Locate Vulnerabilities of Ethereum Smart Contracts with Semi-Automated Analysis

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Senior security researcher, CyCraft

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- CHROOT's member, a local hacker group in Taiwan
- Specialization
  - Web Security / AD Security / Blockchain Security
- Gives talks at
  - OWASP Global AppSec / ROOTCON / HITCON

Outline

- Intro to Blockchain & Web3
- EVM-based Smart Contract Basics
- Reverse Engineering & CFG
- Cases & Futures

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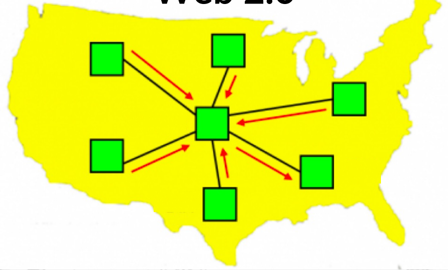
Distributed Ledger Technology (DLT)

- “Bitcoin”, the first cryptocurrency, was invented in 2008 by an unknown person or group of people using the name **Satoshi Nakamoto**
- The term “Blockchain” was later invented due to the release of the white paper and its fundamental cores, **Peer-to-Peer Network** and **Consensus Algorithm**
- “DLT” is later named as a category that covers technologies like Blockchain, having high levels of transparency, integrity and availability in a decentralized framework

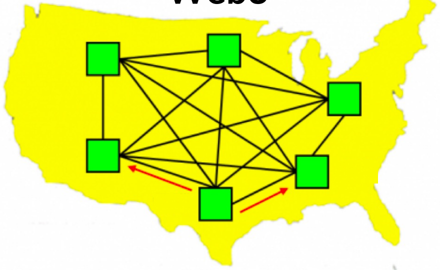
Peer-to-Peer Network

- Web 2.0, known as Social Network, focuses on sharing data and contents under famous entities such as Google, Meta, Apple, ...
- Web3, known as Blockchain-empowered Network, focuses on the controls of owned data and identities

Web 2.0



Web3



Consensus Algorithm

- The most important component of a blockchain that ensures the safety of the network
- Participants need to fulfill certain requirements to make a transaction
- The mainstream ones
  - PoW (Proof-of-Work)
  - PoS (Proof-of-Stake)
  - PoH (Proof-of-History)

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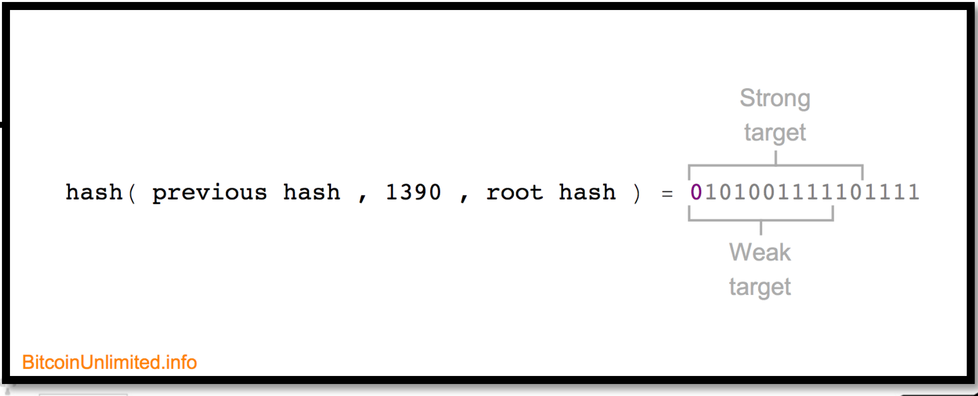
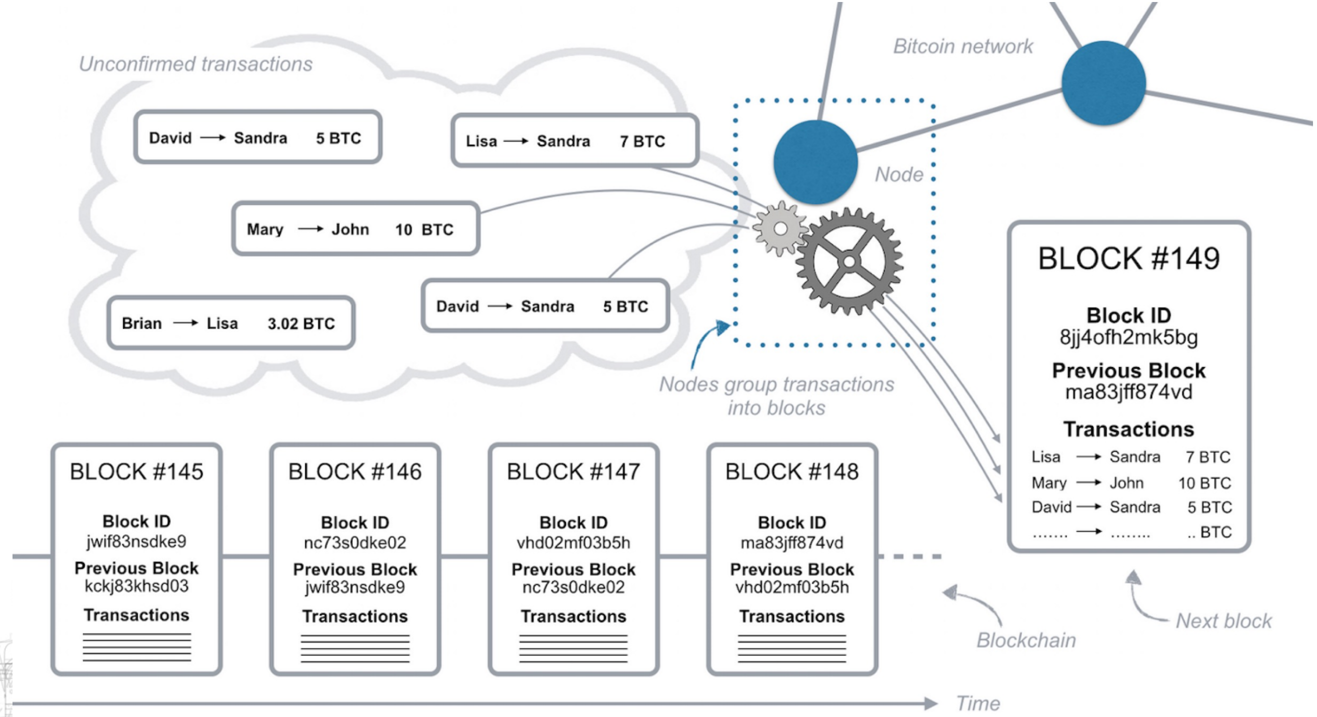
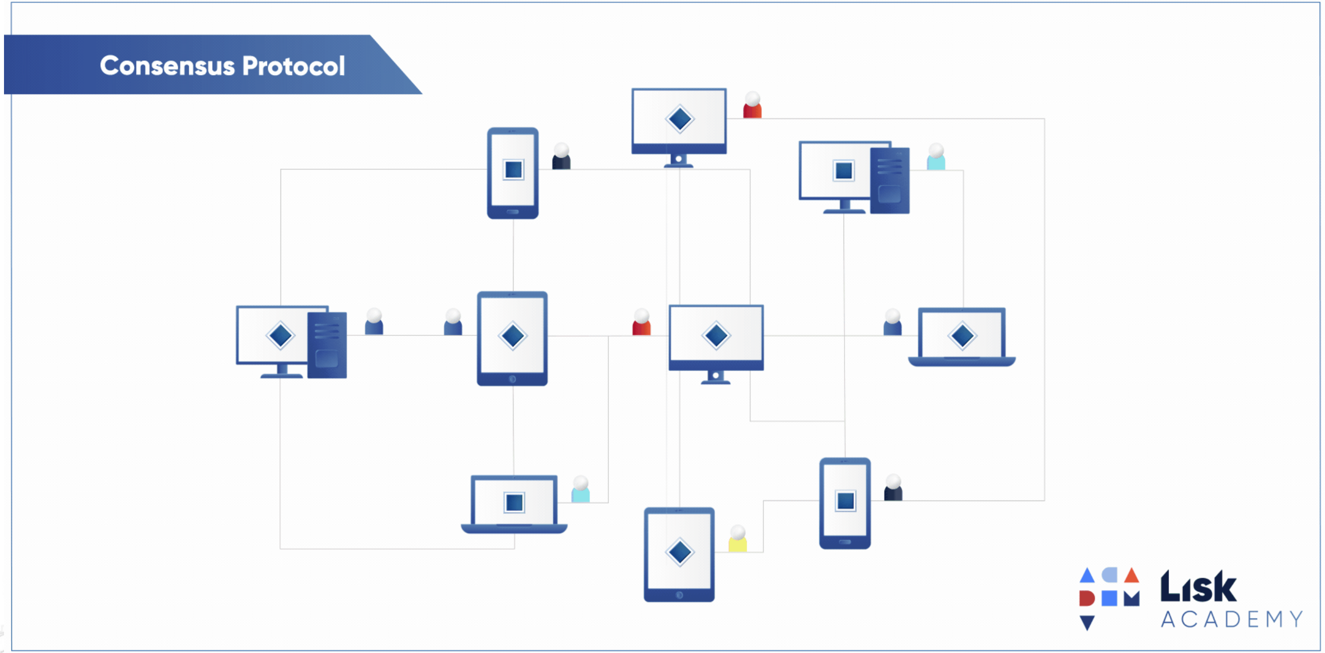


