Block Oriented Programming: Automating Data-Only Attacks

Kyriakos Ispoglou
Purdue University

Bader AlBassam
Purdue University

Trent Jaeger
Penn State University

Mathias Payer
EPFL, Purdue University

Automatic
CFI-aware
Exploitation

Introduction

- Memory corruption results in arbitrary code execution
- Mitigations: DEP, ASLR, Canaries, CFI, Shadow Stacks, ...
- Advanced mitigations call for advanced attacks
- Data-Only attacks are still possible

Approach in a nutshell

- **Perform *Code Reuse* using *Data-Only attacks***
- **Leverage a memory corruption vulnerability**
- **Build Turing-complete payloads as execution traces**
- **Express execution traces as memory writes**

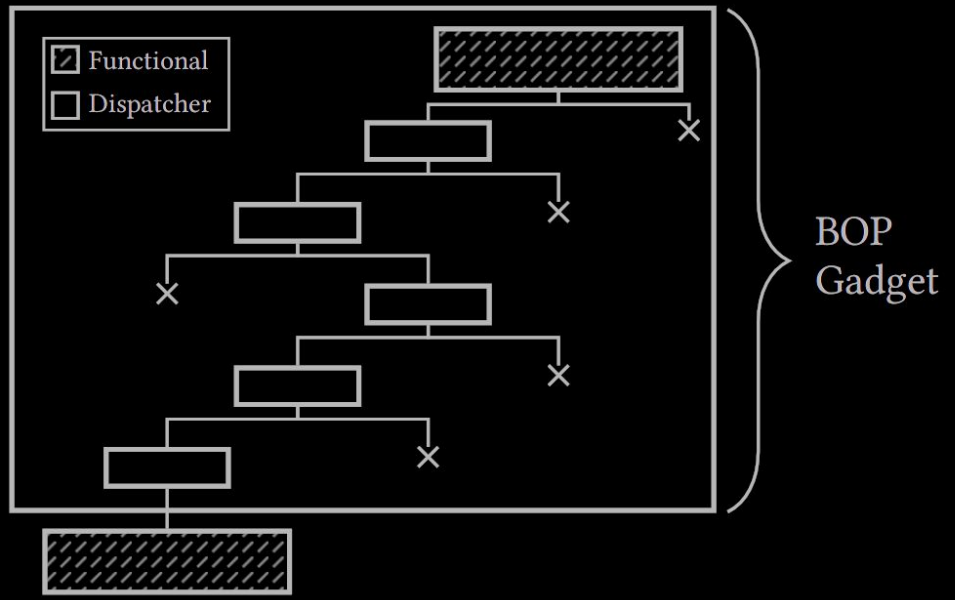
Contributions

- A language for expressing exploit payloads (SPL)
- Block Oriented Programming (BOP)
- Effective concolic execution algorithm to stitch BOP gadgets
- Open source implementation

Block Oriented Programming (BOP)

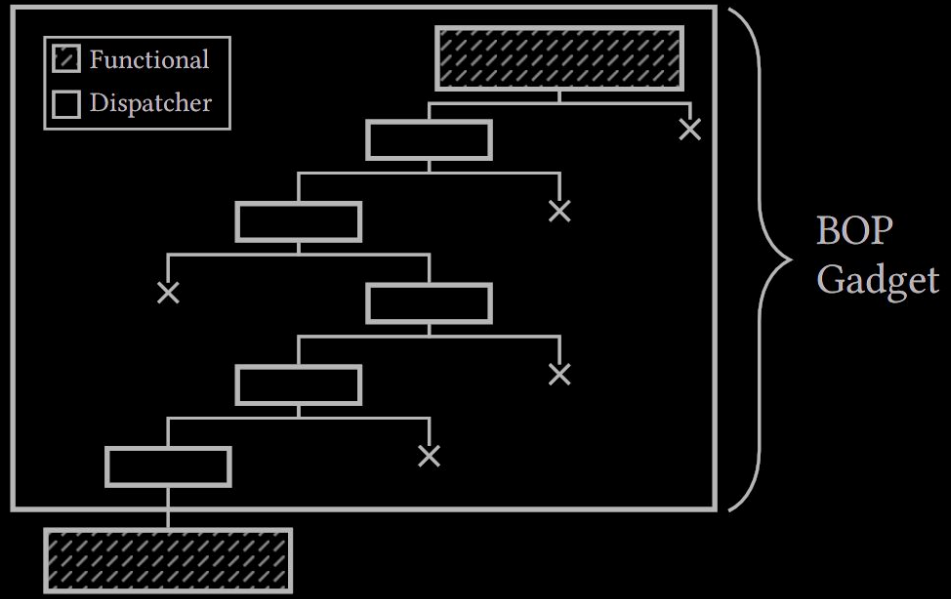
Block Oriented Programming: Gadget

- Gadget: Sequence of basic blocks
- Functional blocks
  - Perform useful computations
- Dispatcher blocks
  - Connect functional blocks
  - Avoid clobbering blocks
- Clobbering blocks
  - Destruct execution context



Block Oriented Programming: Example

```
rax ⟵ 7
```



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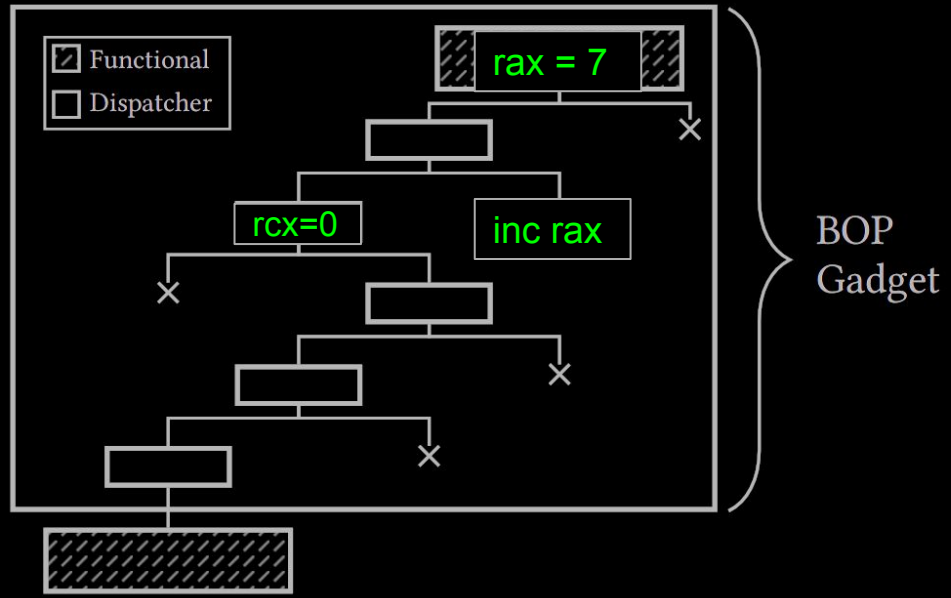
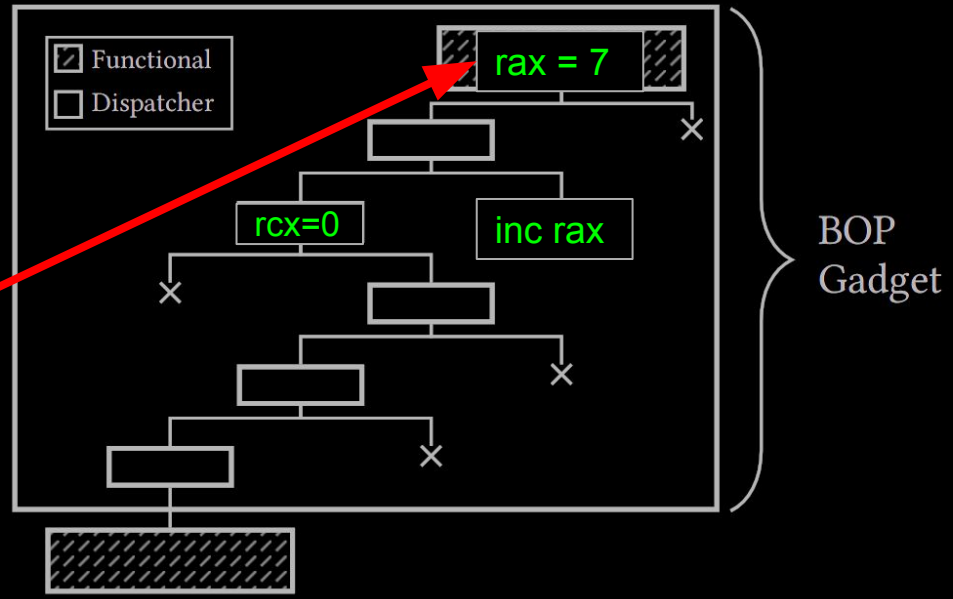


