FIRMWARE SLAP: AUTOMATING DISCOVERY OF EXPLOITABLE VULNERABILITIES IN FIRMWARE

CHRISTOPHER ROBERTS

WHO AM I

- Researcher at REDLattice Inc.
- Interested in finding bugs in embedded systems
- Interested in program analysis
- CTF Player

A QUICK BACKGROUND IN EXPLOITABLE BUGS

DARPA CYBER GRAND CHALLENGE

- Automated cyber reasoning systems:
  - Find vulnerabilities
  - Exploit vulnerabilities
  - Patch vulnerabilities
- Automatically generates full exploits and proof of concepts.

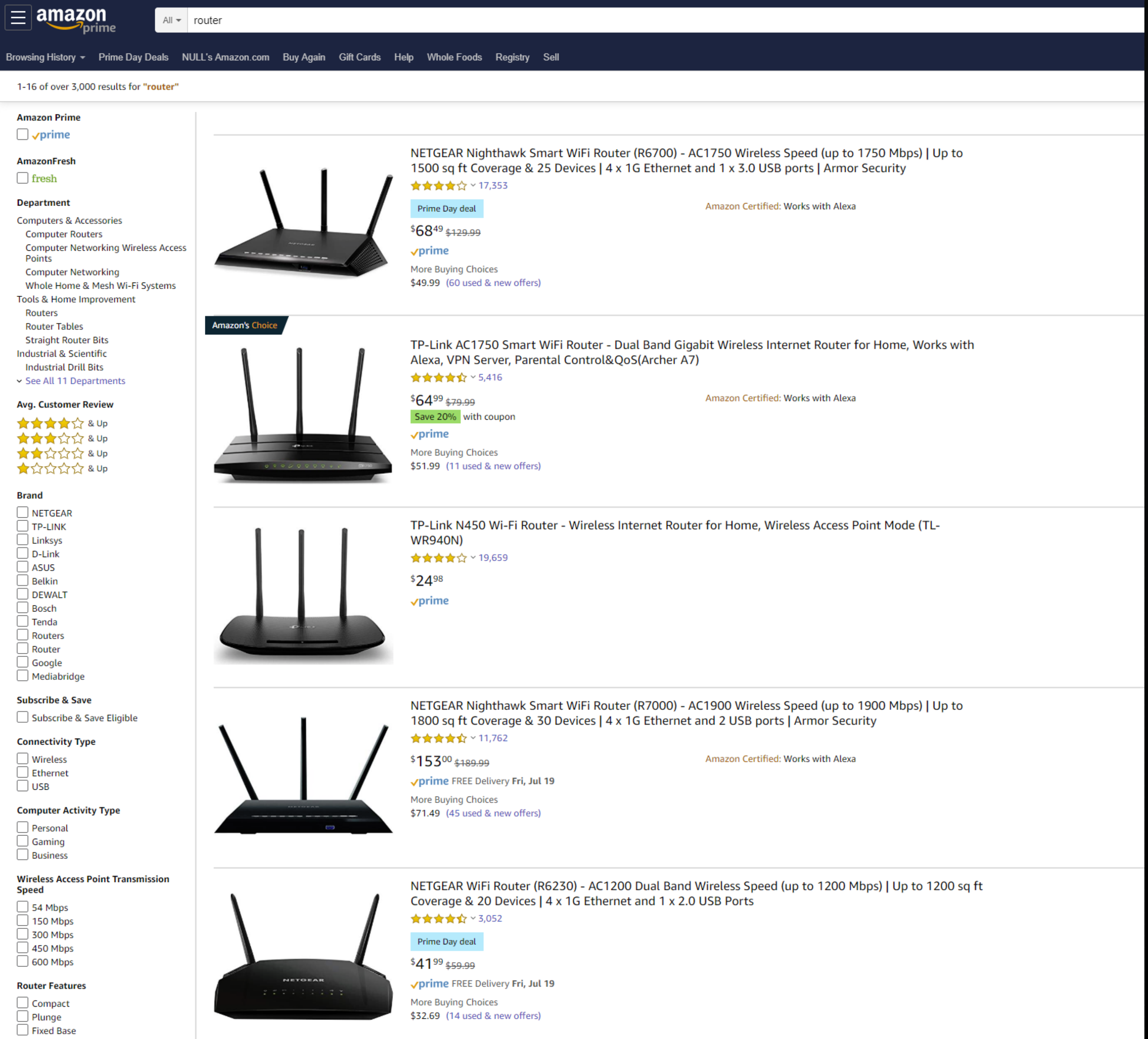
PREVENTING BUGS AUTOMATICALLY

- Source level protections
  - LLVM's Clang static analyzers
- Compile time protections
  - Non-executable stack
  - Stack canaries
  - RELRO
  - _FORTIFY_SOURCE
- Operating system protections
  - ASLR

PREVENTING BUGS AUTOMATICALLY

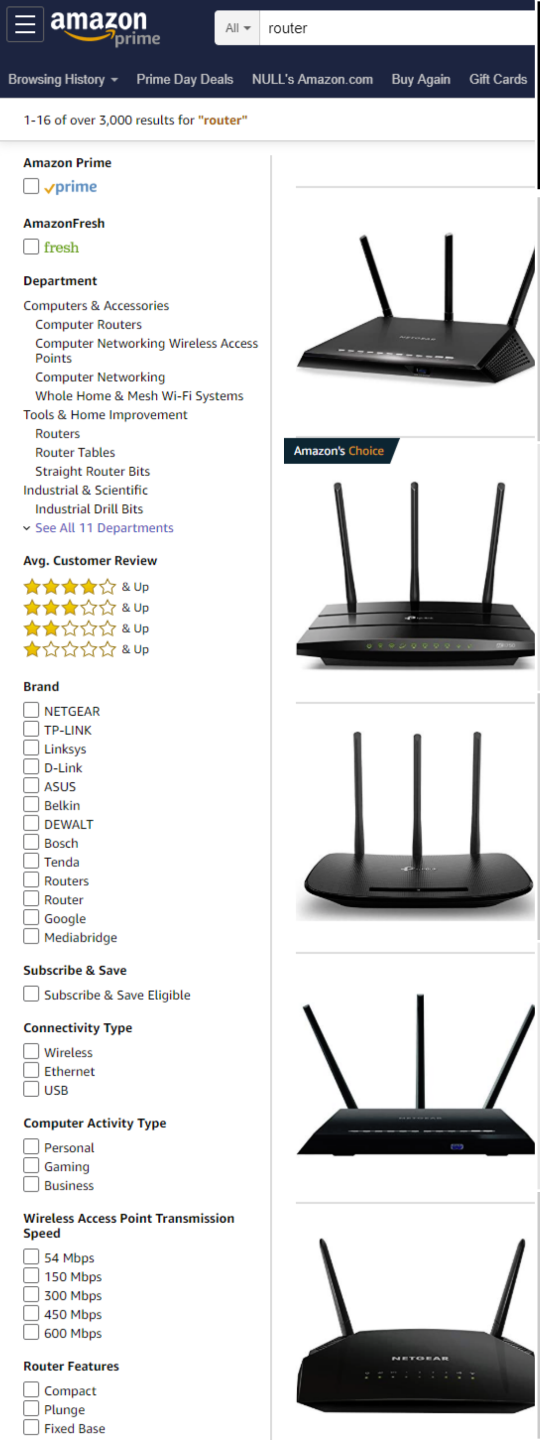
In Embedded Devices

- Source level protections
  - LLVM's Clang static analyzers - Maybe
- Compile time protections
  - Non-executable stack - Maybe
  - ~~Stack canaries~~
  - ~~RELRO~~
  - ~~_FORTIFY_SOURCE~~
- Operating system protections
  - ~~ASLR~~



EXPLOIT MITIGATIONS

- There has to be an exploit to mitigate it, right?



Non-executable stack	Stack Canaries	RELRO	_FORTIFY SOURCE	ASLR
✓	✗	✗	✗	✗
✗	✗	✗	✗	✗
✓	✗	✗	✗	✗
✗	✗	✗	✗	✗
✗	✗	✗	✗	✗

ALMOND 3


Home
Connected Sensors
Add Sensor
Wireless Settings
Range Extender
Status
More

DEMO

- CVE-2019-13087
- CVE-2019-13088
- CVE-2019-13089
- CVE-2019-13090
- CVE-2019-13091
- CVE-2019-13092

CONCOLIC ANALYSIS

- Symbolic Analysis + Concrete Analysis
  - Lots of talks already on this subject.
  - Really good at find specific inputs to trigger code paths
  - For my work in Firmware Slap I used angr!
    - Concolic analysis
    - CFG analysis
    - Used in Cyber Grand Challenge for 3rd place!