How does “blockchain” work?



How does the “network” look like?



Generations

- 1st Gen: Bitcoin blockchain (Payment System)
- 2nd Gen: Ethereum blockchain (On-chain traditional finance)
- Next Gen?
  - IoT (Internet of Things)
  - AI (Artificial Intelligence)

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  - Superconductor (?

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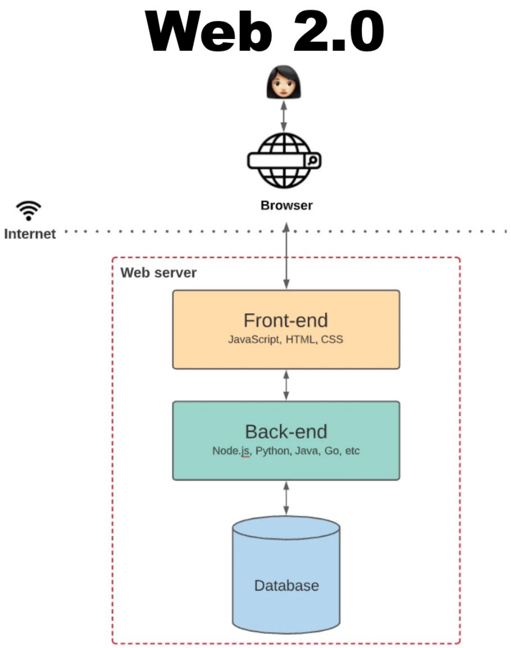
Ethereum blockchain & Smart Contract

- Ethereum blockchain introduces a new function called "Smart Contract", which is simply a program run on the blockchain
- Smart contracts can define rules, like a regular contract, and automatically enforce them via the code
- **Dapps** (Decentralized Apps) have their backend code (smart contracts) running on a blockchain like Ethereum to ensure decentralization and availability
- "DeFi (Decentralized Finance)" then starts thriving

Short ver.



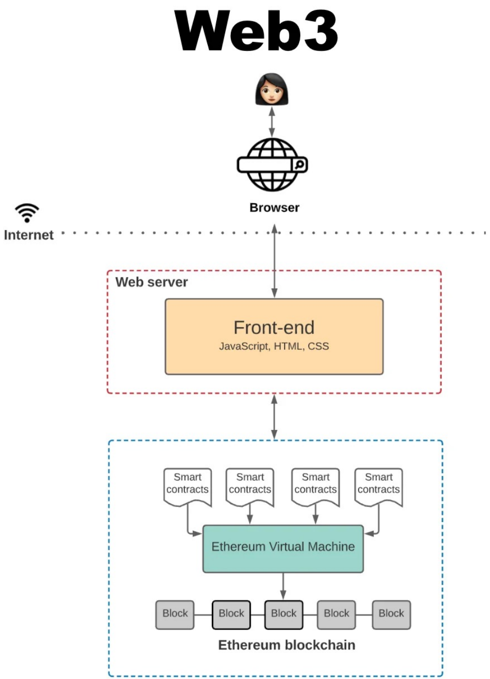


Diagram by Preethi Kasireddy

Ethereum VM (Virtual Machine)

- Smart contracts run on **EVM** (Ethereum VM)
- The EVM executes as a **stack machine**, and each compiled smart contract bytecode executes as a series of EVM opcodes like *XOR*, *AND*, *ADD*, *SUB*, etc
- Each EVM opcode is 1-byte, and therefore, we can have 256 different opcodes at maximum (142 currently)
- Each programmable computation is intrinsically bounded by **fees**, which is **a specific amount of gas**

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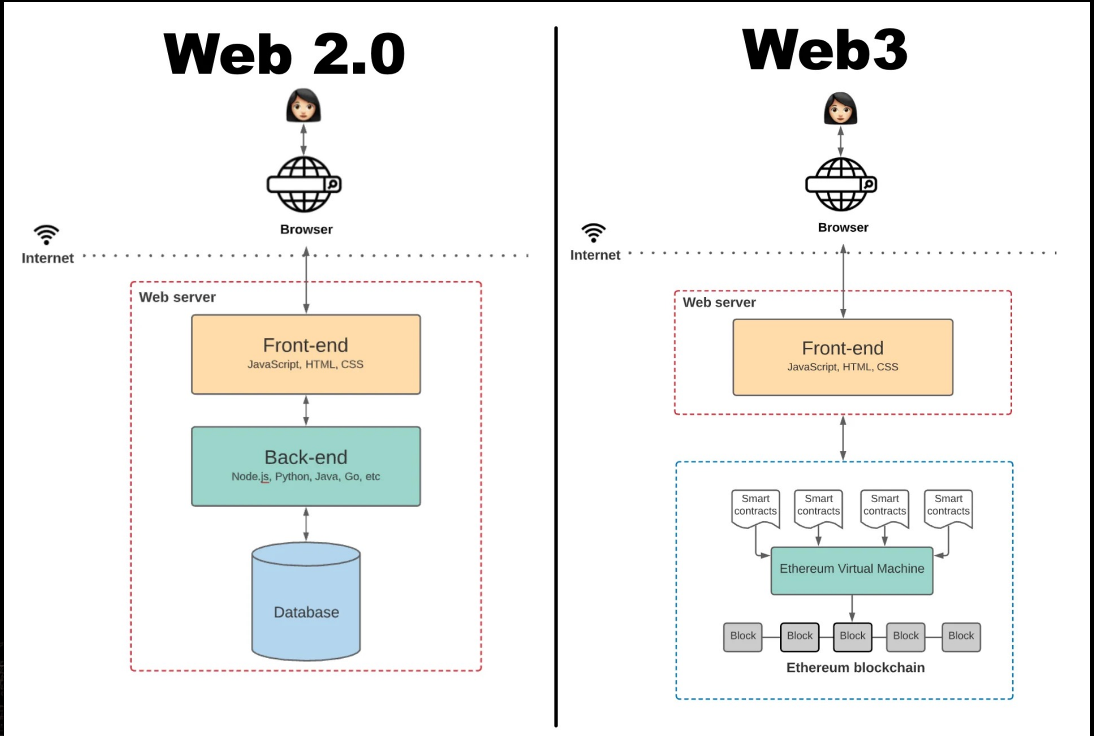
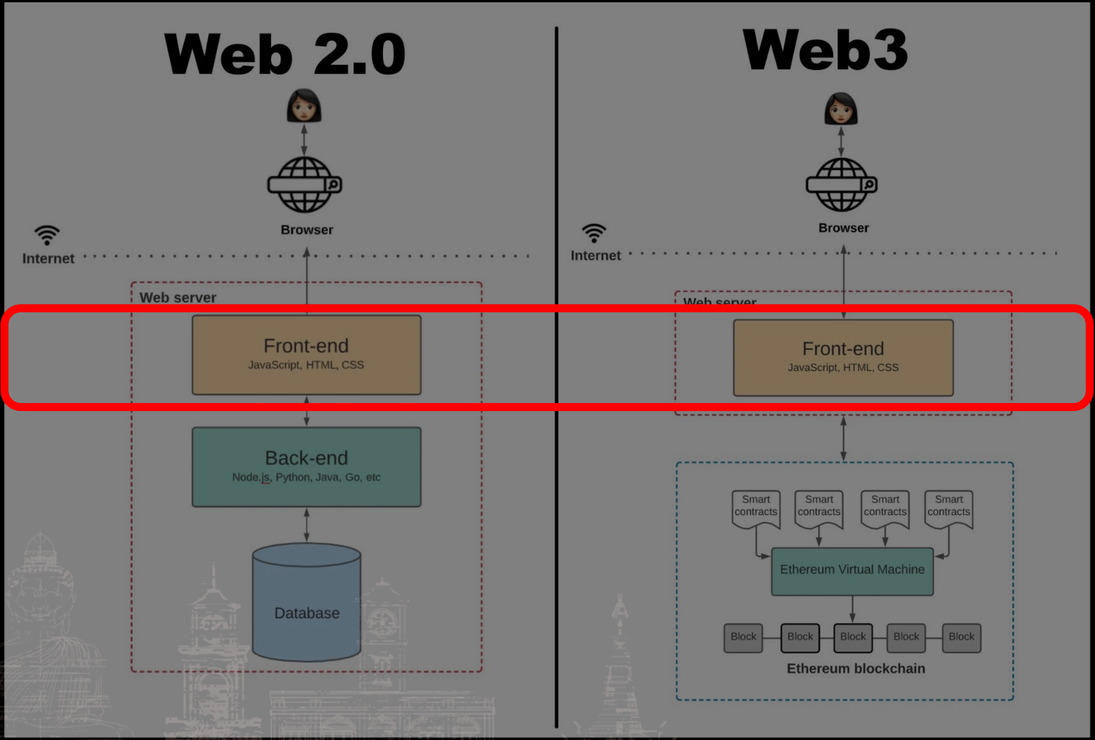
Hacks in Web3



