Data-Oriented Programming

On the Expressiveness of Non-Control Data Attacks

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Control Attacks are Getting Harder

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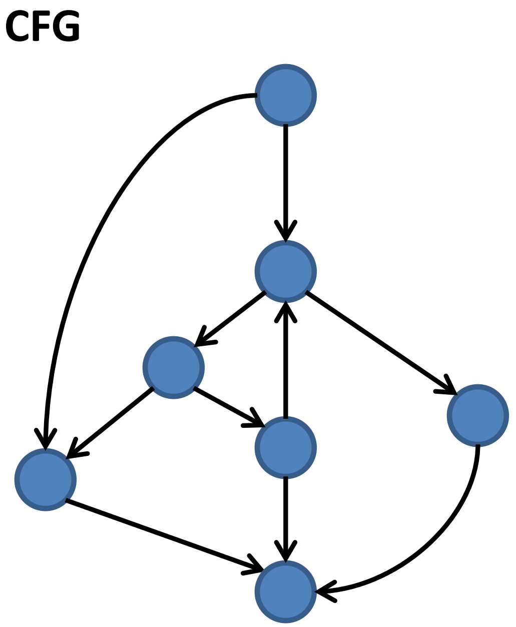
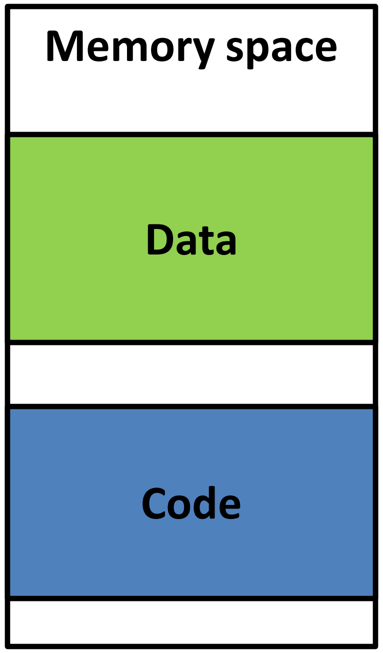
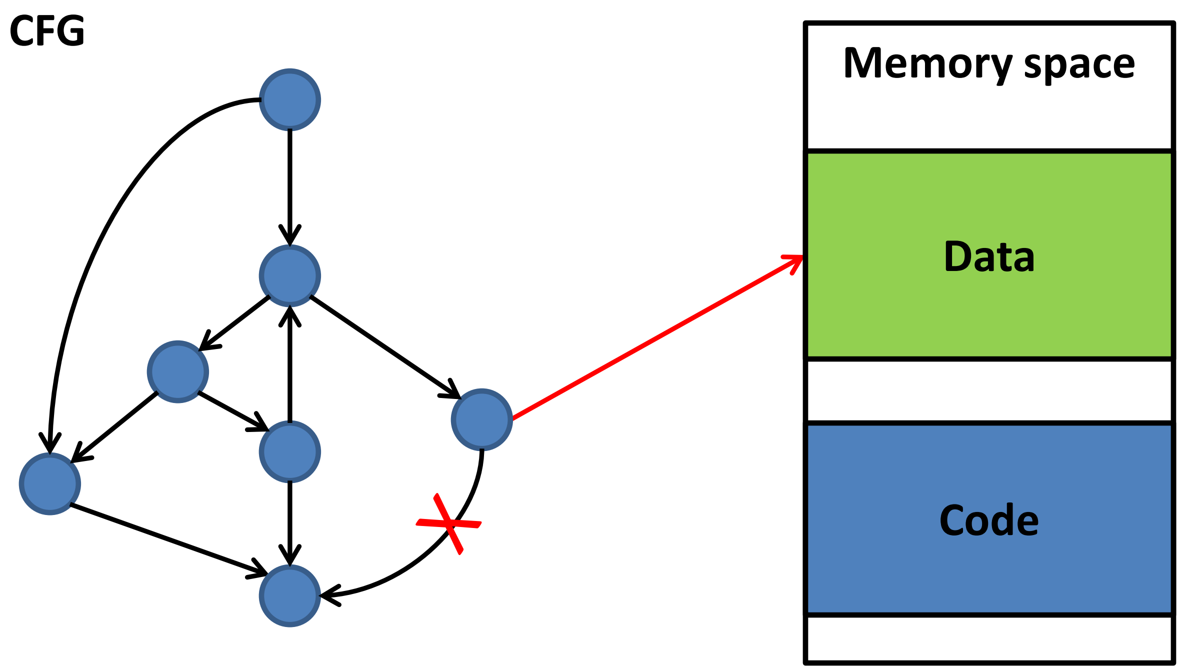




