OpenZeppelin

Data structures

for a Verkle-powered EVM

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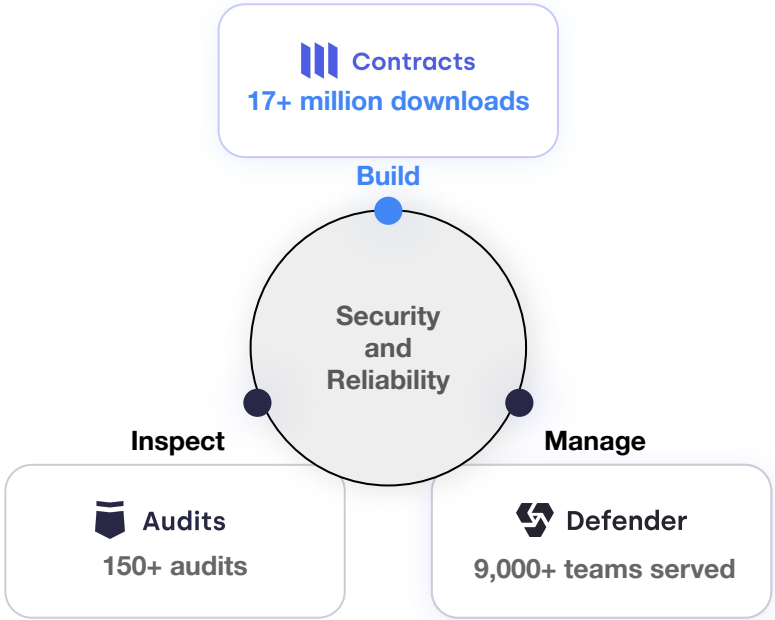
OpenZeppelin's thesis

- There will be a **trillion dollar open economy** built on blockchains and **powered by smart contracts**
- This new, open economy will be **built by teams of creative people developing new applications used by billions of people**
- These teams **will need a set of tools, products and services** to make sure that what they are building is **safe and reliable**
- OpenZeppelin will be a **leading provider of these solutions**, allowing teams to **build faster with lower risk**

OpenZeppelin's products



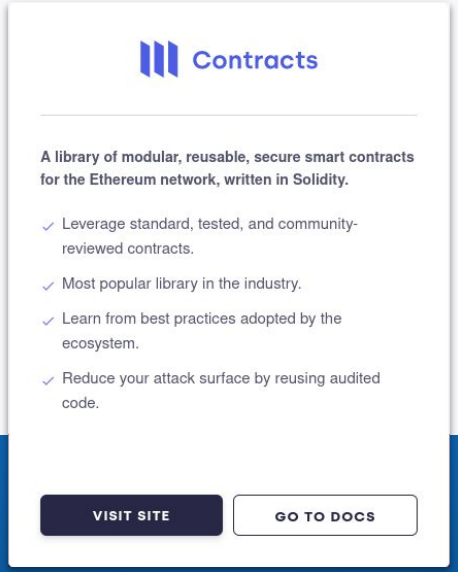
L1 / L2 Networks

ethereum
polygon
Polkadot.
AVALANCHE
ARBITRUM
STARKWARE
OPTIMISM
celo
fantom
BINANCE SMART CHAIN
Hedera