Hacks in Web3 (Front-End)

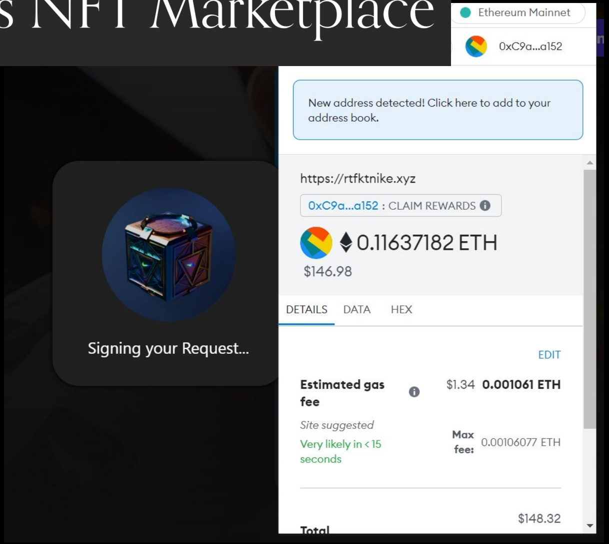


It's Web 2.0 things...

Hacks in Web3 (Front-End)

4/18/22

Palisade identifies Wormable Cross-Site Scripting Vulnerability affecting Rarible's NFT Marketplace



Hacks in Web3 (Front-End)

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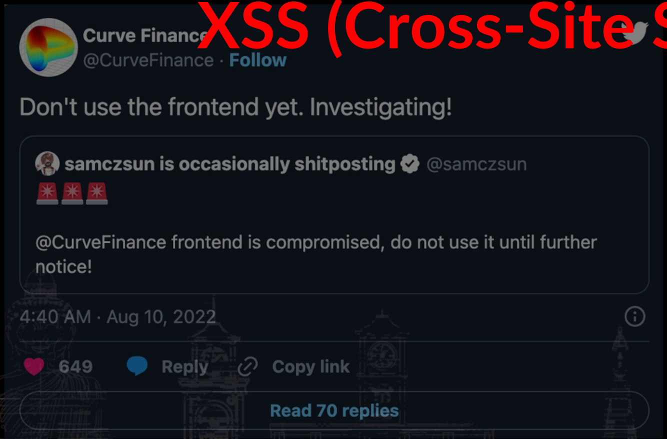
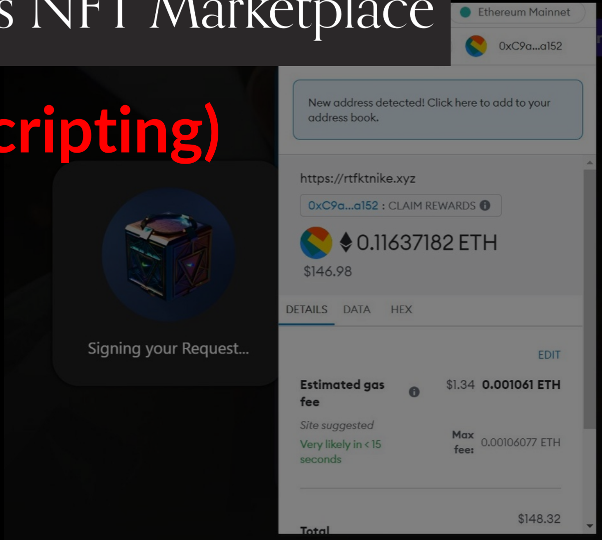
XSS (Cross-Site Scripting)





Hacks in Web3 (Front-End)

4/18/22

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Curve Finance
@CurveFinance · Follow

Don't use the frontend yet. Investigating!

> **samczsun is occasionally shitposting** @samczsun
> 🚨🚨🚨
>
> @CurveFinance frontend is compromised, do not use it until further notice!

