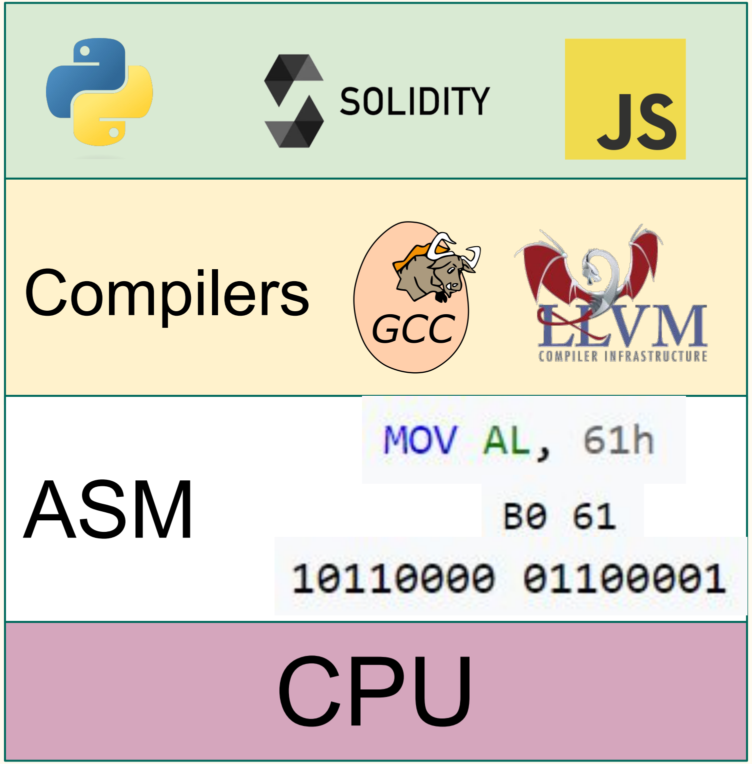
Lecture 11

Gas Optimization

Lecture 1 Refresher - EVM Architecture



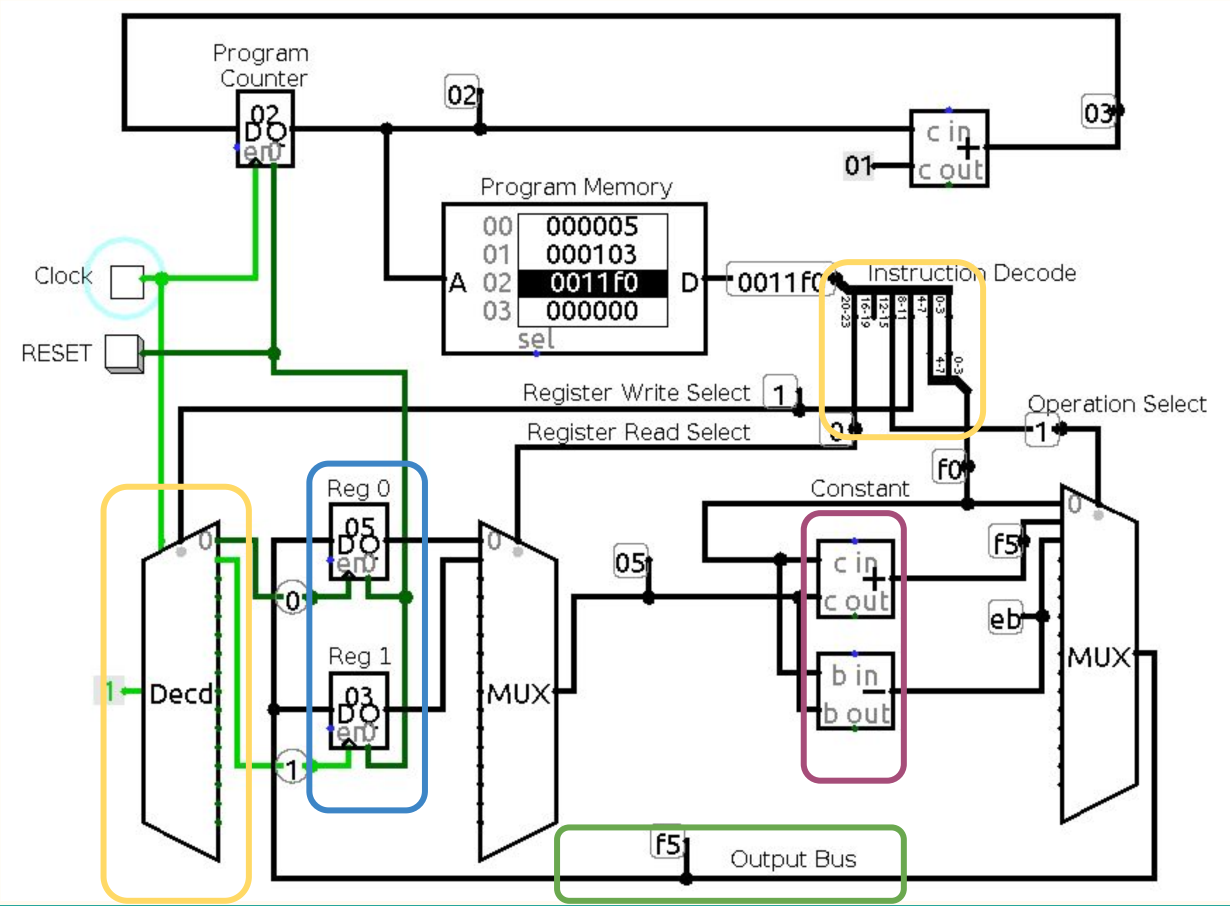
Human readable -
"High Level"

Translation program:
Bytecode -VM
Machine Code - Binary
ASM - Instructions

Machine Language -
"Low Level"