BUILDING REAL INPUTS FROM SYMBOLIC DATA

- Symbolic Variable Here
  - get_user_input()
- To get our “You did it” output
  - angr will create several program states
  - One has the constraints:
    - x >= 200
    - x < 250
  - angr sends these constraints to it’s theorem prover to give:
    - X=231 or x=217 or x=249…

```
int x = get_user_input();
if (x >= 200)
{
    if (x < 250)
    {
        printf("You did it!\n");
    }
    else
    {
        printf("WRONG\n");
    }
}
else
{
    printf("WRONG\n");
}
```

- Symbolically represent more of the program state.
  - Registers, Call Stack, Files
- Query the analysis for more interesting conditions
  - Does a network read influence or corrupt the **program counter**?
  - Does network data get fed into sensitive system calls?
- Can we track all reads and writes required to trigger a vulnerability?

WHERE DOES CONCOLIC ANALYSIS FAIL?

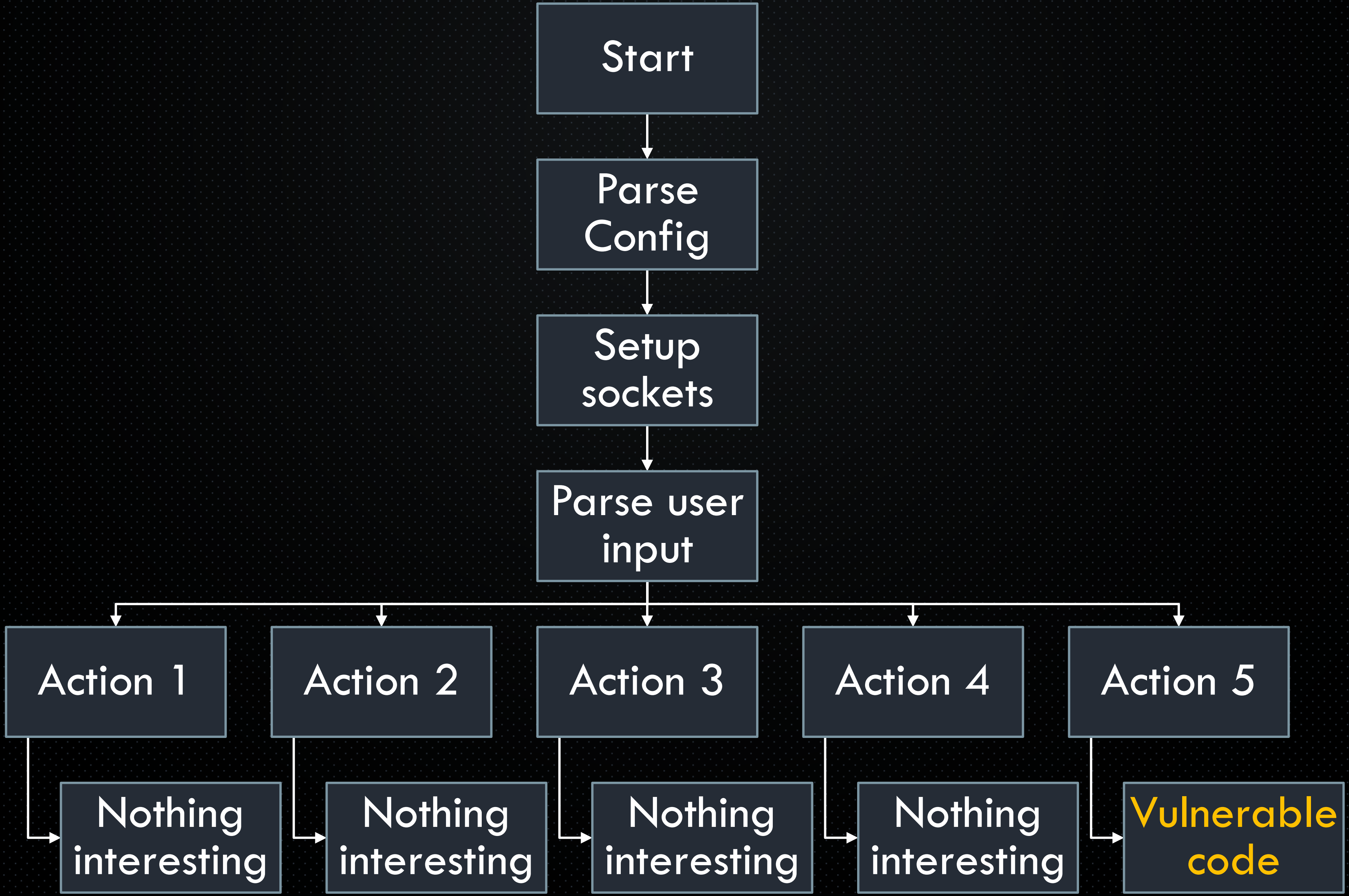
```python
import angr

project = angr.Project('bin/lighttpd')

project.execute()
```

LIGHTTPD
fly light.

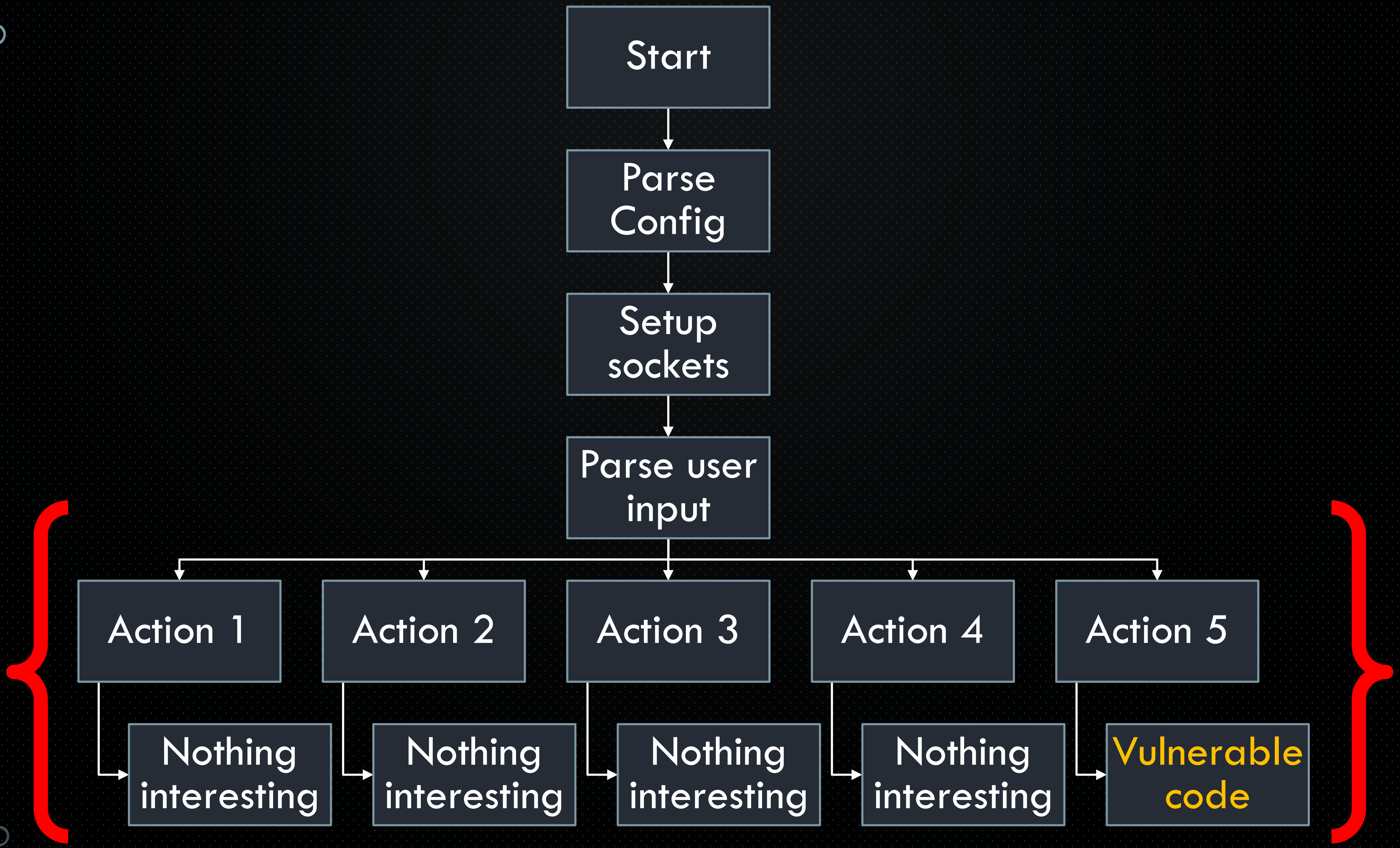
Memory Usage

- **Big code bases**
- Angr is trying to map out every single potential path through a program. Programs of non-trivial size will eat all your resources.
- A compiled lighttpd binary might be ~200KB
- Angr will run your computer out of memory before it can example every potential program state in a webserver
- Embedded system's firmware can be a lot larger…

- Challenge:
  - Model complicated binaries with limited resources
  - Model unknown input
  - Identify vulnerabilities in binaries
  - Find binaries and functions that similar to one-another


Start
Parse Config
Setup sockets
Parse user input
Action 1
Action 2
Action 3
Action 4
Action 5
Nothing interesting
Nothing interesting
Nothing interesting
Nothing interesting
Vulnerable code

- Underconstraining concolic analysis:
  - Values from hardware peripherals and NVRAM are UNKNOWN
  - Spin up and initialization consumes valuable time and resources
  - Configs can be setup any number of ways
- Skip the hard stuff
  - Make hardware peripherals and NVRAM return symbolic variables
  - Start concolic analysis after the initialization steps



Start
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Setup sockets
Parse user input
Action 1
Action 2
Action 3
Action 4
Action 5
Nothing interesting
Nothing interesting
Nothing interesting
Nothing interesting
Vulnerable code

MODELING FUNCTIONS

- angr can analyze code at this level, but it needs to know where to start.
- Ghidra can produce a function prototype that angr can use to analyze a function…

- Finding bugs in binaries
  - Recover every function prototype using ghidra
  - Build an angr program state with information with symbolic arguments from the prototype
  - Run each analysis job in parallel

FINDING BUGS IN FUNCTIONS

- Demo

- With less code to analyze we can introduce more heavy-weight analysis
  - Tracking memory instructions imposed by all instructions
  - Memory regions tainted by user supplied arguments
  - Mapping memory loading actions to values in memory.

