Lesson4

Today's Topics

- Upgradability
- IDEs - general techniques / tools
- Foundry

Upgradability Background

The great advantage to smart contract is that they're immutable, no one can hack them or change their terms once they are deployed

The great drawback to smart contracts is that they're immutable, you can't fix them once they're deployed.

The problems we need to solve are

1. How to change the functionality in the contract
2. How to migrate data if necessary

We will look at some of the patterns used to allow upgradability
I have taken examples from this guide, the guide

applies to truffle or hardhat.

See State of upgrades

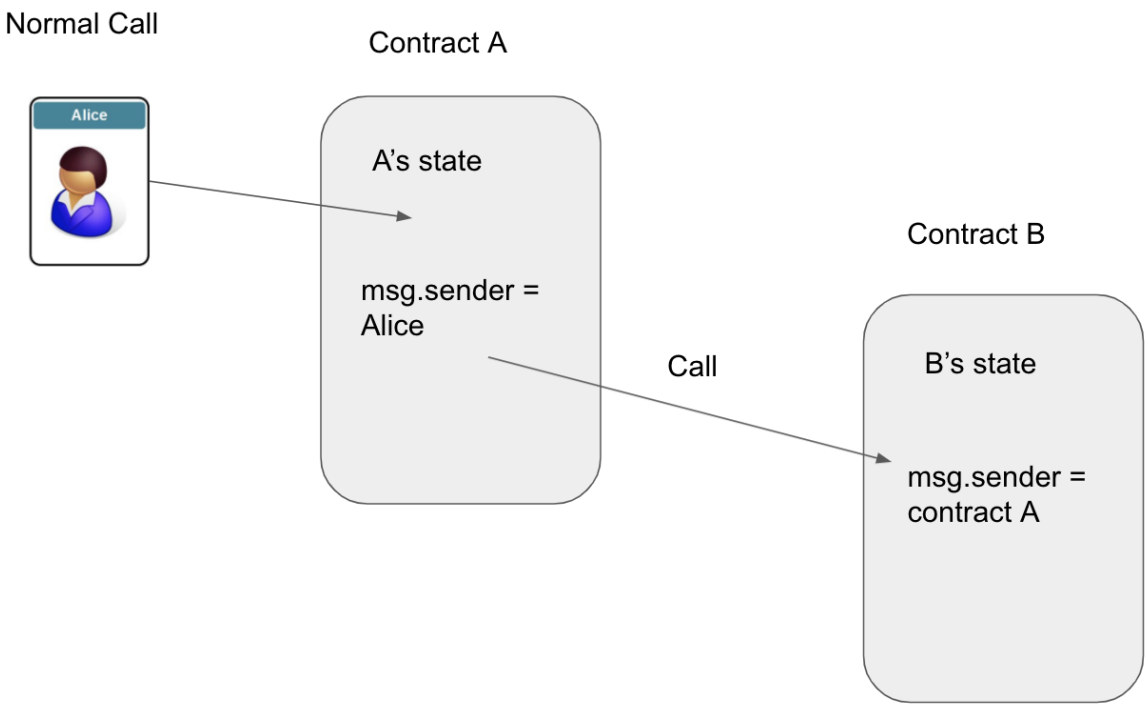
Digression - Message Calls

There are a number of ways for contracts to call each other

See : [Read the Docs : Message Calls]

Message calls have a source (this contract), a target (the other contract), data payload, Ether, gas and return data.

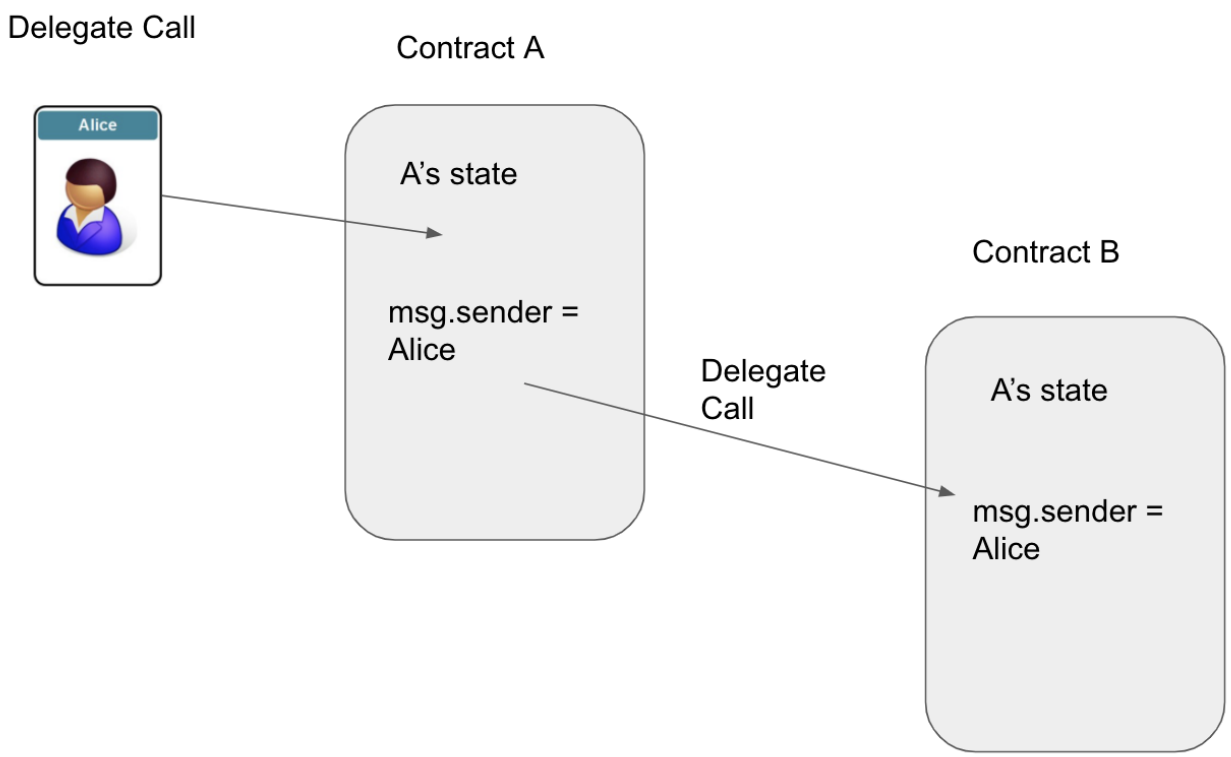
The other contract gets a fresh context to work in, its own contract state as you would expect.



Delegate Call

There is a special type of call, **Delegate Call** which behaves differently in that it executes in the context