Block Oriented Programming: Example

`rax` ⟵ 7

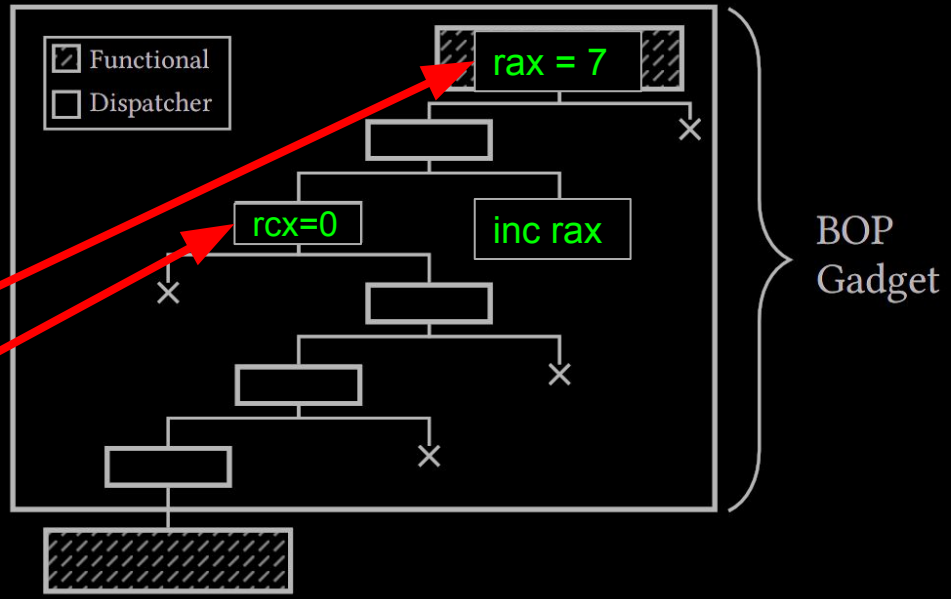
Functional



Block Oriented Programming: Example

`rax` ⟵ 7

Functional
Dispatcher



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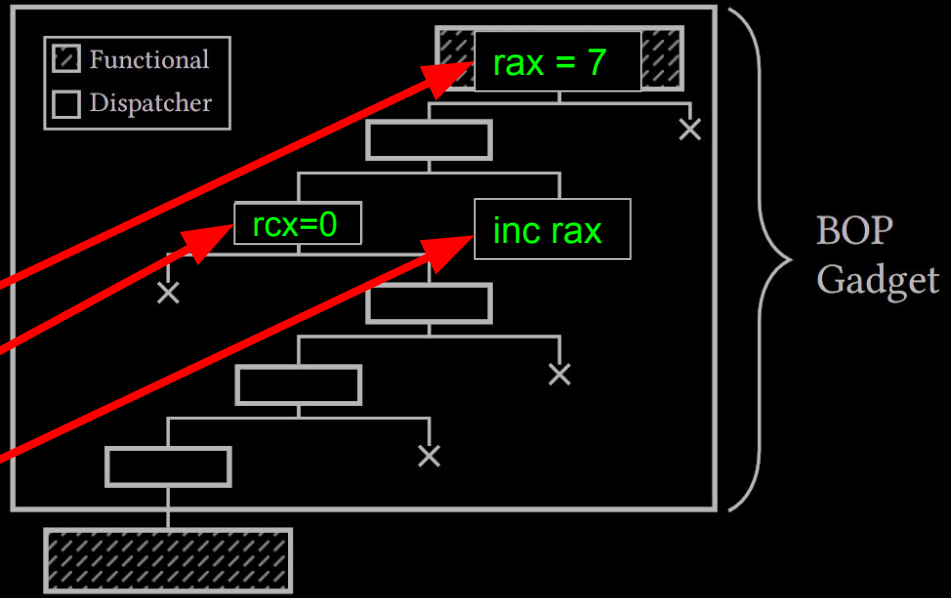


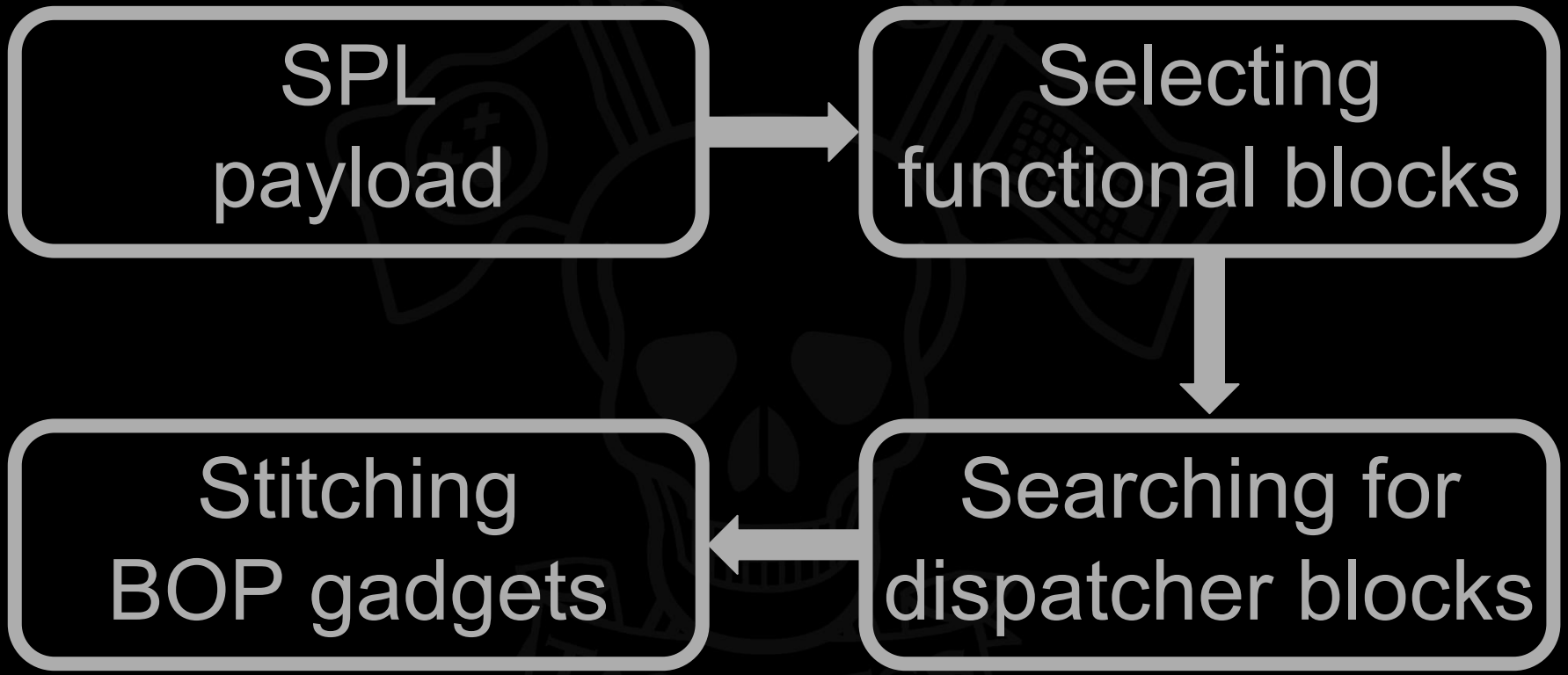
Functional
Dispatcher
Clobbering

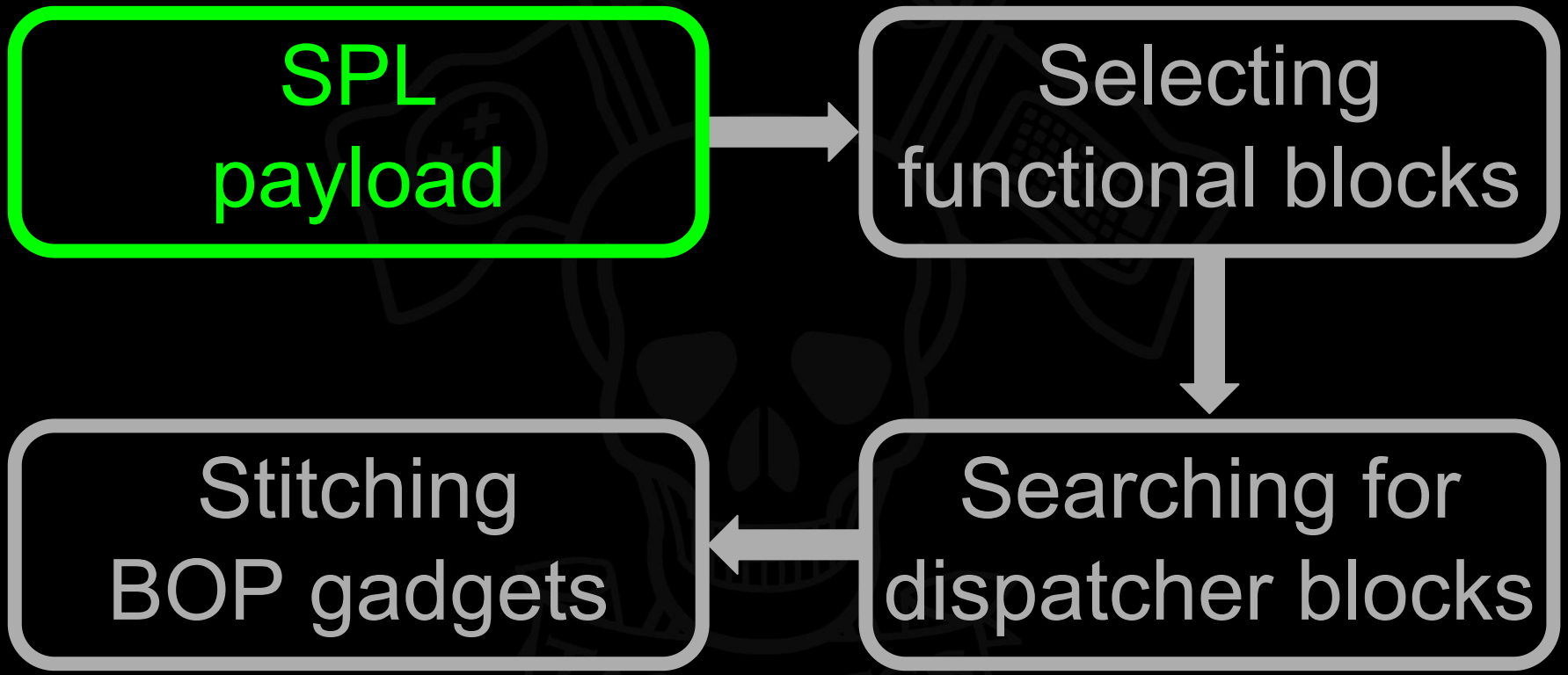
Block Oriented Programming: Concept

- Construct attacker's intended execution
  - As an "exploit program"
- Find and stitch BOP gadgets to implement "exploit program"
  - Follow CFG
- Encode execution trace as a set of memory writes
  - Data-Only Attack

Design

How it’s made


SPL payload
Selecting functional blocks
Searching for dispatcher blocks
Stitching BOP gadgets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SPL payload

- **Payload expression language**
  - **Architecture independent**
  - **Turing-complete**

- **High level; Subset of C**
  - **Variables**
  - **Library Calls**
  - **Conditionals**
  - **…**