Contracts

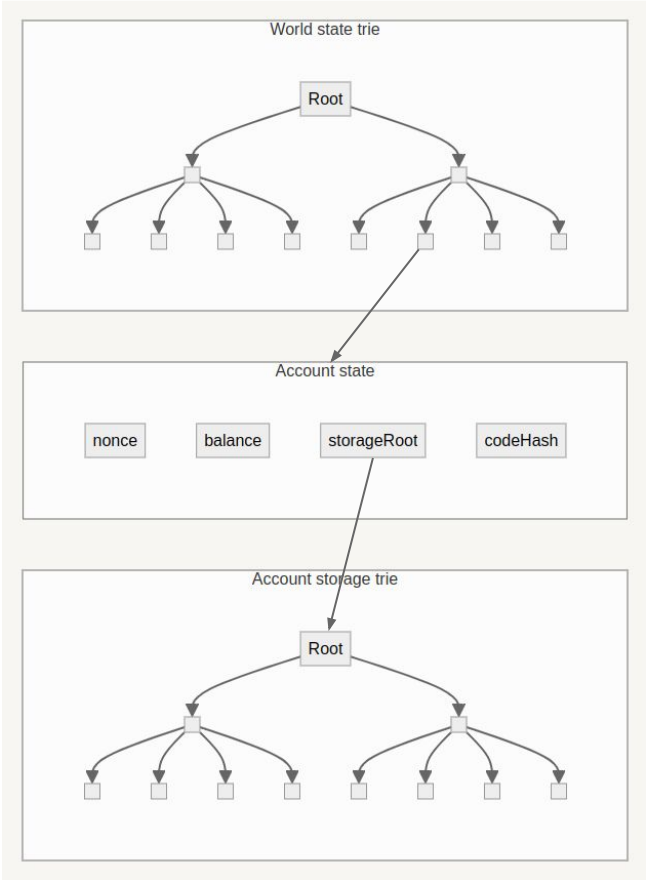
@openzeppelin/contracts@5.0.2

@openzeppelin/contracts-upgradeable@5.0.2



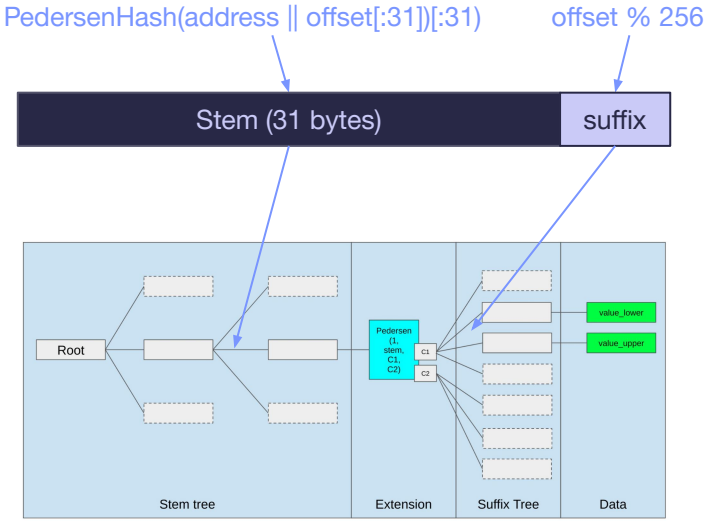
How smart contract state is stored

- **Each account comes with a storage trie**
- **Used for persistent data**
  ERC-20 balances, ERC-721 ownership, everything
- **Storage is divided in slots**
  Each account has 2^{256} slots available
- **Slots must be “warmed up” before use**
  You only pay the warm-up price once per tx
- **All slots are identical**



That all changes with the verge

- **All storage in the same (verkle) trie**
- **Position in that shared trie is a combination of account and offset (“slot number”)**
- **Slots are gathered in buckets**
  For a given account, consecutive slots are in the same bucket (up to 256 slots)
- **Buckets are “warmed up”, not slots**
  So reusing slots in a given bucket is efficient

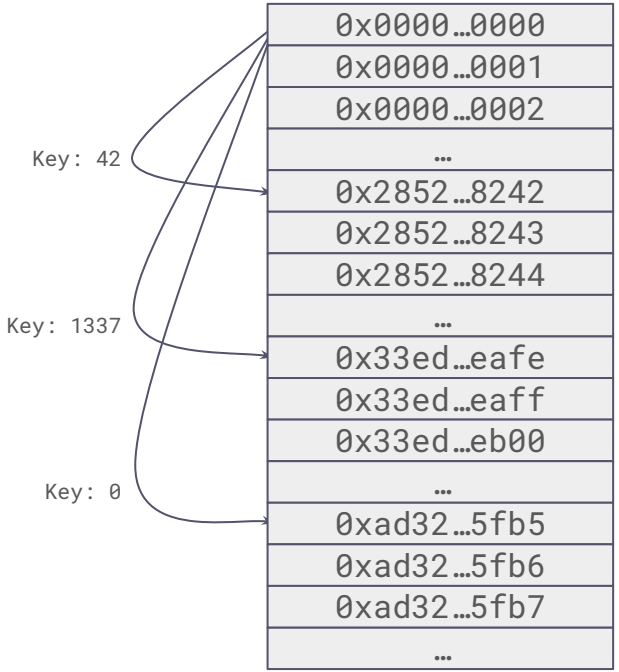


The grammar of storage layouts (Solidity & Vyper)

$$
\begin{aligned}
L_0 := 0 &\leftarrow \text{Contract's root} \\
\mid L_0 + n &\leftarrow \text{State variables, structs, array elements} \\
\mid \texttt{keccak256}(L_0) &\leftarrow \text{Arrays derivation} \\
\mid \texttt{keccak256}(H(k) \oplus L_0) &\leftarrow \text{Mappings (Solidity)} \\
\mid \texttt{keccak256}(L_0 \oplus H(k)) &\leftarrow \text{Mappings (Vyper)}
\end{aligned}
$$