Control Attacks are Getting Harder

- Code injection



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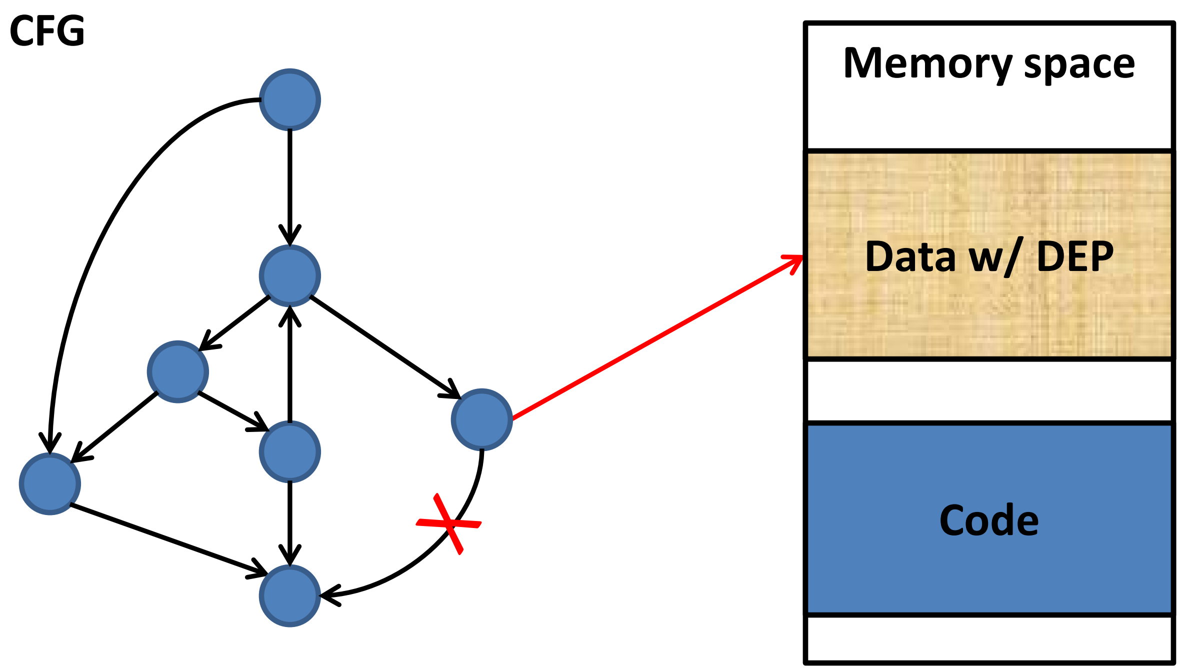
- Code injection ⇐ Data Execution Prevention



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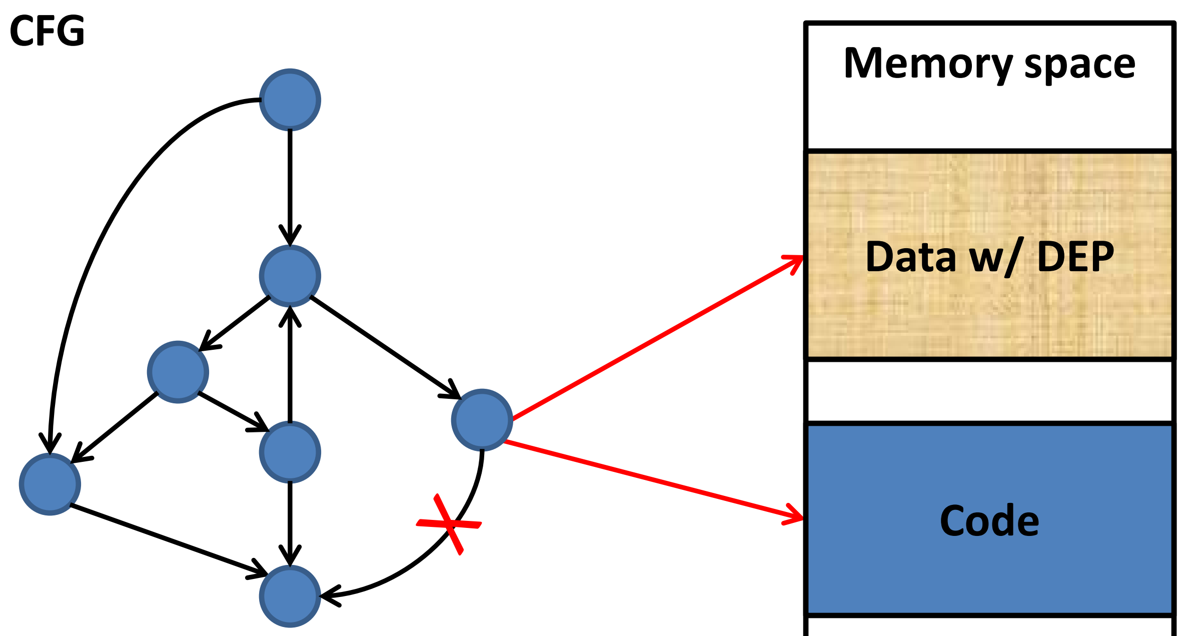
  - return-to-libc
  - return-oriented programming (ROP)