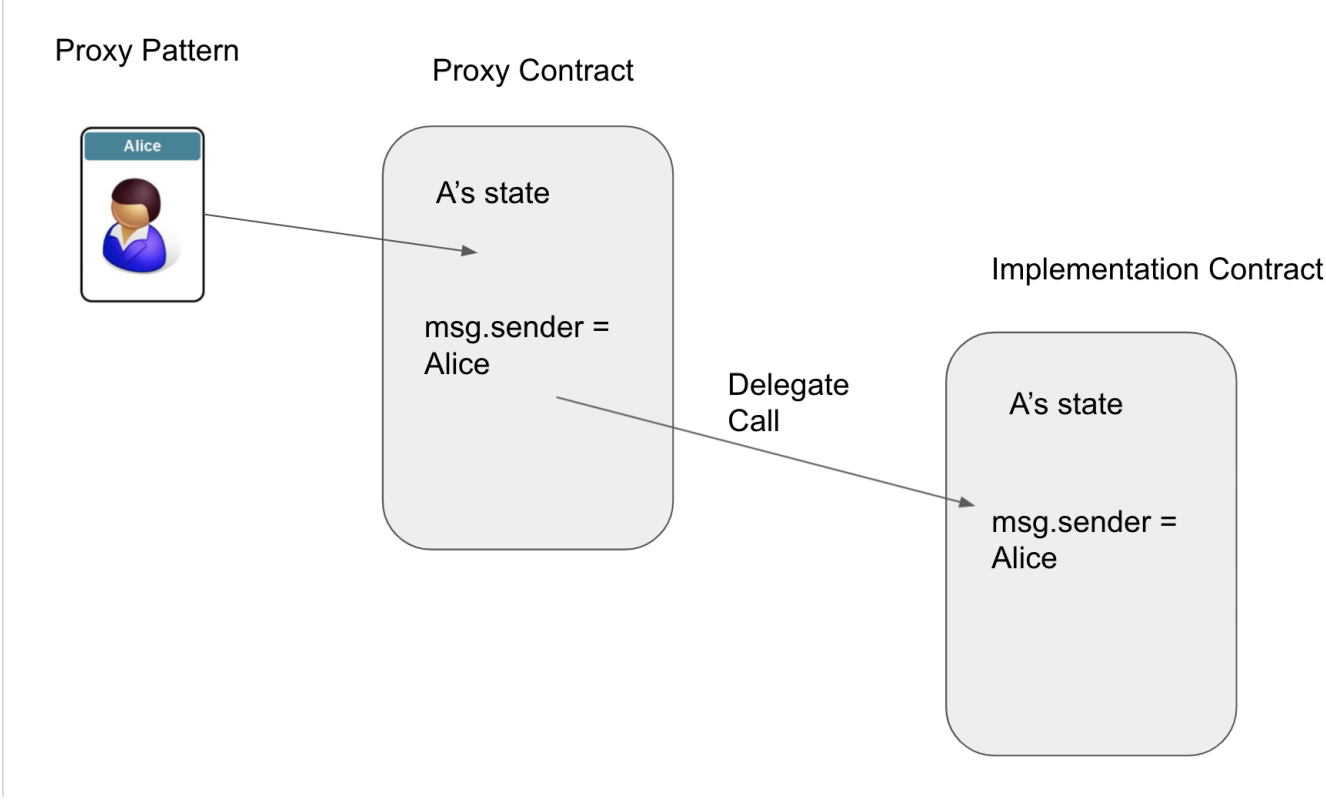
of the calling contract (and msg.sender and msg.value do not change)



Another way to look at this is to think of contract A loading and executing contract B's code.

Proxy patterns

See EIP 897



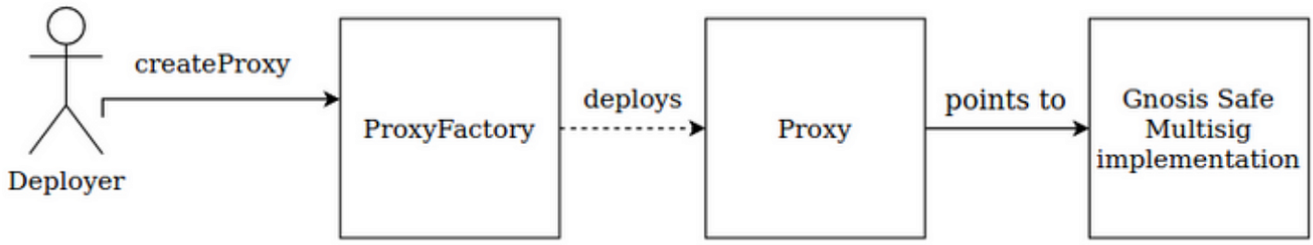
We have a proxy contract and an implementation contract

Users always interact with the Proxy contract and need not be aware of the implementation contract.

It is also possible for multiple proxy contracts to use the same implementation contract (This can be a way of deploying multiple instances of a contract cheaply, see EIP1167).

Open Zeppelin Clones Library

We are cheaply creating a proxy for another contract



Deploying a Gnosis Safe Multisig wallet with the ProxyFactory contract

This function uses the create2 opcode and a `salt` to deterministically deploy the clone. Using the same `implementation` and `salt` multiple time will revert, since the clones cannot be deployed twice at the same address.

Approaches to Upgradability

Upgrading is an anti pattern - don't do it

There **is** an argument for this approach, it favours decentralisation
See Upgradability is a bug

- Smart contracts are useful because they're trustless.
- Immutability is a critical feature to achieve trustlessness.
- Upgradeability undermines a contract's immutability.
- Therefore, upgradeability is a bug.

From the article :
"We strongly advise against the use of these patterns for upgradable smart contracts. Both strategies have the potential for flaws, significantly increase complexity, and introduce bugs, and ultimately decrease trust in your smart contract.

Strive for simple, immutable, and secure contracts rather than importing a significant amount of code to postpone feature and security issues."

It may be sufficient to parameterise your contract and adjust those parameters instead of upgrading For example Maker DAO's stability fee, or a farming reward rate that can be adjusted by the an administrator (or a DAO, or some governance mechanism)

Migrate the data manually

Deploy your V2 contract, and migrate manually any existing data

Advantages

Conceptually simple.
No reliance on libraries.

Disadvantages

Can be difficult and costly (gas and time) in practice, and if the amount of data to migrate is large, it may hit gas limits when migrating.

Use a Registry contract

A registry (similar to ENS) holds the address of the latest version of the contract.
DApps should read this registry to get the correct address

Advantages

Simple to implement

Disadvantages

We rely on the DApp code to choose the correct contract
There is trust involved in the developers, not to switch out a contract with reasonable terms for an unfavourable one.
"Keep in mind that users of your smart contract don’t trust you, and that’s why you wrote a smart contract in the first place."

This doesn't solve the data migration problem

Separate code into function and data contracts

Advantages

Maybe simple to implement
Partially solves data migration

Disadvantages

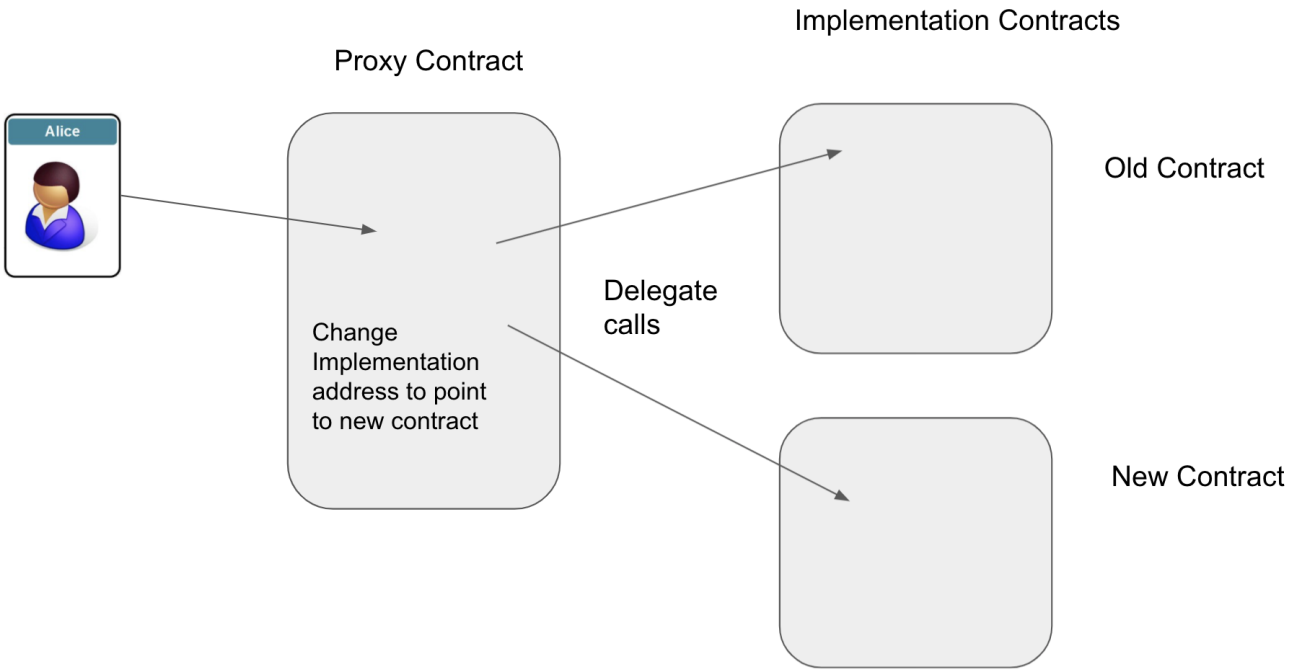
It is difficult to get the security implemented correctly
Fails if your data contract needs to change.

Choose an function at runtime in other contracts or libraries

This is moving towards the Proxy patterns and the Diamond pattern
Essentially the Strategy Pattern
Compound use this approach with their interest rate model
A variant of this is the use of pluggable modules such as in Gnosis Safe
The module approach is additive, if there is a bug in the core code this approach won't fix it.