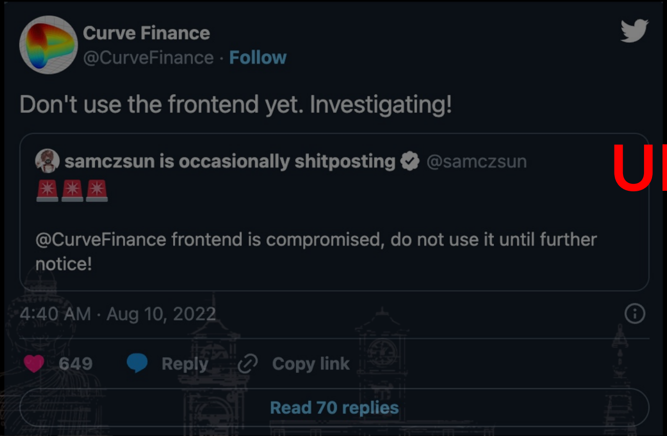
4:40 AM · Aug 10, 2022

649 Reply Copy link

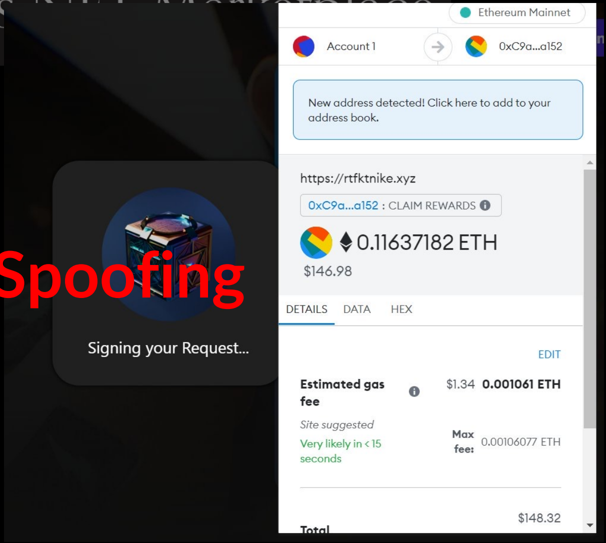
Read 70 replies

DNS Cache Spoofing

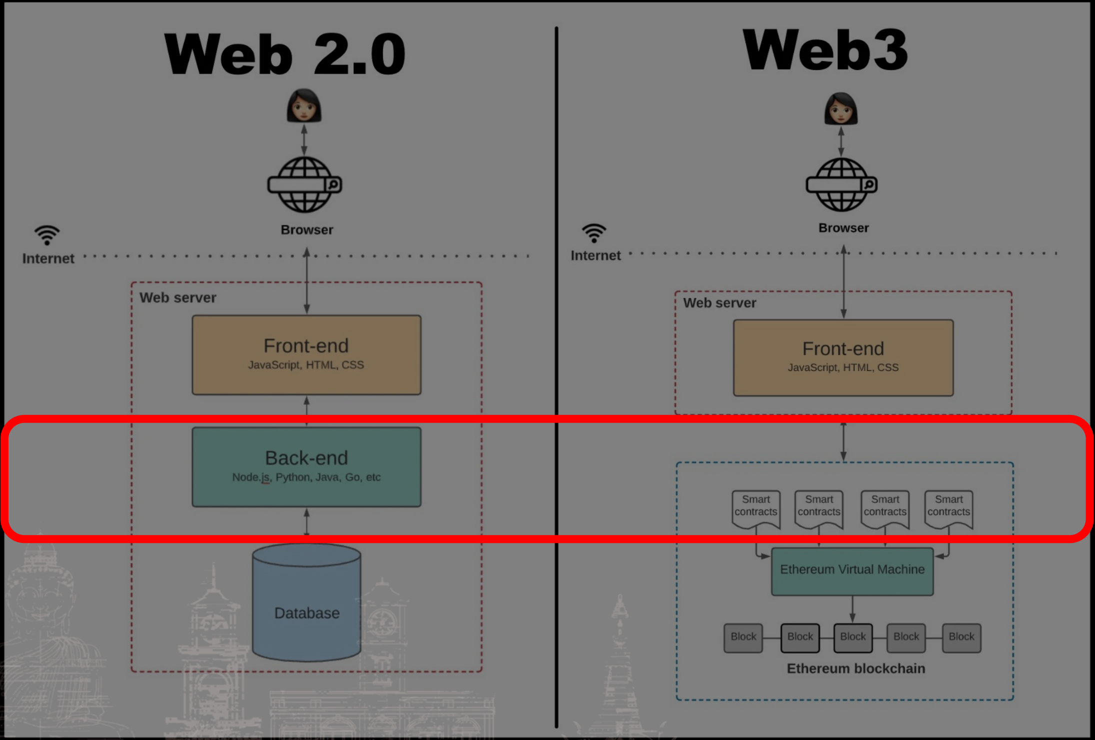
Hacks in Web3 (Front-End)



UI Spoofing



Hacks in Web3 (Back-End)



Smart Contract 📜

Hacks in Web3 (Back-End)

UNISWAP BUG BOUNTY

Uniswap Labs recently advertised a boosted $3M bounty program for bug reports. To our knowledge, ours was the only bug report that Uniswap acted upon.

Harmony 💙
@harmonyprotocol · Follow

1/ The Harmony team has identified a theft occurring this morning on the Horizon bridge amounting to approx. $100MM. We have begun working with national authorities and forensic specialists to identify the culprit and retrieve the stolen funds.

More 🧵

7:13 AM · Jun 24, 2022

Wormhole 🌪
@wormholecrypto · Follow

The wormhole network was exploited for 120k wETH.

ETH will be added over the next hours to ensure wETH is backed 1:1. More details to come shortly.

We are working to get the network back up quickly. Thanks for your patience.

6:25 AM · Feb 3, 2022

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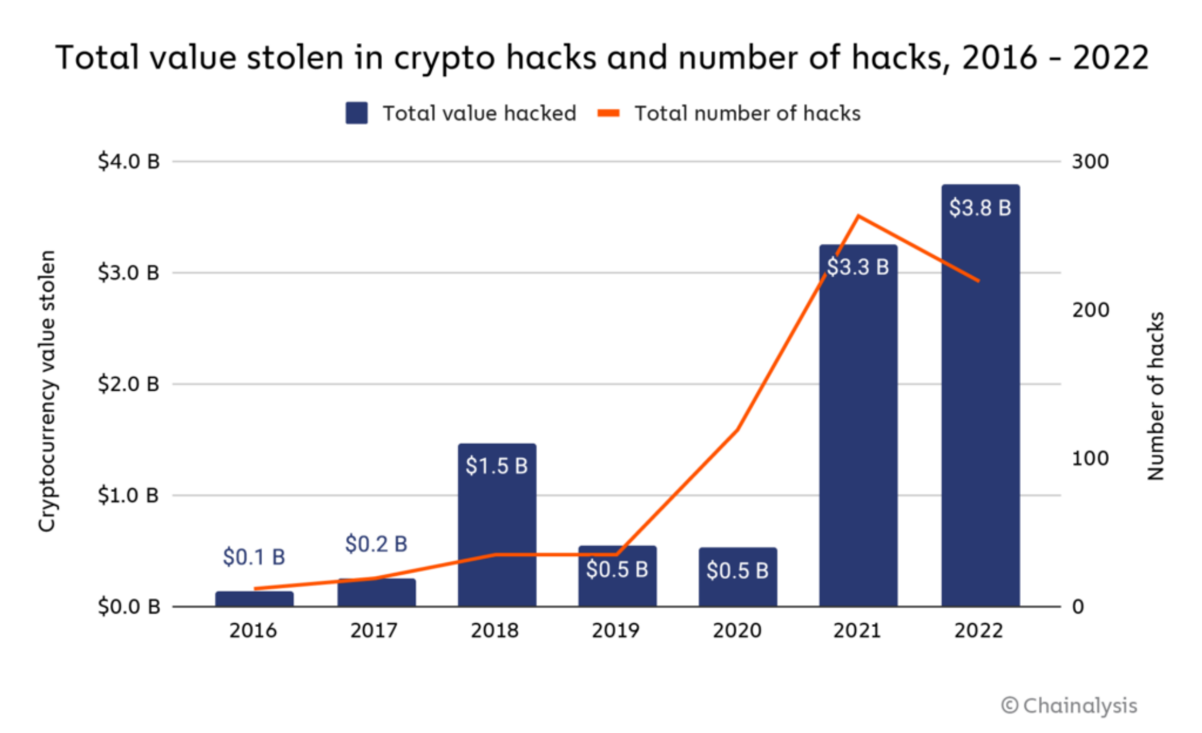

Reverse Engineering a Contract

- Everything uploaded on the blockchain is **consistent**, **verifiable**, and publicly **available**
- For transparency and reputation, some projects will disclose their source code on **GitHub**, **Etherscan**, etc
- If you want, you can always get a copy of a smart contract bytecode even if it's not open-sourced
- There are **no secrets** on the blockchain…

White Box Testing

- Which means that we have the source code

```
function allowListMint(uint256 quantity, bytes32[] calldata proof)
  external
  payable
  callerIsUser
{
  uint256 price = uint256(saleConfig.mintlistPrice);
  require(price != 0, "pre sale has not begun yet");
  require(
    allowlist[msg.sender] < 1,
    "You can only mint once during pre-sale."
  );
  bytes32 leaf = keccak256(abi.encodePacked(msg.sender));
  require(_verify(leaf, proof), "Invalid Signature proof supplied.");
  require(totalSupply() + quantity <= collectionSize, "reached max supply");
  require(price <= msg.value, "Invalid funds provided");
  allowlist[msg.sender]++;
  _safeMint(msg.sender, quantity);
  refundIfOver(price);
}
```

White Box Testing

- Which means that we have the source code
- We can take advantage of static-analysis tools to easily discover flaws

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White Box Testing

- Which means that we have the source code
- We can take advantage of static-analysis tools to easily discover flaws
- Can you spot the vuln?