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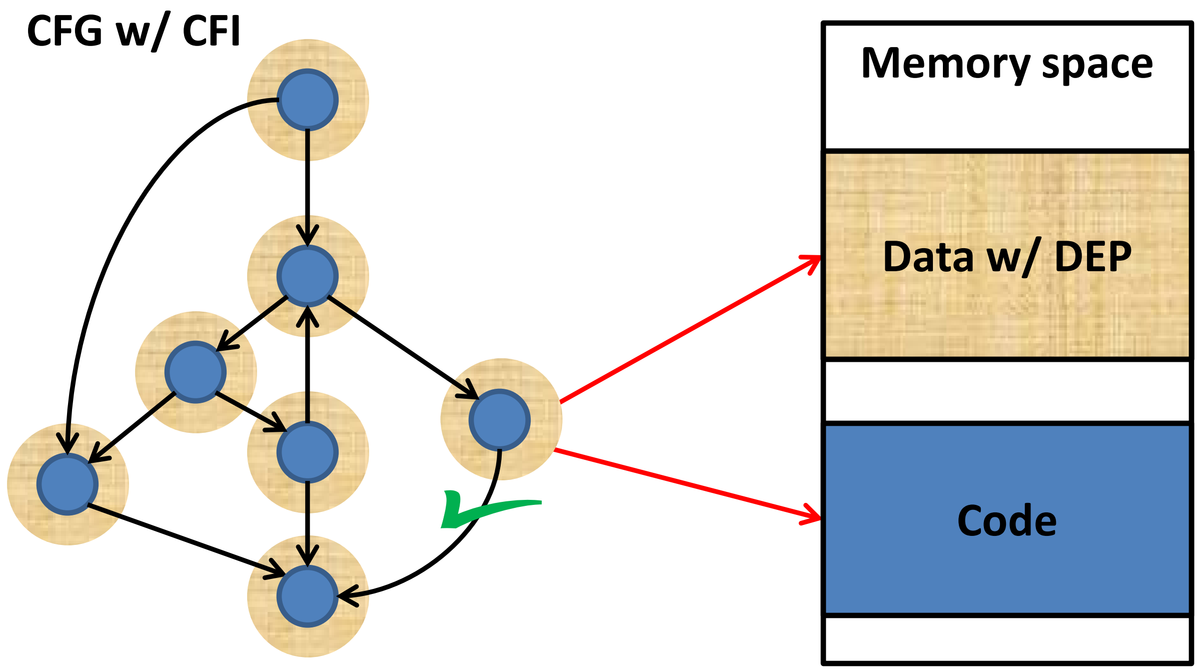