Using Proxy contracts to upgrade

Upgrade Process




```
contract AdminUpgradeableProxy {
    address implementation;
    address admin;

    fallback() external payable {
        // delegate here
    }

    function upgrade(address
newImplementation) external {
        require(msg.sender == admin);
        implementation =
```

```
newImplementation;
    }
}
```

This can be open to vulnerabilities, instead the **Transparent Proxy Contract** can be used

```
contract TransparentAdminUpgradeableProxy
{
    address implementation;
    address admin;

    fallback() external payable {
        require(msg.sender != admin);
        // delegate here
    }

    function upgrade(address
newImplementation) external {
        if (msg.sender != admin)
fallback();
        implementation =
newImplementation;
    }
}
```

This pattern is widely used, but comes at a cost because of the additional lookup of the implementation address and admin address

A cheaper and more recent alternative is the **universal upgradeable proxy standard** (UUPS)

In this pattern, the upgrade logic is placed in the implementation contract.

```
contract UUPSProxy {
    address implementation;

    fallback() external payable {
       // delegate here
    }
}

abstract contract UUPSProxiable {
    address implementation;
    address admin;

    function upgrade(address
newImplementation) external {
        require(msg.sender == admin);
        implementation =
newImplementation;
    }
}
```

Cost Comparison

	Transparent	UUPS
Proxy Deployment	740k + 480k ProxyAdmin	390k
Implementation Deployment	+ 0	+ 320k
Runtime Overhead	7.3k	4.9k

Overwriting data

But what about the data is there a possibility of overwriting data in our proxy contract unintentionally ?

Layout of variables in storage

From Solidity Documentation

State variables of contracts are stored in storage in a compact way such that multiple values sometimes use the same storage slot. Except for dynamically-sized arrays and mappings, data is stored contiguously item after item starting with the first state variable, which is stored in slot 0. For each variable, a size in bytes is determined according to its type.

Mappings and dynamic arrays

Due to their unpredictable size, mappings and dynamically-sized array types cannot be stored “in between” the state variables preceding and following them. Instead, they are considered to occupy only 32 bytes with regards to the rules above and the elements they contain are stored starting at a different storage slot that is computed using a Keccak-256 hash.

FiatTokenV2_1 <<Contract>> 0xa2327a938febf5fec13bacfb16ae10ecbc4cbdcf			
slot	type: <inherited contract>.variable (bytes)		
0	unallocated (12)	address: Ownable._owner (20)	
1	unallocated (11)	bool: Pausable.paused (1)	address: Pausable.pauser (20)
2	unallocated (12)	address: Blacklistable.blacklister (20)	
3	mapping(address=>bool): Blacklistable.blacklisted (32)		
4	string: FiatTokenV1.name (32)		
5	string: FiatTokenV1.symbol (32)		
6	unallocated (31)	uint8: FiatTokenV1.decimals (1)	
7	string: FiatTokenV1.currency (32)		
8	unallocated (11)	bool: FiatTokenV1.initialized (1)	address: FiatTokenV1.masterMinter (20)
9	mapping(address=>uint256): FiatTokenV1.balances (32)		
10	mapping(address=>mapping(address=>uint256)): FiatTokenV1.allowed (32)		
11	uint256: FiatTokenV1.totalSupply_ (32)		
12	mapping(address=>bool): FiatTokenV1.minters (32)		
13	mapping(address=>uint256): FiatTokenV1.minterAllowed (32)		
14	unallocated (12)	address: Rescuable._rescuer (20)	
15	bytes32: EIP712Domain.DOMAIN_SEPARATOR (32)		
16	mapping(address=>mapping(bytes32=>bool)): EIP3009._authorizationStates (32)		
17	mapping(address=>uint256): EIP2612._permitNonces (32)		
18	unallocated (31)	uint8: FiatTokenV2._initializedVersion (1)	

If we have our proxy and implementation like this

```
contract UUPSProxy {
    address implementation;

    fallback() external payable {
       // delegate here
    }
}

abstract contract UUPSProxiable {
    uint256 counter;
    address implementation;
    address admin;

function foo() public {
    counter ++;
}

    function upgrade(address
newImplementation) external {
        require(msg.sender == admin);
        implementation =
newImplementation;
    }
}
```

If our implementation contract writes to the slot that it sees as counter, then it will overwrite the implementation variable.

To prevent this we use **Unstructured storage**
Open Zeppelin puts the implementation address at a 'random' address in storage

```
bytes32 private constant
implementationPosition = bytes32(uint256(

keccak256('eip1967.proxy.implementation'))
- 1
));
```

This solves the problem for the implementation variable, but what about our other values in storage ?

Say our versions of the implementation contracts looks like this

Implementation_v0	**Implementation_v1**
address owner	address lastContributor
mapping balances	address owner
uint256 supply	mapping balances
...	uint256 supply

Implementation_v0	Implementation_v1
	...

Then we will have a storage collision when writing to lastContributor

The correct approach is only to **append** to the storage when we upgrade

Implementation_v0	**Implementation_v1**
address owner	address owner
mapping balances	mapping balances
uint256 supply	uint256 supply
...	address lastContributor
	...

Question - What about the constructor in the implementation contract ?

For upgradeable contracts we use an initialiser function rather than the constructor.

Eternal Storage

An alternative to the above is to split up our data types and store them in mappings

```
// Sample code, do not use in production!
contract EternalStorage {
    mapping(bytes32 => uint256) internal
uintStorage;
    mapping(bytes32 => string) internal
stringStorage;
    mapping(bytes32 => address) internal
addressStorage;
    mapping(bytes32 => bytes) internal
bytesStorage;
    mapping(bytes32 => bool) internal
boolStorage;
    mapping(bytes32 => int256) internal
intStorage;
}

contract Box is EternalStorage {
    function setValue(uint256 newValue)
public {
        uintStorage[‘value’] = newValue;
    }
```

```
}
```

I include this for completeness but do not recommend it.

Using the UUPS plugin

What the plugins do

Both plugins provide two main functions, deployProxy and upgradeProxy, which take care of managing upgradeable deployments of your contracts. In the case of deployProxy, this means:

- Validate that the implementation is upgrade safe.
- Deploy a proxy admin for your project.
- Deploy the implementation contract.
- Create and initialize the proxy contract.

And when you call upgradeProxy:

- Validate that the new implementation is upgrade safe and is compatible with the previous one.
- Check if there is an implementation contract deployed with the same bytecode, and deploy one if not.
- Upgrade the proxy to use the new implementation contract.

Writing your contract

1. You need to include an initialising function and ensure it is called only once.
   Open Zeppelin provide a base contract to do this for you, you just need to inherit from it.

```
// contracts/MyContract.sol
// SPDX-License-Identifier: MIT
pragma solidity ^0.6.0;

import "@openzeppelin/contracts-
upgradeable/
proxy/utils/Initializable.sol";

contract MyContract is
Initializable,UUPSUpgradeable {
    uint256 public x;

    function initialize(uint256 _x) public
initializer {
        x = _x;
    }
}
```

Since this is not a constructor, the constructors of parent contracts will not be called, you will need to

do this manually.

