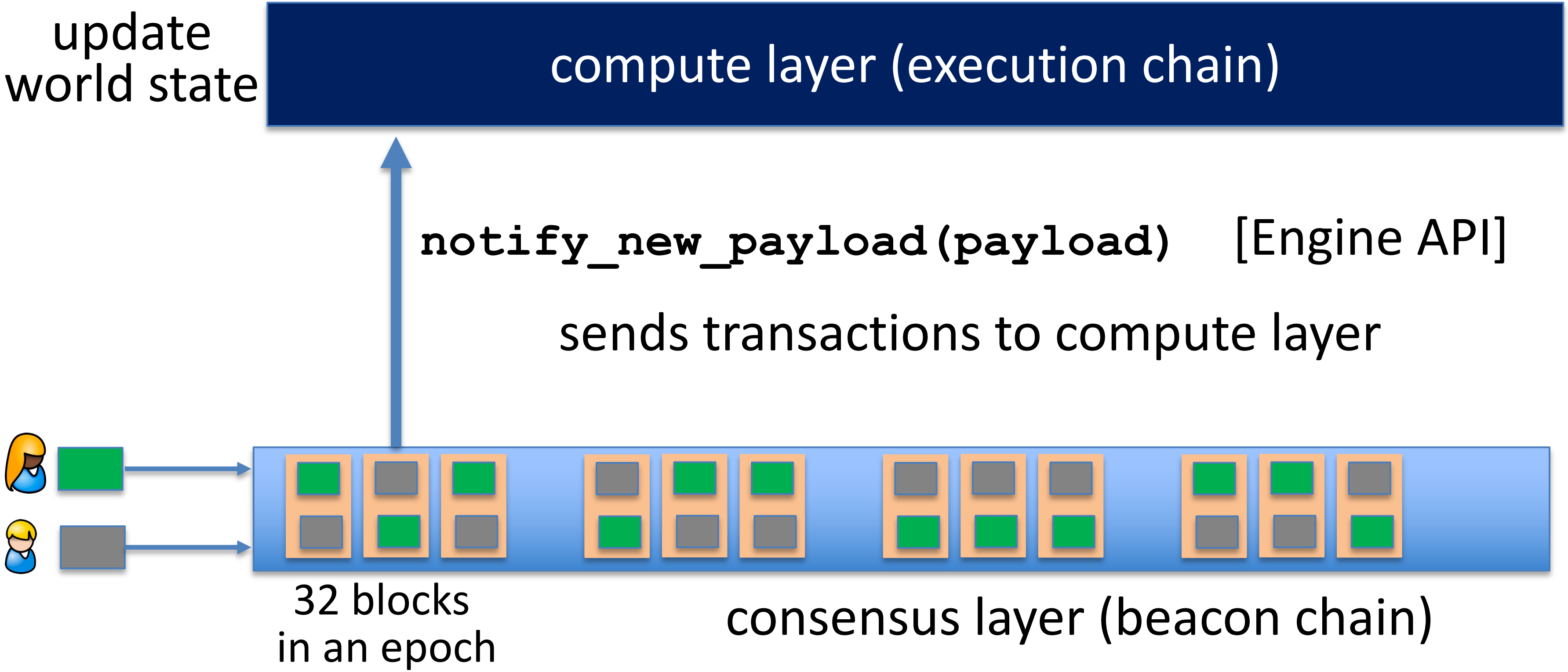
- Issuance: 1.0 ETH
- Tx fees: 0.4 ETH
- MEV: 0.4 ETH
- Total: 1.8 ETH   (5.6% return on 32 ETH staked)

Can be adjusted
(BASE_REWARD_FACTOR)

A function of congestion

In practice: staking provider (e.g., Lido) takes a cut of the returns

The Ethereum system



The Ethereum Compute Layer: The EVM

Ethereum compute layer: the EVM

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

Two types of accounts:

(1) externally owned accounts (EOA):