A New Attack Class

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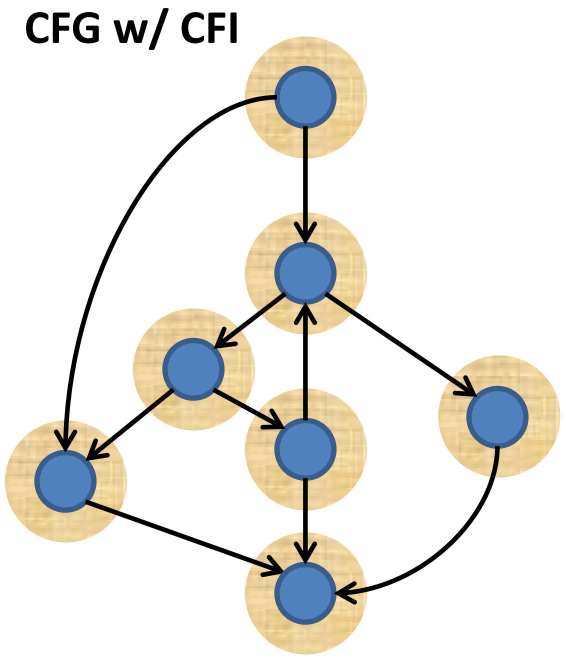
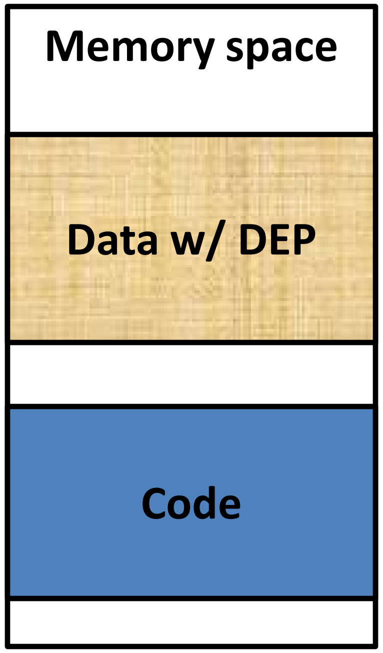
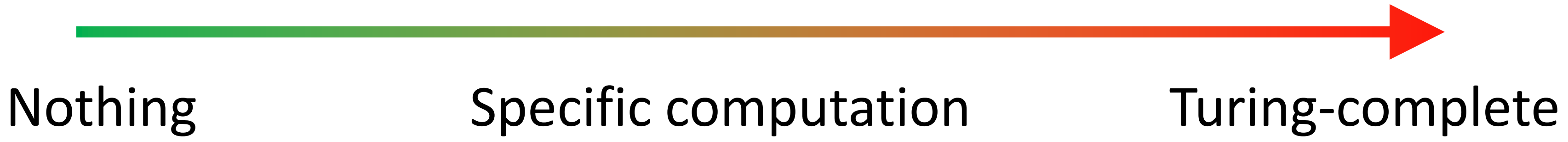
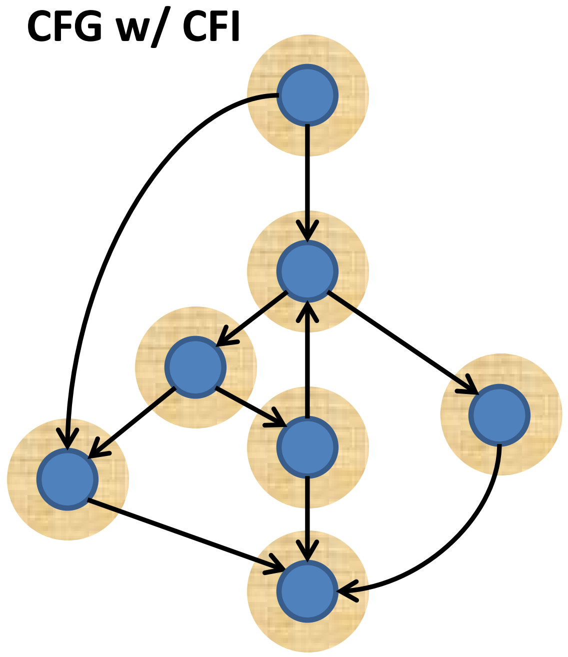


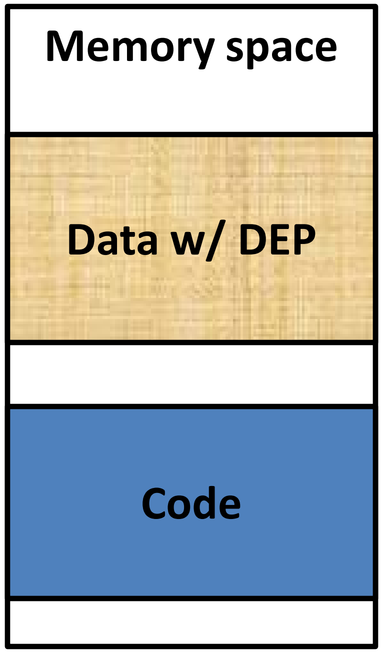


A New Attack Class

- Assume: conform to CFI & DEP
- Attackers' capability on arbitrary vul. programs?