This also applies to initial values applied to variables (but constant is ok)
e.g.

```
contract MyContract {
    uint256 public hasInitialValue = 42;
    // equivalent to setting in the
constructor
}
```

2. If you are using standard Open Zeppelin libraries, you need to switch to their upgradeable versions. It is recommended that your new version of the implementation contract inherits from your previous version
3. Use the plugins to deploy and upgrade your contracts for you
   Instead of the usual migration scripts in hardhat / truffle you will need something like this

---

Hardhat

```
// In Hardhat config
require('@openzeppelin/hardhat-upgrades');



// scripts/create-box.js
const { ethers, upgrades } =
require("hardhat");

async function main() {
  const Box = await
ethers.getContractFactory("Box");
  const box = await
upgrades.deployProxy(Box, [42]);
  await box.deployed();
  console.log("Box deployed to:",
box.address);
}

main();
```

Truffle

```
const { deployProxy } =
require('@openzeppelin/truffle-upgrades');
```

```
const Box = artifacts.require('Box');

module.exports = async function (deployer)
{
  const instance = await deployProxy(Box,
[42],{ kind: 'uups' });
  console.log('Deployed',
instance.address);
};
```

The deployProxy function has a number of options :

```
async function deployProxy(
  Contract: ContractClass,
  args: unknown[] = [],
  opts: {
    deployer: Deployer,
    initializer: string | false,
    unsafeAllow: ValidationError[],
    kind: 'uups' | 'transparent',
  } = {},
): Promise<ContractInstance>
```

Performing the upgrade

See documentation

```
const { upgradeProxy } =
require('@openzeppelin/truffle-upgrades');

const Box = artifacts.require('Box');
const BoxV2 = artifacts.require('BoxV2');

module.exports = async function (deployer)
{
  const existing = await Box.deployed();
  const instance = await
upgradeProxy(existing.address, BoxV2, {
kind: 'uups' });
  console.log("Upgraded",
instance.address);
};
```

Testing the upgrade process

You can add the upgrade process to a unit test

```
const { deployProxy, upgradeProxy } =
require('@openzeppelin/truffle-upgrades');
```

```
const Box = artifacts.require('Box');
const BoxV2 = artifacts.require('BoxV2');

describe('upgrades', () => {
  it('works', async () => {
    const box = await deployProxy(Box,
[42] { kind: 'uups' });
    const box2 = await
upgradeProxy(box.address, BoxV2);

    const value = await box2.value();
    assert.equal(value.toString(), '42');
  });
});
```

Other functions

prepareUpgrade

Use this to allow the plugin to check that your contracts are upgrade safe and deploy a new implementation contract `

admin.changeAdminForProxy

Use this to change the administrator of the proxy contract.

Security Considerations

1. Always initialise your contract
2. Do not allow self destruct or delegatecall in your implementation contracts.

The closest I have found for Foundry is this project

Diamond pattern

Based on EIP 2535

From Aavegotchi (https://docs.aavegotchi.com/overview/diamond-standard)

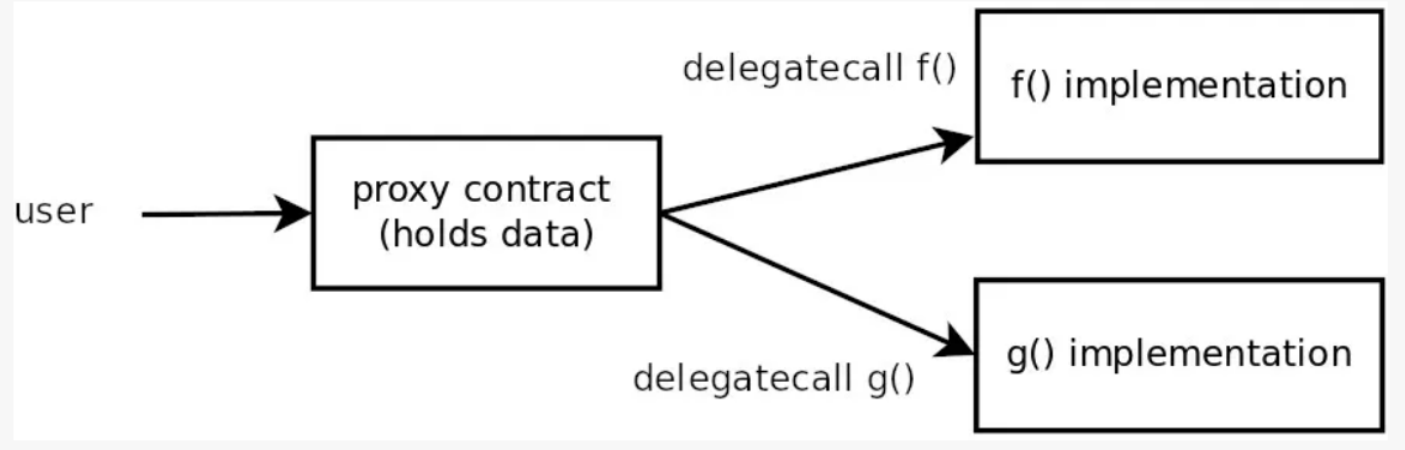
The diamond pattern is a contract that uses a fallback function to delegate function calls to multiple other contracts called facets. Conceptually a diamond can be thought of as a contract that gets its external functions from other contracts. A diamond has four standard functions (called the loupe) that report what functions and facets a diamond has. A diamond has a `DiamondCut` event that reports all functions/facets that are added/replaced/removed on a diamond, making upgrades on diamonds transparent.

The diamond pattern is a code implementation and organization strategy. The diamond pattern makes it possible to implement a lot of contract functionality that is compartmented into separate areas of functionality, but still using the same Ethereum address. The code is further simplified and saves gas because state variables are shared between facets.

Diamonds are not limited by the maximum contract size which is 24KB.

Facets can be deployed once and reused by any number of diamonds.

From Trail of Bits Audit

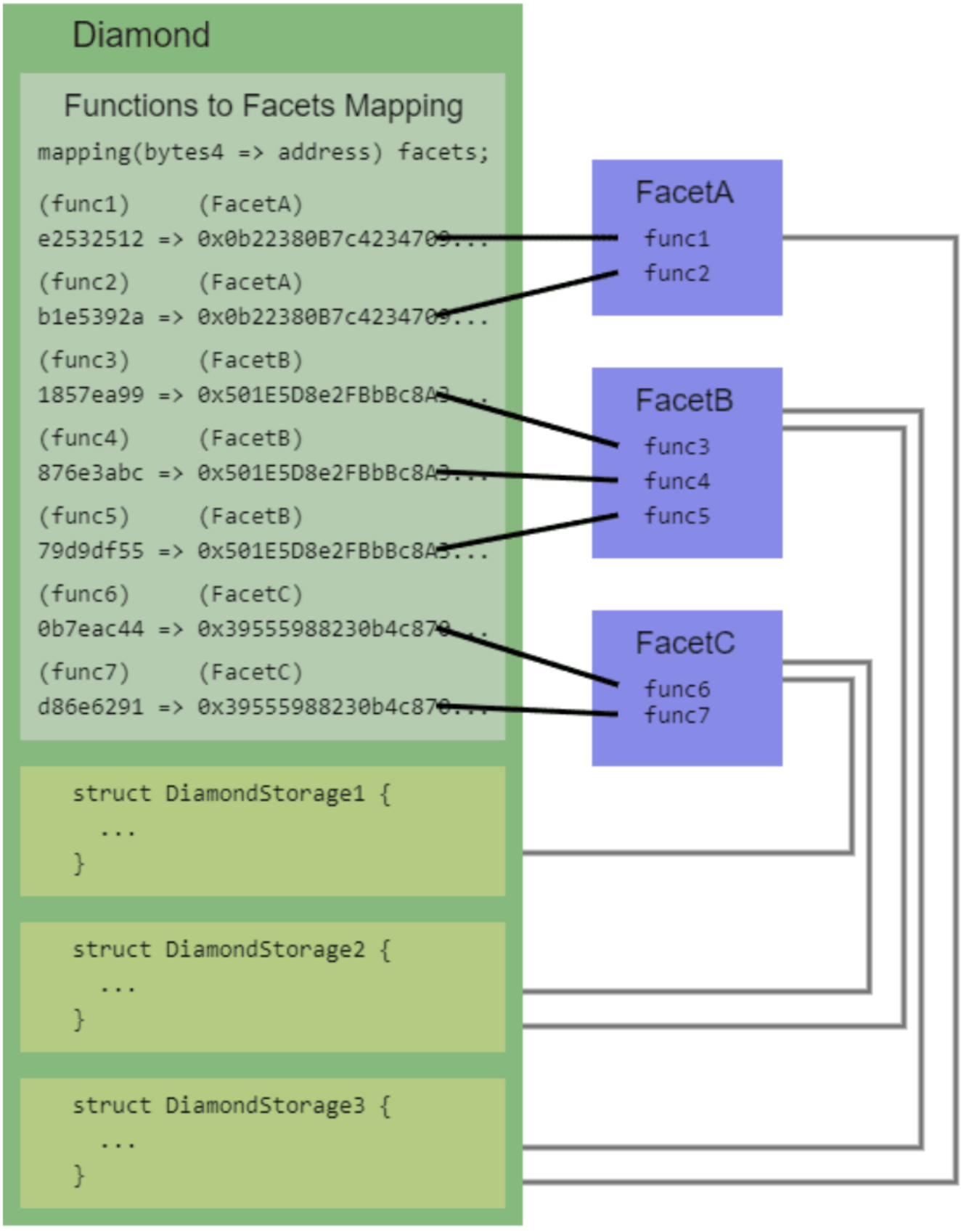



```
bytes32 constant POSITION = keccak256(
    "some_string"
);

struct MyStruct {
    uint var1;
    uint var2;
}

function get_struct() internal pure
returns(MyStruct storage ds) {
    bytes32 position = POSITION;
    assembly { ds_slot := position }
}
```

(The _slot suffix gives the storage address)



Trail of Bits Audit - Good idea, bad design

https://blog.trailofbits.com/2020/10/30/good-idea-bad-design-how-the-diamond-standard-falls-short/

"The code is over-engineered, with lots of

unnecessary complexities, and we can’t recommend it at this time."