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- Which means that we have the source code
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- You can mint as many items as you want by paying only the price of one item

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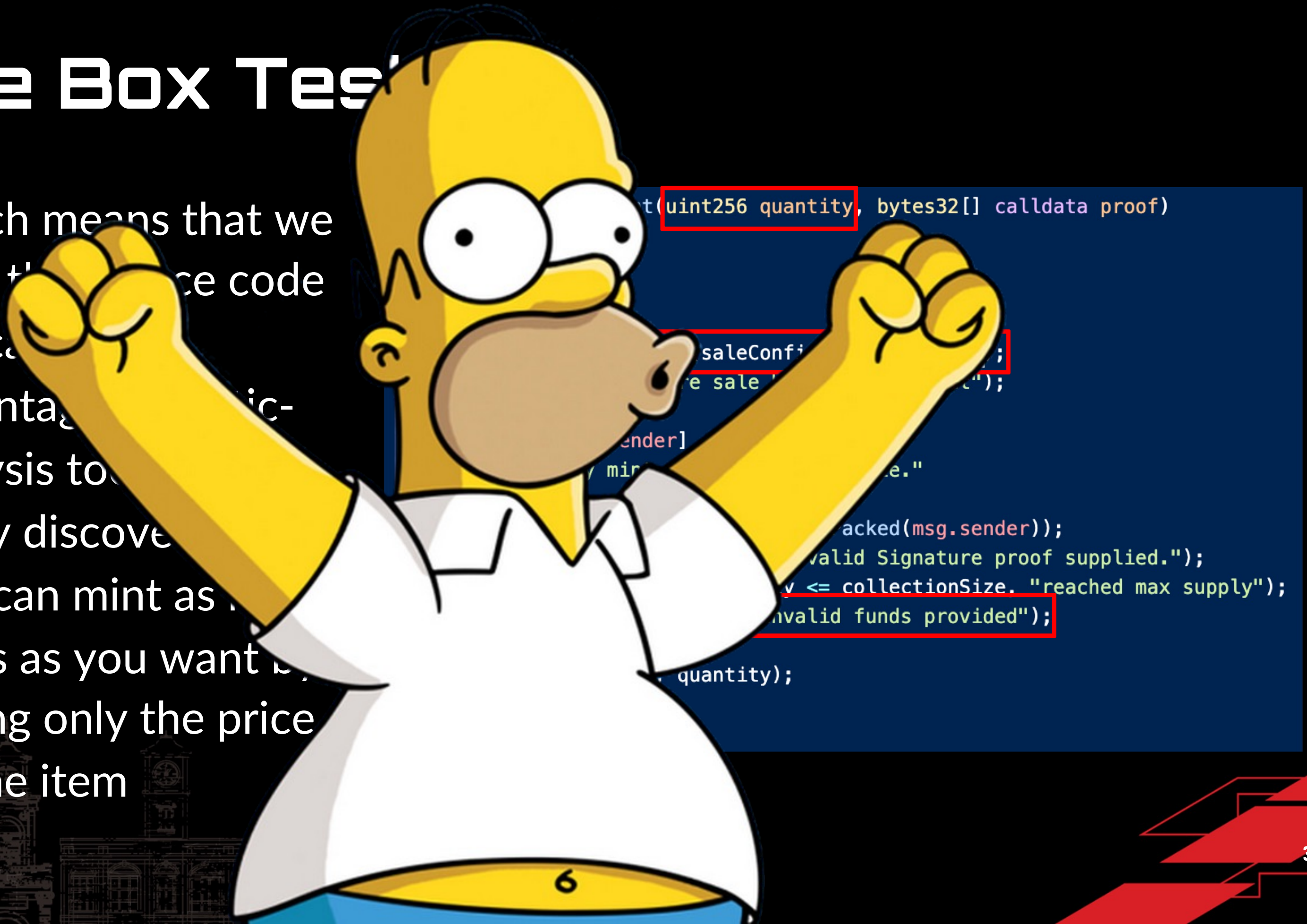
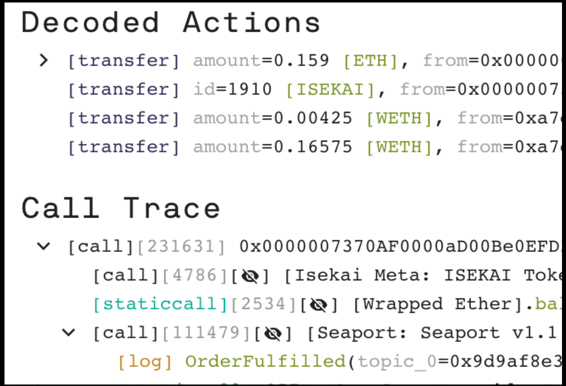


Black Box Testing

- You can try “Replay Attack”, which simply means you replay the Tx to see if you’re able to reproduce the outcome
- Some will also analyze transactions to understand internal operations

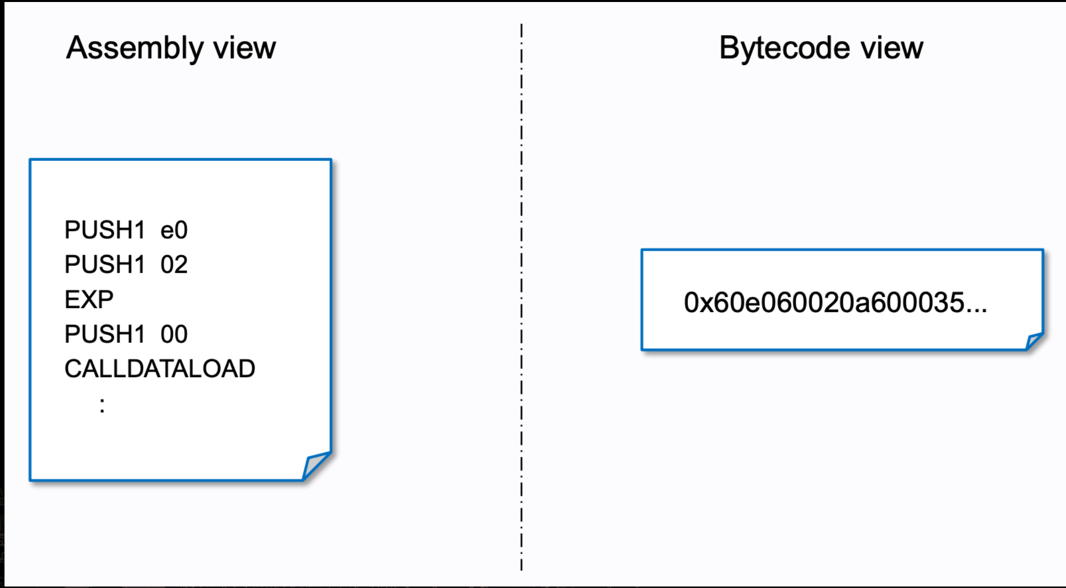


Black Box Testing

- You can try “Replay Attack”, which simply means you replay the Tx to see if you’re able to reproduce the outcome
- Some will also analyze **Txs** to understand internal operations
- Or, you can **reverse** smart contracts, and it will give you a much clearer view of what smart contracts do actually

Disassembly

- No matter what compiled binaries we have, it's a must to firstly disassemble machine code into disassembly



CFG (Control Flow Graph)

```
w = 0;
x = x + y;
y = 0;
if( x > z)
  {
   y = x;
   x++;
  }
else
  {
   y = z;
   z++;
  }
w = x + z;
```