- Every step through a program
  - Store any new constraints to user input
  - Does user input influence a system() call or corrupt the program counter
  - Does user input taint a stack or heap variable

```
Command Injection found in internet.cgi at remove_routing_rule
void remove_routing_rule(undefined4 uParm1,undefined4 uParm2,undefined4 uParm3);
        a0:4 : 0xffffe000 -> b'`reboot` @@@@@ @@  '
        a1:4 : 0xffffffc0 -> b'255.255.255.255'
        a2:4 : 0xfffffffc -> b'@ @   @  @@ @    @ @@'
Injected Memory Location
        0x7ffefed8 -> b'route del -host `reboot` @@@@@ @@    dev @ @   @  @@ @
'

Tainted memory values
remove_routing_rule+0x7c in internet.cgi (0x4019d8)
        Memory load addr 0xffffe000
        Memory load value b'`reboot` @@@@@ @@  '

remove_routing_rule+0xc4 in internet.cgi (0x401a20)
        Memory load addr 0x7ffefed8
        Memory load value b'route del -host `reboot` @@@@@ @@  '

remove_routing_rule+0x140 in internet.cgi (0x401a9c)
        Memory load addr 0x7ffefed8
        Memory load value b'route del -host `reboot` @@@@@ @@   '

remove_routing_rule+0x160 in internet.cgi (0x401abc)
        Memory load addr 0x7ffefee8
        Memory load value b'`reboot`'
```

```c
void remove_routing_rule(char *iptable_arg,char *netmask_arg,char *inet_device_arg)
{
  int iVar1;
  size_t buf_len;
  size_t sVar2;
  size_t buf_len2;
  char *user_buf;
  char acStack276 [256];

  strlcpy(&user_buf,"route del ",0x100);
  iVar1 = strcmp(netmask_arg,"255.255.255.255");
  if (iVar1 == 0) {
    buf_len = strlen((char *)&user_buf);
                    /* -host */
    *(undefined4 *)((int)&user_buf + buf_len) = 0x736f682d;
    acStack276[buf_len] = 't';
    acStack276[buf_len + 1] = ' ';
    acStack276[buf_len + 2] = 0;
  }
  else {
    buf_len2 = strlen();
                    /* -net */
    *(undefined4 *)((int)&user_buf + buf_len2) = 0x74656e2d;
    acStack276[buf_len2] = ' ';
    acStack276[buf_len2 + 1] = 0;
  }
  strcat((char *)&user_buf,iptable_arg);
  sVar2 = strlen((char *)&user_buf);
  *(undefined *)((int)&user_buf + sVar2) = 0x20;
  *(undefined *)((int)&user_buf + sVar2 + 1) = 0;
  iVar1 = strcmp(netmask_arg,"255.255.255.255");
  if (iVar1 != 0) {
    snprintf((char *)&user_buf,0x100,"%s netmask %s",&user_buf,netmask_arg);