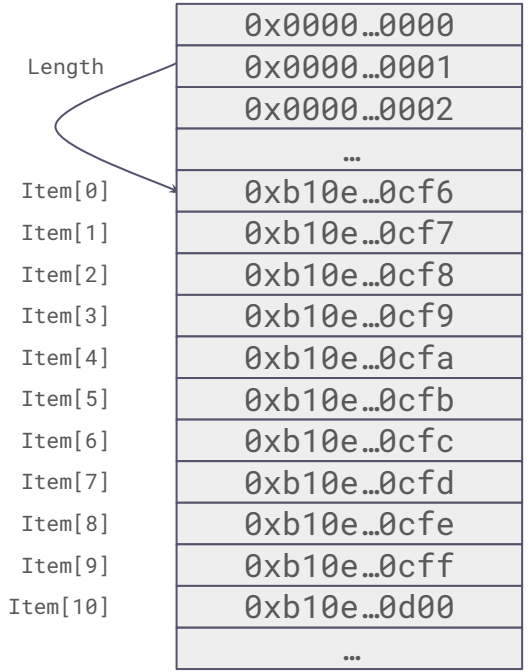
Where the grammar fails: Mappings

- **Mappings are extensively used in solidity**
  Balances, ownership, allowance, …
- **Mappings work by pointing to a pseudo-random location**
  Virtually impossible to get a collision + all slots are equally good
- **Data is scattered everywhere**
  Very poor data locality for verkle, each key point to a different bucket



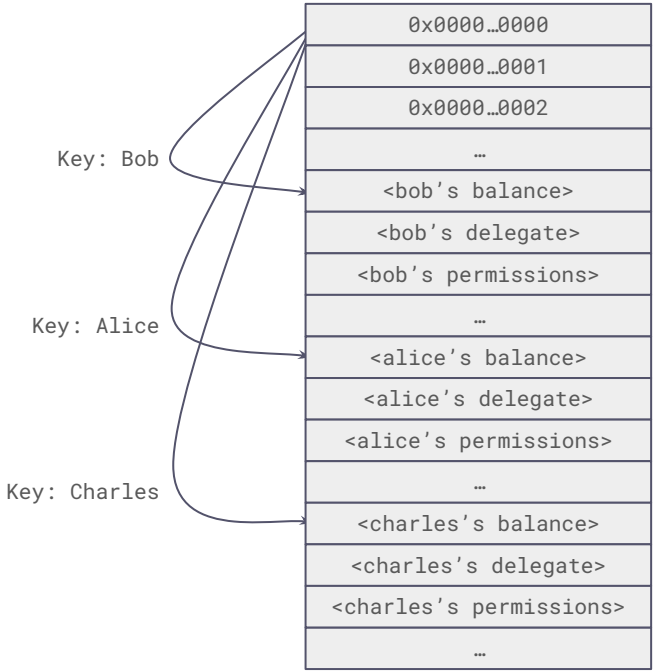
Where the grammar fails: Arrays

- **Arrays have way better data locality then mappings**
- **Each array access check that length is within bounds**
  Length information is located at the root (different bucket)
- **The start of the array is unlikely to coincide with the start of a bucket**
  Sub-optimal for small arrays, tapers off when the array length increases