Source Code

B1

```
w = 0;
x = x + y;
y = 0;
if( x > z)
```

B2

```
y = x;
x++;
```

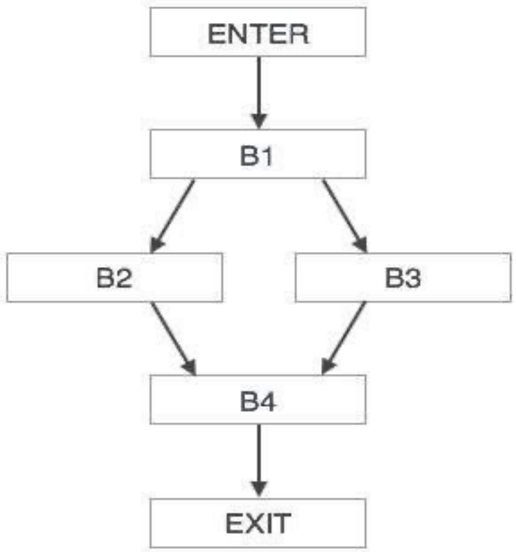
B3

```
y = z;
z++;
```

B4

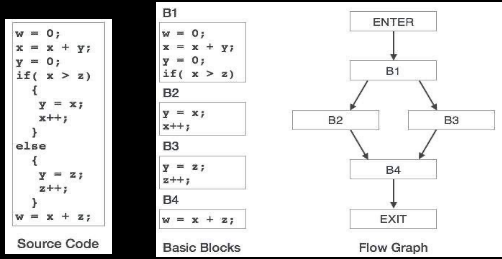
```
w = x + z;
```

Basic Blocks



Flow Graph

CFG (Control Flow Graph)



- Why do we need to construct a CFG
  1. To have correct executing logics

```
L1:     MOV   EAX, $2
L2:     MUL   EAX, ECX
L3:     MOV   DWORD [0x402000], EAX
```

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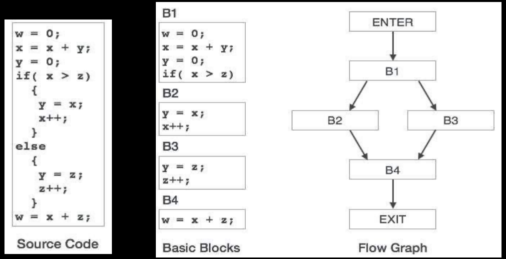


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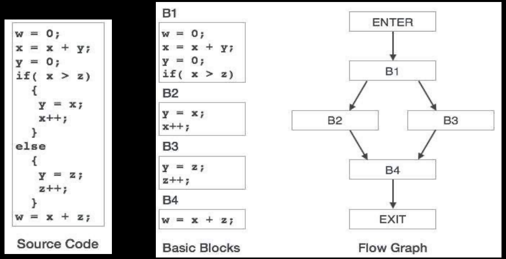

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= ECX * EAX
= ECX * 2

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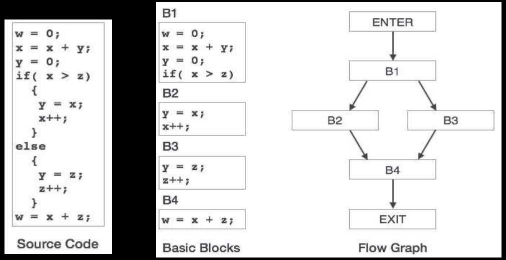

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CFG (Control Flow Graph)

- Why do we need to construct a CFG
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L0:     MOV   EAX, $3
        CMP   EBX, $0
        JNE   L2
L1:     MOV   EAX, $2
L2:     MUL   EAX, ECX
L3:     MOV   DWORD [0x402000], EAX
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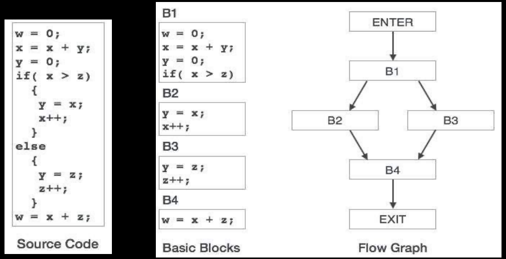

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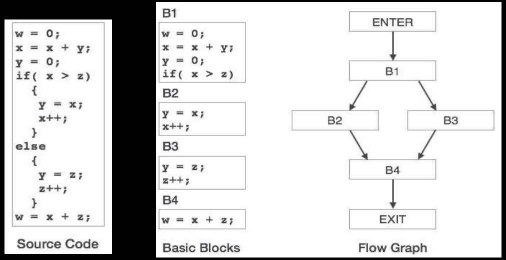

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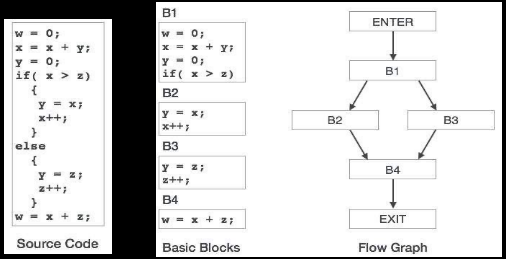

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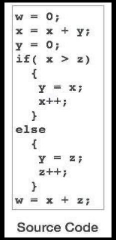
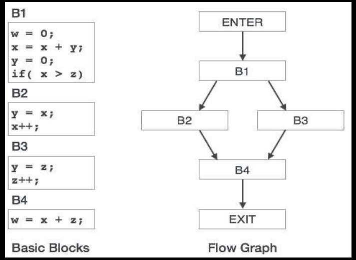
```

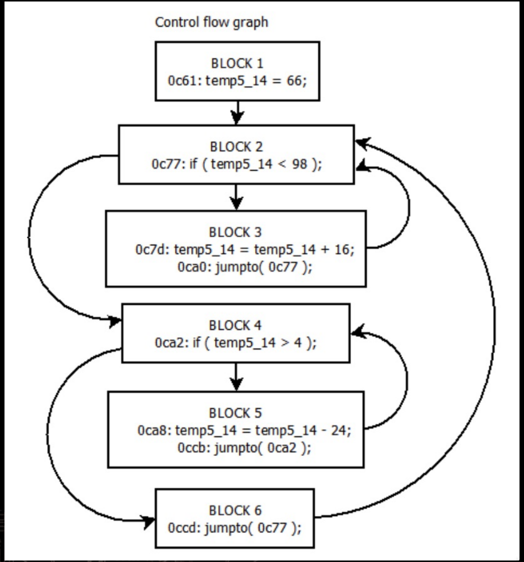
= ECX * EAX
= ECX * (EAX == 0) ? 2 : 3

CFG (Control Flow Graph)

- Why do we need to construct a CFG
    1. To have correct executing logics
    2. To eliminate loops







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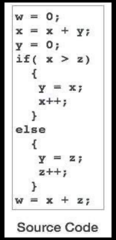

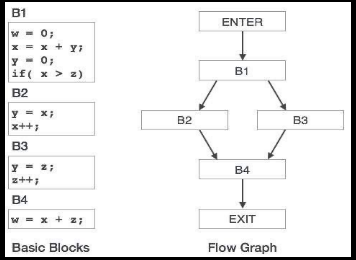

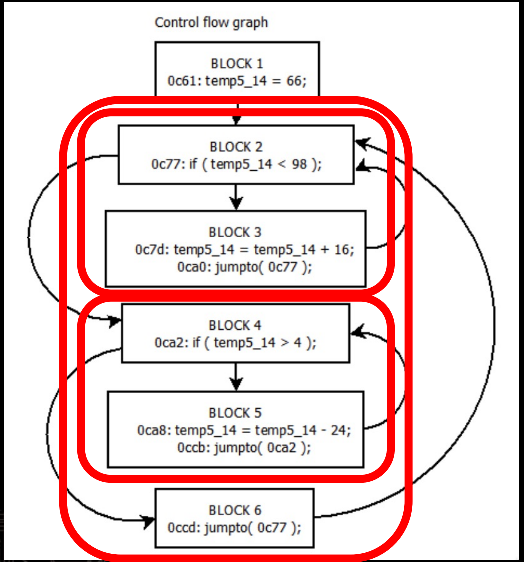

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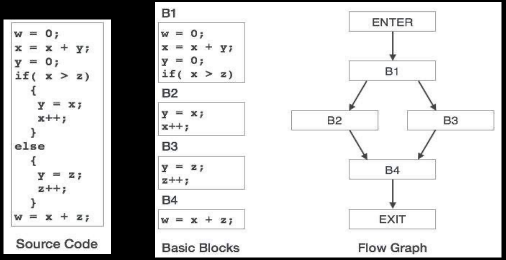

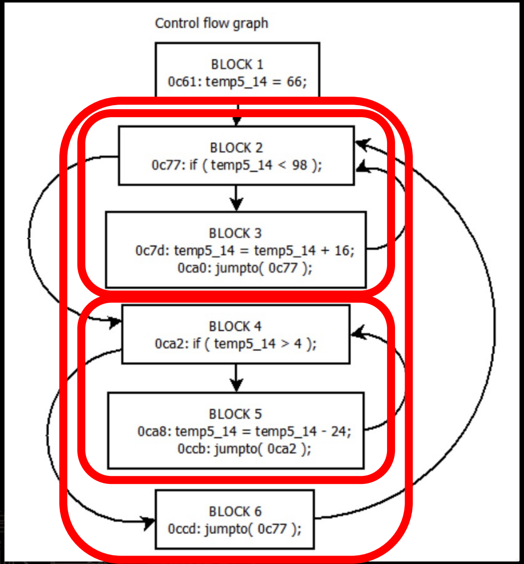

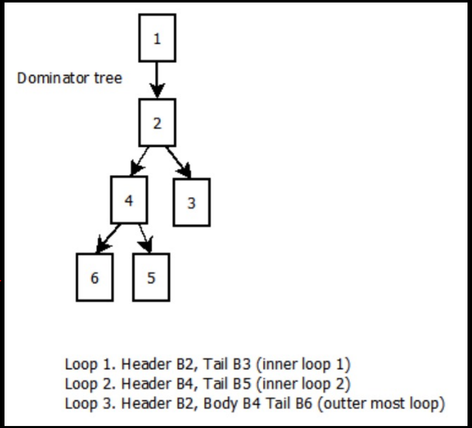

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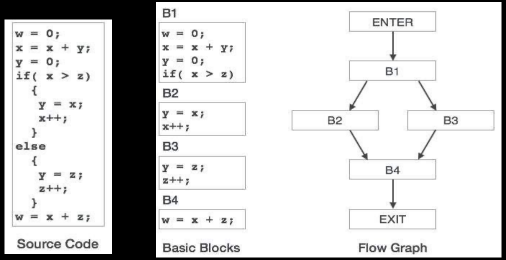
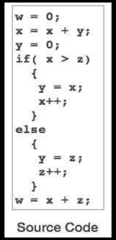


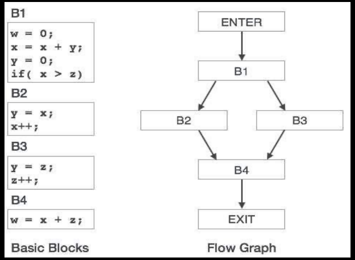
- Why do we need to construct a CFG
  1. To have correct executing logics
  2. To eliminate loops
  3. To transform into SSA form and lift to a higher-level abstraction