  }
  snprintf((char *)&user_buf,0x100,"%s dev %s ",&user_buf,inet_device_arg);
  system((char *)&user_buf);
  return;
}
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  char *user_buf;
  char acStack276 [256];

  strlcpy(&user_buf,"route del ",0x100);
  iVar1 = strcmp(netmask_arg,"255.255.255.255");
  if (iVar1 == 0) {
    buf_len = strlen((char *)&user_buf);
                    /* -host */
    *(undefined4 *)((int)&user_buf + buf_len) = 0x736f682d;
    acStack276[buf_len] = 't';
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    acStack276[buf_len + 2] = 0;
  }
  else {
    buf_len2 = strlen();
                    /* -net */
    *(undefined4 *)((int)&user_buf + buf_len2) = 0x74656e2d;
    acStack276[buf_len2] = ' ';
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  }
  strcat((char *)&user_buf,iptable_arg);
  sVar2 = strlen((char *)&user_buf);
  *(undefined *)((int)&user_buf + sVar2) = 0x20;
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  if (iVar1 != 0) {
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  }
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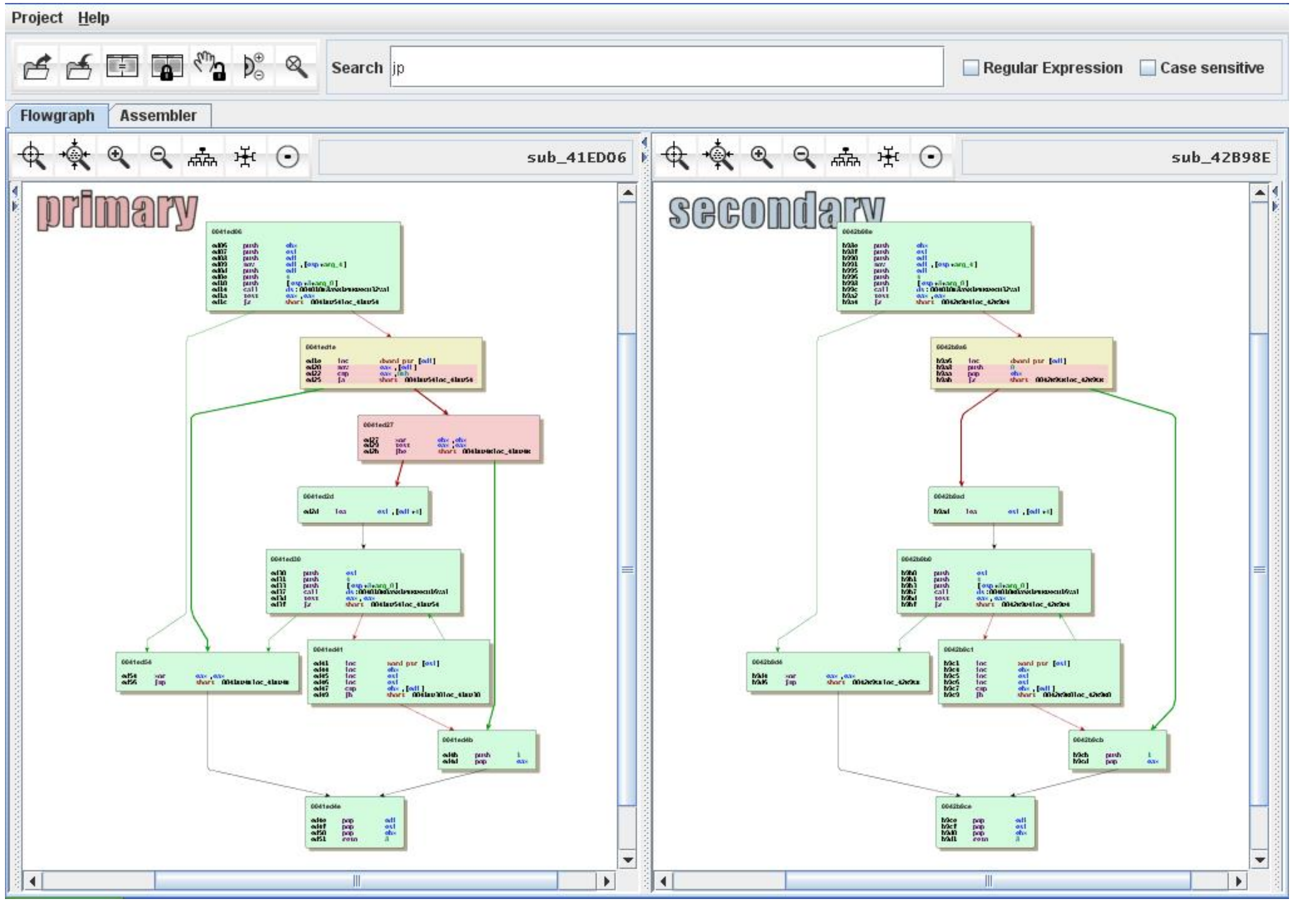
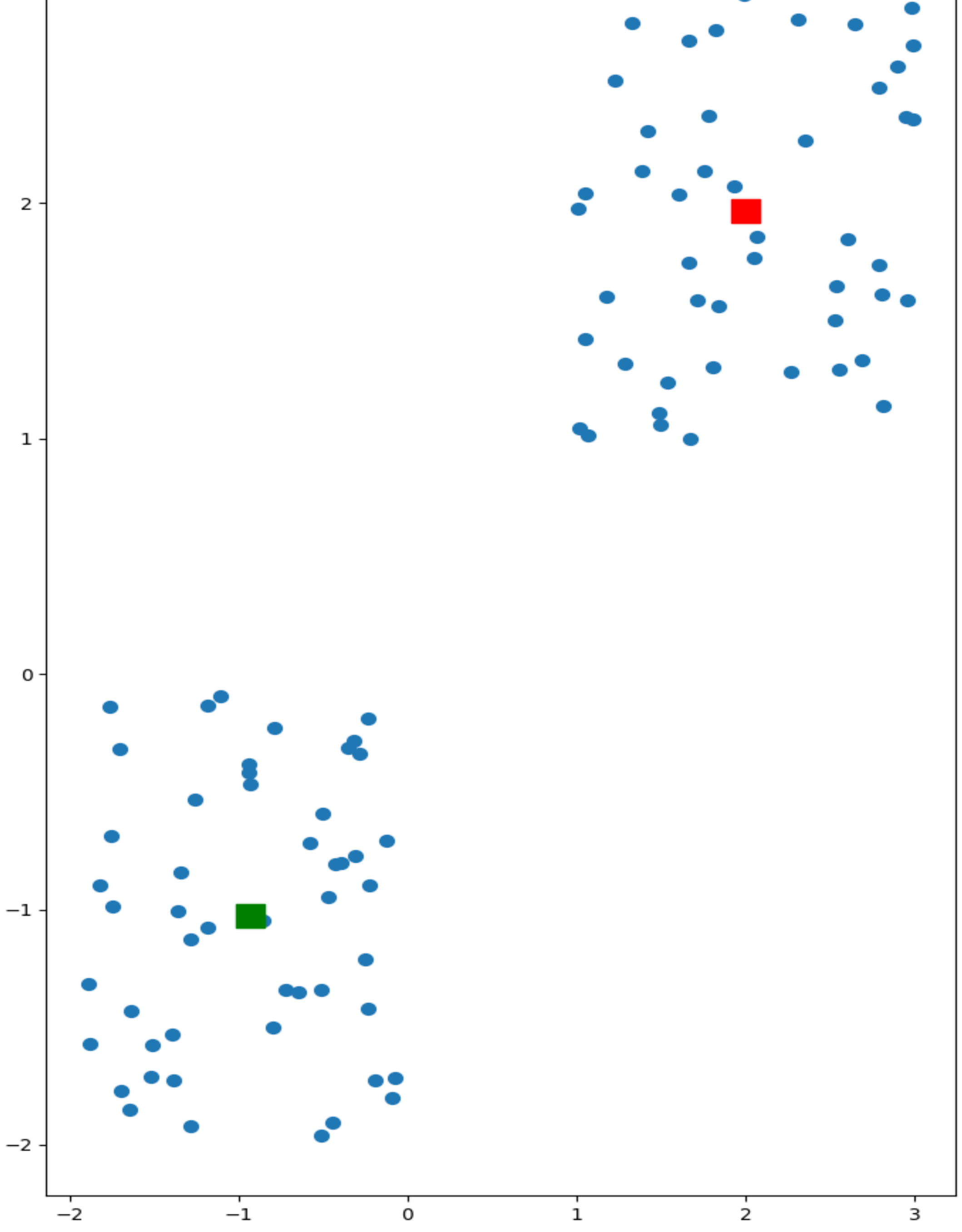


FUNCTION SIMILARITY

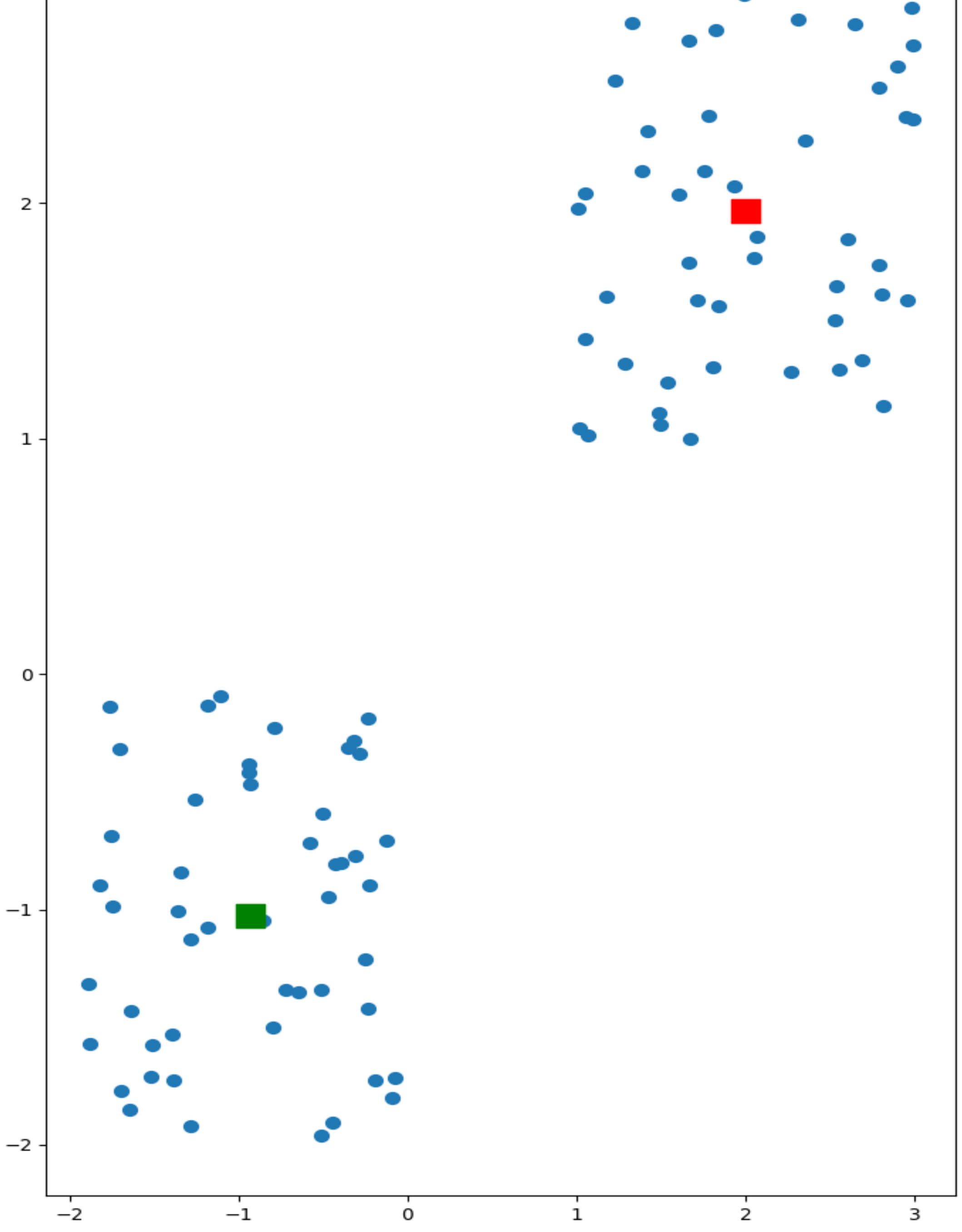
- Bindiff and diaphora are the standard for binary diffing.
- They help us find what code was actually patched when a CVE and a patch is published.
- Uses a set of heuristics to build a signature for every function in a binary
  - Basic block count
  - Basic block edges
  - Function references

- Both of these tools are tied to IDA
- The workflow is built around one-off comparisons



CLUSTERING

- Helps us understand how similar are two things?
- Extract features from each thing
  - For dots on a grid it can be:
    - X location
    - Y location



K-MEANS CLUSTERING

Extract features

Pick two random points

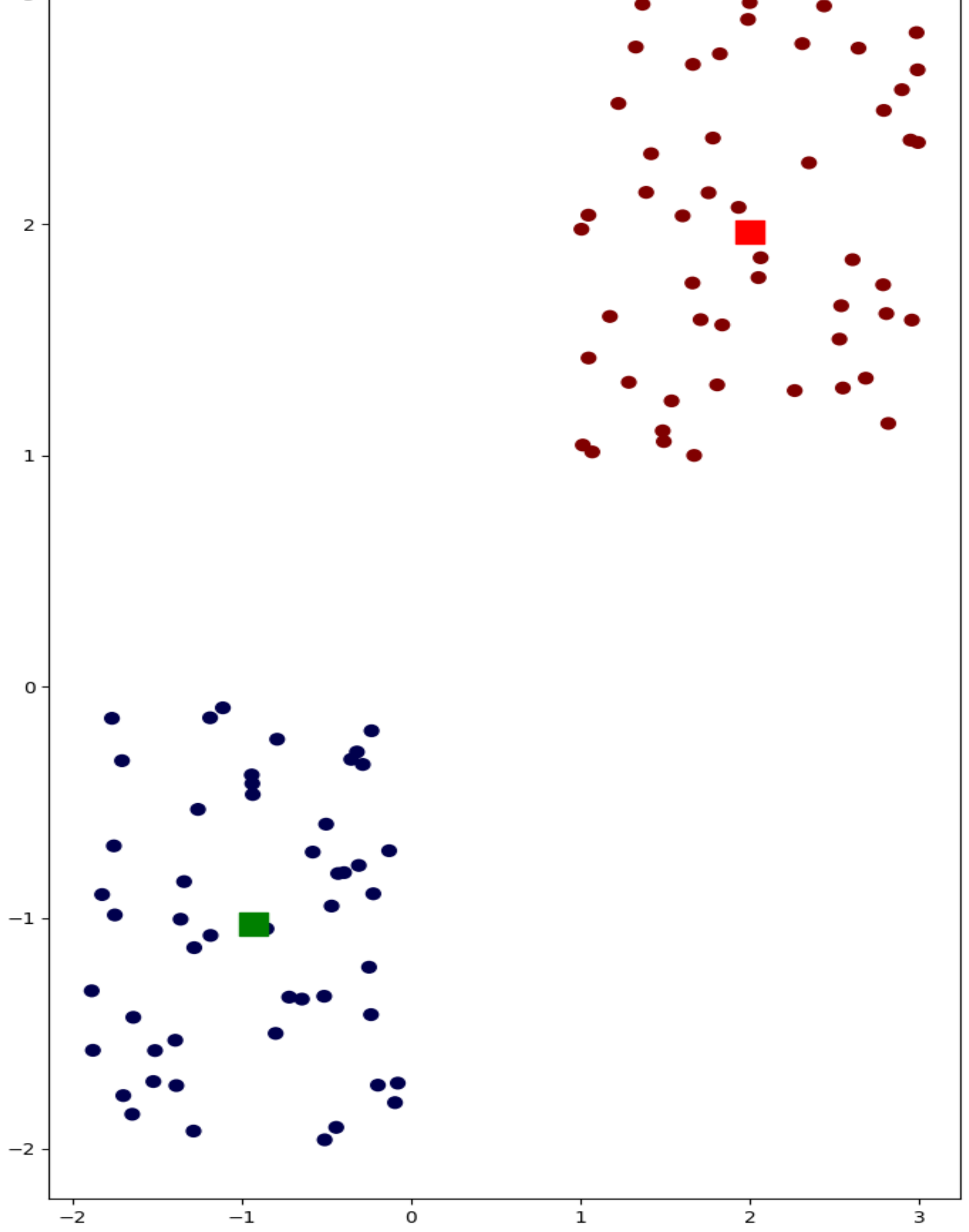
Categorize each point to one of those random points

- Use Euclidian or cosine distance to find which is closest

Pick new cluster center by averaging each category by feature and using the point closest.

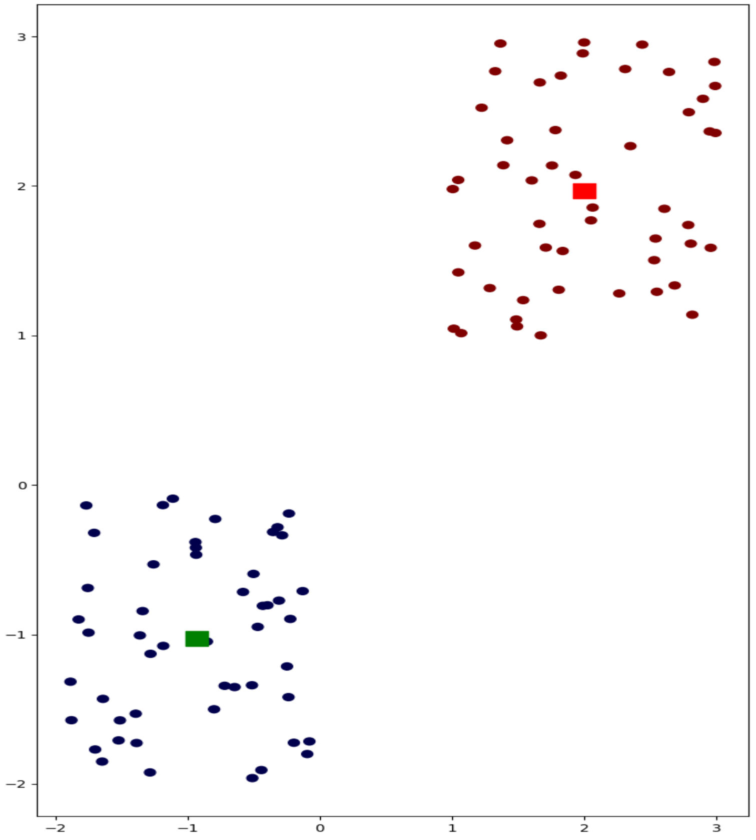
Recategorize all the points into categories.

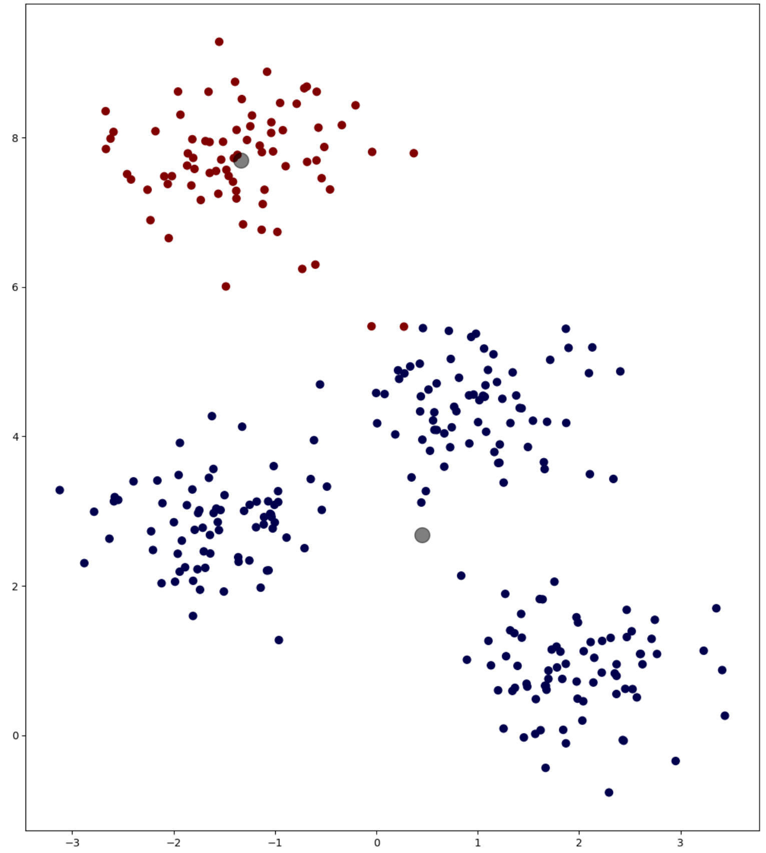