But.. projects are using it
For example Aavegotchi

"AavegotchiDiamond provides a single Ethereum address for Aavegotchi functionality. All contract interaction with Aavegotchis is done with AavegotchiDiamond."

From Nick Mudge article
Diamonds solve these problems:

1. The maximum size a smart contract can be on Ethereum is 24kb. But sometimes larger smart contracts are needed or desired. Diamonds solve that problem.
2. Provides a structure to systematically and logically organize and extend larger smart contract systems so they don't turn into a spaghetti code mess.
3. Provides fine-grained upgrades. Other upgrade approaches require replacing functionality in bulk. With a diamond you can add, replace, or remove just the functionality that needs to be

added, replaced or removed without affecting or touching other smart contract functionality.

4. Provides a single address for a lot of smart contract functionality. This makes integration with smart contracts and user interfaces and other software easier.

Question - How is this different to using a library ?

Metamorphic Contracts

CREATE and CREATE2 and selfdestruct

CREATE gives the address that a contract will be deployed to

```
keccak256(rlp.encode(deployingAddress, nonce))[12:]
```

CREATE2 introduced in Feb 2019

```
keccak256(0xff + deployingAddr + salt + keccak256(bytecode))[12:]
```

Contracts can be deleted from the blockchain by calling selfdestruct.

selfdestruct sends all remaining Ether stored in the contract to a designated address.

This can be used to preserve the contract address among upgrades, but not its state. It relies on the contract calling selfdestruct then being re deployed via CREATE2

Seen as 'an abomination' by some

See Metamorphic contracts

and

Abusing CREATE2 with Metamorphic Contracts

and

Efficient Storage

IDE General Techniques

Importing from Github in Remix

See Documentation

You can import directly from github or npm

```
import
"https://github.com/OpenZeppelin/openzeppe
lin-contracts
/contracts/access/Ownable.sol";
```

or

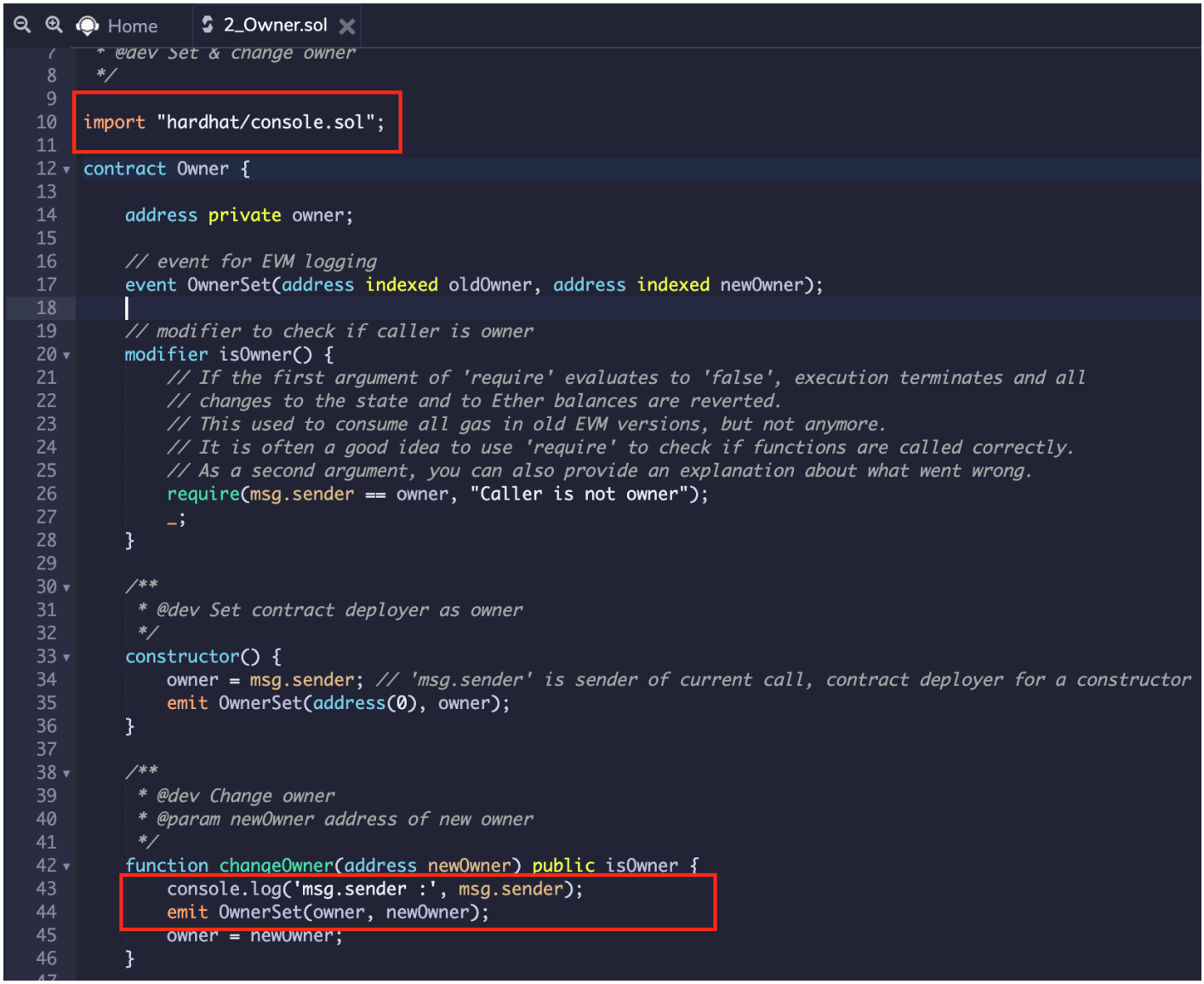
```
import
"@openzeppelin/contracts@4.2.0/token/ERC20
/ERC20.sol";
```

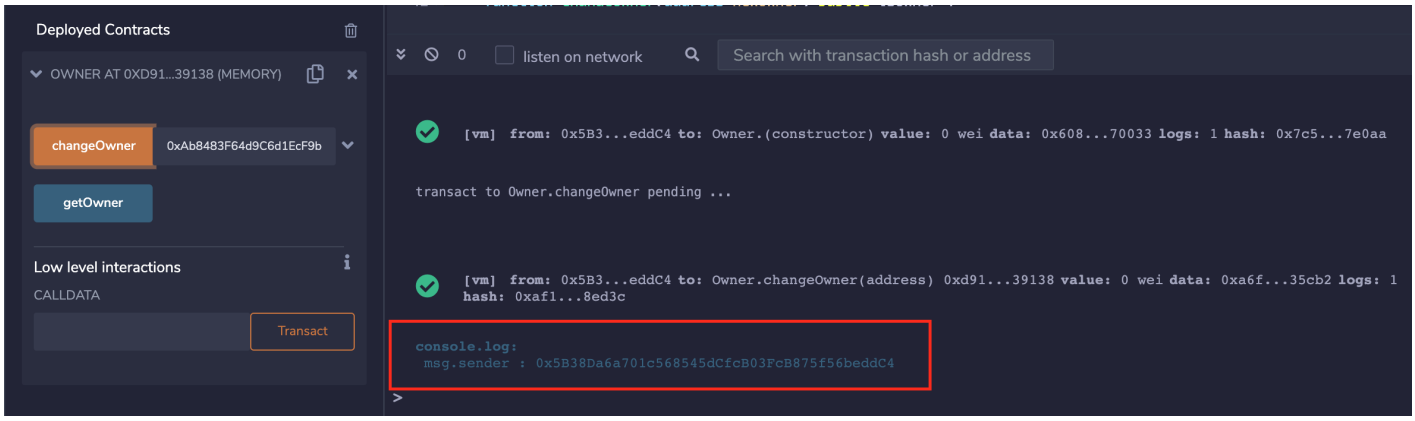
Logging in Remix

https://remix-ide.readthedocs.io/en/latest/hardhat_console.html

Remix IDE supports hardhat console library while using `JavaScript VM`. It can be used while making a transaction or running unit tests.