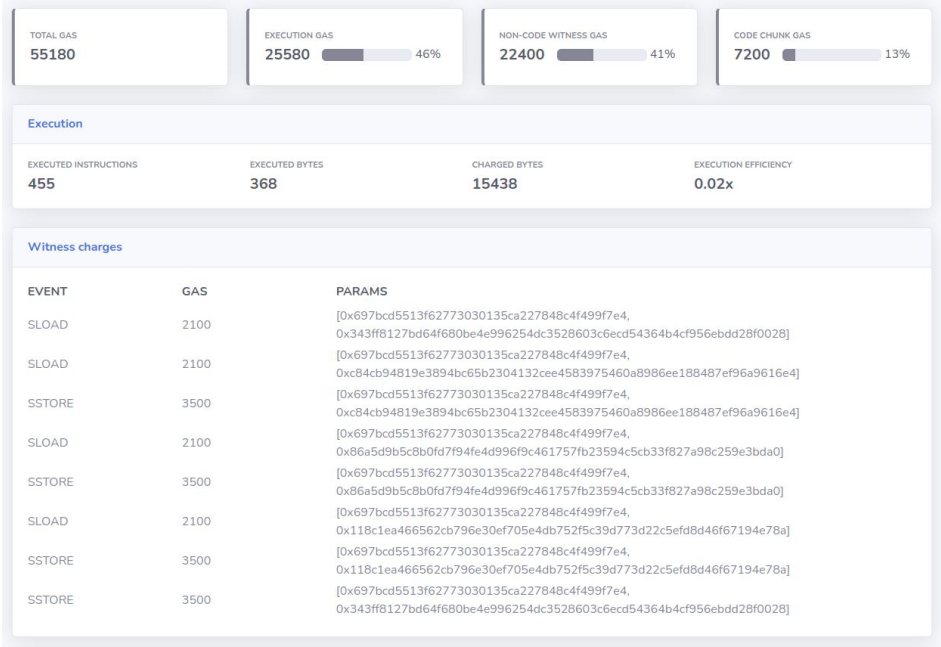
What you can do as a developer: consolidate mappings

- **Merge mappings that use the same key**
  Map to a structure that contains all the values
- **Easy to do, but will occasionally not work**
  If the key points to the end of a bucket, the structure may span over two buckets
- **Limited to some cases**
  In ERC-20, balances and approvals have different key patterns, so they cannot be consolidated



34 contracts/token/ERC721/ERC721.sol

```
@@ -25,13 +25,19 @@ abstract contract ERC721 is Context, ERC165, IERC721, IERC721Metadata, IERC721Er
25 25      // Token symbol
26 26      string private _symbol;
27 27
28    -    mapping(uint256 tokenId => address) private _owners;
   28 +    struct TokenDetails {
   29 +        address owner;
   30 +        address approval;
   31 +    }
29 32
30    -    mapping(address owner => uint256) private _balances;
   33 +    struct AccountDetails {
   34 +        uint256 balance;
   35 +        mapping(address => bool) operators;
   36 +    }
31 37
32    -    mapping(uint256 tokenId => address) private _tokenApprovals;
   38 +    mapping(uint256 tokenId => TokenDetails) private _tokens;
33 39
34    -    mapping(address owner => mapping(address operator => bool)) private _operatorApprovals;
   40 +    mapping(address owner => AccountDetails) private _accounts;
35 41
36 42      /**
37 43       * @dev Initializes the contract by setting a `name` and a `symbol` to the token collection.
@@ -58,7 +64,7 @@ abstract contract ERC721 is Context, ERC165, IERC721, IERC721Metadata, IERC721Er
58 64          if (owner == address(0)) {
59 65              revert ERC721InvalidOwner(address(0));
60 66          }
61    -        return _balances[owner];
   67 +        return _accounts[owner].balance;
62 68      }
63 69
64 70      /**
@@ -128,7 +134,7 @@ abstract contract ERC721 is Context, ERC165, IERC721, IERC721Metadata, IERC721Er
128 134       * @dev See {IERC721-isApprovedForAll}.
129 135       */
130 136      function isApprovedForAll(address owner, address operator) public view virtual returns (bool) {
131   -        return _operatorApprovals[owner][operator];
   137 +        return _accounts[owner].operators[operator];
132 138      }
```