- Rinse and repeat until points don't move!



CLUSTERING – WHY THIS WORKS

- Features don't have to be numbers…
- They can be the existence (0 or 1) of:
    - String references
    - Data references
    - Function arguments
    - Basic block count
- All of these features can be extracted from reverse engineering tools like…
- Ghidra, Radare2, or Binary Ninja





IT ONLY WORKS IF YOU GUESS THE RIGHT NUMBER OF CLUSTERS

SUPERVISED CLUSTERING

- Supervised anything machine learning uses KNOWN values to cluster data
- We also know how many clusters there should be
- Our functions inside our binaries could be supervised if every function was known to be vulnerable or benign
- Embedded systems programming gives us no assurances.

SEMI-SUPERVISED CLUSTERING

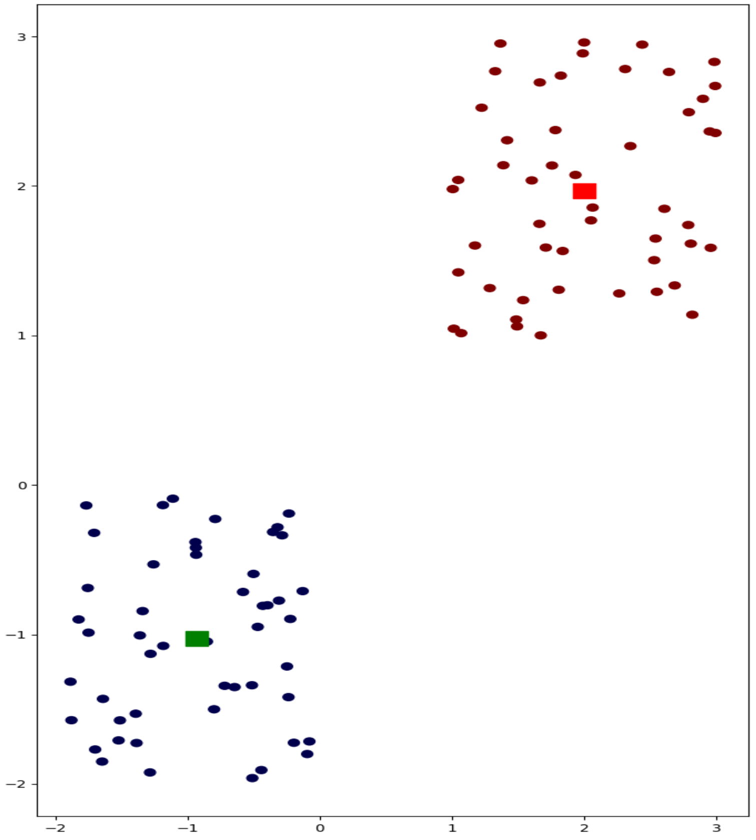
- Semi-Supervised clustering uses SOME KNOWN values to cluster data
- If we use public CVE information to find which functions in a binary are KNOWN vulnerable, we can guess that really similar functions might also be vulnerable.
- We can set our cluster count to the number of known vulnerable functions in a binary

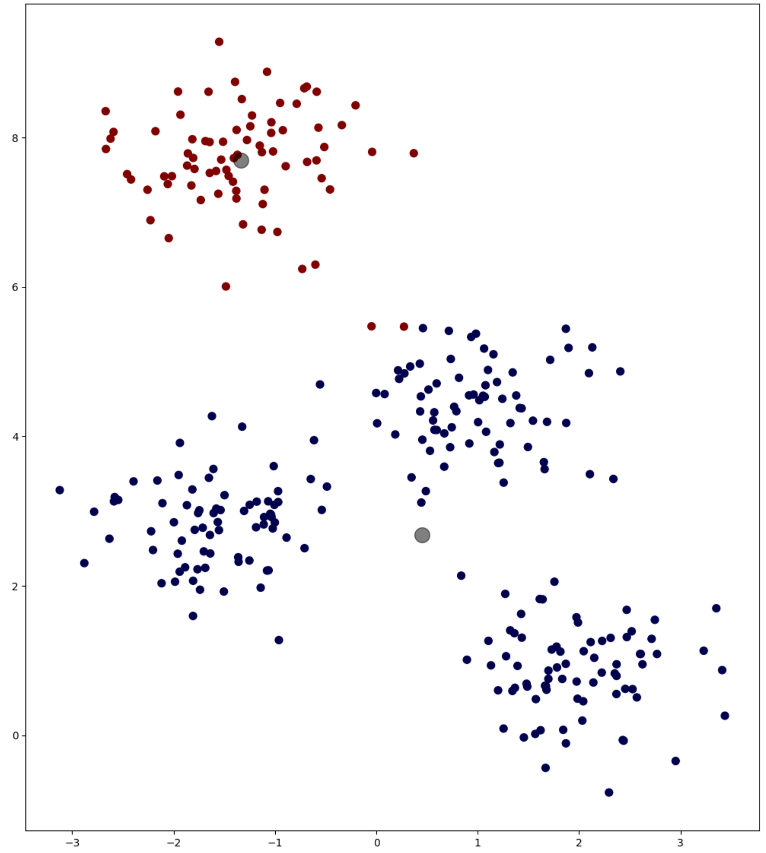
```
'CallFixup': None,
'CallingConvention': 'None',
'CallingConventionName': 'unknown',
'CallingFunctions': [{'Addr': '00400de0', 'Name': 'main'}],
'DefaultCallingConventionName': '__stdcall',
'EntryPoint': {'offset': '4207200', 'physicalAddress': '00403260'},
'ExternalLocation': None,
'HiFuncProto': 'void set_vpnpass(undefined4 uParm1);',
'HiParameterCount': 1,
'HiParameters': [{'dataType': 'undefined4',
  'name': 'uParm1',
  'size': '4',
  'slot': '0',
  'storage': 'a0:4'}],
'HiRetType': 'void',
'Key': 208,
'LocalVariables': [{'dataType': 'undefined4',
  'firstUseOffset': '0',
  'length': '4',
  'name': 'local_4',
  'register': 'None',
  'registerVariable': 'False',
  'registers': 'None',
  'source': 'DEFAULT',
  'stackOffset': '-4',
  'stackVariable': 'True',
  'uniqueVariable': 'False',
  'valid': 'True',
  'variableStorage': 'Stack[-0x4]:4'},
 {'dataType': 'undefined4',
  'firstUseOffset': '0',
  'length': '4',
  'name': 'local_8',
  'register': 'None',
  'registerVariable': 'False',
  'registers': 'None',
  'source': 'DEFAULT',
  'stackOffset': '-8',
  'stackVariable': 'True',