```
x := n
y := m
x := x + y
return x
```

```
x0 := n
y0 := m
x1 := x0 + y0
return x1
```

CFG (Control Flow Graph)





- Why do we need to construct a CFG
  1. To have correct executing logics
  2. To eliminate loops
  3. To transform into SSA form and lift to a higher-level abstraction

- Okay, then how do we get our hands dirty in making a CFG?
- To make it easy, **intermediate-language-based analysis** could make it easy for us (**BNIL**, **P-Code**, **Microcode**, **AIL**)

CFG (Control Flow Graph)

Ethereum Bytecode ▾ Linear ▾ Low Level IL ▾

```
00000000  int256_t _dispatcher()
⚠ This function has been analyzed with basic analysis only. Enable full analysis of this function.

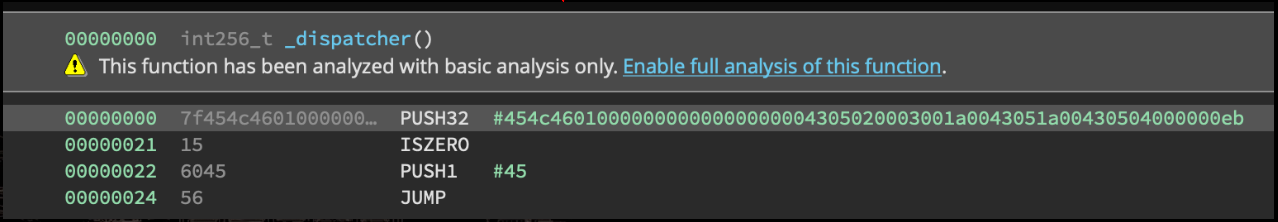
   0 @ 00000000  push(0x430504000000eb)
   1 @ 00000021  push(pop == 0)
   2 @ 00000022  push(0x45)
   3 @ 00000024  temp0.32 = pop
   4 @ 00000024  temp0.32 = 0x45
   5 @ 00000024  jump(temp0.32 => 6 @ 0x46)

   6 @ 00000046  push(0x2c20776f726c640a)
   7 @ 00000054  push(0)
   8 @ 00000055  temp0.32 = pop
   9 @ 00000055  temp0.32 = 0
  10 @ 00000055  temp1.32 = pop
  11 @ 00000055  temp1.32 = 0x2c20776f726c640a
  12 @ 00000055  [temp0.32].32 = temp1.32
  13 @ 00000056  push(0xc)
  14 @ 00000058  push(0x13)
  15 @ 0000005a  <return> jump(pop)

00000025                00 00 00-00 00 20 00 01 00 00 00-00 00 00 00 00 00 00 b9-47 00 43 05 b2 0d cd 80      ..... .............G.C.....
00000040  34 0d 93 cd 80                                                                                   4....
```

CFG from Binary Ninja

- To guide BN to construct a CFG from an unknown architecture, we firstly need to convert the machine code to the disassembly



CFG from Binary Ninja

- Secondly, we need to tell BN when to branch out, and therefore, BN will construct the CFG for us

CFG from Binary Ninja

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  - Having said that, branches information are sometimes hard to be deduced
  - VSA (Value Set Analysis) is a static analysis approach that finds an over-approximation of the values that a location could take at a given program point
  - This can be used to understand the possible targets of indirect jumps, or the possible targets of memory / register write operations

CFG from Binary Ninja

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  - Having said that, branches information are sometimes hard to be deduced
  - VSA (Value Set Analysis) is a static analysis approach that finds an over-approximation of the values that a location could take at a given program point
  - This can be used to understand the possible targets of indirect jumps, or the possible targets of memory / register write operations
  - Though it suffers from a lack of accuracy, it’s sound

CFG from Binary Ninja

- Secondly, we need to tell BN when to branch out, and therefore, BN will construct the CFG for us
  - Due to the introduction of the “Gas”, we can simulate every execution steps of smart contracts
  - We set an upper bound of the remaining amount of the gas, there will be no infinite steps to follow, or issues like DoS (Denial of Service)

CFG from Binary Ninja

- Secondly, we need to tell BN when to branch out, and therefore, BN will construct the CFG for us
  - Due to the introduction of the “Gas”, we can simulate every execution steps of smart contracts
  - We set an upper bound of the remaining amount of the gas, there will be no infinite steps to follow, or issues like DoS (Denial of Service)
  - We can now get accurate values that a location could take at a given program point of stacks / memories / and built-in functions

CFG from Binary Ninja

Thanks to [EthereumJS Monorepo]

```
function compute_CFG() {
    function getBranch(instruction, stack) {
        const branch = {
            instruction,
            nextPc: -1,
            trueBranch: parseInt(stack[0], 16),
            falseBranch: instruction.pc + 1,

            runState: {
                rawMemory: undefined,
                rawStack: undefined,
            }
        };
```

```
        if (instruction.name === 'JUMPI' && stack.length >= 2) {
            branch.nextPc = (stack[1] > 0) ? branch.falseBranch : branch.trueBranch;

            return branch;
        }

        if (instruction.name === 'JUMP' && stack.length >= 1) {
            if (this.jumpTable.hasOwnProperty(instruction.pc)) {
                this.jumpTable[instruction.pc].instructions.push(branch.instruction);
                this.jumpTable[instruction.pc].trueBranches.push(branch.trueBranch);
            } else {
                this.jumpTable[instruction.pc] = { instructions: [instruction], trueBranches: [branch.trueBranch] };
            }
        }
```

CFG from Binary Ninja