A Turing Complete,
Finite State Machine

Lecture 1 Refresh - CPU execution



Decode Instructions into opcode and data

Registers to hold **program** essentials: Data, loops state, pointers

Algorithmic Logic Unit

Ram read write, towards more permanent storage. Indexed by **Addresses**

In summary - Compilation Flow

Solidity Code → Bytecode → Instruction

uint a = 1+2

60016002016052

PUSH1 1
PUSH1 2
ADD
PUSH1 result
MSTORE

https://ethereum.org/en/developers/docs/evm/opcodes/

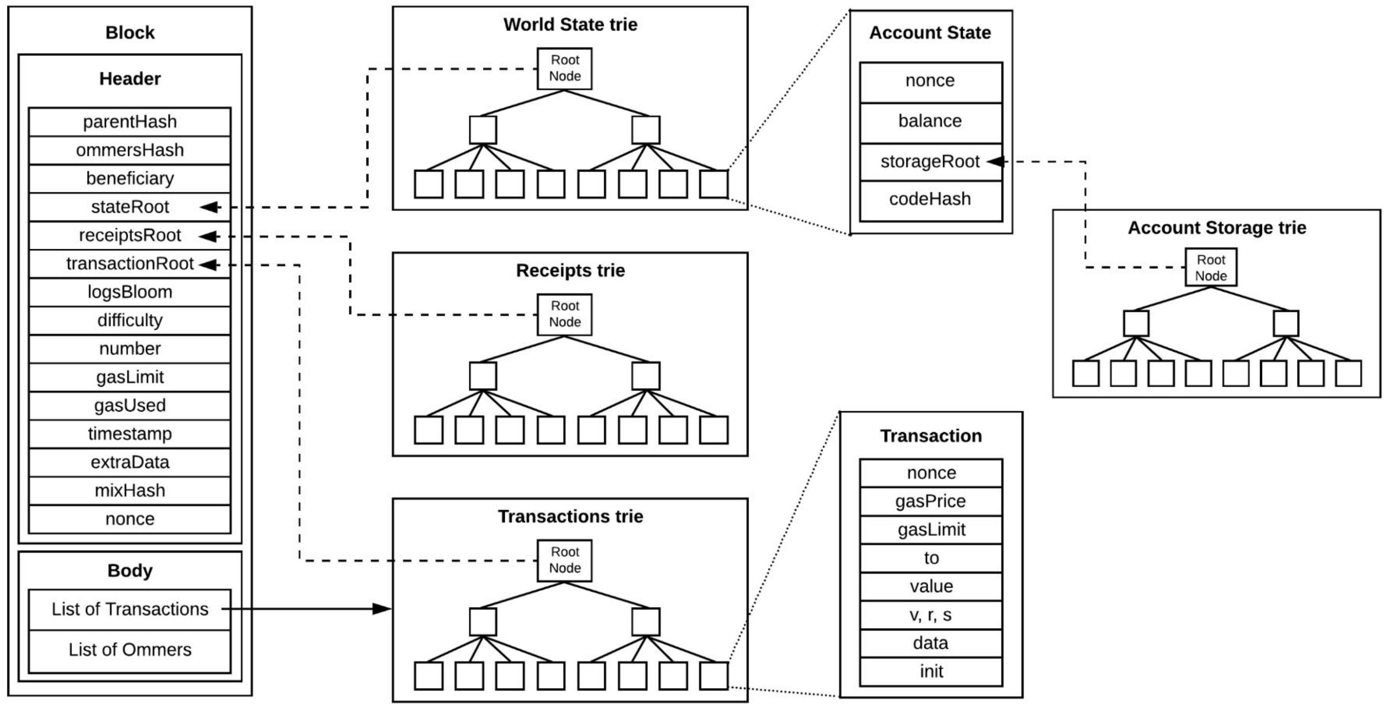
3+3+3+3+3 = 15 Wei

EVM Memory

6 types of memory

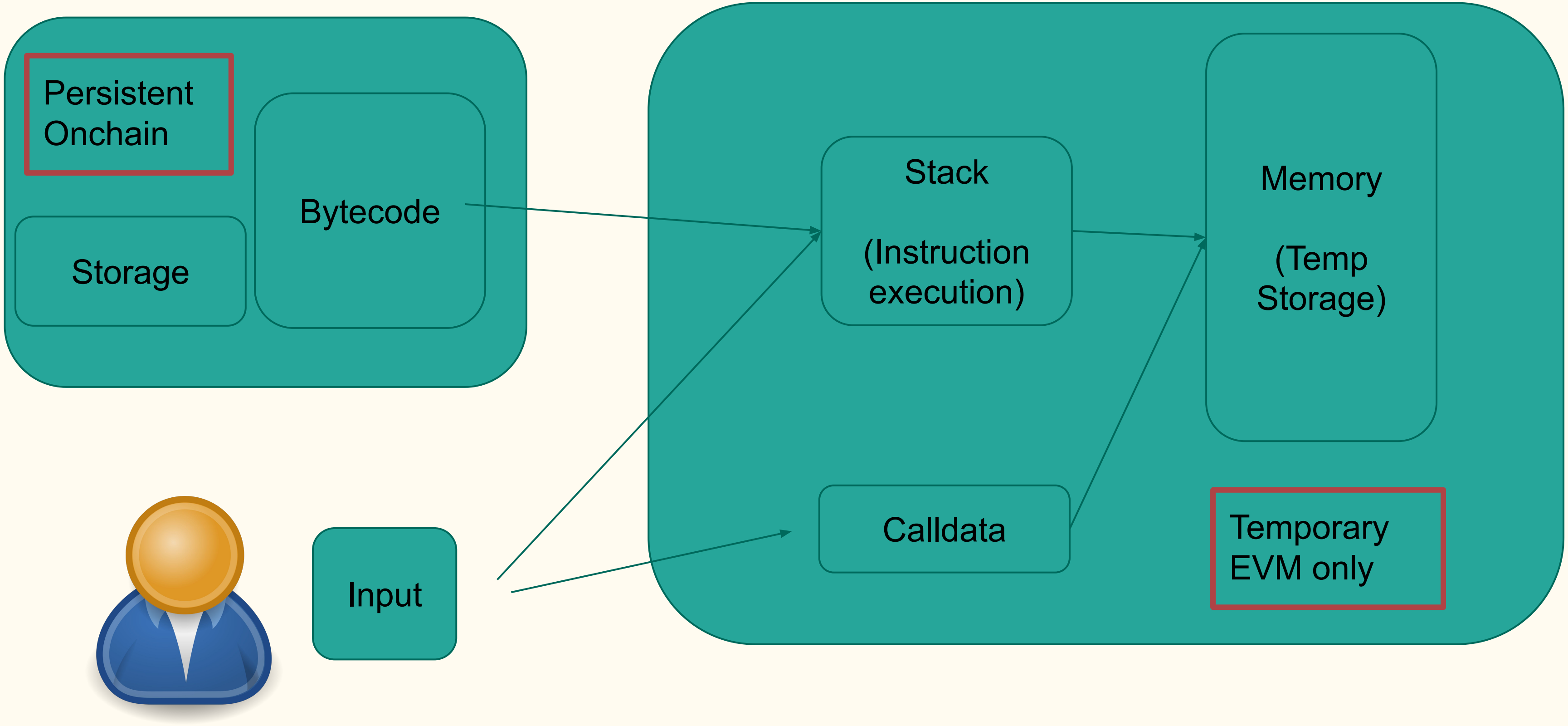
Memory Type	**Size**	**Usage**
Storage	Large	For all global variable which needs to be stored onchain. Very Expensive
Memory	Medium	For all local variables that only live for the duration of the contract execution.
Stack	Small	Immediate execution
Calldata	Tiny	Immutable user inputs
Bytecode	Small / Medium	A hash of contract bytecode
Logs	Onchain	Emitted events. onchain logs