To try it out, you need to put an import statement and use `console.log` to print the value as shown in image.





Forking from mainnet

The easiest way to try this feature is to start a node from the command line:

```
npx hardhat node --fork https://eth-mainnet.alchemyapi.io/v2/<key>
```

You can also configure Hardhat Network to always do this:

```js
networks: {
  hardhat: {
    forking: {
      url: "https://eth-mainnet.alchemyapi.io/v2/<key>",
    }
  }
}
```

Solidity Templates

Paul Berg has created some useful templates

Solidity Template

Repo

This will give you

- Hardhat: compile, run and test smart contracts
- TypeChain: generate TypeScript bindings for smart contracts
- Ethers: renowned Ethereum library and wallet implementation
- Solhint: code linter
- Solcover: code coverage
- Prettier Plugin Solidity: code formatter

COVERAGE REPORTS

```
yarn coverage
```

all files contracts/

100% Statements 5/5 100% Branches 0/0 75% Functions 3/4 83.33% Lines 5/6

File	Statements		Branches		Functions		Lines	
Greeter.sol	100%	5/5	100%	0/0	75%	3/4	83.33%	5/6

all files / contracts/ Greeter.sol

100% Statements 5/5 **100%** Branches 0/0 **75%** Functions 3/4 **83.33%** Lines 5/6

```
1    // SPDX-License-Identifier: MIT
2    pragma solidity >=0.8.4;
3
4    import "hardhat/console.sol";
5
6    error GreeterError();
7
8    contract Greeter {
9        string public greeting;
10
11       constructor(string memory _greeting) {
12   1×      console.log("Deploying a Greeter with greeting:", _greeting);
13   1×      greeting = _greeting;
14       }
15
16       function greet() public view returns (string memory) {
17   2×      return greeting;
18       }
19
20       function setGreeting(string memory _greeting) public {
21   12×     console.log("Changing greeting from '%s' to '%s'", greeting, _greeting);
22   12×     greeting = _greeting;
23       }
24
25       function throwError() external pure {
26           revert GreeterError();
27       }
28   }
29
```

Gas report

```
REPORT_GAS=true yarn test
```

```
    ✓ should return the new greeting once it's changed

·----------------------------|----------------------------|-------------|-----------------------------·
|  Solc version: 0.8.9       ·  Optimizer enabled: true   ·  Runs: 800  ·  Block limit: 30000000 gas  |
·----------------------------|----------------------------|-------------|-----------------------------·
|  Methods                                                                                            |
·--------------|-------------|-------------|-------------|-------------|---------------|-------------·
|  Contract    ·  Method     ·  Min        ·  Max        ·  Avg        ·  # calls      ·  usd (avg)  |
·--------------|-------------|-------------|-------------|-------------|---------------|-------------·
|  Greeter     ·  setGreeting  ·          -  ·          -  ·      34489  ·            1  ·          -  |
·--------------|-------------|-------------|-------------|-------------|---------------|-------------·
|  Deployments                               ·                                        ·  % of limit   ·             |
·----------------------------|-------------|-------------|-------------|---------------|-------------·
|  Greeter                   ·          -  ·          -  ·     428178  ·        1.4 %  ·          -  |
·----------------------------|-------------|-------------|-------------|---------------|-------------·

  1 passing (2s)
```

Foundry Template

Repo

This gives you :

- Forge: compile, test, fuzz, debug and deploy smart contracts
- PRBTest: modern collection of testing assertions and logging utilities
- Forge Std: collection of helpful contracts and cheatcodes for testing
- Solhint: code linter
- Prettier Plugin Solidity: code formatter

You can install from the github template button, or from the command line with

```
forge init my-project --template
https://github.com/PaulRBerg/foundry-
template
cd my-project
yarn install # install solhint and
prettier etc.
```

Sol2UML Visualisation Tool

See repo

It provides visualisation of storage, plus UML diagrams for the contract.

Foundry

There's a bit of a trend toward writing "clever" Solidity code and it's not a good one. Boring code is better code.

Quote

Foundry is a smart contract development toolchain written in Solidity. It can:

- manage dependencies
- compile your project
- run tests
- deploy contracts
- interact with the chain via scripts and CMD

Forge is the CLI tool to initialise, build and test Foundry projects.

Foundry allows fast (milliseconds) and sophisticated Solidity tests, e.g. reading and writing directly to storage slots.

Getting Started

1. Install Foundry
    - Steps for various operation systems.
2. Initialise a project called **lets_forge**
    - `forge init lets_forge`
3. Build the project
    - `forge build`
4. Verify install has worked by running the tests
    - `forge test`

You can also use this Foundry template.

Project structure is as follows:

```
$ cd hello_foundry
$ tree . -d -L 1
.
├── lib
├── script
├── src
└── test

4 directories
```

Build command will generate the folders `out` and `cache` to store the contract artifact (ABI) and cached data, respectively.

You configure your project in the `foundry.toml` file. See ref: https://book.getfoundry.sh/reference/config/

General documentation available in the Foundry Book. **Highly recommended**.

Testing: Basics

> Smart contracts are tested using smart contracts, which is the secret to Foundry's speed since there is no additional compilation being carried out.

A smart contract e.g. MyContract.sol is tested using a file named MyContract.t.sol:

```
├── src\
│   └── MyContract.sol\
└── test\
    └── MyContract.t.sol
```

MyContract.t.sol will import the contract under test in order to access it's functions.

First Contract

Create a contract called `A.sol` and save it in `src` with the following contents:

```
// SPDX-License-Identifier: UNLICENSED
pragma solidity ^0.8.13;

/// @title Encode smart contract A
/// @author Extropy.io
```

```
contract A {
    uint256 number;

    /**
     * @dev Store value in variable
     * @param num value to store
     */
    function store(uint256 num) public {
        number = num;
    }

    /**
     * @dev Return value
     * @return value of 'number'
     */
    function retrieve() public view
returns (uint256) {
        return number;
    }
}
```

Then create a file to test the smart contract, for example `A.t.sol` in `test` with the following contents:

```
// SPDX-License-Identifier: UNLICENSED
pragma solidity ^0.8.13;

// Standard test libs
import "forge-std/Test.sol";
import "forge-std/Vm.sol";

// Contract under test
import {A} from "../src/A.sol";

contract ATest is Test {
    // Variable for contract instance
    A private a;

    function setUp() public {
        // Instantiate new contract
instance
        a = new A();
    }

    function test_Log() public {
        // Various log examples
        emit log("here");
```

```
        emit log_address(address(this));
        // HEVM_ADDRESS is a special
reserved address for the VM
        emit log_address(HEVM_ADDRESS);
    }

    function test_GetValue() public {
        assertTrue(a.retrieve() == 0);
    }

    function test_SetValue() public {
        uint256 x = 123;
        a.store(x);
        assertTrue(a.retrieve() == 123);
    }

    // Define the value(s) being fuzzed as
an input argument
    function test_FuzzValue(uint256
_value) public {
        // Define the boundaries for the
fuzzing, in this case 0 and 99999
        _value = bound(_value, 0, 99999);
        // Call contract function with
value
        a.store(_value);
        // Perform validation
        assertTrue(a.retrieve() ==
```

```
_value);
    }
}
```

Finally run the test with `forge test -vv` to see the results and all logs.

Run tests

```
forge test
```

To print event logs:

```
forge test -vv
```

To print trace of any failed tests:

```
forge test -vvv
```

To print trace of all tests:

```
forge test -vvvv
```

To run a specific test:

```
forge test --match-test test_myTest
```

Dependencies

Forge uses git submodules so it works with any GitHub repo that contains smart contracts.

Adding Dependencies

To install e.g. OpenZeppelin contracts from the repo one would run `forge install OpenZeppelin/openzeppelin-contracts`.
The repo will have been cloned into the `lib` folder.