- **Abstract registers as volatile vars**

```
void payload() {
  string prog = "/bin/sh\0";
  int64* argv = {&prog, 0x0};

  __r0 = &prog;
  __r1 = &argv;
  __r2 = 0;

  execve(__r0, __r1, __r2);
}
```

SPL payload

- Payload expression language
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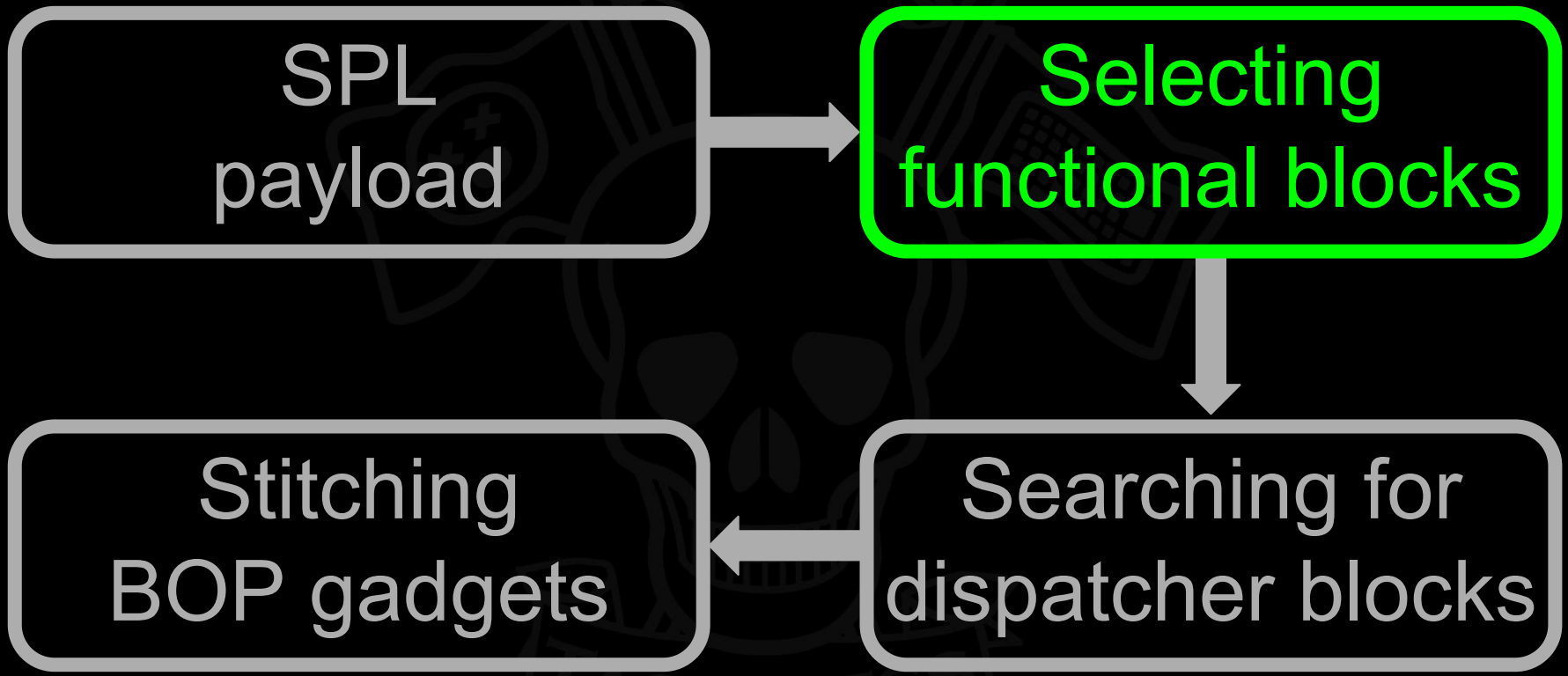
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Selecting Functional Blocks

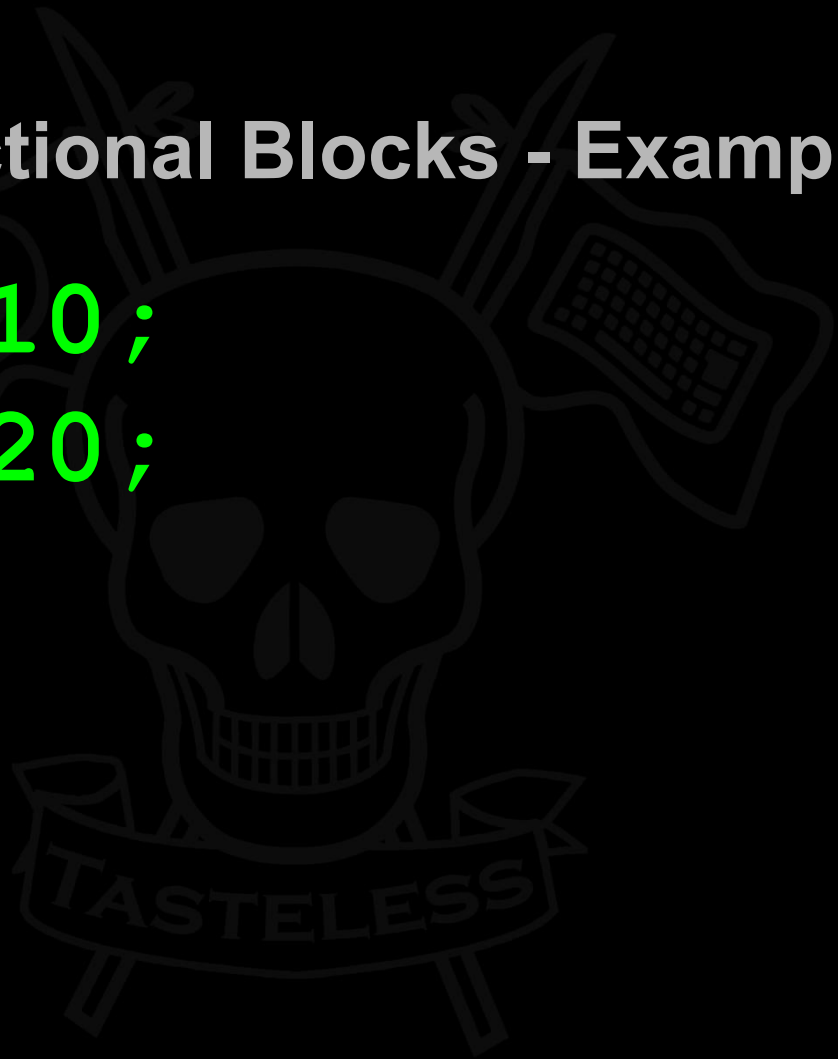
- For each SPL statement: find implementing blocks
  - “Candidate” functional blocks
  - Results in a set of candidates for each SPL statement

- Select all candidate blocks for search process (next step)

- Maximum bipartite matching problem

Selecting Functional Blocks - Example

```
__r0 = 10;
__r1 = 20;
```



Selecting Functional Blocks - Example

```
__r0 = 10;
__r1 = 20;
```

```
rax = 10
```

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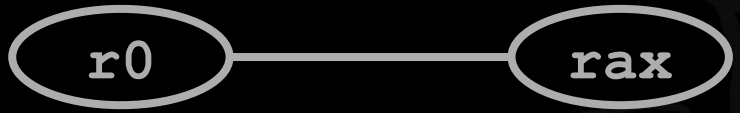

Selecting Functional Blocks - Example

```
__r0 = 10;
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```
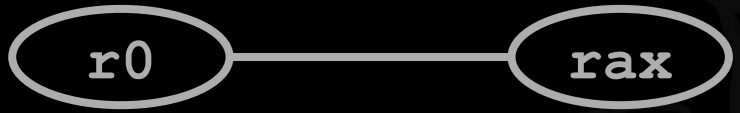

```
rax = 10
```

```
rdi = 10
```



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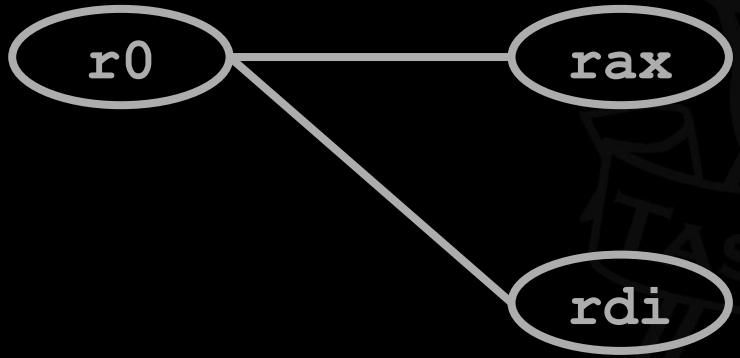

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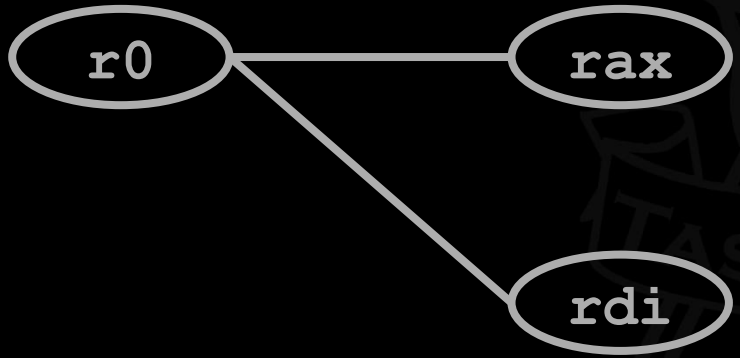


```
rax = 10
```

```
rdi = 10
```

```
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```

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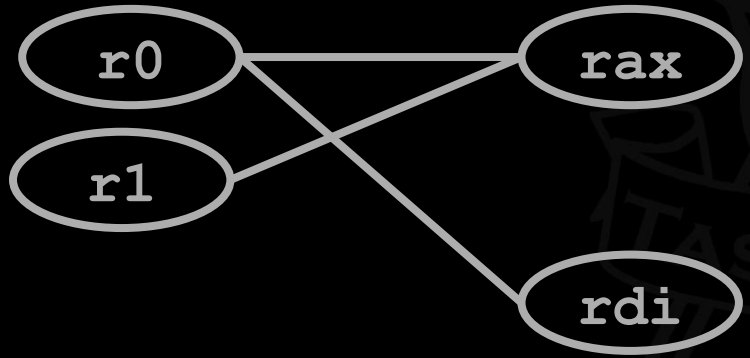