Data Location - Storage, Code, Log (Lecture 4)



Block, transaction, account state objects and Ethereum tries

Data Location - Memory, Stack, Calldata



A Solidity contract in memory

Storage:
naughty_list
names

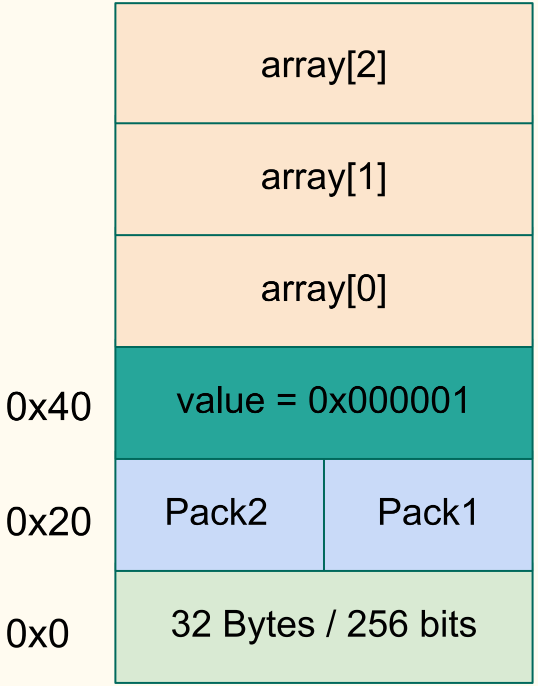
Constructor:
Hashed inside bytecode

Memory:
name - user input
i - index in for loop

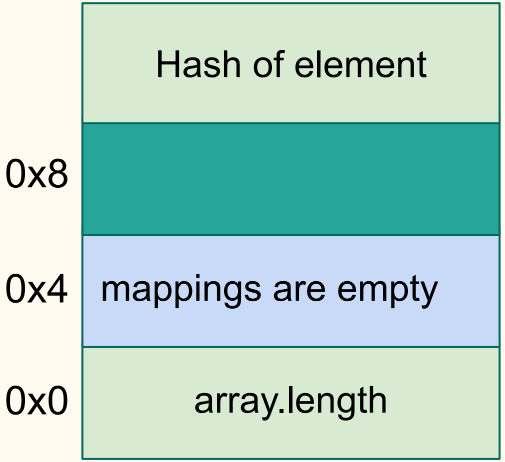
```
//SPDX-License-Identifier: MIT
pragma solidity ^0.8.17;

contract christmas{
    mapping(string => uint) private naughty_list;
    string[] private names;

    constructor (){
        names = ["Annie", "Tim", "Mark"];
        naughty_list["Annie"] = 0;
        naughty_list["Tim"] = 0;
        naughty_list["Mark"] = 0;
    }

    function increase_naughty_score(string memory name) public {
        for(uint i = 0; i < names.length; i++){
            if (keccak256(abi.encodePacked(names[i]))== keccak256(a
                naughty_list[name] += 10;
            } else {
                naughty_list[name] = 10;
            }
        }
    }
}
```

Storage Layout

Value Type



Dynamic Type

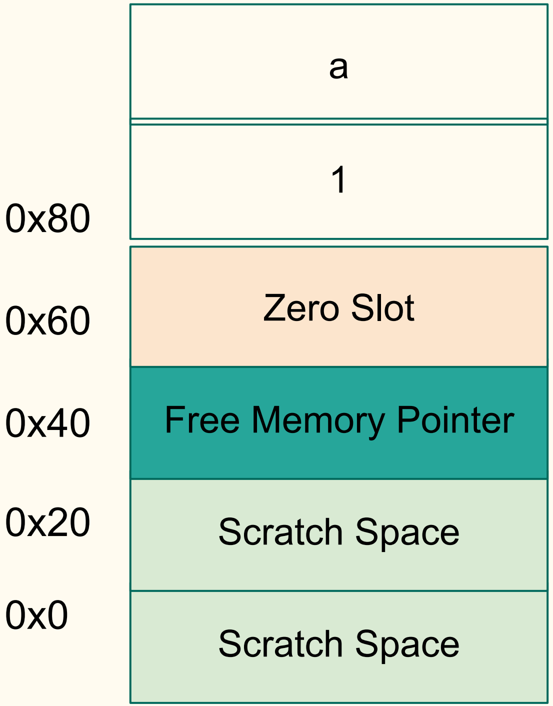


array = [235,12,0]
location = keccak256(256)

Points to remember:

- Declared arrays and structs are assigned a block together and considered a value type
- Packed blocks may incur additional gas when not updated at the same time
- Recursive hashing possible
- What about inheritance?