Dependencies can be updated by running `forge update`.

Removing Dependencies

Dependencies can be removed by running `forge remove openzeppelin-contracts`, which is equivalent to `forge remove OpenZeppelin/openzeppelin-contracts`.

Integrating with Existing Hardhat project

Foundry can work with Hardhat-style projects where dependencies are npm packages (stored in `node_modules`) and contracts are stored in `contracts` as opposed to source.

1. Copy lib/forge-std from a newly-created empty Foundry project to this Hardhat project directory.
2. Copy foundry.toml configuration to this Hardhat project directory and change src, out, test, cache_path in it:

```
[default]
src = 'contracts'
out = 'out'
libs = ['node_modules', 'lib']
test = 'test/foundry'
cache_path  = 'forge-cache'
```

3. Create a remappings.txt to make Foundry project work well with VS Code Solidity extension:

```
ds-test/=lib/forge-std/lib/ds-
test/src/
forge-std/=lib/forge-std/src/
```

4. Make a sub-directory test/foundry and write Foundry tests in it.

Foundry test works in this existing Hardhat project. As the Hardhat project is not touched and it can work as before.

See folder `hardhat-foundry`. Both test suites function:

`npx hardhat test`

`forge test -vvv`

Deploying Contracts

`forge create` allows you to deploy contracts to a blockchain.

To deploy the previous contract to e.g. Ganache using an account with private key `4e0...9b` you would type:

```
forge create A --legacy --contracts src/A.sol --private-key 4e0...9b --rpc-url http://127.0.0.1:8545
```

Result:

```
Deployer: 0x536f8222c676b6566ff34e539022de6c1c22cc06
Deployed to: 0x79bb7a73d02b6d7e2e98848d26ad911720421df0
Transaction hash: 0xc5bb34ee82dc2f57bd7f7862eec440576a7cc7cfe4533392192704fd44653b68
```

The `--legacy` flag is used since Ganache doesn't support EIP-1559 transactions. Hardhat (`npx hardhat node`) circumvents this issue.

Solidity Scripting

> Solidity scripting is a way to declaratively deploy contracts using Solidity, instead of using the more limiting and less user friendly forge create.

Similar to Hardhat scripting but faster with dry-run capabilities (because it runs in Foundry EVM).

Scripts go in the `/scripts` folder and file extension is `.s.sol`.

Running a script. You should add the variables to the .env beforehand & run from root:

```
# To load the variables in the .env file
source .env

# To deploy and verify our contract
forge script script/NFT.s.sol:MyScript --
rpc-url $GOERLI_RPC_URL --broadcast --
verify -vvvv
```

Example of a deployment script:

```
// SPDX-License-Identifier: UNLICENSED
pragma solidity 0.8.18;

import "forge-std/Script.sol"; // Import
script lib
import "../src/ContractA.sol";
import "../src/ContractB.sol";
import "../src/ContractC.sol";

contract Deployment is Script {
    function run() public {

        //Load key/unlock wallet. Use with
caution if in production
        uint256 deployerPrivateKey =
vm.envUint("DEPLOY_KEY");

vm.startBroadcast(deployerPrivateKey);

        //Deploy contracts
        ContractA contractA = new
ContractA();
        ContractB contractB = new
ContractB();
        ContractC contractC = new
```

```
ContractC();

        //Do some complex deployment logic
        contractA.callSomeFunction();
        uint256 result =
contractB.anotherFunction(address(contract
A));

contractC.someOtherFunction(result);

        vm.stopBroadcast();
    }
}
```

Cast

> Perform Ethereum RPC calls from the comfort of your command line.

For example:

- `cast chain-id` Get the Ethereum chain ID.
- `cast publish` Publish a raw - transaction to the network.
- `cast receipt` Get the transaction receipt for a transaction.
- `cast send` Sign and publish a transaction.
- `cast call` Perform a call on an account without publishing a transaction.
- `cast block-number` Get the latest block number.
- `cast abi-encode` ABI encode the given function arguments, excluding the selector.

How to use Cast

```
cast [options] command [args] cast
[options] --version cast [options] --help
```

eg:

```
cast call
0x79bb7a73d02b6d7e2e98848d26ad911720421df0
"retrieve()" --rpc-url
http://127.0.0.1:8545
```

There are **a lot** of cast commands. Take a look at the reference: https://book.getfoundry.sh/reference/cast/cast

---

Debugging in Foundry

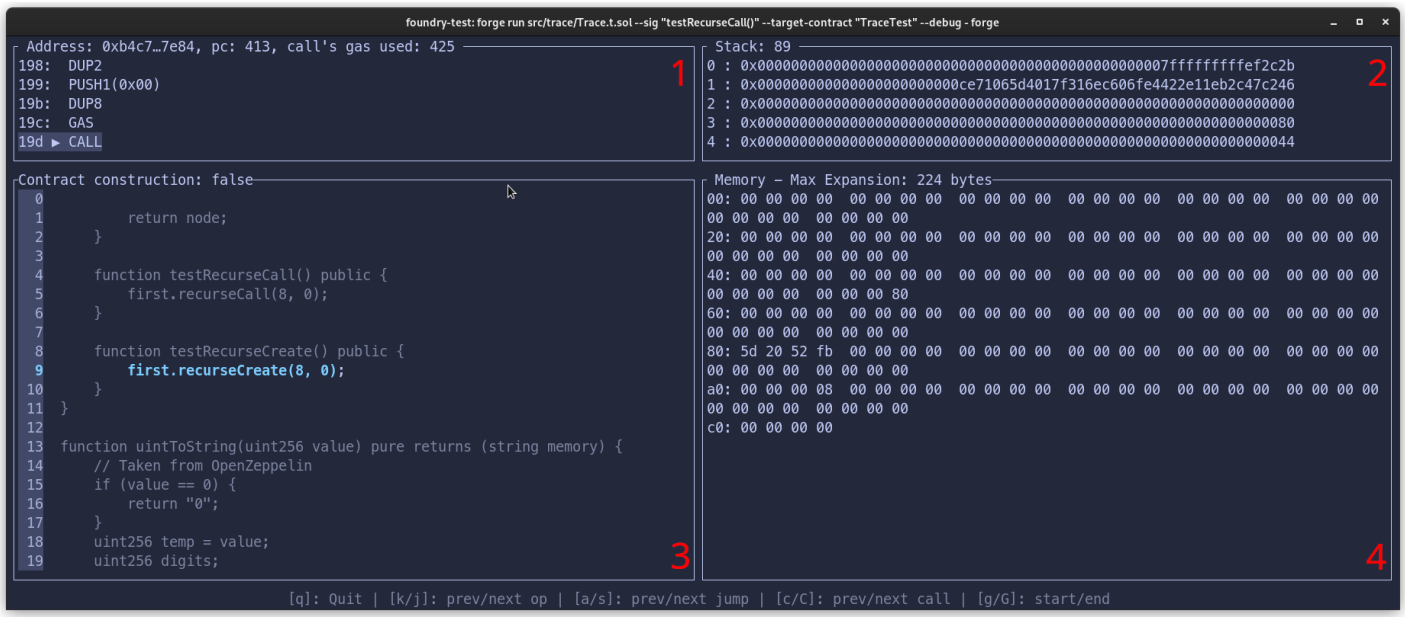
There are 2 ways to debug:

- With `forge test` passing a function from tests `forge test --debug $FUNC`

Example `forge test --debug "testSomething()"`

- With `forge debug` passing a file `forge debug --debug $FILE --sig $FUNC`

Example: `forge debug --debug src/SomeContract.sol --sig "myFunc(uint256,string)" 123 "hello"`



When the debugger is run, you are presented with a terminal divided into four quadrants:

- 1: The opcodes in the debugging session

- 2: The current stack, as well as the size of the stack
- 3: The source view
- 4: The current memory of the EVM

> If you have multiple contracts with the same function name, you need to limit the matching functions down to only one case using --match-path and --match-contract.

> If the matching test is a fuzz test, the debugger will open the first failing fuzz scenario, or the last successful one, whichever comes first.