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Selecting Functional Blocks - Example

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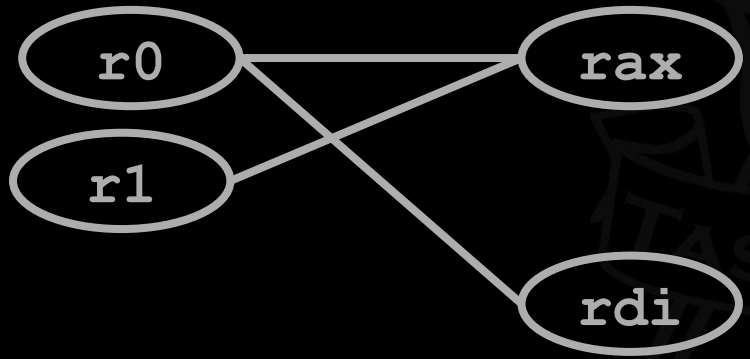


```
rax = 10
```

```
rdi = 10
```

```
rax = 20
```

```
rcx = 10
```

Selecting Functional Blocks - Example

```
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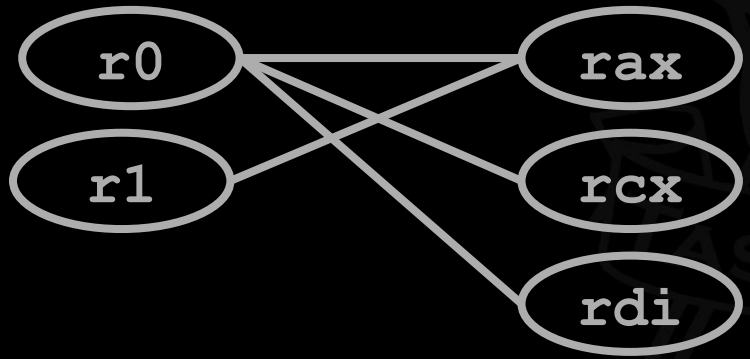


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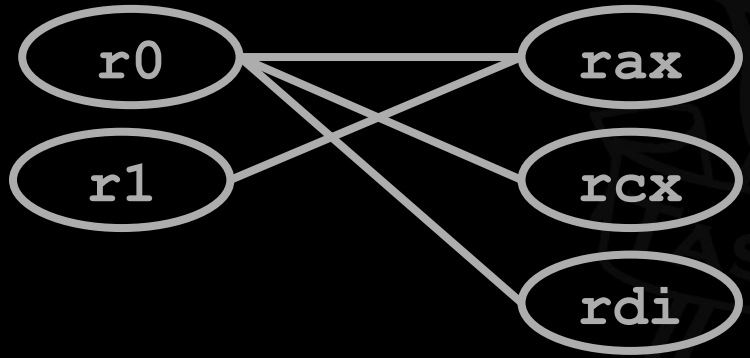



```
rax = 10
```

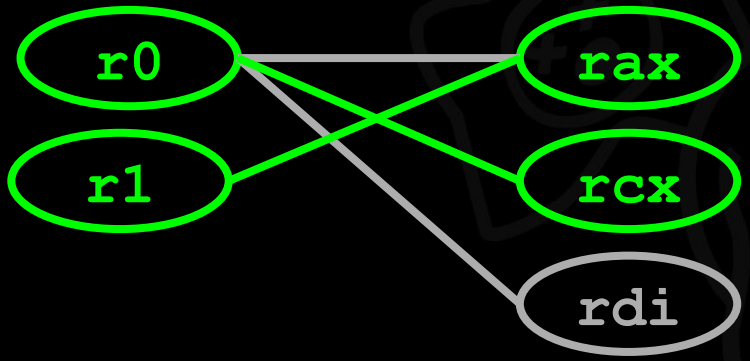
```
rdi = 10
```

```
rax = 20
```

```
rcx = 10
```

```
rcx = 30
```

Selecting Functional Blocks: Example



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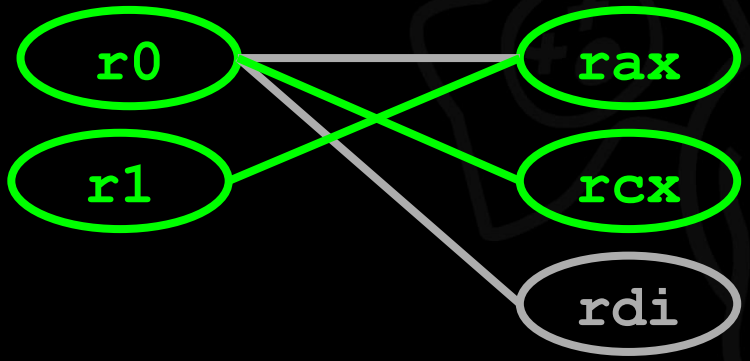


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rax = 10
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```

```
rcx = 30
```

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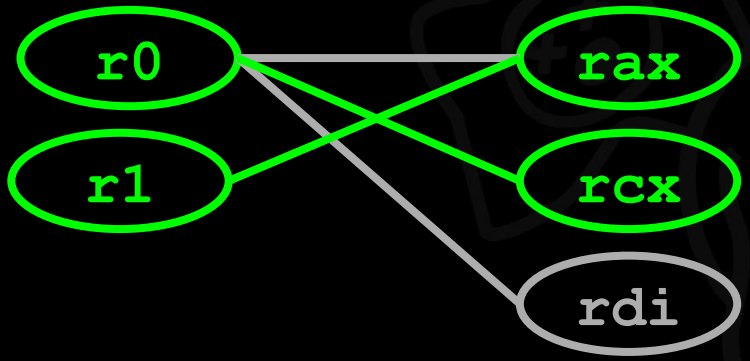
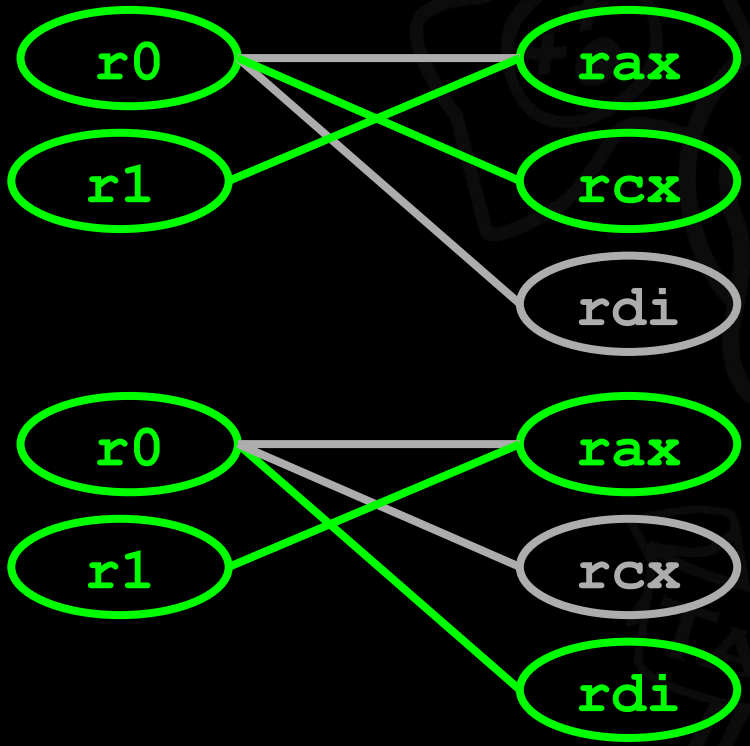


`rax = 10`	Clobbering
`rdi = 10`	Dispatcher
`rax = 20`	Functional
`rcx = 10`	Functional
`rcx = 30`	Clobbering

Selecting Functional Blocks: Example




```
rax = 10
```
Clobbering

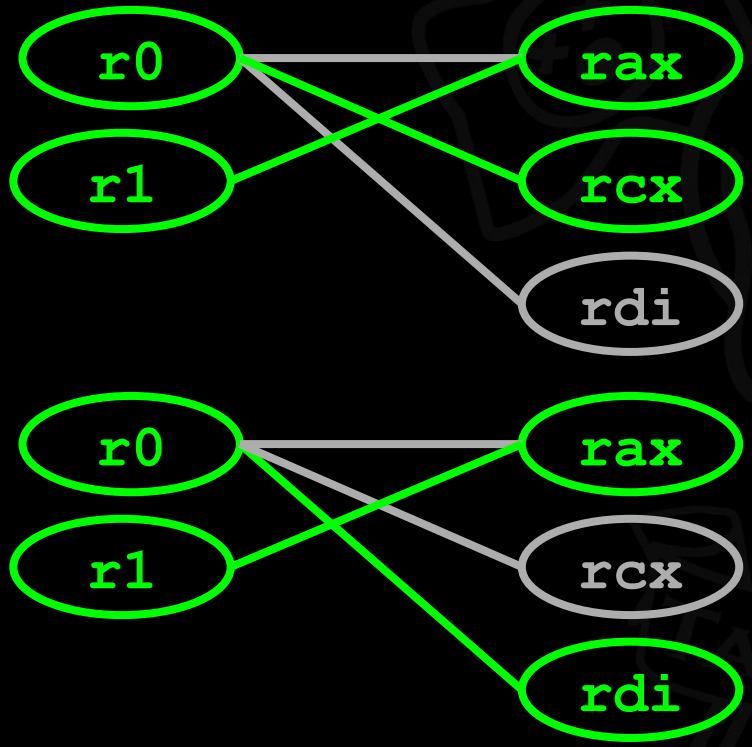
```
rdi = 10
```
Dispatcher