```
[00]  PUSH32  454c46010
[21]  ISZERO
[22]  PUSH1   45
[24]  JUMP
[25]  STOP
[26]  STOP
[27]  STOP
```

STACK

45
0


```
  null,
  null,
  {
    "instructions": [
      {
        "pc": 36,
        "name": "JUMP"
      }
    ],
    "trueBranches": [
      69
    ]
  }
]%
```

CFG from Binary Ninja

```
// Now, we get the interpreter
this.interpreter = new Interpreter((await this.startExecution(value, data)).interpreter);

// start!
this.round += 1;
this.interpreter.reset(this.gasLimit);
await this.interpreter.run();

while (grey.length) {
    const branch = grey.shift();

    this.round += 1;
    this.interpreter.reset(this.gasLimit);
    await this.interpreter.run(branch);
```

```
bb.walked = true;

// get the branch that won't follow this time
const branch = getBranch.call(this, this.instructions[pc], stack);

if (branch) {
    branch.runState.rawMemory = Buffer.from(this.interpreter._interpreter._runState.memory._store);
    branch.runState.rawStack = Array.from(this.interpreter._interpreter._runState.stack._store);
    branch.runState.rawStack.pop();
    branch.runState.rawStack.pop();
    grey.unshift(branch);
}
```

CFG from Binary Ninja

```
if (this.instructions[pc].name === 'MSTORE') {
    this.mStores[pc] = [stack[0], stack[1]];
}

if (this.instructions[pc].name === 'RETURNDATASIZE') {
    this.returnDataSizes[pc] = bigIntToHex(this.interpreter.getReturnDataSize());
}
```

```
null,
null,
null,
null,
null,
[
  "0x0",
  "0x68656c6c6f2c20776f726c640a"
]
```

```
const funcPc = (bb.funcSig) ? ((branch) ? branch.trueBranch : parseInt(stack[0], 16)) : null;

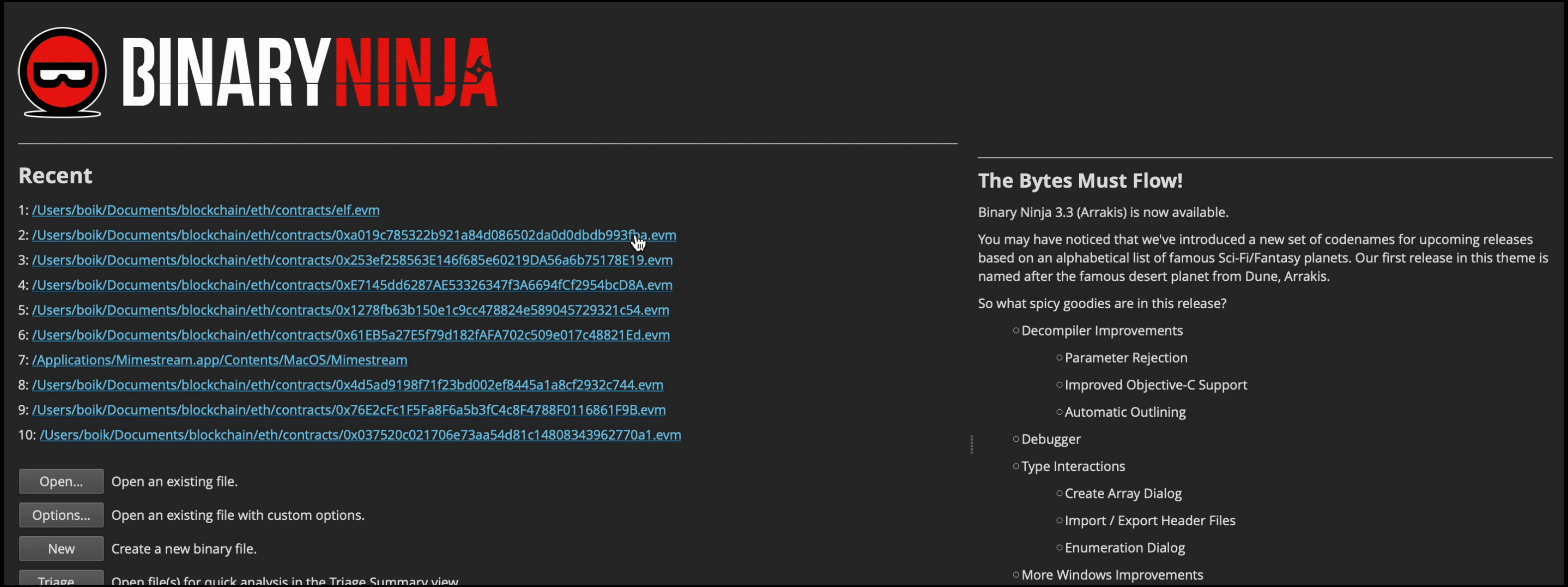
// if we just found a possible function signature, we label the function
if (funcPc) {
    this.add_function({ pc: funcPc, name: bb.funcSig });
}
```

```
null,
null,
null,
null,
null,
"0x0"
```

CFG from Binary Ninja

- Finally, we give BN these pieces of information via its APIs
  - **get_instruction_text**
    - A list of InstructionTextToken objects for the instruction at the given virtual address with data
  - **get_instruction_info**
    - An InstructionInfo object for the instruction at the given virtual address with data
  - **get_instruction_low_level_il**
    - Appends LowLevelILExpr objects to the il variable for the instruction at the given virtual address with data

CFG from Binary Ninja



Outline

- Intro to Blockchain & Web3
- EVM-based Smart Contract Basics
- Reverse Engineering & CFG
- Cases & Futures

Cases & Futures

- SAG? from DEF CON 2018 Quals
  - It gives us a proxy contract

```
contract SagProxy {
    event PrizeRequest(bytes32 msgHash, uint8 v, bytes32 r, bytes32 s);
    event PrizeReady(address winner, bytes prize);

    Sag private sag;

    address private owner;
```

Cases & Futures

- SAG? from DEF CON 2018 Quals
    - It gives us a proxy contract to interact with the private contract behind

```
contract SagProxy {
    event PrizeRequest(bytes32 msgHash, uint8 v, bytes32 r, bytes32 s);
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```

58b0f492ac22be013a619afc0486aaa433dad38d928098dabe8657
26020018360001916600019168152602001826000191660001916
05b9493505050505600a165627a7a72305820563788b2b3c0a0289
0000000000000a019c785322b921a84d086502da0d0dbdb993fba

Cases & Futures

- SAG? from DEF CON 2018 Quals
  - It gives us a proxy contract to interact with the private contract behind
  - All we know is to pass the function: **gamble(guess, seed)**

```
    function gamble(uint256 guess, uint256 seed) public
    {
        sag.gamble(guess, seed);
    }
```

Cases & Futures

- SAG? from DEF CON 2018 Quals
  - It gives us a proxy contract to interact with the private contract behind
  - All we know is to pass the function: **gamble(guess, seed)**
  - Then, we request the prize

```
function requestPrize(bytes32 msgHash, uint8 v, bytes32 r, bytes32 s) public
    returns (bool is_winner)
{
    if (ecrecover(msgHash, v, r, s) == msg.sender && sag.isWinner(msg.sender)) {
        emit PrizeRequest(msgHash, v, r, s);
        return true;
    }
    return false;
}
```

Cases & Futures

- SAG? from DEF CON 2018 Quals
    - It gives us a proxy contract to interact with the private contract behind
    - All we know is to pass the function: **gamble(guess, seed)**
    - Then, we request the prize
    - The Sag contract isn't published and verified, so we reverse it

Cases & Futures

Cases & Futures

- To-dos in the future
  - Make it more “smart-contract-like” in decompilation, not c-like
  - Have a plugin like IDA F.L.I.R.T. Technology
    - Fast Library Identification and Recognition Technology
  - Best-effort to decode the 4-byte signatures

References

- REVERSE ENGINEERING A CONTRACT
- Decompiler - how to structure loops
- CS153: Compilers Lecture 23: Static Single Assignment Form
- crytic/ethersplay

THANK YOU!

HAVE QUESTIONS?

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