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 (EOA)	Contracts	
address (computed):	H(pk)	H(CreatorAddr, CreatorNonce)	
code:	$\perp$	CodeHash	
storage root (state):	$\perp$	StorageRoot	
balance (in Wei):	balance	balance	(1 Wei = 10^{-18} ETH)
nonce:	nonce	nonce	

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

Account state: persistent storage

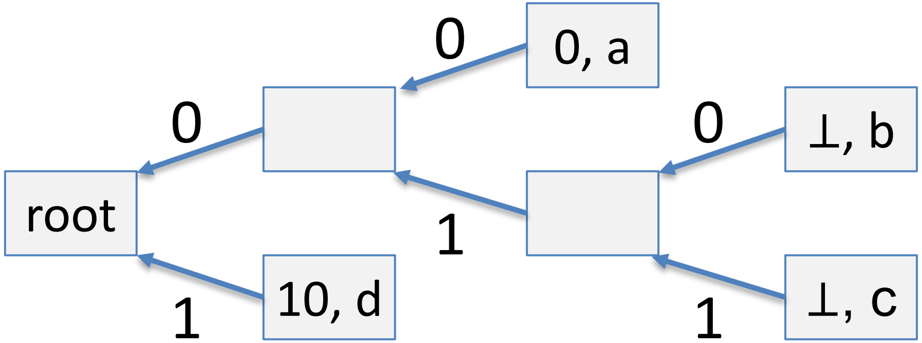
Every contract has an associated **storage array S**[]:

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:
$\leq 2 \times |S|$

|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 (1 Wei = 10^{-18} ETH)
- 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)
- chain_id: ensures Tx can only be submitted to the intended chain

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

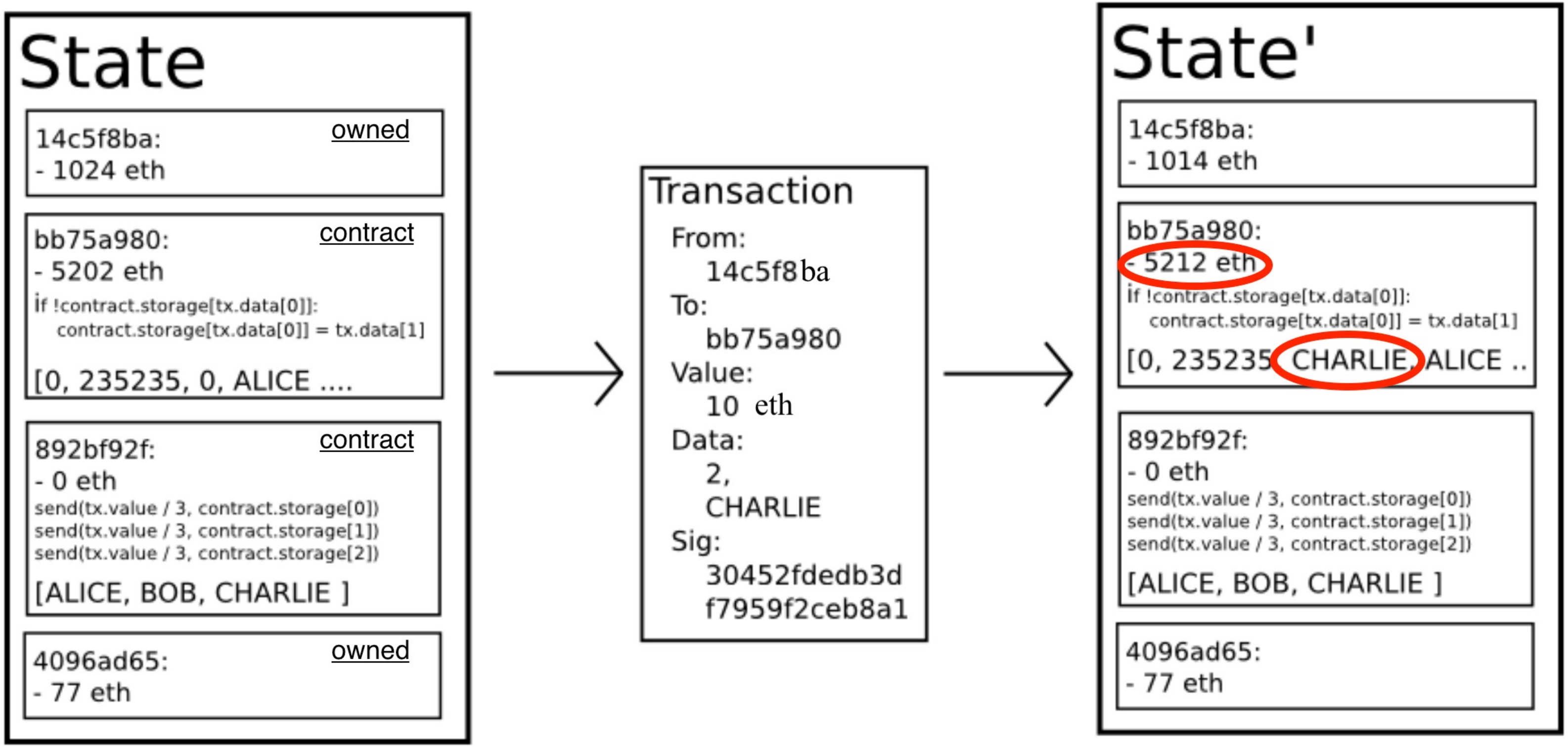
contract ⇾ contract: one program calls another (and sends funds)