Memory Layout



No packing!

a = 0x61000000000001 (high order alignment)

1 = 0x00000000000001 (low order alignment)

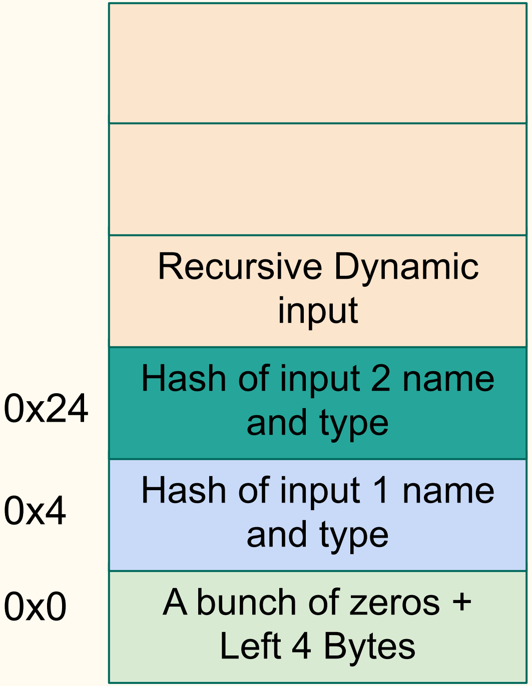
Always 0. Optimized initialization

Pointer to the next free slot address where a new variable can be added.

Use for intermediate executions in inline-assembly

Calldata Layout

keccak256(function name, address, input name, type)



Dynamic inputs(strings, arrays mappings) work the same way as storage for - They point to different locations in memory of their elements

Each input must be padded to 32 Bytes

Hash of the type, name and value of the function input

This is the function signature. Matches input to function

Costs and Testing

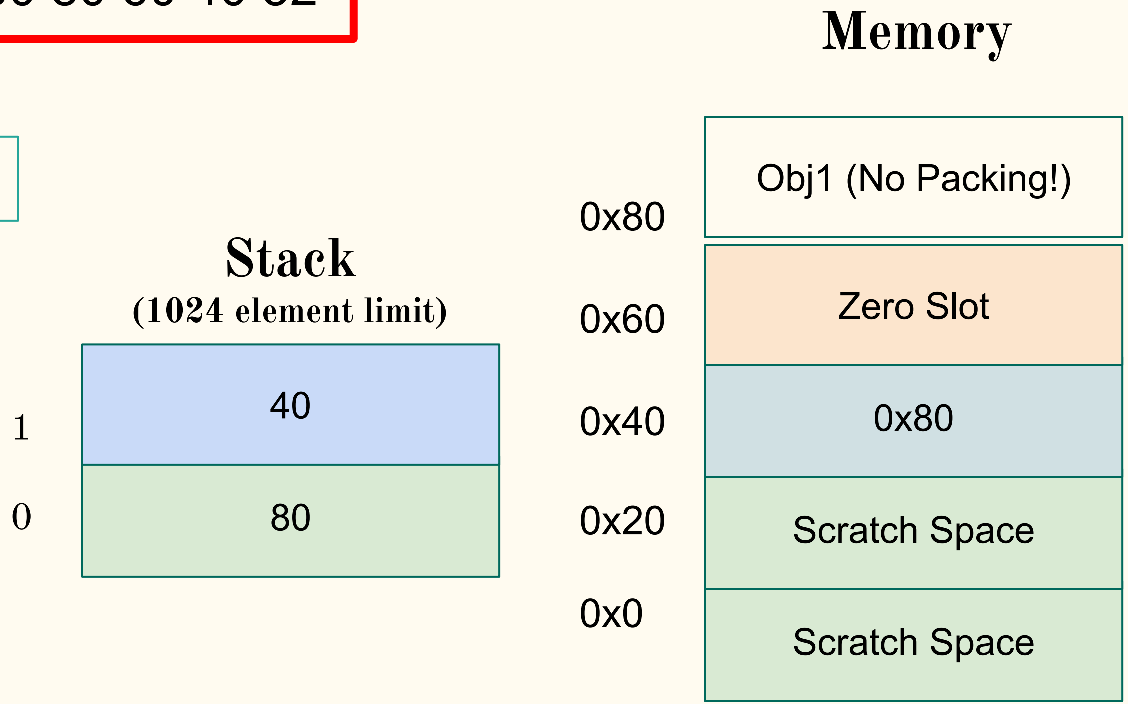
Solidity Contract Creation

60 80 60 40 52

https://github.com/crytic/evm-opcodes

PUSH1 80
PUSH1 40
MLOAD

Free Memory Pointer established!



Why does it matter? - Gas Cost Testing

https://www.npmjs.com/package/hardhat-gas-reporter

Solc version: 0.8.18		Optimizer enabled: false		Runs: 200	Block limit: 30000000 gas	
Methods						
Contract	Method	Min	Max	Avg	# calls	eur (avg)
christmas	increase_naughty_score	58389	83733	71061	2	-
Deployments					% of limit	
christmas		-	-	666290	2.2 %	-