  'uniqueVariable': 'False',
  'valid': 'True',
  'variableStorage': 'Stack[-0x8]:4'},
 {'dataType': 'undefined4',
  'firstUseOffset': '0',
  'length': '4',
  'name': 'local_10',
  'register': 'None',
  'registerVariable': 'False',
  'registers': 'None',
  'source': 'DEFAULT',
  'stackOffset': '-16',
  'stackVariable': 'True',
  'uniqueVariable': 'False',
```


- Finding features in binaries to cluster
  - Wrote a Ghidra headless plugin to dump all function information
  - Data/String/Call references are changed to binary (0/1) it exists or it doesn't
  - All numbers are normalized
    - Being at offset 0x80000000 shouldn't matter more then having 2 function arguments.
  - Throw away useless information
    - A Chi^2 squared test is used to see how much a feature defines an item.
    - If every function has the same calling convention, the Chi^2 squared test will throw it away.

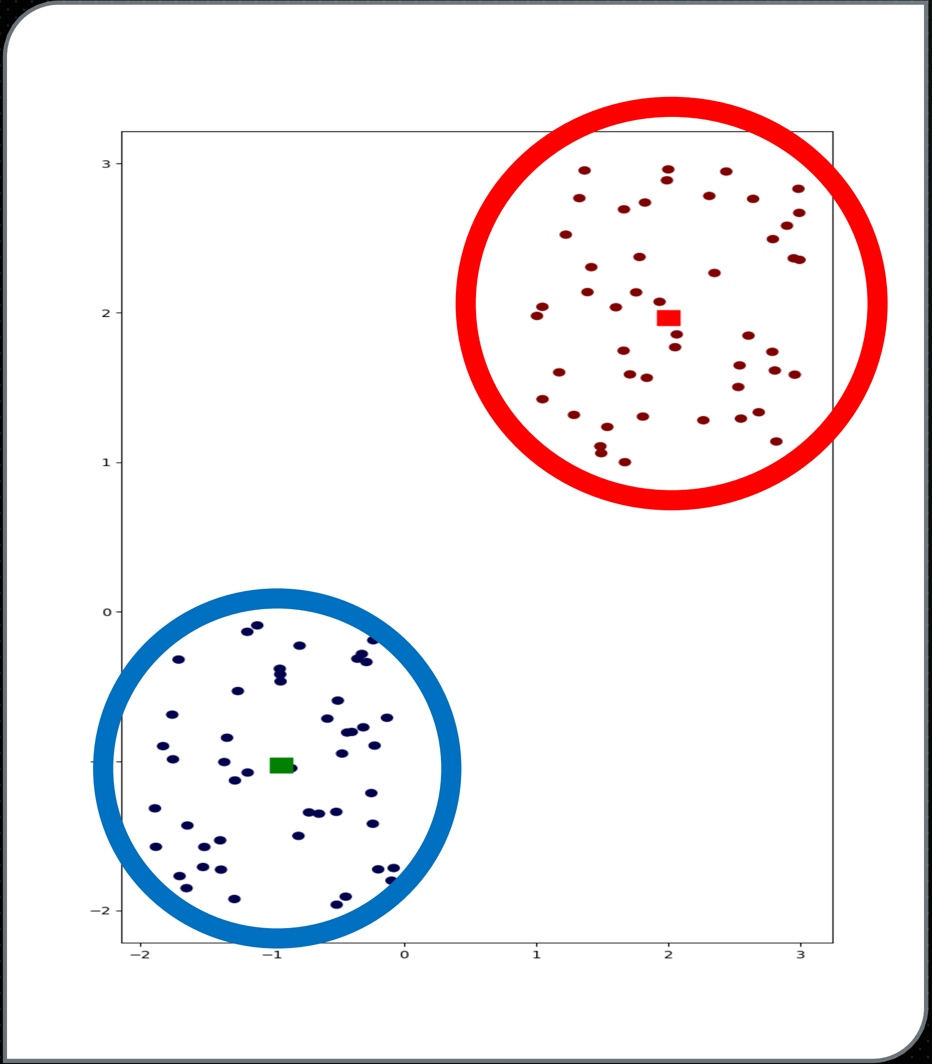
- Taking it further…
  - Selecting a better number of clusters through cluster scoring
  - Silhouette score ranks how similar each cluster of functions are

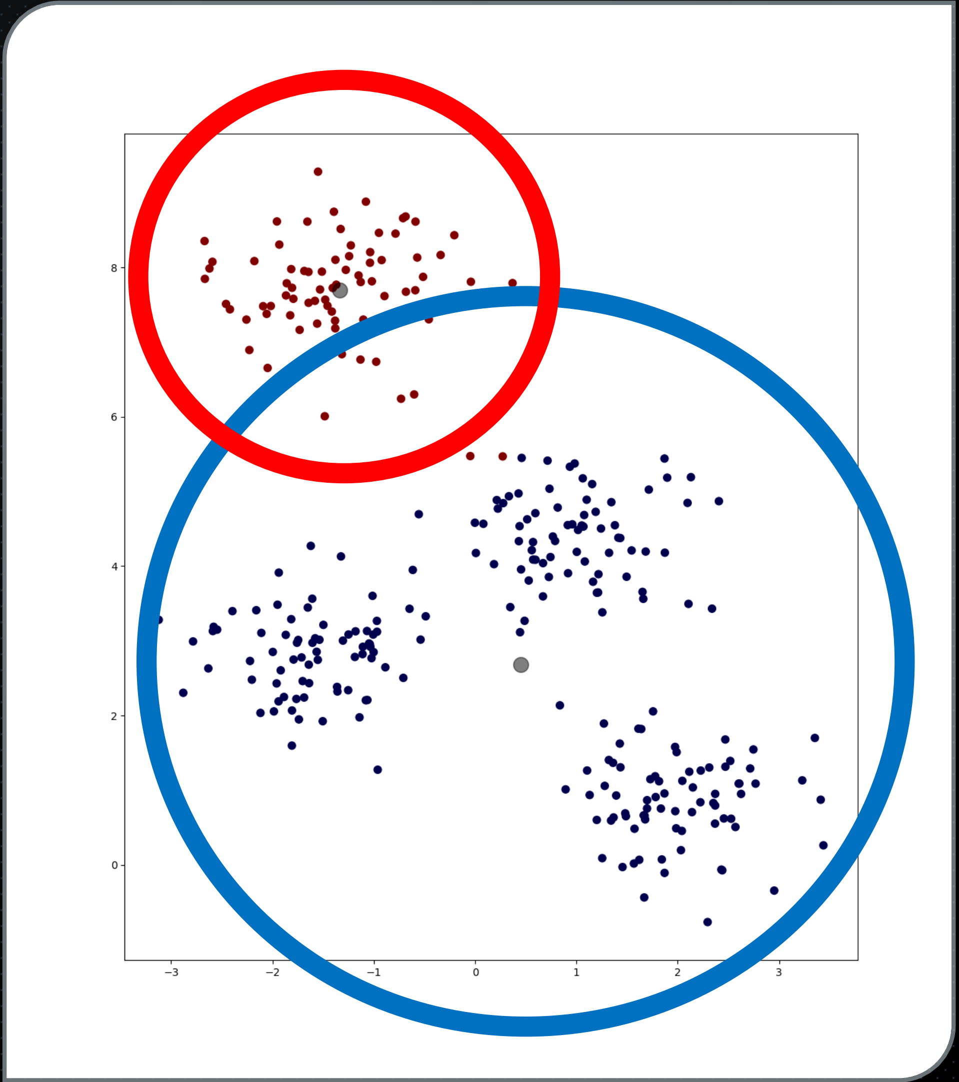
- This separates functions into clusters of similar tasks
  - String operation functions
  - Destructors/Constructors
  - File manipulation
  - Web request handling
  - etc..





SILHOUETTE SCORE





SILHOUETTE SCORE

DATA MINING + CONCOLIC ANALYSIS

- Demo
- CVE-2019-13087

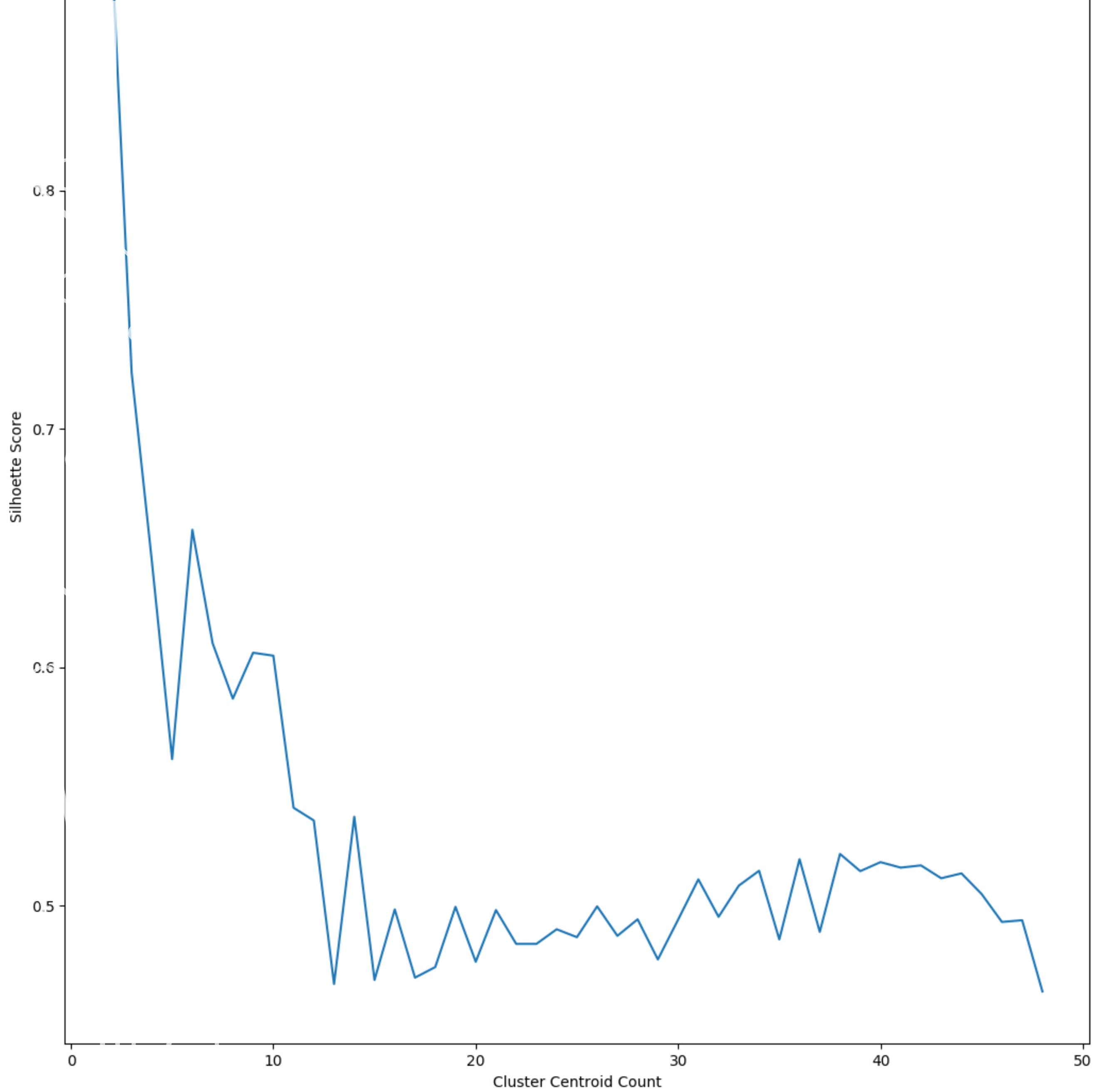
```
Similar Functions With Distances
sym.mtd_write_firmware         in upload_bootloader.cgi
        > 0.0
sym.mtd_write_firmware         in upload.cgi
        > 1.868202467580904e-05
sym.mtd_write_bootloader       in upload_bootloader.cgi
        > 0.00015272111900810348
sym.mtd_write_bootloader       in upload.cgi
        > 0.00016208252348248742
sym.write_flash_kernel_version in upload.cgi
        > 0.0013812828298550572
sym.write_flash_kernel_version in upload_bootloader.cgi
        > 0.001381969125964222
sym.access_policy_handle       in wireless.cgi
        > 0.0030522430530255384
sym.compile_regex              in wireless.cgi
        > 0.003158924286679299
```

- Findings
  - Code clones
  - Calling patterns
  - Similar function calls
  - Similar data references
  - Similar file access