```
rax = 20
```
Functional

```
rcx = 10
```
Functional

```
rcx = 30
```
Clobbering

Selecting Functional Blocks: Example



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`rdi = 10`	Dispatcher	Functional
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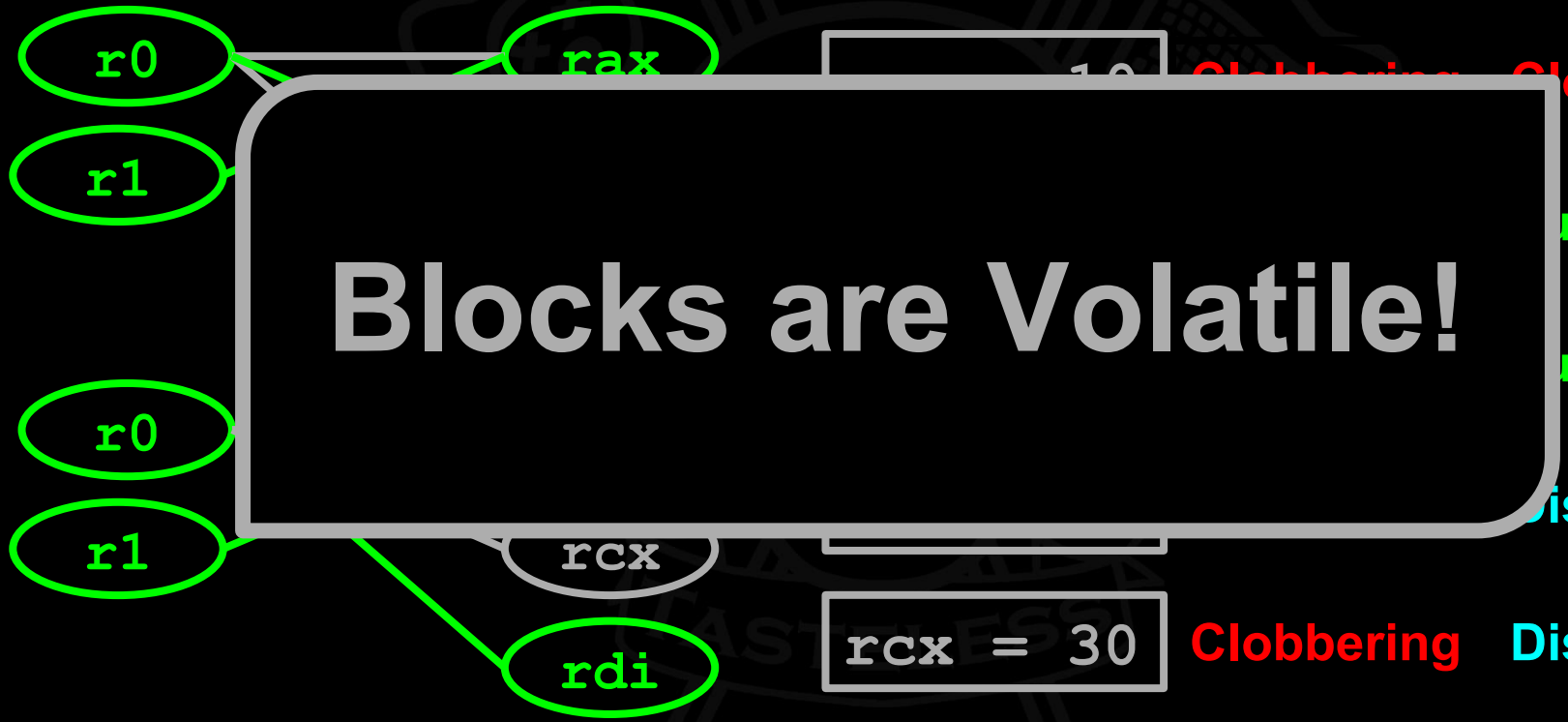
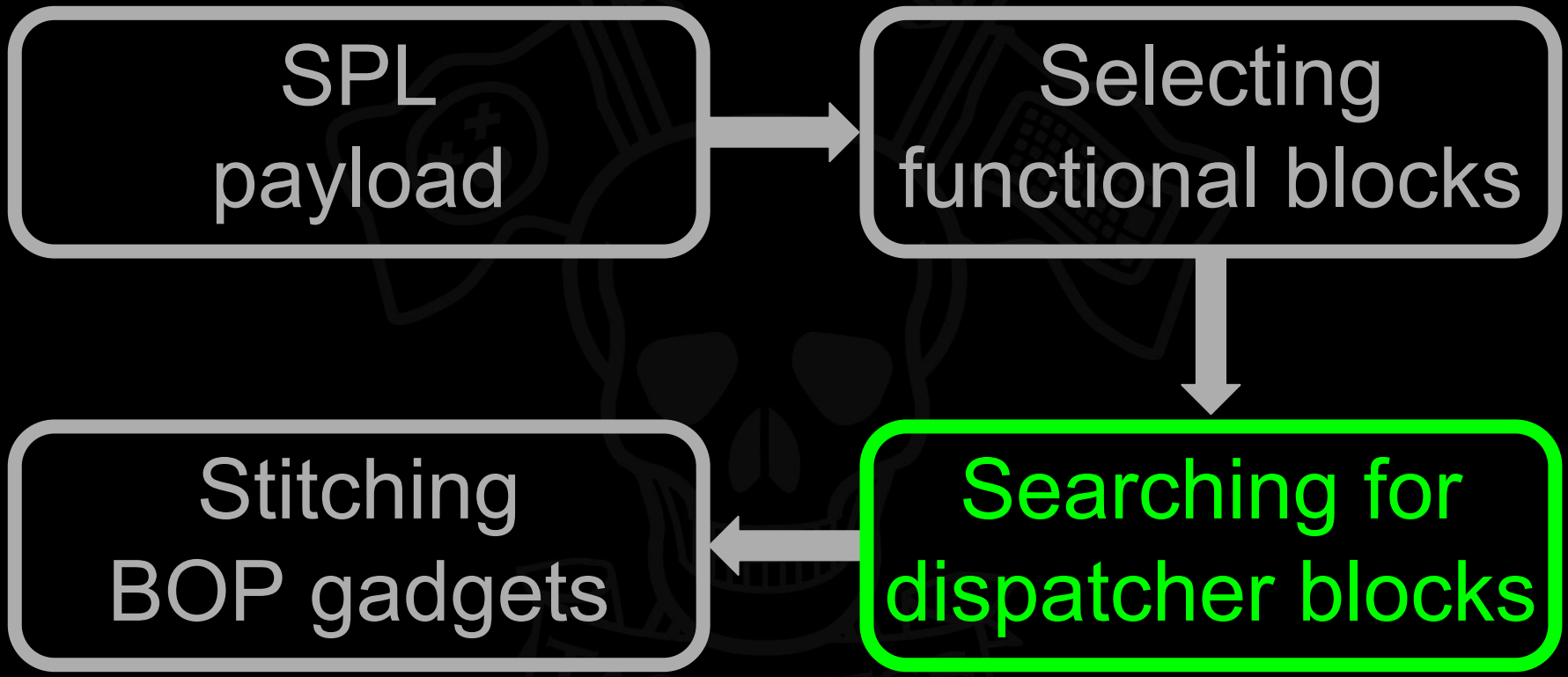
Selecting Functional Blocks: Example

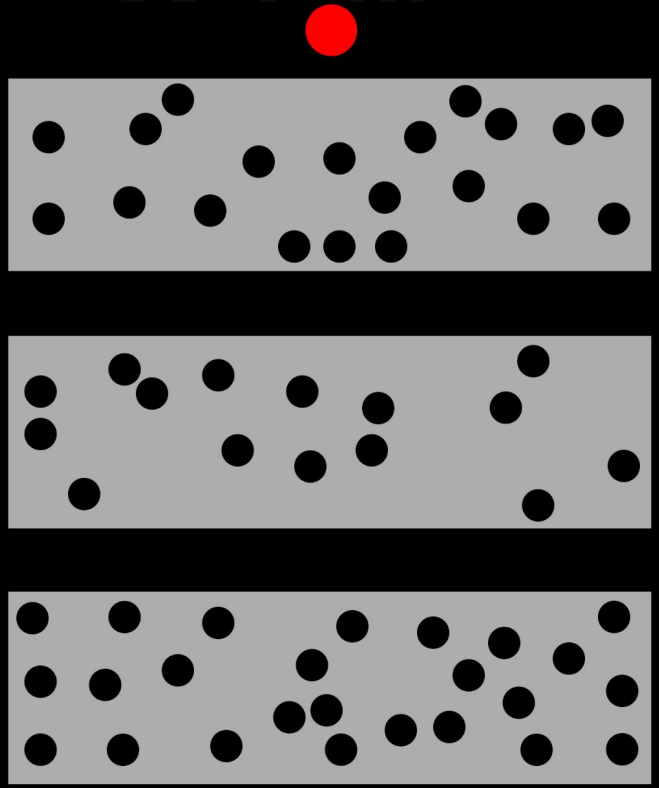



SPL payload
Selecting functional blocks
Searching for dispatcher blocks
Stitching BOP gadgets

Searching for dispatcher blocks: Concerns

- **BOP gadgets are *volatile***
- **BOP gadgets not arbitrarily chainable**
- **Stitching of BOP Gadgets is NP-hard (unlike ROP Gadgets)**
  - **Problem cannot even be approximated (proven)**
- **Backtracking (iterative process)**

BOP Gadgets: Volatility



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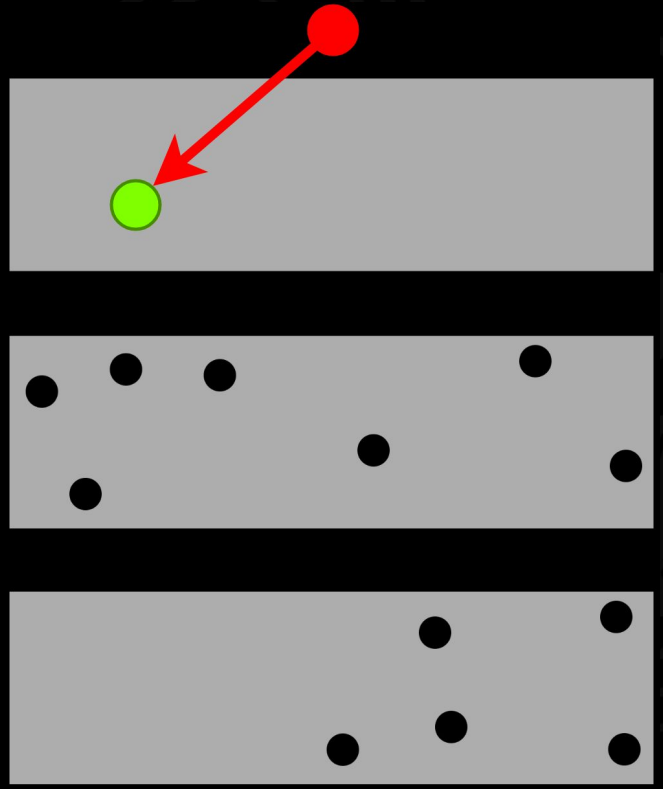

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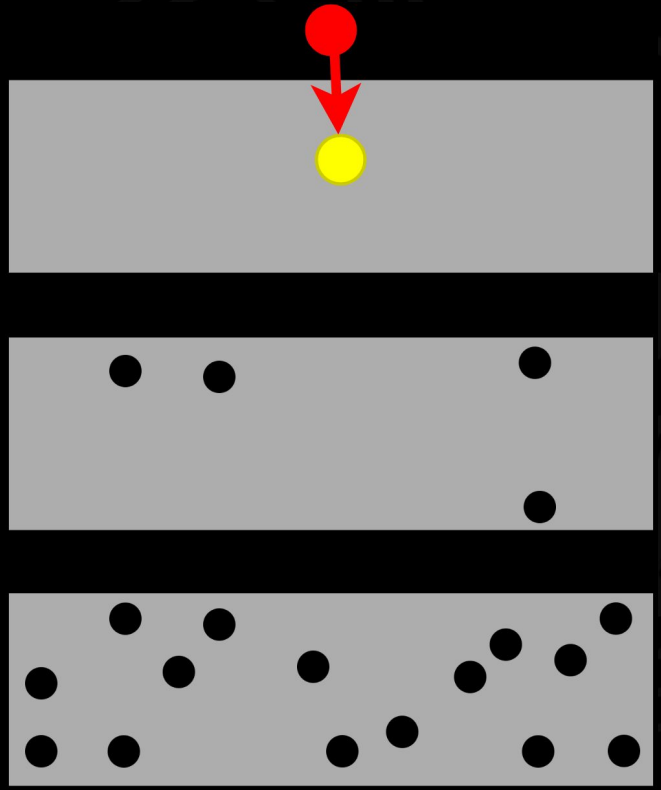
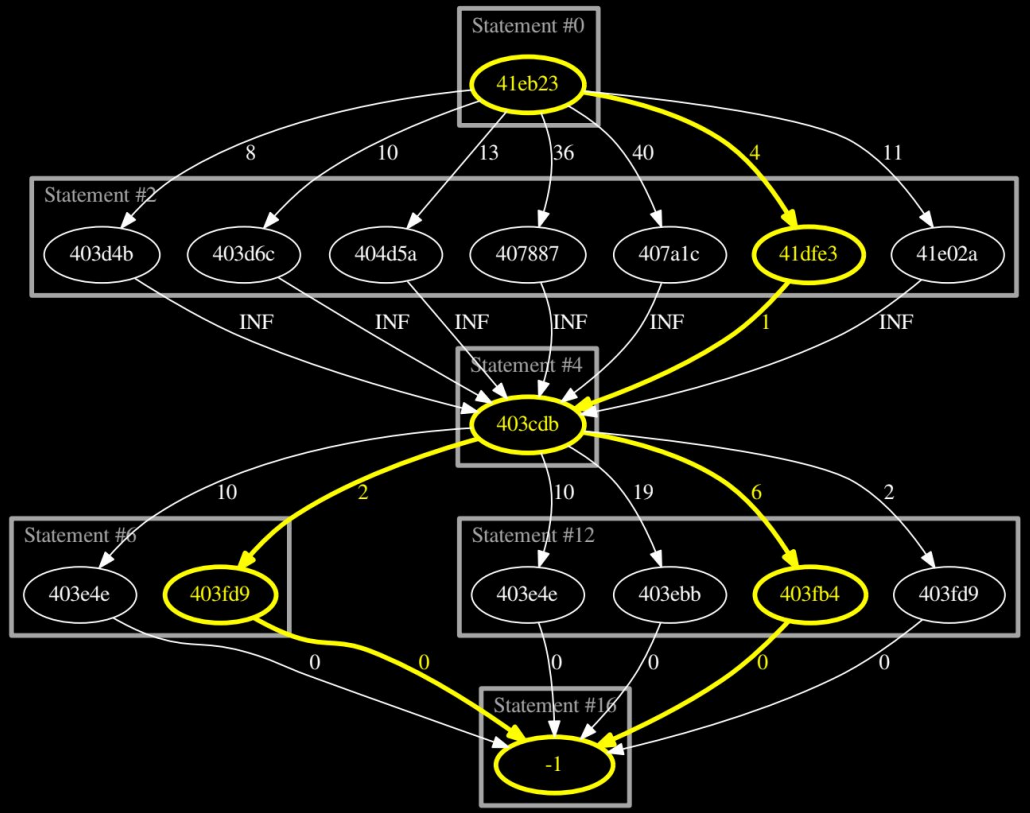


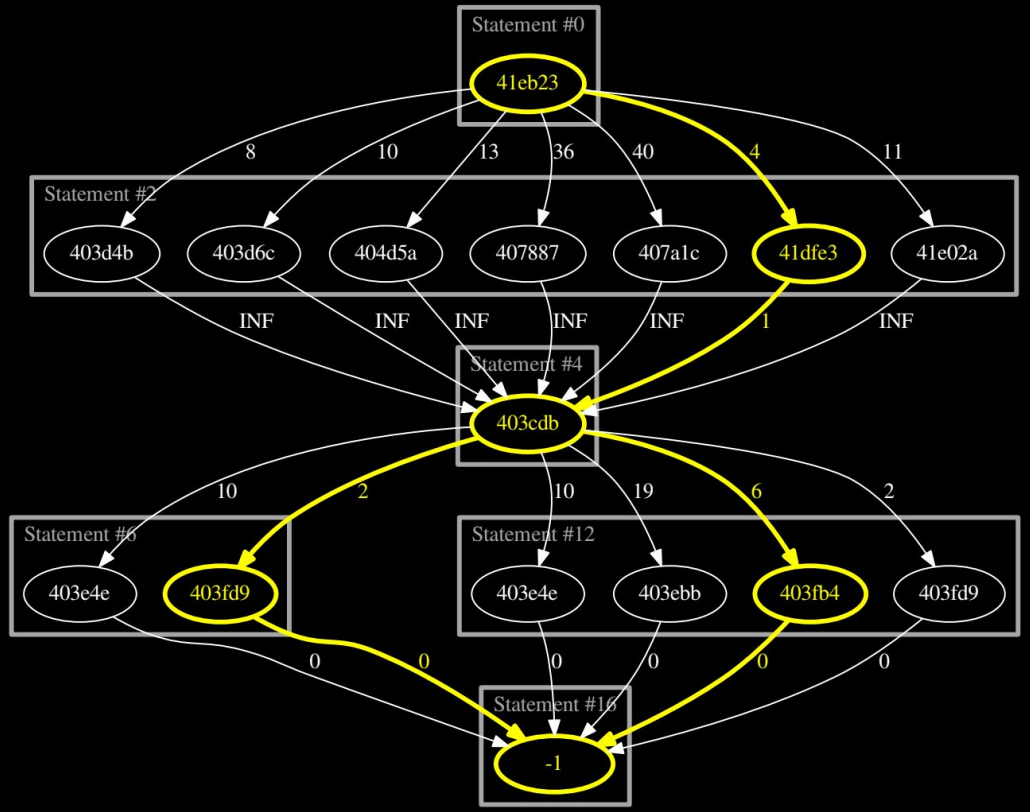
The Delta Graph

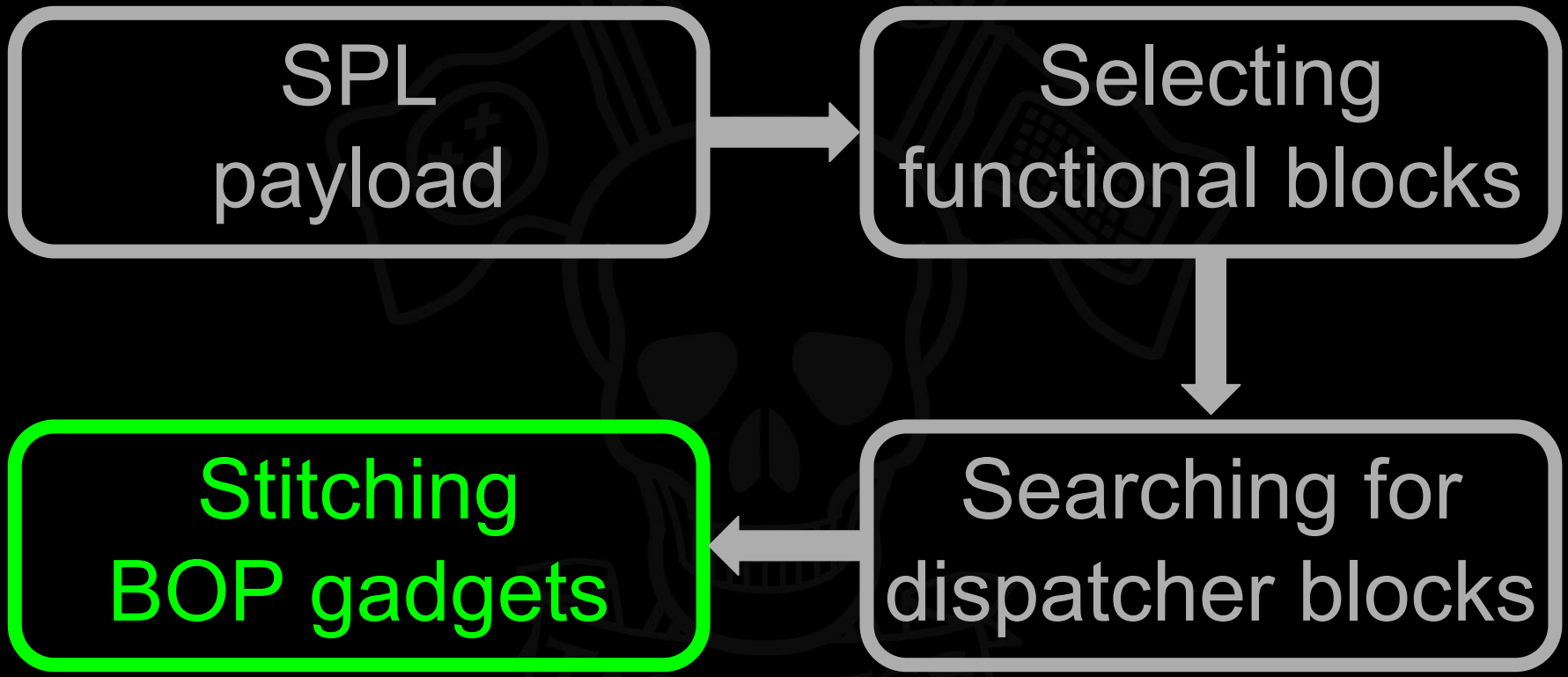
- **Layers: Functional blocks for each SPL statement**
- **Nodes: Functional blocks**
- **Edges: Proximity of functional blocks**
- **Goal: Select *exactly* one "node" from each layer (yellow)**



The Delta Graph

- Rank potential solutions
  - Block proximity as a metric
- Find N *min. induced subgraphs*
  - Candidate execution trace
  - Problem is NP-hard
- Functional blocks to reconstruct attacker's payload
- Context Sensitive Shortest Paths
  - Follow CFG + Shadow Stacks




SPL payload
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Stitching BOP Gadgets

- Induced subgraph fulfills exploit program
  - All functional blocks can be connected together

- “Verify” that induced subgraph is valid:
  - Many constraints come from multiple dimensions
    - Local constraints
    - SPL constraints
    - Execution constraints

- Verify using *concolic execution + constraint solving*

Stitching BOP Gadgets

- **Utilize concolic execution**
  - **Keep track of <u>every</u> action and extract constraints**

- **Upon failure, try to patch “locally”**
  - **K shortest paths for every edge of the induced subgraph**

- **Once a solution found encode constraints as memory writes**

Evaluation

Proof of Work

Vulnerable Applications & SPL Payloads

Program	Vulnerability	Nodes	RegSet	RegMod	MemRd	MemWr	Call	Cond	Total
ProFTPd	CVE-2006-5815	27,087	40,143	387	1,592	199	77	3,029	45,427
nginx	CVE-2013-2028	24,169	31,497	1,168	1,522	279	35	3375	37,876