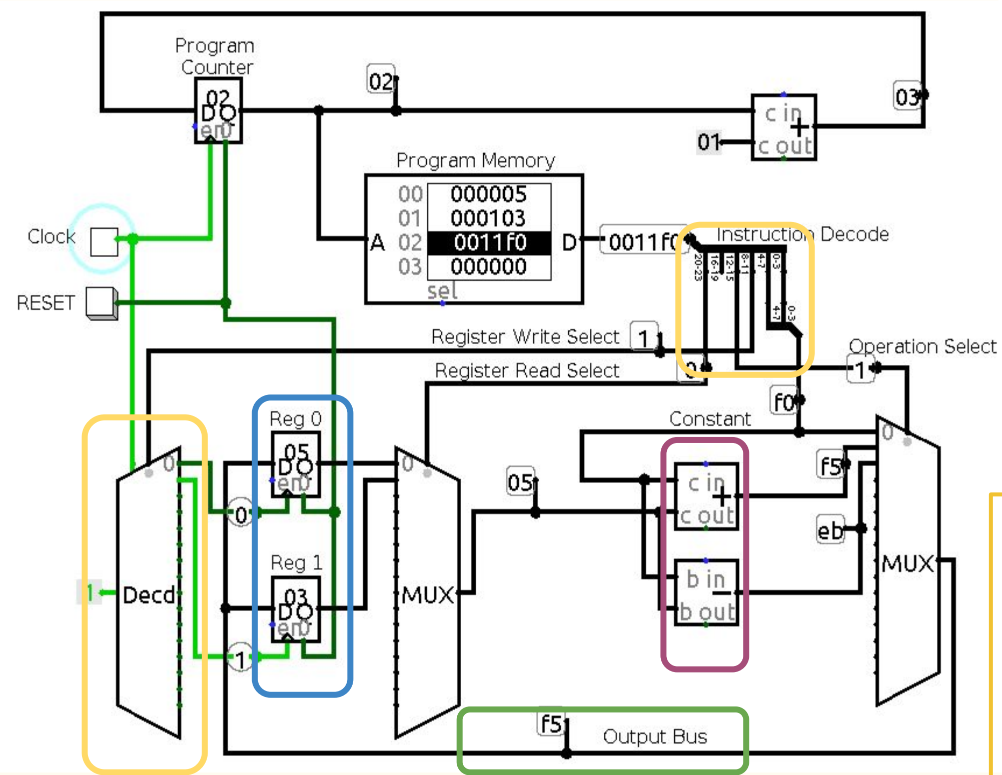
666290 gwei = 0,000724 ETH = 1,19 EUR

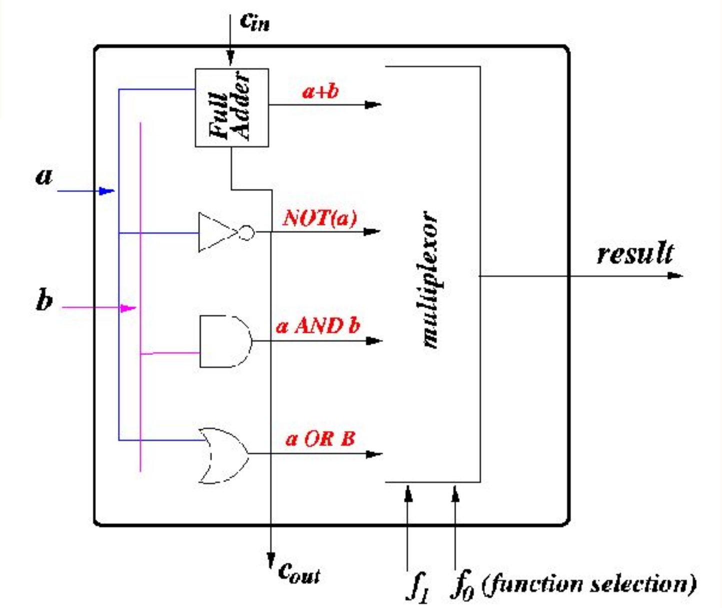
For every naughty act of every child, Santa has to pay 1,2 EUR. There are potentially millions of naughty in children in the world doing naughty things everyday! This is a very expensive list for Santa to keep. Can he get it cheaper?

The Cost of Operations

Stack	Name	Gas	Initial Stack	Resulting Stac
00	STOP	0		
01	ADD	3	`a, b`	`a + b`
02	MUL	5	`a, b`	`a * b`
03	SUB	3	`a, b`	`a - b`
04	DIV	5	`a, b`	`a // b`
05	SDIV	5	`a, b`	`a // b`
06	MOD	5	`a, b`	`a % b`
07	SMOD	5	`a, b`	`a % b`
08	ADDMOD	8	`a, b, N`	`(a + b) % N`
09	MULMOD	8	`a, b, N`	`(a * b) % N`

Binary Arithmetic Operations





Multiplication and division is realised as an addition with bit rotation. This means that a 32 bit binary integer must be rotated 32 times to arrive at the multiplicative result. This takes 32 clock cycles! Instruction stuffing by compiler

The Cost of Memory

CREATE	32000 + memory expansion + per-byte bytecode hash cost
MLOAD	3 + offset cost (how many slots from start)
MSTORE	3 + offset cost
SLOAD	Cold Access (1st time): 2100 ; Warm Access: 100
SSTORE	highly variable

Cost of SSTORE - Setup simple checks

```
gas_cost = 0
gas_refund = 0 - provided for cleaning state. Only available in sstore

If gas_left <= 2300:
        throw OUT_OF_GAS_ERROR (can not sstore with < 2300 gas for backwards compatibility)
If (context_addr, target_storage_key) not in touched_storage_slots (cold access/SLOAD):
        gas_cost += 2100
If new_val == current_val (no-op):
        gas_cost += 100
```

Cost of SSTORE - A Zero Game

```
Else new_val != current_val:
	If current_val == orig_val ("clean slot"):
		If orig_val == 0 (zero ->  zero -> nonzero):
			gas_cost += 20000
		Else orig_val != 0 ( nonzero -> nonzero ->  nonzero):
			gas_cost += 2900
			If new_val == 0 (nonzero -> nonzero -> zero):
				gas_refund += 4800
	Else current_val != orig_val ("dirty slot", already updated in current execution context):
		gas_cost += 100
		If orig_val != 0 (execution context started with a nonzero value in slot):
			If current_val == 0 ( nonzero -> zero - > nonzero):
				gas_refund -= 4800
			Else if new_val == 0 (nonzero -> different nonzero -> zero):
				gas_refund += 4800
			If new_val == orig_val (slot is reset to the value it started with):
				If orig_val == 0 (zero -> nonzero ->  zero):
					gas_refund += 19900
				Else orig_val != 0 (nonzero ->different nonzero -> orig nonzero):
					gas_refund += 2800
```

Gas Optimization techniques

Reducing transaction costs

Santa's naughty list

```solidity
//SPDX-License-Identifier: MIT
pragma solidity ^0.8.17;

contract christmas{
    mapping(string => uint) public naughty_list;
    string[] public names;

    constructor (){
        names = ["Annie", "Tim", "Mark"];
        naughty_list["Annie"] = 0;
        naughty_list["Tim"] = 0;
        naughty_list["Mark"] = 0;
    }

    function get_score(string memory name) public view returns(uint){
        return naughty_list[name];
    }

    function increase_naughty_score(string memory name) public {
        bool not_in_list = true;

        for(uint i = 0; i < names.length; i++){
            if (keccak256(abi.encodePacked(names[i]))== keccak256(abi.encodePacked(name))){
                not_in_list = false;
                naughty_list[names[i]] += 10;
            }
        }

        if (not_in_list){
            names.push(name);
            naughty_list[name] = 10;
        }
    }
}
```

According to some Christmas traditions, Santa keeps a list of naughty children. If you were very naughty, there will be no presents under the Christmas tree for you. In fact, there will be some coal if you were extra naughty.

Santa is now keeping his naughty list on the blockchain! How expensive is it for him?