TOTAL GAS	EXECUTION GAS	NON-CODE WITNESS GAS	CODE CHUNK GAS
55180	25580 46%	22400 41%	7200 13%

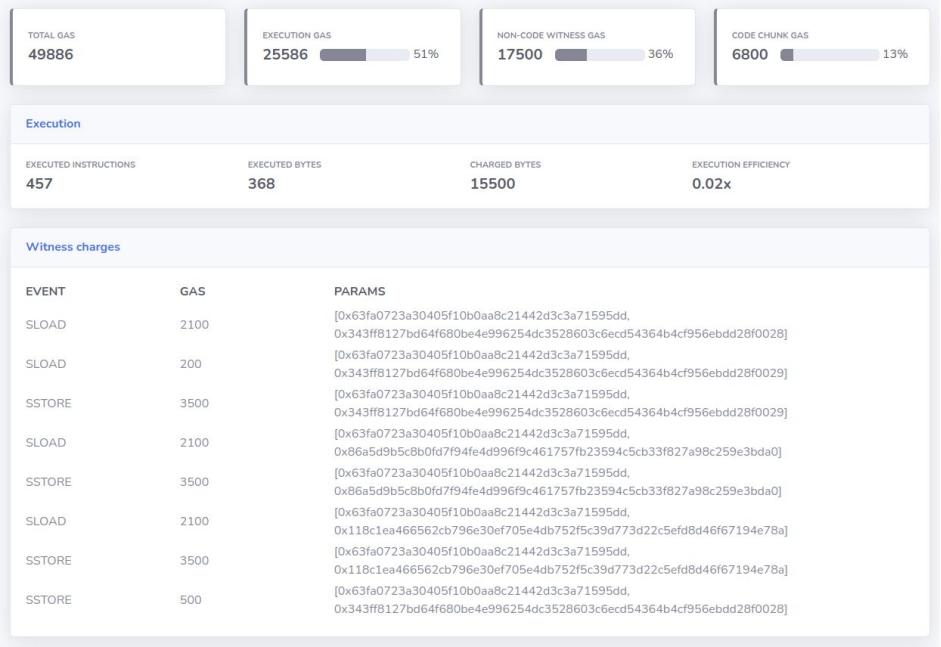
Execution

EXECUTED INSTRUCTIONS	EXECUTED BYTES	CHARGED BYTES	EXECUTION EFFICIENCY
455	368	15438	0.02x

Witness charges

EVENT	GAS	PARAMS
SLOAD	2100	[0x697bcd5513f62773030135ca227848c4f499f7e4, 0x343ff8127bd64f680be4e996254dc3528603c6ecd54364b4cf956ebdd28f0028]
SLOAD	2100	[0x697bcd5513f62773030135ca227848c4f499f7e4, 0xc84cb94819e3894bc65b2304132cee4583975460a8986ee188487ef96a9616e4]
SSTORE	3500	[0x697bcd5513f62773030135ca227848c4f499f7e4, 0xc84cb94819e3894bc65b2304132cee4583975460a8986ee188487ef96a9616e4]
SLOAD	2100	[0x697bcd5513f62773030135ca227848c4f499f7e4, 0x86a5d9b5c8b0fd7f94fe4d996f9c461757fb23594c5cb33f827a98c259e3bda0]
SSTORE	3500	[0x697bcd5513f62773030135ca227848c4f499f7e4, 0x86a5d9b5c8b0fd7f94fe4d996f9c461757fb23594c5cb33f827a98c259e3bda0]
SLOAD	2100	[0x697bcd5513f62773030135ca227848c4f499f7e4, 0x118c1ea466562cb796e30ef705e4db752f5c39d773d22c5efd8d46f67194e78a]
SSTORE	3500	[0x697bcd5513f62773030135ca227848c4f499f7e4, 0x118c1ea466562cb796e30ef705e4db752f5c39d773d22c5efd8d46f67194e78a]
SSTORE	3500	[0x697bcd5513f62773030135ca227848c4f499f7e4, 0x343ff8127bd64f680be4e996254dc3528603c6ecd54364b4cf956ebdd28f0028]

[transferFrom on a “Normal ERC-721”]