See guide for more info book

Forking

Forge supports testing in a forked environment with two different approaches:

- Forking Mode — use a single fork for all your tests via the forge test `--fork-url` flag.

```
forge test --fork-url <your_rpc_url>
```

- Forking Cheatcodes in tests — create, select, and manage multiple forks directly in Solidity test code via forking cheatcodes

```
contract ForkTest is Test {
    // the identifiers of the forks
    uint256 mainnetFork;
    uint256 optimismFork;

    //Access variables from .env file via
vm.envString("varname")
    //Replace ALCHEMY_KEY by your alchemy
key or Etherscan key, change RPC url if
need
    //inside your .env file e.g:
    //MAINNET_RPC_URL = 'https://eth-
mainnet.g.alchemy.com//v2/ALCHEMY_KEY'
    //string MAINNET_RPC_URL =
```

```
vm.envString("MAINNET_RPC_URL");
    //string OPTIMISM_RPC_URL =
vm.envString("OPTIMISM_RPC_URL");

    // create two _different_ forks during
setup
    function setUp() public {
        mainnetFork =
vm.createFork(MAINNET_RPC_URL);
        optimismFork =
vm.createFork(OPTIMISM_RPC_URL);
    }

    // demonstrate fork ids are unique
    function testForkIdDiffer() public {
        assert(mainnetFork !=
optimismFork);
    }

    // select a specific fork
    function testCanSelectFork() public {
        // select the fork
        vm.selectFork(mainnetFork);
        assertEq(vm.activeFork(),
mainnetFork);

        // from here on data is fetched
from the `mainnetFork` if the EVM requests
```

```
it and written to the storage of
`mainnetFork`
    }

    // manage multiple forks in the same
test
    function testCanSwitchForks() public {
        vm.selectFork(mainnetFork);
        assertEq(vm.activeFork(),
mainnetFork);

        vm.selectFork(optimismFork);
        assertEq(vm.activeFork(),
optimismFork);
    }

    // forks can be created at all times
    function
testCanCreateAndSelectForkInOneStep()
public {
        // creates a new fork and also
selects it
        uint256 anotherFork =
vm.createSelectFork(MAINNET_RPC_URL);
        assertEq(vm.activeFork(),
anotherFork);
    }
```

```
    // set `block.timestamp` of a fork
    function
testCanSetForkBlockTimestamp() public {
        vm.selectFork(mainnetFork);
        vm.rollFork(1_337_000);

        assertEq(block.number, 1_337_000);
    }
}
```

Cheatcodes

Cheatcodes allow you to change the block number, your identity, and more. They are invoked by calling specific functions on a specially designated address: `0x7109709ECfa91a80626fF3989D68f67F5b1DD12D`.

You can access cheatcodes easily via the 'vm' instance available in Forge Standard Library's Test contract. Forge Standard Library is explained in greater detail in the following section.

Below are some subsections for the different Forge cheatcodes.

- Environment: Cheatcodes that alter the state of the EVM.
- Assertions: Cheatcodes that are powerful assertions
- Fuzzer: Cheatcodes that configure the fuzzer
- External: Cheatcodes that interact with external state (files, commands, ...)
- Utilities: Smaller utility cheatcodes
- Forking: Forking mode cheatcodes
- Snapshots: Snapshot cheatcodes
- File: Cheatcodes for working with files

See cheatcodes reference in docs:

https://book.getfoundry.sh/cheatcodes/

```
// Set block.timestamp
function warp(uint256) external;

// Set block.number
function roll(uint256) external;

// Set block.basefee
function fee(uint256) external;

// Set block.difficulty
function difficulty(uint256) external;

// Set block.chainid
function chainId(uint256) external;

// Loads a storage slot from an address
function load(address account, bytes32
slot) external returns (bytes32);

// Stores a value to an address' storage
slot
function store(address account, bytes32
slot, bytes32 value) external;

// Signs data
```

```
function sign(uint256 privateKey, bytes32
digest)
    external
    returns (uint8 v, bytes32 r, bytes32
s);

// Computes address for a given private
key
function addr(uint256 privateKey) external
returns (address);
```

Broadcast will emulate your deployment on chain and return a comprehensive trace of the execution.

```
➜  forge-template git:(master) ✗ forge script script/Script.sol --rpc-url $ETH_RPC_URL -vvvv --broadcast --private-key $PRIVKEY
[⠒] Compiling...
[⠢] Compiling 6 files with 0.8.13
[⠆] Solc 0.8.13 finished in 666.82ms
Compiler run successful
Traces:
  [87942] MyScript::run()
    ├─ [0] VM::startBroadcast()
    │   └─ ← ()
    ├─ [51587] → new Contract@0xe2d5bb16874adb5de7c257919feff7610624865b
    │   └─ ← 147 bytes of code
    ├─ [238] Contract::test()
    │   └─ ← ()
    ├─ [261] Contract::x() [staticcall]
    │   └─ ← 12345
    └─ ← ()


Script ran successfully.
Gas used: 87942
==========================
Simulated On-chain Traces:

  [107343] → new Contract@0xe2d5bb16874adb5de7c257919feff7610624865b
    └─ ← 147 bytes of code

  [26202] Contract::test()
    └─ ← ()


==========================

Estimated total gas used for script: 133545
==========================

###
Finding wallets for all the necessary addresses...

#####
✅ Hash: 0xe1ba914f63259139a18561509730db39703a8c73dd81581da29943081447eb2e
Contract Address: 0xe2d5bb16874adb5de7c257919feff7610624865b
Block: 10762422
Nonce: 21
Paid: 0.00032862900109543 ETH (109543 gas * 3.00000001 gwei)

#####
✅ Hash: 0x99dbde7eec0977b26a8f667949eb43efffc6fbae8ea61e3610ff239500743145
Block: 10762422
Nonce: 22
Paid: 0.00007860600026202 ETH (26202 gas * 3.00000001 gwei)


==========================

ONCHAIN EXECUTION COMPLETE & SUCCESSFUL. Transaction receipts written to "broadcast/Script.sol/4/run-latest.json"

Transactions saved to: broadcast/Script.sol/4/run-latest.json

➜  forge-template git:(master) ✗
```

Chisel

Chisel is a Solidity REPL (short for "read-eval-print loop") that allows developers to write and test Solidity code snippets. It provides an interactive environment for writing and executing Solidity code, as well as a set of built-in commands for working with and debugging your code. This makes it a useful tool for quickly testing and experimenting with Solidity code without having to spin up a sandbox foundry test suite.

When you install foundry with `curl -L https://foundry.paradigm.xyz | bash`, **chisel** is one of the binaries that get installed. Other binaries included are `forge`, `anvil` and `cast`

See Documentation on chisel

Getting Started With Chisel

1. Enter the REPL using the command on your terminal

```
chisel
```

2. Type `!help` to see available command options

```
!help
```

3. Lets create a global variable `number`

```
uint256 public number = 1;
```

```
number;
```

Output:

```
Type: uint
 ├ Hex: 0x1
 └ Decimal: 1
```

> View your solidity contract using `!so` command

4. Create a function to store a `number`

```
function store(uint256 num) public {
number = num; }
```

5. Create a function to get `number`

```
function getNumber() public view
returns (uint256) { return number; }
```

6. Store `42` using out `store()` function

```
store(42);
```

7. Get the number we just stored

```
getNumber();
```

Expected output:

```
Type: uint
├ Hex: 0x2a
└ Decimal: 42
```

8. View the contract we just created using the `!so` command
9. Bonus: Use the `!sd` or `!stackdump` and `!md` or `!memdump` to visualize how strings are encoded in memory

```
string memory word = 'Hello Chisel';
```

Our stack:

```
[0]:
0x0000000000000000000000000000000000000000000000000000000000000080
[1]:
0x0000000000000000000000000000000000000000000000000000000000000093
[2]:
0x000000000000000000000000000000000000000000000000c0406226
```

Expected memory layout:

```
[0x00:0x20]:
0x0000000000000000000000000000000000000000000000000000000000000000
[0x20:0x40]:
0x0000000000000000000000000000000000000000000000000000000000000000
[0x40:0x60]:
0x00000000000000000000000000000000000000000000000000000000000000c0
[0x60:0x80]:
0x0000000000000000000000000000000000000000000000000000000000000000
[0x80:0xa0]:
0x0000000000000000000000000000000000000000
```

```
0000000000000000000000000c
[0xa0:0xc0]:
0x48656c6c6f2043686973656c000000000000
0000000000000000000000000000
```

Using Chisel can boost development speed without setting up a foundry project or remixIDE every time you need to test out your solidity logic.