Cost of transactions - Gas Calculations

```
require("@nomicfoundation/hardhat-toolbox");
require("hardhat-gas-reporter");

module.exports = {
  solidity: "0.8.18",
  gasReporter: {
    currency: "EUR",
    gasPrice: 15,
    enabled: true
  }
};
```

Gas exists to prevent denial of service attacks.

gas units = units per opcode

gas price = gwei per unit gas you are willing to pay

gas limit = max amount willing to pay

Solc version: 0.8.18		Optimizer enabled: false		Runs: 200	Block limit: 30000000 gas	
Methods		15 gwei/gas			1667.06 eur/eth	
Contract	Method	Min	Max	Avg	# calls	eur (avg)
christmas	increase_naughty_score	58433	83777	71105	2	1.78
Deployments					% of limit	
christmas		-	-	781291	2.6 %	19.54

Technique 1 - restrict scope in functions and variables

- Everytime a public global variable is defined, Solidity automatically creates a getter and setter function for that variable.
- function scope
  - Public functions have arguments copied into memory
  - External functions have args copied into calldata
  - private / internal is very cheap

Optimizer enabled: false		Runs: 200	Block limit: 30000000 gas	
15 gwei/gas			1670.23 eur/eth	
Min	Max	Avg	# calls	eur (avg)
58389	83733	71061	2	1.78
			% of limit	
-	-	666290	2.2 %	16.69

```
//SPDX-License-Identifier: MIT
pragma solidity ^0.8.17;

contract christmas{
    mapping(string => uint) private naughty_list;
    string[] private names;

    constructor (){
        names = ["Annie", "Tim", "Mark"];
        naughty_list["Annie"] = 0;
        naughty_list["Tim"] = 0;
        naughty_list["Mark"] = 0;
    }

    function get_score(string memory name) external view returns(uint){
        return naughty_list[name];
    }

    function increase_naughty_score(string memory name) external {
        bool not_in_list = true;
```

Technique 2 - Global variable packing

Always declare globals in a way that fits into 32 Bytes/256 bits

```
contract Integers{
  uint16 a;
  uint b;
  uint16c;
}
```

→

```
contract Integers{
  uint16 a;
  uint16 c;
  uint b;
}
```

We just made our contract more expensive!!!

- mappings and dynamic arrays use hashes and are not stored sequentially like structs
- we had to add an extra check function since we had the score a lot smaller. Checks are good though!

```
contract christmas{
    mapping(string => uint8) private naughty_list;
    string[] private names;

    constructor (){
        names = ["Annie", "Tim", "Mark"];
        naughty_list["Annie"] = 0;
        naughty_list["Tim"] = 0;
        naughty_list["Mark"] = 0;
    }

    function increase_naughty_score(string memory name) external {
        bool not_in_list = true;

        for(uint i = 0; i < names.length; i++){
            if (keccak256(abi.encodePacked(names[i]))== keccak256(abi.encodePacked(name))){
                not_in_list = false;
                if(naughty_list[names[i]] >= 245){
                    return;
                }
                naughty_list[names[i]] += 10;
            }
        }
```

Optimizer enabled: false		Runs: 200
15 gwei/gas		
Min	Max	Avg
59494	83787	71641
-	-	703980

Technique 3 - User calldata as much as possible

Recap: Calldata is much smaller and immutable as compared to memory. Therefore it is much cheaper. Try to not mutate user inputs when creating functions. If you do need to change the variable value inside the function, then use memory.

```
function increase_naughty_score(string calldata name) external {
```

```
function get_score(string calldata name) external view returns(uint){
```

```
|---------------------------|-------------|
·  Optimizer enabled: false  ·  Runs: 200  ·
|···························|·············|
·              15 gwei/gas                 ·
|·············|·············|·············|
·  Min        ·  Max        ·  Avg        ·
|·············|·············|·············|
·       58622 ·       82802 ·       70712 ·
|·············|·············|·············|
·                                          ·
|·············|·············|·············|
·           - ·           - ·      659530 ·
|-------------|-------------|-------------|
```

Technique 4 - Work in memory, avoid loops and repetition

SLOAD is much more expensive than MLOAD. if you need to work on your global variables, copy it into memory. Reduce the number of read and writes to storage.

Avoid dynamic arrays if possible. Rather have a large continuous block of memory than pointers. Alternatively, change arrays to mappings or combine them. Note, strings are just a dynamic Byte array.

Avoid repeating functions in loops! Your loops should have as much pre-computed variables as possible.

Optimizer enabled: false		Runs: 200
15 gwei/gas		
Min	Max	Avg
56416	82055	69236
-	-	617322

```
function increase_naughty_score(string calldata name) public {
    bool not_in_list = true;
    bytes32 inputHash = keccak256(abi.encodePacked(name));

    for(uint i = 0; i < names.length; i++){
        if (keccak256(abi.encodePacked(names[i]))== inputHash){
            not_in_list = false;
            naughty_list[name] += 10;
        }
    }
```

Technique 5 - Respect Solidity's way of thinking

Solidity represents a huge mind shift from traditional programming. It is hard to manipulate strings and mappings because Solidity is meant to support transactions. Try to think like a bank and anonymous accounts are submitting transactions to you.

```
//SPDX-License-Identifier: MIT
pragma solidity ^0.8.17;

contract christmas{
    mapping(address => uint) private naughty_list;

    function get_score(address user) external view returns(uint){
        return naughty_list[user];
    }

    function increase_naughty_score(address user) public {
        naughty_list[user] += 10;
    }
}
```

Solc version: 0.8.18		Optimizer enabled: false		Runs: 200	Block limit: 30000000 gas	
Methods		15 gwei/gas			1656.13 eur/eth	
Contract	Method	Min	Max	Avg	# calls	eur (avg)
christmas	increase_naughty_score	27192	44292	38592	3	0.96
Deployments					% of limit	
christmas		-	-	192181	0.6 %	4.77

Technique 6 - Enable the compiler optimizer

The solidity optimizer will do a number of operations to automatically make your code more efficient

- Code sanitization through dependency graph
  - unused, duplicate variables
- Opcode Based optimization
  - CommonSubexpressionEliminator
  - In Ammsebly memory management

```
module.exports = {
  solidity: {
    version: "0.8.18",
    settings: {
      optimizer: {
        enabled: true,
        runs: 10000
      }
    }
  },
  gasReporter: {
    currency: "EUR",
    gasPrice: 15,
    enabled: true
  },
};
```

Optimizer enabled: true		Runs: 200
15 gwei/gas		
Min	Max	Avg
26894	43994	38294
-	-	124273

Optimizer enabled: true		Runs: 10000
15 gwei/gas		
Min	Max	Avg
26870	43970	38270
-	-	137809

The number of runs indicate the number of times your contract will be called.
The optimiser will try to reduce function call cost at the expense of deployment cost.
We have a very scalable contract here!