TOTAL GAS	EXECUTION GAS	NON-CODE WITNESS GAS	CODE CHUNK GAS
49886	25586 51%	17500 36%	6800 13%

Execution

EXECUTED INSTRUCTIONS	EXECUTED BYTES	CHARGED BYTES	EXECUTION EFFICIENCY
457	368	15500	0.02x

Witness charges

EVENT	GAS	PARAMS
SLOAD	2100	[0x63fa0723a30405f10b0aa8c21442d3c3a71595dd, 0x343ff8127bd64f680be4e996254dc3528603c6ecd54364b4cf956ebdd28f0028]
SLOAD	200	[0x63fa0723a30405f10b0aa8c21442d3c3a71595dd, 0x343ff8127bd64f680be4e996254dc3528603c6ecd54364b4cf956ebdd28f0029]
SSTORE	3500	[0x63fa0723a30405f10b0aa8c21442d3c3a71595dd, 0x343ff8127bd64f680be4e996254dc3528603c6ecd54364b4cf956ebdd28f0029]
SLOAD	2100	[0x63fa0723a30405f10b0aa8c21442d3c3a71595dd, 0x86a5d9b5c8b0fd7f94fe4d996f9c461757fb23594c5cb33f827a98c259e3bda0]
SSTORE	3500	[0x63fa0723a30405f10b0aa8c21442d3c3a71595dd, 0x86a5d9b5c8b0fd7f94fe4d996f9c461757fb23594c5cb33f827a98c259e3bda0]
SLOAD	2100	[0x63fa0723a30405f10b0aa8c21442d3c3a71595dd, 0x118c1ea466562cb796e30ef705e4db752f5c39d773d22c5efd8d46f67194e78a]
SSTORE	3500	[0x63fa0723a30405f10b0aa8c21442d3c3a71595dd, 0x118c1ea466562cb796e30ef705e4db752f5c39d773d22c5efd8d46f67194e78a]
SSTORE	500	[0x63fa0723a30405f10b0aa8c21442d3c3a71595dd, 0x343ff8127bd64f680be4e996254dc3528603c6ecd54364b4cf956ebdd28f0028]

[transferFrom on a “Packed ERC-721”]

What you can do as a developer: use (custom) arrays

Mapping

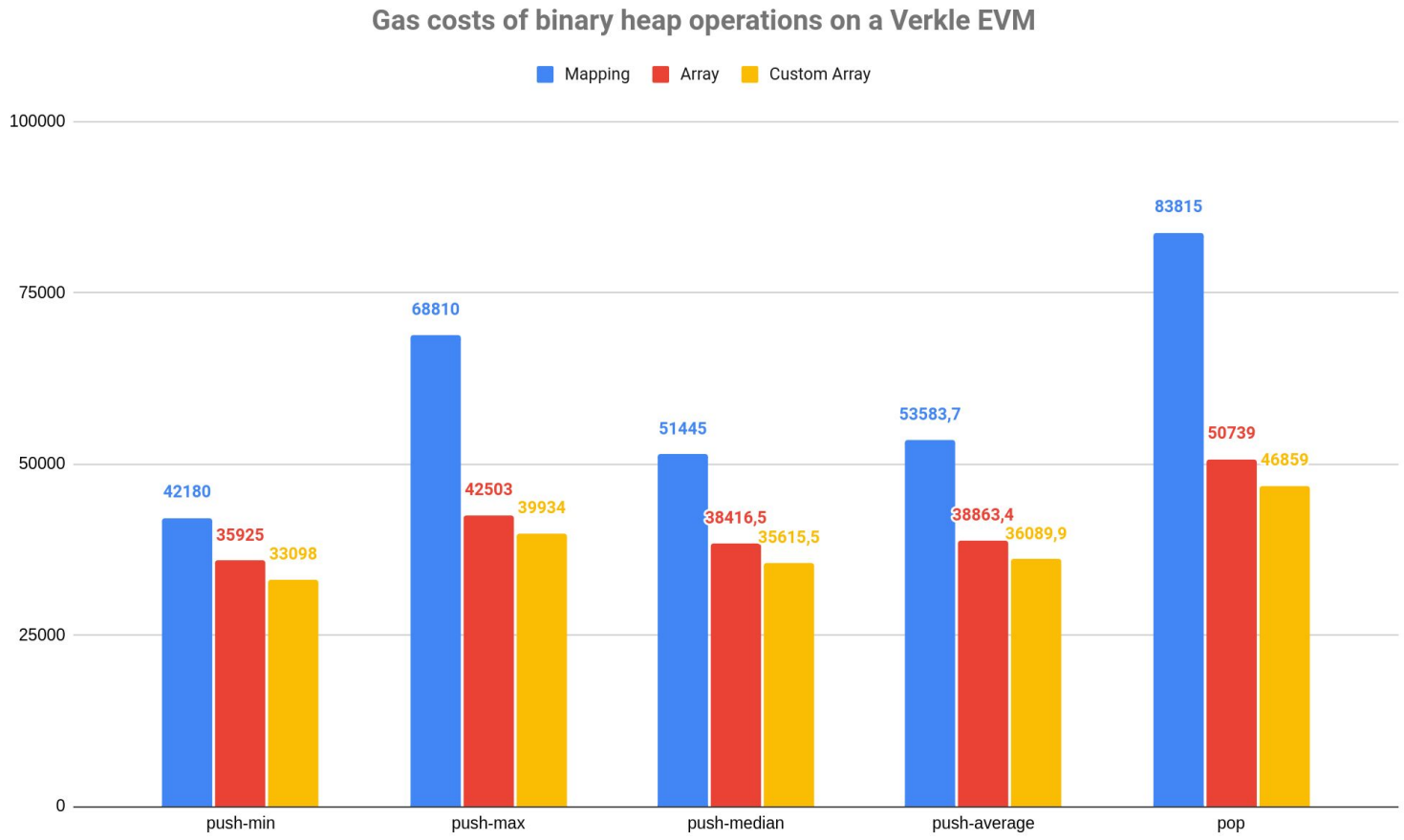
```
library HeapMapping {
    using SafeCast for *;

    struct Uint256Heap {
        mapping(uint32 => uint32) tree;
        mapping(uint32 => Node) items;
        uint32 size;
        uint32 nextItemIdx;
    }

    struct Node {
        uint256 value;
        uint32 heapIndex; // value -> position
    }
```