Non-Control Data Attacks

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//set root privilege   *
seteuid(0);
......
//set normal user privilege
seteuid(pw->pw_uid);
//execute user's command
```

```
//offset depends on IE version +
safemode = *(DWORD *)
             (jsobj + offset);
if(safemode & 0xB == 0) {
    Turn_on_God_Mode();
}
```

* Shuo Chen, Jun Xu, Emre C. Sezer, Prachi Gauriar, and Ravishankar K. Iyer. Non-Control-Data Attacks Are Realistic Threats. In USENIX 2005.

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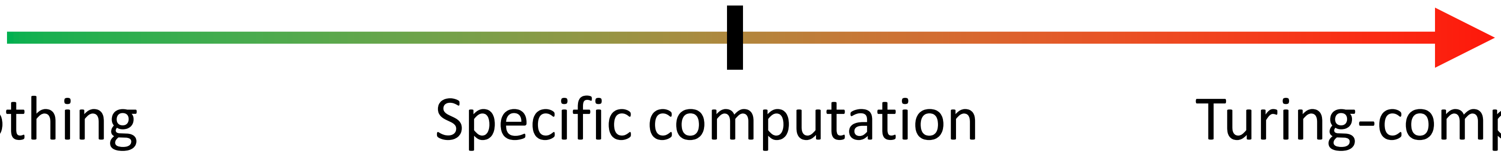
- Special cases relying on particular data/functions
  - user id, safemode, private key, etc
  - interpreter – printf() (with "%n"), etc



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- Data-Oriented Programming (DOP)
  - build expressive non-control data attacks
  - independent of any specific data / functions
- DOP builds attacks on real-world programs
  - bypass ASLR w/o address leakage
  - simulate a network bot
  - enable code injection

Motivating Example

```c
struct server{int *cur_max, total, typ;} *srv;
int quota = MAXCONN; int *size, *type;
char buf[MAXLEN];
size = &buf[8]; type = &buf[12]
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while (quota--) {
  readData(sockfd, buf);       // stack bof
  if(*type == NONE ) break;
  if(*type == STREAM)
      *size = *(srv->cur_max);
  else {
      srv->typ = *type;
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  } //...(following code skipped)...
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Vulnerable Program

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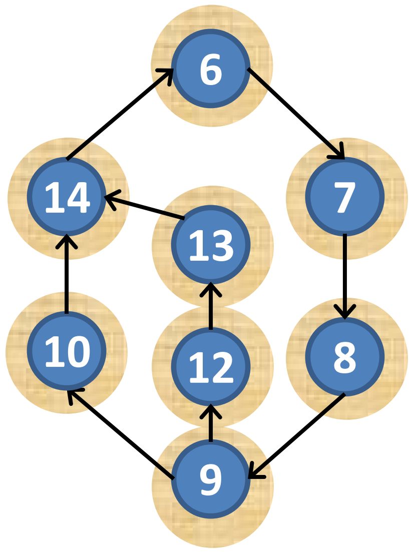
Vulnerable Program

CFG w/ CFI



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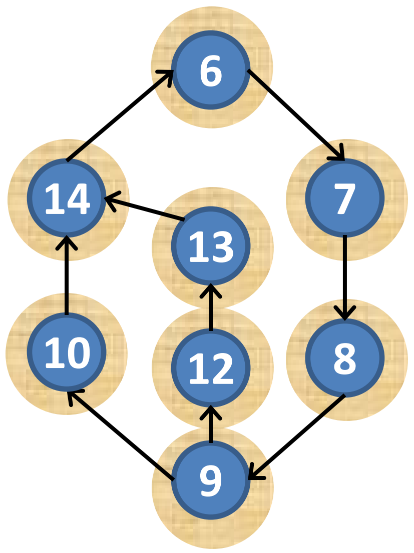

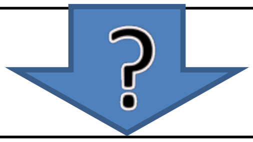

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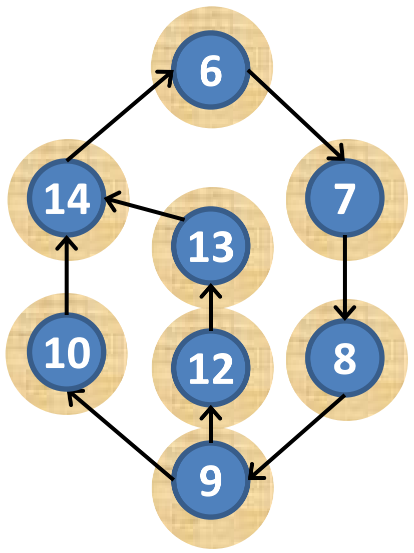