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

Tx from owned addr ⇾ contract ⇾ another contract

another contract ⇾ different owned

Example Tx



world state (four accounts)

updated world state

An Ethereum Block

Block proposer creates a block of n Tx: (from Txs submitted by users)

- To produce a block do:
  - for i=1,…,n: execute state change of Tx_i sequentially

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

Other validators re-execute all Tx to verify block $\Rightarrow$

sign block if valid $\Rightarrow$ enough sigs, epoch is finalized.

Block header data (simplified)

(1) consensus data: proposer ID, parent hash, votes, etc.

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

(3) world state root: updated world state

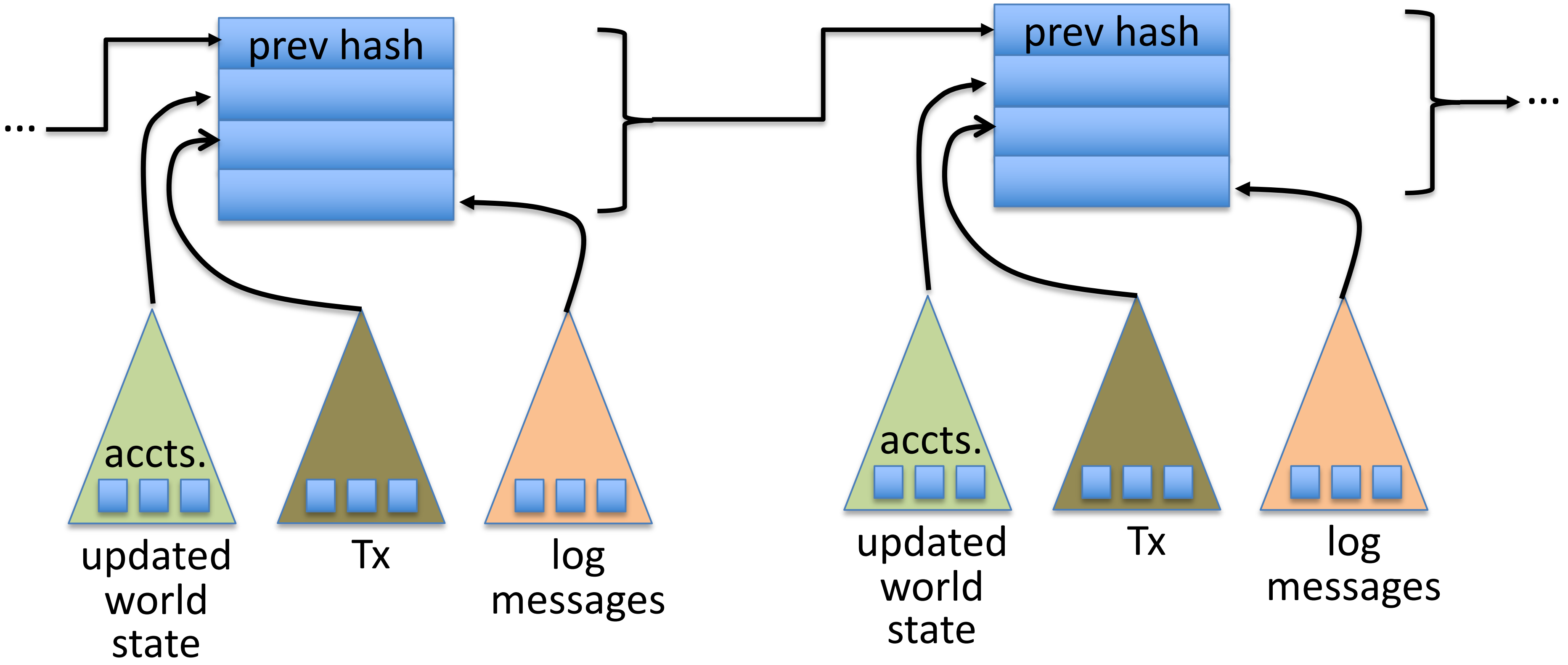
Merkle Patricia Tree hash of <u>all</u> accounts in the system