```c
int mtd_write_firmware(int param_1,int param_2,char *param_3)
{
  uint uVar1;
  char sys_buffer [516];

  snprintf(sys_buffer,0x200,
           "/bin/mtd_write -o %d -l %d write %s Kernel",param_2,
  uVar1 = system(sys_buffer);
  return uVar1;
}
```

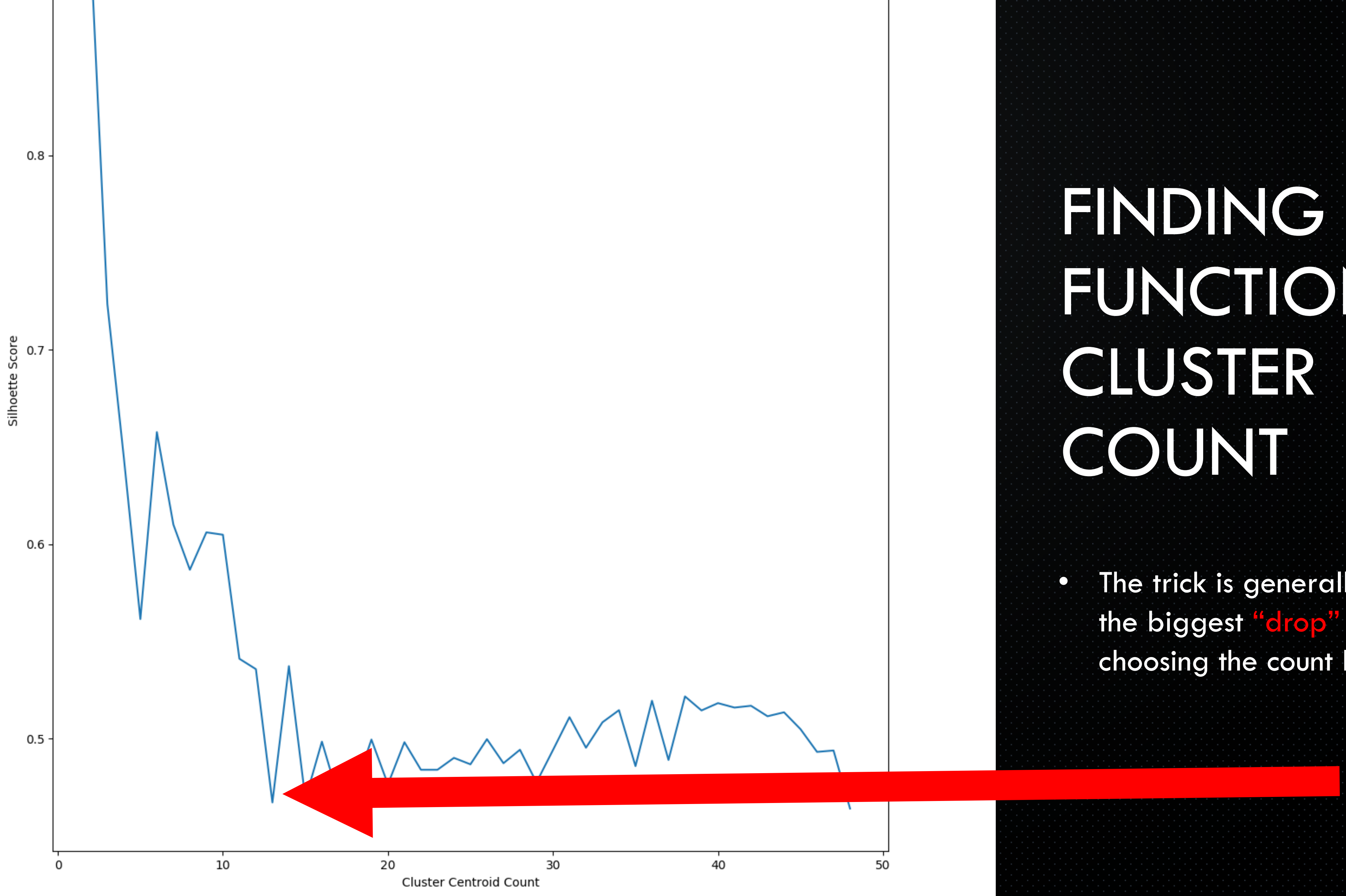
```c
void mtd_write_bootloader(int param_1,int param_2,char *param_3)
{
  char sys_buf [516];