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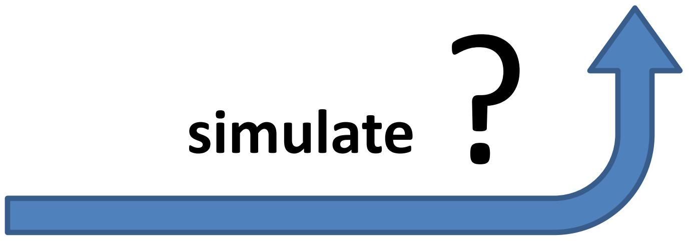

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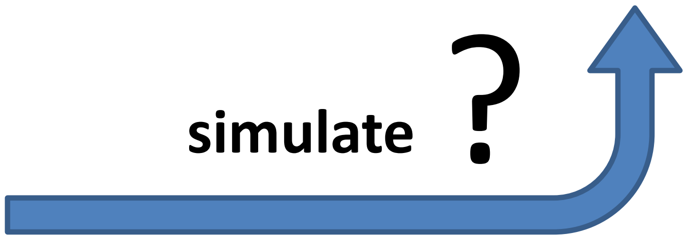

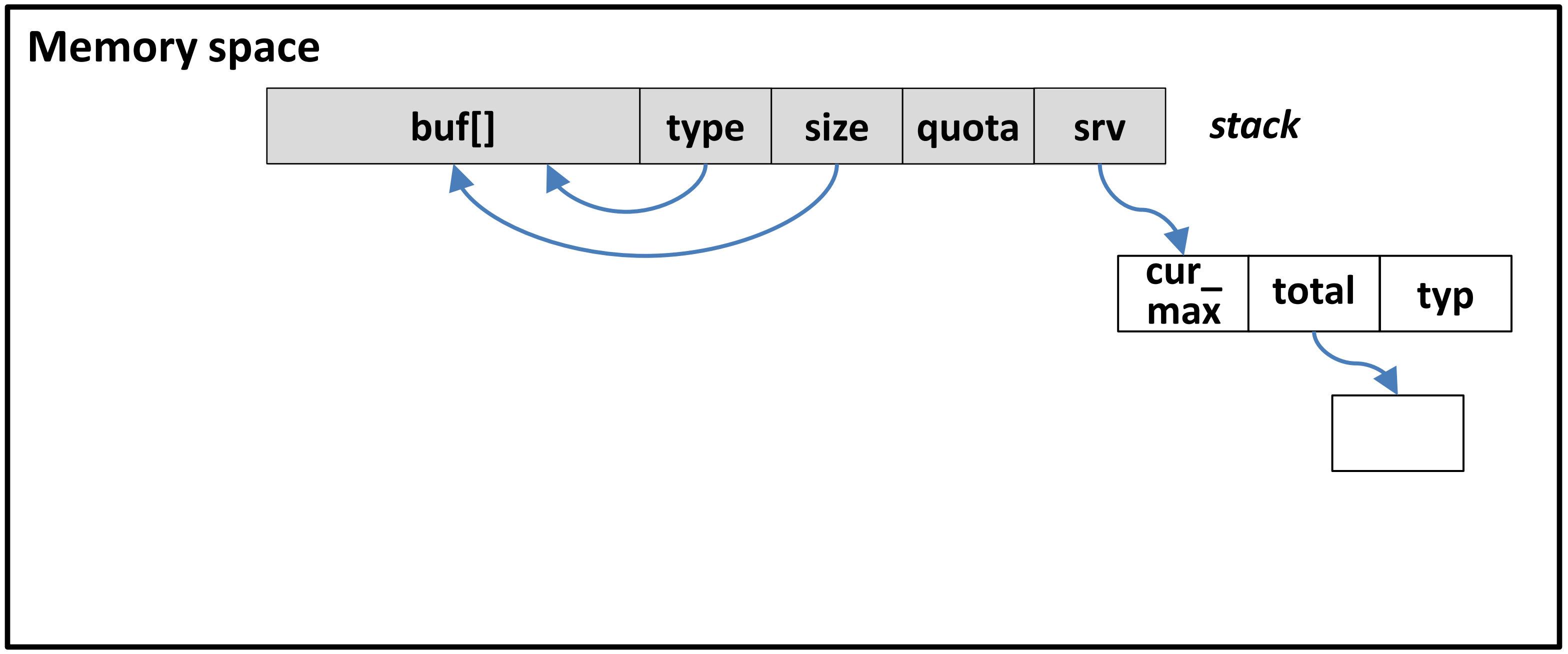