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

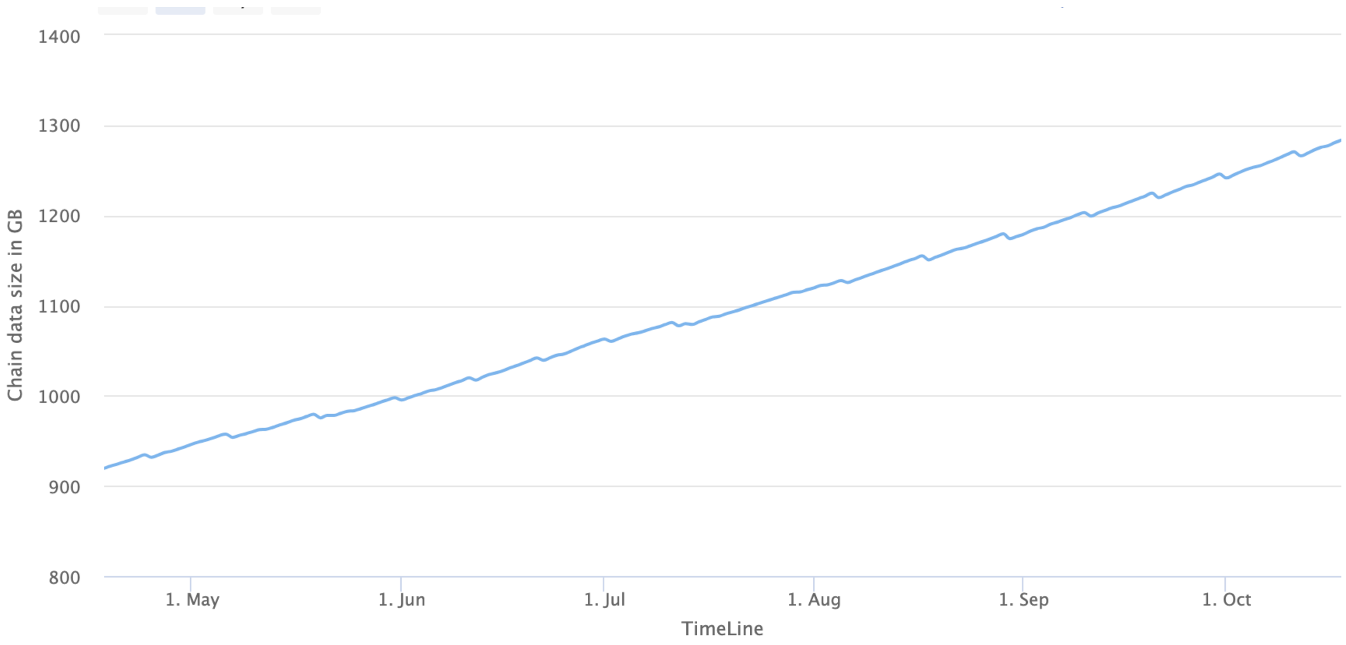
(5) **Tx receipt root**: Merkle hash of log messages generated in block