Blockchain Data Indexing

Event - Declaration and Actualization

```
contract Transaction {
    event makeATransfer(address indexed _from, address indexed _to, uint amount);

    function payRent(address receiver, uint deposit) external {
        require(msg.sender.balance >= msg.value);
        emit makeATransfer(msg.sender, receiver, amount);
    }
}
```

Events - ABI representation

```
{
    "returnValues": {
        "_from": "0x1111…FFFFCCCC",
        "_to": "0x50…sd5adb20",
         "amount": "0x420042"
     },
    "raw": {
        "data": "0x7f…91385",
        "topics": ["0xfd4…b4ead7", "0x7f…1a91385","0xf28…d21297" ]
     }
}
```

A0	LOG0	offset	length				
A1	LOG1	offset	length	topic0			
A2	LOG2	offset	length	topic0	topic1		
A3	LOG3	offset	length	topic0	topic1	topic2	
A4	LOG4	offset	length	topic0	topic1	topic2	topic3

More events, less Solidity

In Solidity we often have functions which track the state of things. Example, get proposal state in a DAO. However, a lot of the information is logged onchain already and should not require a transaction of SLOAD to read the state. Instead, check the logged event!

```
// Call the play function
contract.methods.play(userGuess).call().then(function(bool) {
  if (bool) {
    alert("Correct guess!");
  } else {
    alert("Wrong guess!");
  }
});
```

Web3 allows reading of the logs
web3.eth.filter

This example here, we can have the function return nothing and just emit a game status event. The dApp can then read the logs to determine win / loss.

Blockchain Data Indexing

Similar to the field of Data Science, there is huge potential in unlocking and making sense of Blockchain data. By pulling every transaction, receipt and event log, we can build a huge amount of insight:

- The full transaction history of a wallet
- Every trade on a DEX to determine price
- A handwritten note from Santa to a naughty child of all of his transgressions

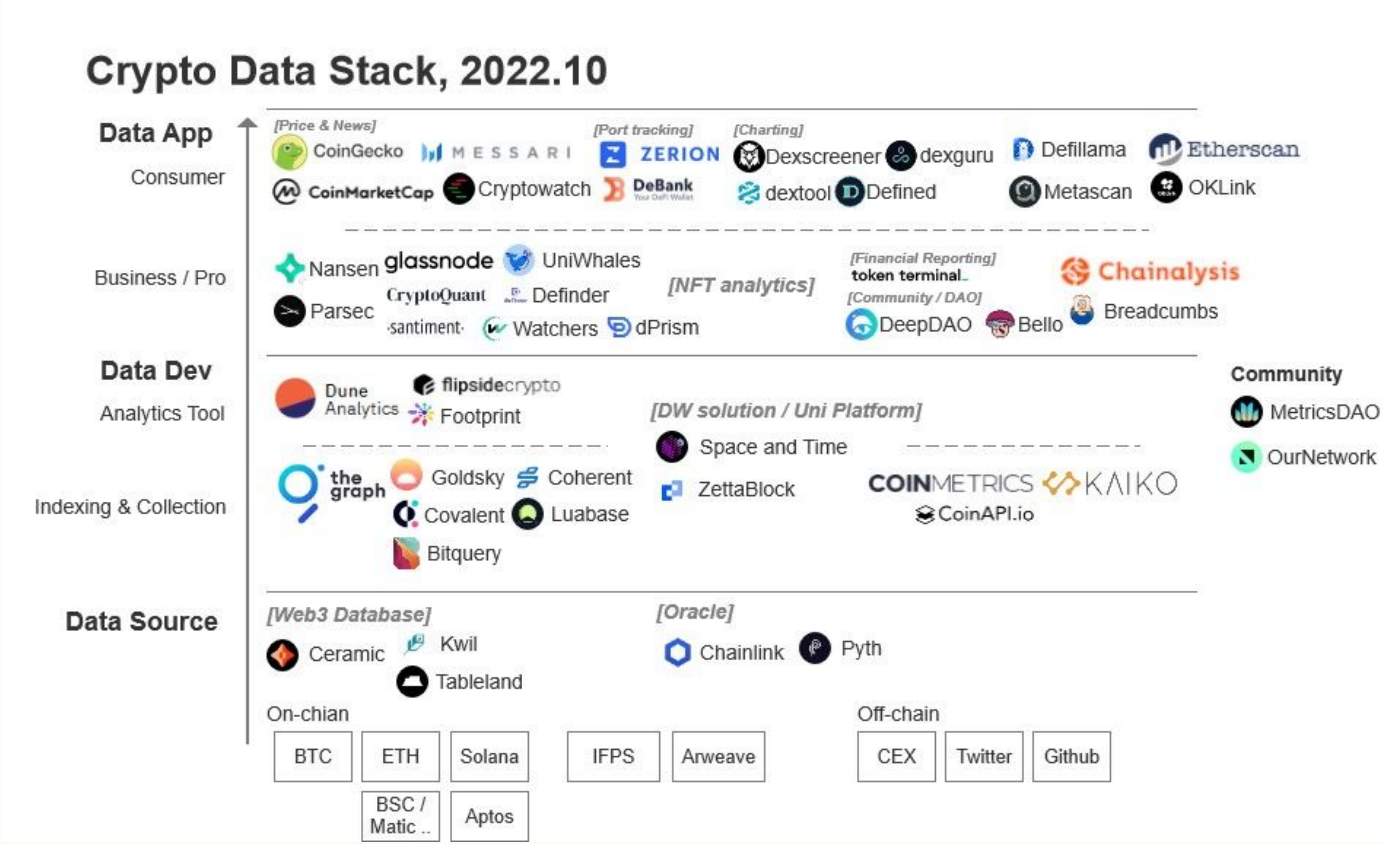
Data Indexers follow the ETL process:

Extract - Get data from onchain (block/s)

Transform - clean, sanitized, extract insights

Load - Serve data in the appropriate query format

Data Landscape



Inline Assembly

Programming in Opcodes

Yul - Operations

Instruction	Explanation
let	This is required before defining a variable. Since all values are bytes, there is no need to assign a value type.
:=	Solidity equivalent: x = y
add(x,y)	Solidity equivalent: x + y
sub(x,y)	Solidity equivalent: x - y
mul(x,y)	Solidity equivalent: x * y
div(x,y)	Solidity equivalent: x / y (or 0 if y equals 0)
mod(x,y)	Solidity equivalent: x % y (or 0 if y equals 0)
lt(x,y)	Solidity equivalent: x < y
gt(x,y)	Solidity equivalent: x > y
eq(x,y)	Solidity equivalent: x == y
iszero(x)	Solidity equivalent: x == 0

Yul - Loops

For Loop

```
{
    let x := 0
    for { let i := 0 } lt(i, 0x100) { i := add(i, 0x20) } {
        x := add(x, mload(i))
    }
}
```

This compute the sum of values in a continuous block in memory. What does it mean practically?

While Loop

```
{
    let x := 0
    let i := 0
    for { } lt(i, 0x100) { } {      // while(i < 0x100)
        x := add(x, mload(i))
        i := add(i, 0x20)
    }
}
```

There are no while loops. They are for loops with less inputs.

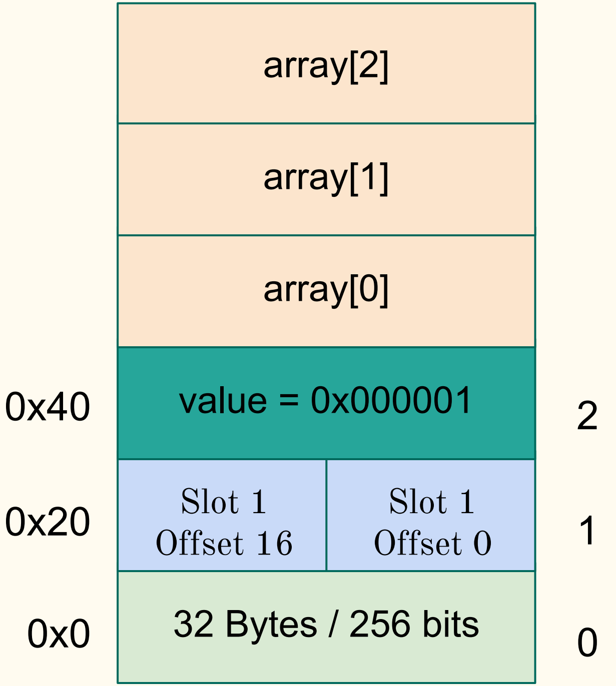
What does this function do?

Yul - Storage

Think of storage manipulation in terms of **slots** rather than addresses. The first declared global variable goes into slot 0 and the next declared follows on.

Recap on storage mechanics:
Fixed arrays - continuous after pointer
Dynamic arrays - pointer location filled with length. Data storage is continuous at keccak256(pointer, length)
Mappings - pointer location empty. Data stored at keccak256(pointer, key)

Instruction	Explanation
sload(p)	Loads the variable in slot p from storage.
sstore(p,v)	Assigns storage slot p value v.
v.slot	Returns the storage slot of variable v.
v.offset	Returns the index in bytes of where variable v begins in a storage slot.



Yul - Packed Storage

offset: 16	offset: 0
0000 0000 0000 0010	0000 0000 0000 0001

Get left block (2) => shr(offset, slot) => 0000 0000 0000 0000 0000 0000 0000 00010

Get right block (1) => use a mask => 0000 0000 0000 0000 1111 1111 1111 1111
and(mask, sload(slot, offset)) => 0000 0000 0000 0010 0000 0000 0000 0001

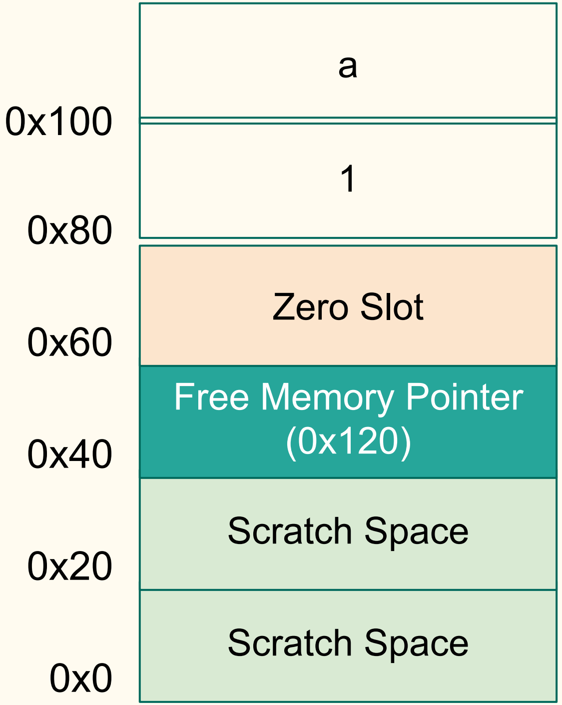
Instruction	Explanation
and(x, y)	bitwise "and" of x and y
or(x, y)	bitwise "or" of x and y
xor(x, y)	bitwise "xor" of x and y
shl(x, y)	a logical shift left of y by x bits
shr(x, y)	a logical shift right of y by x bits

Loading into packed storage gets a bit more complicated. You need to use different types of masks combined to insert the value correctly.

Masks can also be OR (rare) or XOR (used in binary addition cases)

Yul - Memory

Instruction	Explanation
mload(p)	Similar to `sload()`, but we are saying load the next 32 bytes after p
mstore(p, v)	Similar to `sstore()`, but we are saying store value v in p plus 32 bytes
mstore8(p, v)	Similar to `mstore()`, but only for a single byte
msize()	Returns the largest accessed memory index
pop(x)	Discard value x
return(p, s)	End execution, and return data from memory locations p - v
revert(p, s)	End execution without saving state changes, and return data from memory



Yul - Memory

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