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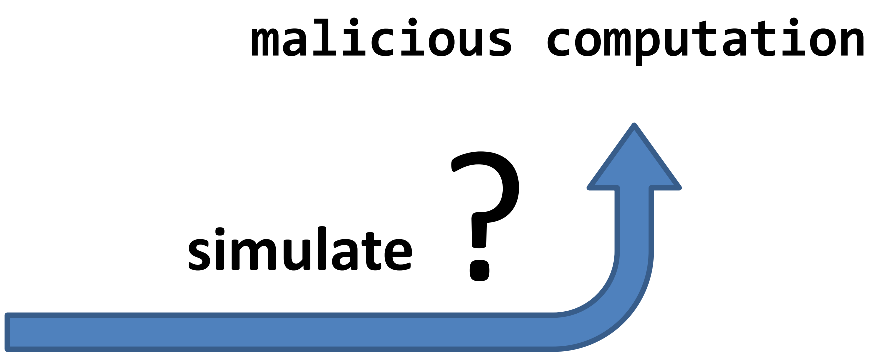

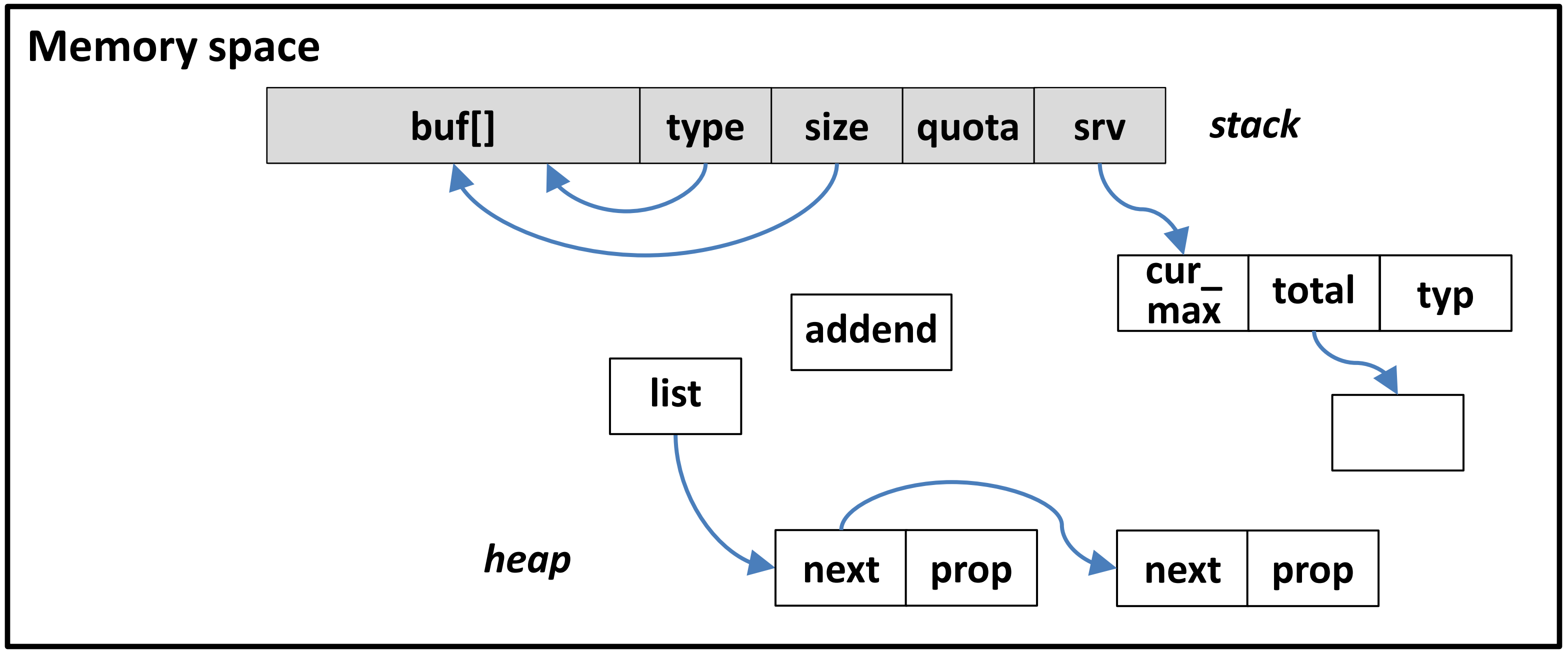

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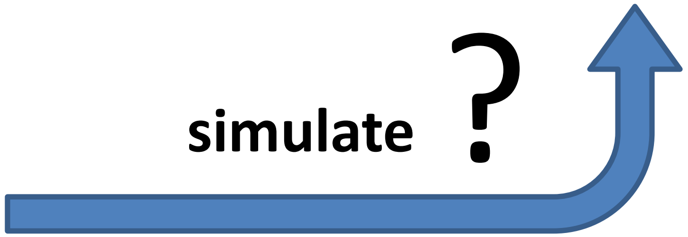