Array

```
library HeapArray {
    using SafeCast for *;

    struct Uint256Heap {
        Uint256HeapNode[] data;
    }

    struct Uint256HeapNode {
        uint256 value;
        uint32 index; // position -> value
        uint32 lookup; // value -> position
    }

    function _unsafeNodeAccess(
        Uint256Heap storage self,
        uint32 pos
    ) private pure returns (Uint256HeapNode storage result) {
        assembly ("memory-safe") {
            mstore(0x00, self.slot)
            result.slot := add(keccak256(0x00, 0x20), mul(pos, 2))
        }
    }
```

Custom array implementation

```
library HeapArray2 {
    using SafeCast for *;

    struct Uint256Heap {
        bytes32 _placeholder_do_not_use;
    }

    struct Uint256HeapNode {
        uint256 value;
        uint32 index; // position -> value
        uint32 lookup; // value -> position
    }

    struct Uint256HeapLength {
        uint256 value;
    }

    function _unsafeNodeAccess(
        Uint256Heap storage self,
        uint32 pos
    ) private pure returns (Uint256HeapNode storage result) {
        assembly ("memory-safe") {
            mstore(0x00, self.slot)
            result.slot := add(keccak256(0x00, 0x20), add(mul(pos, 2), 1))
        }
    }

    function _unsafeLengthAccess(
        Uint256Heap storage self
    ) private pure returns (Uint256HeapLength storage result) {
        assembly ("memory-safe") {
            mstore(0x00, self.slot)
            result.slot := keccak256(0x00, 0x20)
        }
    }
```



What we ultimately need: compiler support!

Compiler must evolve to optimize for Verkle storage costs …

- **Replace “keccak256(...)” with “keccak256(...) & ~0xFF”**
  for Array and mapping derivation
- **Move the length of the array to the same “space” as the elements**
- **Provide in-language mechanism to “extend” a mapping from a parent contract**

… but this is breaking

```
abstract contract ERC721 is Context, ERC165, IERC721, IERC721Metadata, IERC721Errors {
    using Strings for uint256;

    // Token name
    string private _name;

    // Token symbol
    string private _symbol;

    mapping(uint256 tokenId => address) private _owners;

    mapping(address owner => uint256) private _balances;

    mapping(uint256 tokenId => address) private _tokenApprovals;

    mapping(address owner => mapping(address operator => bool)) private _operatorApprovals;


abstract contract ERC721Enumerable is ERC721, IERC721Enumerable {
    mapping(address owner => mapping(uint256 index => uint256)) private _ownedTokens;
    mapping(uint256 tokenId => uint256) private _ownedTokensIndex;

    uint256[] private _allTokens;
    mapping(uint256 tokenId => uint256) private _allTokensIndex;


abstract contract ERC721URIStorage is IERC4906, ERC721 {
    using Strings for uint256;

    // Interface ID as defined in ERC-4906. This does not correspond to a traditional interfac
    // defines events and does not include any external function.
    bytes4 private constant ERC4906_INTERFACE_ID = bytes4(0x49064906);

    // Optional mapping for token URIs
    mapping(uint256 tokenId => string) private _tokenURIs;
```

@openzeppelin/contracts

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Thank you for your attention

Slides

Source code & results

POAP