sudo	CVE-2012-0809	3,399	5,162	26	157	18	45	307	5715
orzhttpd	BugtraqID 41956	1,345	2,317	9	39	8	11	89	2473
wuftpd	CVE-2000-0573	8,899	14,101	62	274	11	94	921	15,463
nullhttpd	CVE-2002-1496	1,488	2,327	77	54	7	19	125	2,609
opensshd	CVE-2001-0144	6,688	8,800	98	214	19	63	558	9,752
wireshark	CVE-2014-2299	74,186	124,053	639	1,736	193	100	4555	131276
apache	CVE-2006-3747	18,790	33,615	212	490	66	127	1,768	36,278
smbclient	CVE-2009-1886	166,081	265,980	1,481	6,791	951	119	28,705	304,027

RegSet: Register Assignment Gadgets
RegMod: Register Modification Gadgets
MemRd: Memory Read Gadgets
MemWr: Memory Write Gadgets
Call: Function/System Call Gadgets
Cond: Conditional Statement Gadgets
Total: Total number of Functional Gadgets

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Payload	Description
"regset4	Initialize 4 registers with arbitrary values
regref4	Initialize 4 registers with pointers to arbitrary memory
regset5	Initialize 5 registers with arbitrary values
regref5	Initialize 5 registers with pointers to arbitrary memory
regmod	Initialize a register with an arbitrary value and modify it
memrd	Read from arbitrary memory
memwr	Write to arbitrary memory
print	Display a message to stdout using write
execve	Spawn a shell through execve
abloop	Perform an arbitrarily long bounded loop utilizing regmod
infloop	Perform an infinite loop that sets a register in its body
ifelse	An if-else condition based on a register comparison
loop	Conditional loop with register modification

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nginx	CVE-2013-2028	24,169	31,497	1,168	1,522	279	35	3375	37,876
sudo	CVE-2012-0809	3,399	5,162	26	157	18	45	307	5715
orzhttpd	BugtraqID 41956	1,345	2,317	9	39	8	11	89	2473
wuftpd	CVE-2000-0573	8,899	14,101	62	274	11	94	921	15,463
nullhttpd	CVE-2002-1496	1,488	2,327	77	54	7	19	125	2,609
opensshd	CVE-2001-0144	6,688	8,800	98	214	19	63	558	9,752
wireshark	CVE-2014-2299	74,186	124,053	639	1,736	193	100	4555	131276
apache	CVE-2006-3747	18,790	33,615	212	490	66	127	1,768	36,278
smbclient	CVE-2009-1886	166,081	265,980	1,481	6,791	951	119	28,705	304,027

RegSet: Register Assignment Gadgets
RegMod: Register Modification Gadgets
MemRd: Memory Read Gadgets
MemWr: Memory Write Gadgets
Call: Function/System Call Gadgets
Cond: Conditional Statement Gadgets
Total: Total number of Functional Gadgets

Payload	Description
"regset4	Initialize 4 registers with arbitrary values
regref4	Initialize 4 registers with pointers to arbitrary memory
regset5	Initialize 5 registers with arbitrary values
regref5	Initialize 5 registers with pointers to arbitrary memory