  snprintf(sys_buf,0x200,
           "/bin/mtd_write -o %d -l %d write %s Bootloader",param_2,p
  printf("write bootloader");
  system(sys_buf);
  return;
}
```

```
Similar Functions With Distances
sym.mtd_write_firmware          in
        > 0.0
sym.mtd_write_firmware          in
        > 1.868202467580904e-05
sym.mtd_write_bootloader        in
        > 0.00015272111900810348
```



FINDING THE FUNCTION CLUSTER COUNT

The trick is generally finding the biggest "drop" and choosing the count before that

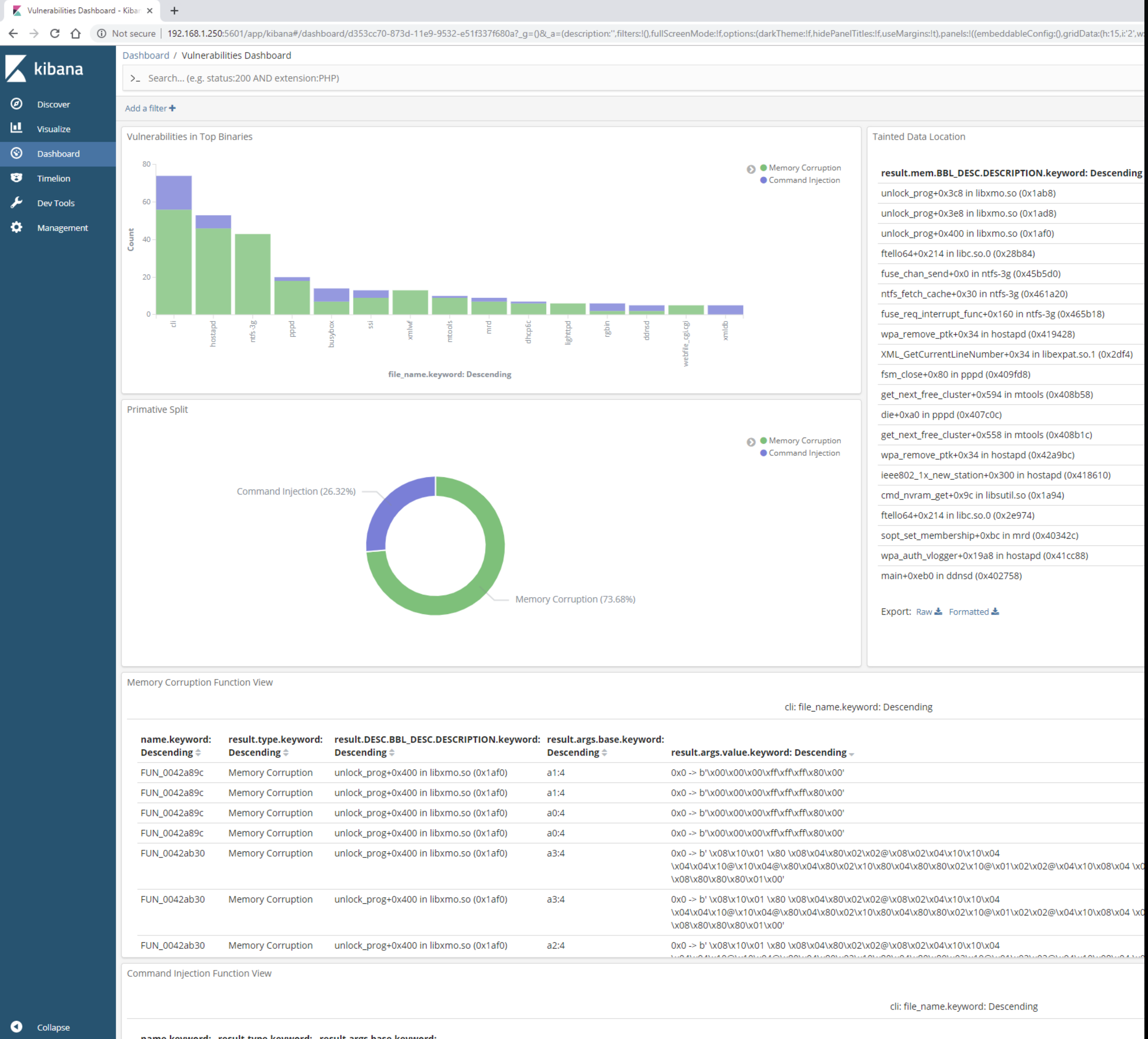


FINDING THE FUNCTION CLUSTER COUNT

- The trick is generally finding the biggest "drop" and choosing the count before that

FIRMWARE SLAP

Extract	Firmware
Locate	System root
Recover	Function prototypes from every binary
Build and run	angr analysis jobs
Extract	Best function features using SKlearn
Cluster	Functions according to best feature set
Export	Data to JSON and send into elastic search



VISUALIZING VULNERABILITY RESULTS

- All information generated as JSON from both concolic and data mining pass
- Includes script to load information into Elasticsearch and Kibana

MITIGATIONS

- Use compile time protections
- Enable your operating system's ASLR
- Buy a better router

- It’s time to bring more automation into checking our embedded systems
- Don’t blindly trust third-party embedded systems
  - I’m giving you the tools to find the bugs yourself

RELEASING

- Firmware Slap – The tool behind the demos
- The Ghidra function dumping plugin
- The cleaned-up PoCs
  - CVE-2019-13087 - CVE-2019-13092

- Code:
  - https://github.com/ChrisTheCoolHut/Firmware_Slap
- Feedback? Questions?
  - @0x01_chris