(5) Gas used: used to adjust gas price (target 15M gas per block)

The Ethereum blockchain: abstractly



Amount of memory to run a node



≈1.3 TB

ETH total blockchain size (archival): 16 TB (Oct. 2023)

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
```

Used by other contracts

Humans do not need this
(use etherscan.io)

EVM mechanics: execution environment

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

$\Rightarrow$ compile to EVM bytecode

(some projects use WASM or BPF bytecode)

$\Rightarrow$ validators 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; block proposer keeps gas
- contract can <u>create</u> or <u>call</u> 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://www.evm.codes

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 (for a cold slot)
- non-zero → zero: 15,000 gas refund (example)

Refund is given for reducing size of blockchain state

CREATE : 32,000 + 200 × (code size) gas;

CALL **gas**, addr, **value**, args

SELFDESTRUCT addr: kill current contract (5000 gas)

Gas calculation

Why charge gas?

- Tx fees (gas) prevents submitting Tx that runs for many steps.
- During high load: block proposer chooses Tx from mempool that maximize its income.

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

- Every Tx contains a gasPrice ``bid'' (gas $\rightarrow$ Wei conversion price)
- Producer chooses Tx with highest gasPrice (max sum(gasPrice × gasLimit))

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

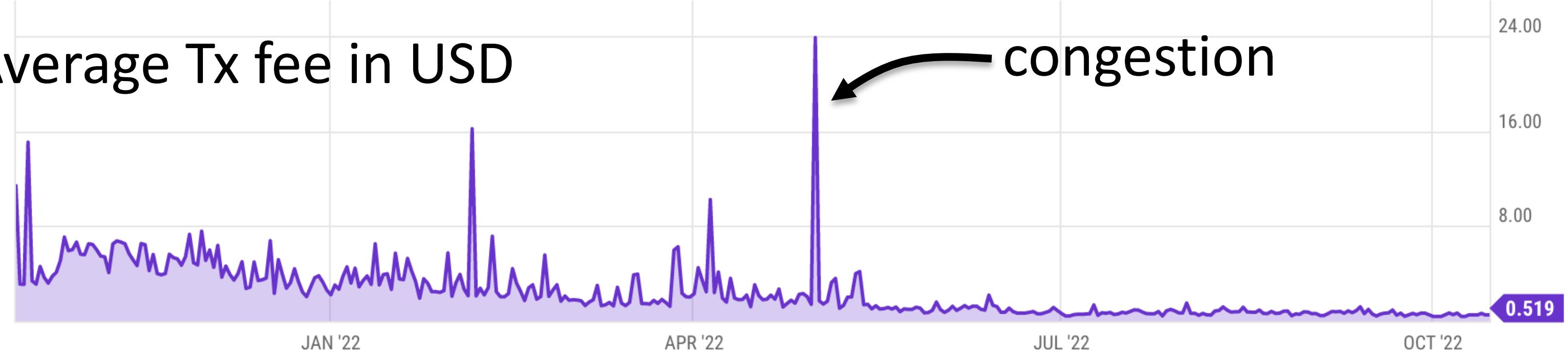
Gas prices spike during congestion

GasPrice in Gwei:

86 Gwei = 86 × 10^{-9} ETH

Average Tx fee in USD

congestion



Gas calculation: EIP1559 (since 8/2021)

EIP1559 goals (informal):

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