regmod	Initialize a register with an arbitrary value and modify it
memrd	Read from arbitrary memory
memwr	Write to arbitrary memory
print	Display a message to stdout using write
execve	Spawn a shell through execve
ablоop	Perform an arbitrarily long bounded loop utilizing regmod
infloop	Perform an infinite loop that sets a register in its body
ifelse	An if-else condition based on a register comparison
loop	Conditional loop with register modification

Results of payload execution

Program	SPL payload												
	regset4	*regref4*	*regset5*	*regref5*	*regmod*	*memrd*	*memwr*	*print*	*execve*	*abloop*	*infloop*	*ifelse*	*loop*
ProFTPd	✓	✓	✓	✓	✓	✓	✓	✓ 32	✗$_1$	✓ 128+	✓ ∞	✓	✓ 3
nginx	✓	✓	✓	✓	✓	✓	✓	✗$_4$	✓	✓ 128+	✓ ∞	✓	✓ 128
sudo	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗$_4$	✓ 128+	✗$_4$	✗$_4$
orzhttpd	✓	✓	✓	✓	✓	✓	✓	✗$_4$	✗$_1$	✗$_4$	✓ 128+	✗$_4$	✗$_3$
wuftdp	✓	✓	✓	✓	✓	✓	✓	✓	✗$_1$	✓ 128+	✓ 128+	✗$_4$	✗$_3$
nullhttpd	✓	✓	✓	✓	✓	✓	✗$_3$	✗$_3$	✓	✓ 30	✓ ∞	✗$_4$	✗$_3$
opensshd	✓	✓	✓	✓	✓	✓	✗$_4$	✗$_4$	✗$_4$	✓ 512	✓ 128+	✓	✓ 99
wireshark	✓	✓	✓	✓	✓	✓	✓	✓ 4	✗$_1$	✓ 128+	✓ 7	✓	✓ 8
apache	✓	✓	✓	✓	✓	✓	✓	✗$_4$	✗$_4$	✓ ∞	✓ 128+	✓	✗$_4$
smbclient	✓	✓	✓	✓	✓	✓	✓	✓ 1	✗$_1$	✓ 1057	✓ 128+	✓	✓ 256

✓ The SPL payload was successfully executed on the target binary
✗$_1$ Not enough candidate blocks
✗$_2$ No valid register/variable mappings
✗$_3$ No valid paths between functional blocks
✗$_4$ Un-satisfiable constraints or solver timeout

Results of payload execution

Program	SPL payload												
	regset4	*regref4*	*regset5*	*regref5*	*regmod*	*memrd*	*memwr*	*print*	*execve*	*abloop*	*infloop*	*ifelse*	*loop*
ProFTPd	✓	✓	✓	✓	✓	✓	✓	✓ 32	✗$_1$	✓ 128+	✓ ∞	✓	✓ 3
nginx	✓	✓	✓	✓	✓	✓	✓	✗$_4$	✓	✓ 128+	✓ ∞	✓	✓ 128
sudo	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗$_4$	✓ 128+	✗$_4$	✗$_4$
orzhttpd	✓	✓	✓	✓	✓	✓	✓	✗$_4$	✗$_1$	✗$_4$	✓ 128+	✗$_4$	✗$_3$
wuftdp	✓	✓	✓	✓	✓	✓	✓	✓	✗$_1$	✓ 128+	✓ 128+	✗$_4$	✗$_3$
nullhttpd	✓	✓	✓	✓	✓	✓	✗$_3$	✗$_3$	✓	✓ 30	✓ ∞	✗$_4$	✗$_3$
opensshd	✓	✓	✓	✓	✓	✓	✗$_4$	✗$_4$	✗$_4$	✓ 512	✓ 128+	✓	✓ 99
wireshark	✓	✓	✓	✓	✓	✓	✓	✓ 4	✗$_1$	✓ 128+	✓ 7	✓	✓ 8
apache	✓	✓	✓	✓	✓	✓	✓	✗$_4$	✗$_4$	✓ ∞	✓ 128+	✓	✗$_4$
smbclient	✓	✓	✓	✓	✓	✓	✓	✓ 1	✗$_1$	✓ 1057	✓ 128+	✓	✓ 256

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✗$_4$ Un-satisfiable constraints or solver timeout

Results of payload execution

Program	SPL payload												
	regset4	*regref4*	*regset5*	*regref5*	*regmod*	*memrd*	*memwr*	*print*	*execve*	*abloop*	*infloop*	*ifelse*	*loop*
ProFTPd	✓	✓	✓	✓	✓	✓	✓	✓ 32	✗$_1$	✓ 128+	✓ ∞	✓	✓ 3
nginx	✓	✓	✓	✓	✓	✓	✓	✗$_4$	✓	✓ 128+	✓ ∞	✓	✓ 128
sudo	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗$_4$	✓ 128+	✗$_4$	✗$_4$
orzhttpd	✓	✓	✓	✓	✓	✓	✓	✗$_4$	✗$_1$	✗$_4$	✓ 128+	✗$_4$	✗$_3$
wuftdp	✓	✓	✓	✓	✓	✓	✓	✓	✗$_1$	✓ 128+	✓ 128+	✗$_4$	✗$_3$
nullhttpd	✓	✓	✓	✓	✓	✓	✗$_3$	✗$_3$	✓	✓ 30	✓ ∞	✗$_4$	✗$_3$
opensshd	✓	✓	✓	✓	✓	✓	✗$_4$	✗$_4$	✗$_4$	✓ 512	✓ 128+	✓	✓ 99
wireshark	✓	✓	✓	✓	✓	✓	✓	✓ 4	✗$_1$	✓ 128+	✓ 7	✓	✓ 8
apache	✓	✓	✓	✓	✓	✓	✓	✗$_4$	✗$_4$	✓ ∞	✓ 128+	✓	✗$_4$
smbclient	✓	✓	✓	✓	✓	✓	✓	✓ 1	✗$_1$	✓ 1057	✓ 128+	✓	✓ 256

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- ✗$_3$ No valid paths between functional blocks
- ✗$_4$ Un-satisfiable constraints or solver timeout

Results of payload execution

Program	SPL payload												
	regset4	*regref4*	*regset5*	*regref5*	*regmod*	*memrd*	*memwr*	*print*	*execve*	*abloop*	*infloop*	*ifelse*	*loop*
ProFTPd	✓	✓	✓	✓	✓	✓	✓	✓ 32	✗$_1$	✓ 128+	✓ ∞	✓	✓ 3
nginx	✓	✓	✓	✓	✓	✓	✓	✗$_4$	✓	✓ 128+	✓ ∞	✓	✓ 128
sudo	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗$_4$	✓ 128+	✗$_4$	✗$_4$
orzhttpd	✓	✓	✓	✓	✓	✓	✓	✗$_4$	✗$_1$	✗$_4$	✓ 128+	✗$_4$	✗$_3$
wuftdp	✓	✓	✓	✓	✓	✓	✓	✓	✗$_1$	✓ 128+	✓ 128+	✗$_4$	✗$_3$
nullhttpd	✓	✓	✓	✓	✓	✓	✗$_3$	✗$_3$	✓	✓ 30	✓ ∞	✗$_4$	✗$_3$
opensshd	✓	✓	✓	✓	✓	✓	✗$_4$	✗$_4$	✗$_4$	✓ 512	✓ 128+	✓	✓ 99
wireshark	✓	✓	✓	✓	✓	✓	✓	✓ 4	✗$_1$	✓ 128+	✓ 7	✓	✓ 8
apache	✓	✓	✓	✓	✓	✓	✓	✗$_4$	✗$_4$	✓ ∞	✓ 128+	✓	✗$_4$
smbclient	✓	✓	✓	✓	✓	✓	✓	✓ 1	✗$_1$	✓ 1057	✓ 128+	✓	✓ 256

✓ The SPL payload was successfully executed on the target binary
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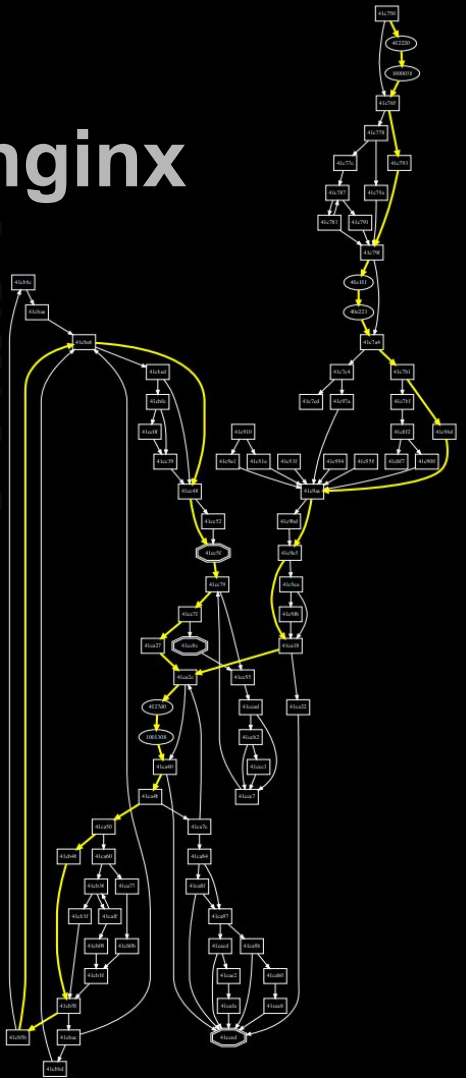
✗$_4$ Un-satisfiable constraints or solver timeout

Success Rate: *81%*

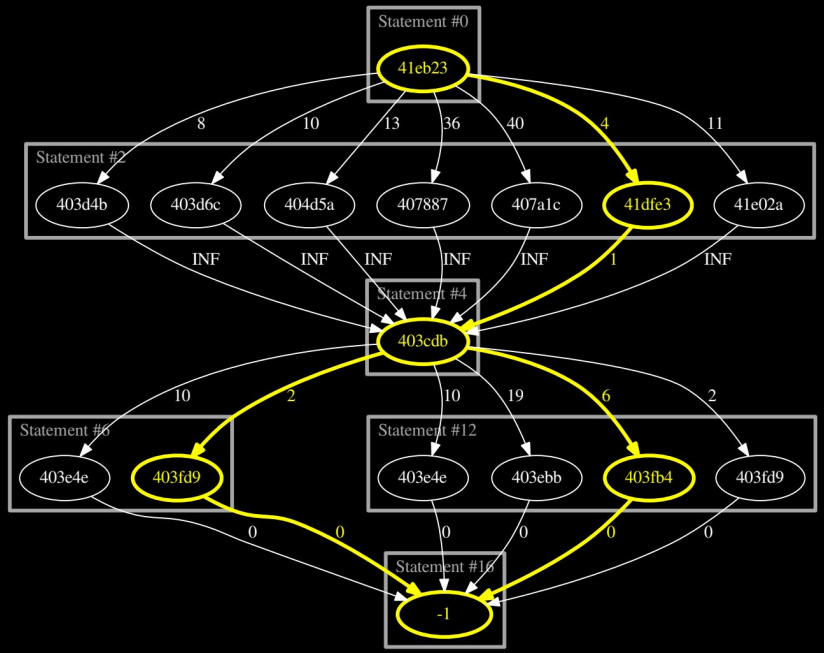
Case Study: infloop payload on nginx

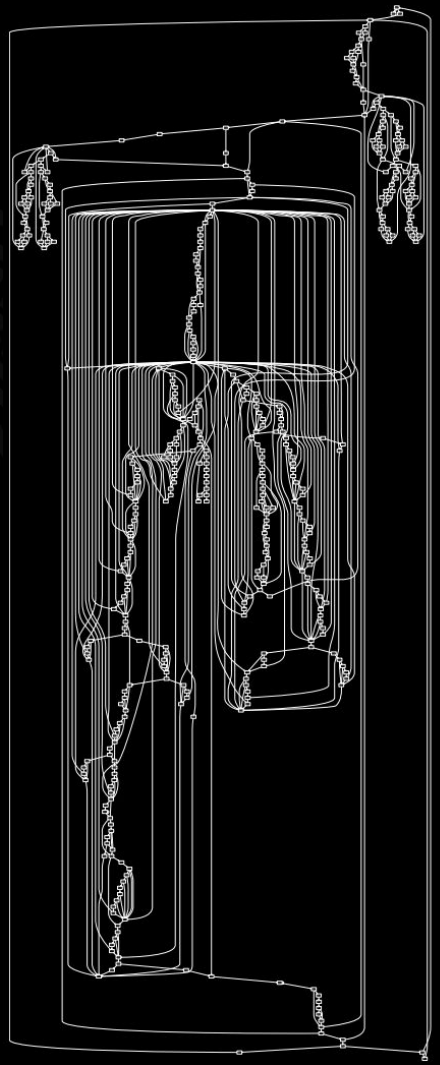
ngx_signal_handler()

```
41C765: signals.signo == 0
40E10F: ngx_time_lock != 0
41C7B1: ngx_process 3 > 1
41C9AC: ngx_cycle = $alloc_1
        $alloc_1 > log = $alloc_2
        $alloc_2 > log_level <= 5
41CA18: signo == 17
41CA4B: waitpid() return value != {0, 1}
41cA50: ngx_last_process == 0
41CB50: *($stack 0x03C) & 0x7F != 0
41CB5B: $alloc_2 > log_level <= 1
41CBE6: *($stack 0x03C + 1) != 2
41CC48: ngx_accept_mutex_ptr == 0
41CC5F: ngx_cycle> shared_memory.part.elts = 0
        __r0 = r14 = 0
41CC79: ngx_cycle > shared_memory.part.nelts <= 0
41CC7F: ngx_cycle > shared_memory.part.next == 0
```



Case Study: ifelse on nginx





Conclusion

- **Automatic CFI-aware Exploitation is feasible**
- **Block Oriented Programming automates Data-Only attacks**
- **Evaluation shows that this can be done in *81%* of the cases**
- **Open Source + VM: https://github.com/HexHive/BOPC**
- **Contact: ispo@purdue.edu**