[Transaction Fee Mechanism Design, by T. Roughgarden, 2021]

Gas calculation: EIP1559

Every block has a "baseFee":

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

baseFee is computed from total gas in earlier blocks:

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

interpolate in between

If earlier blocks at "target size" (15M gas) $\Longrightarrow$ 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 block proposer

Computed **gasPrice** bid:

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

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

Gas calculation (informal)

gasUsed ⇽ gas used by Tx

Send **gasUsed** × (**gasPrice** – **baseFee**) to block proposer

BURN **gasUsed** × **baseFee** 

⇒ total supply of ETH can decrease

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 (proposer 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 block producer

Example baseFee and effect of burn

block #	gasUsed	baseFee (Gwei)	ETH burned
15763570	21,486,058	16.92 ↓	0.363
15763569	**14,609,185** (<15M)	16.97	0.248
15763568	25,239,720	15.64	0.394
15763567	29,976,215	13.90 ↓	0.416
15763566	**14,926,172** (<15M)	13.91 ↓	0.207
15763565	**1,985,580** (<15M)	15.60	0.031

≈ gasUsed × baseFee

beacon chain

baseFee < 16Gwei ⇒ new issuance > burn ⇒ ETH inflates

baseFee > 16Gwei ⇒ new issuance < burn ⇒ ETH deflates

Why burn ETH ???

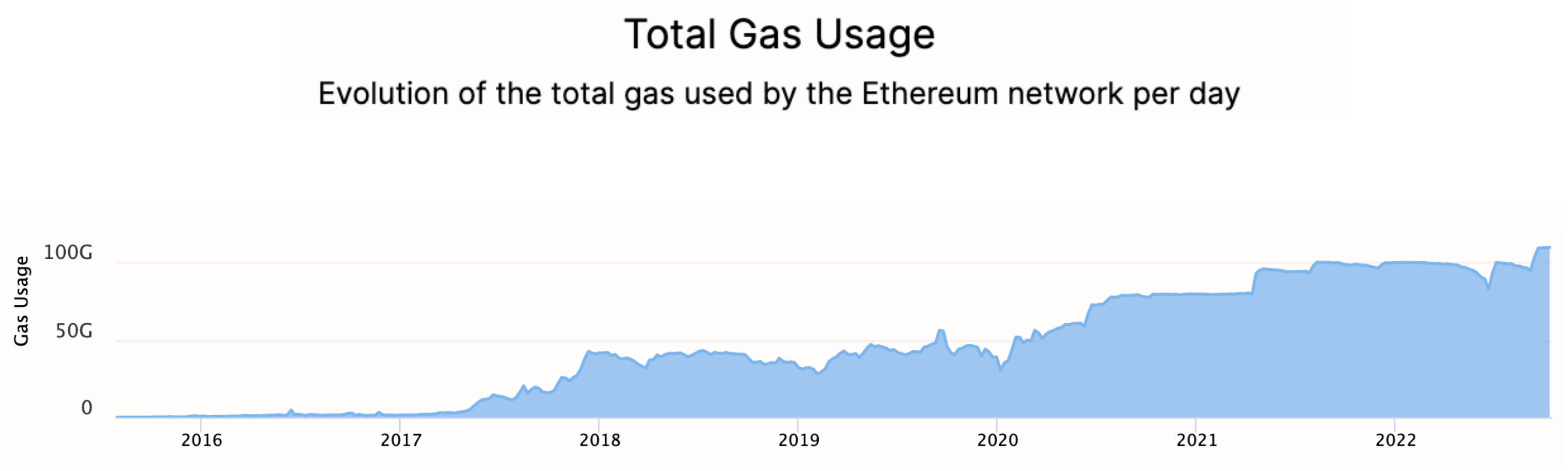
Recall: EIP1559 goals (informal)

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

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

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

Note: transactions are becoming more complex



Gas usage is increasing $\Rightarrow$ each Tx takes more instructions to execute

END OF LECTURE

Next lecture: writing Solidity contracts