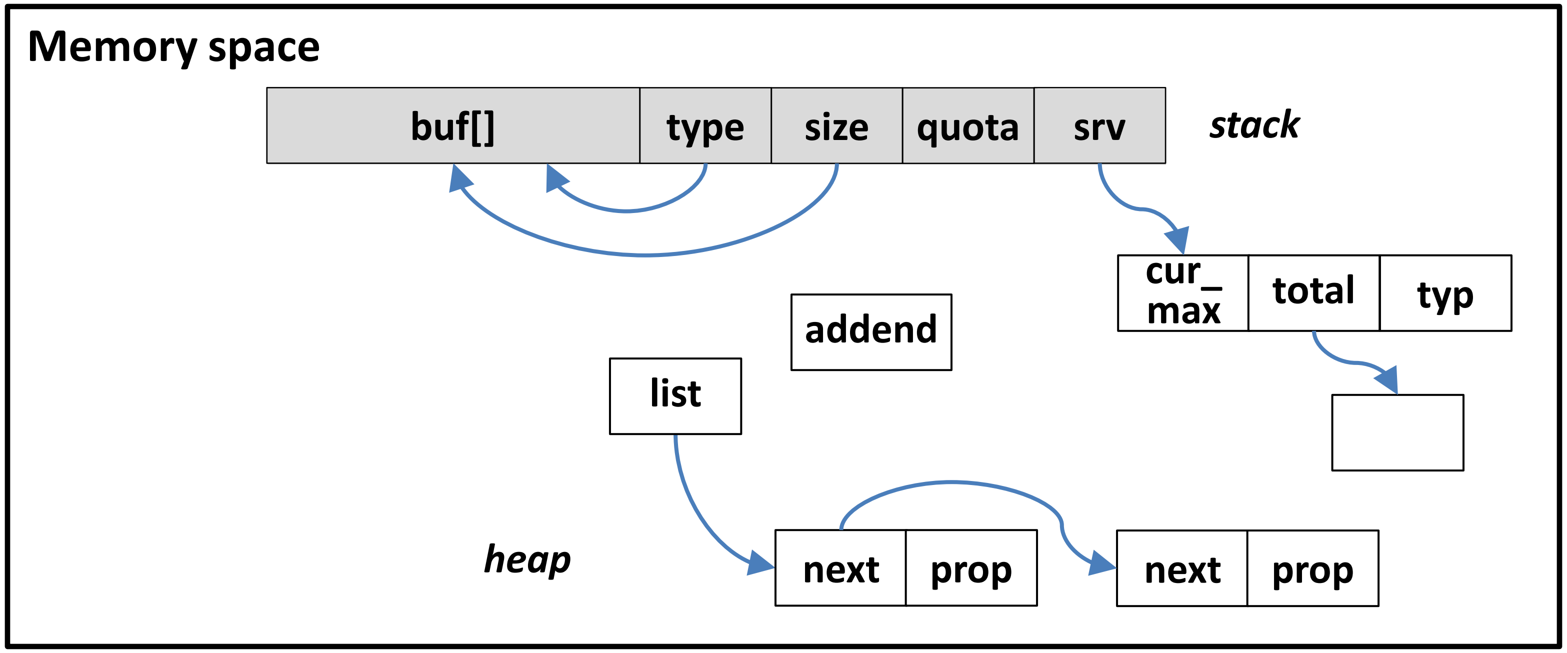

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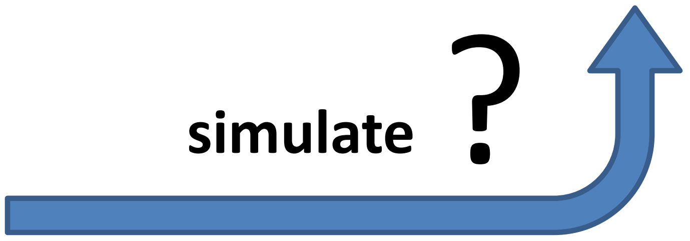

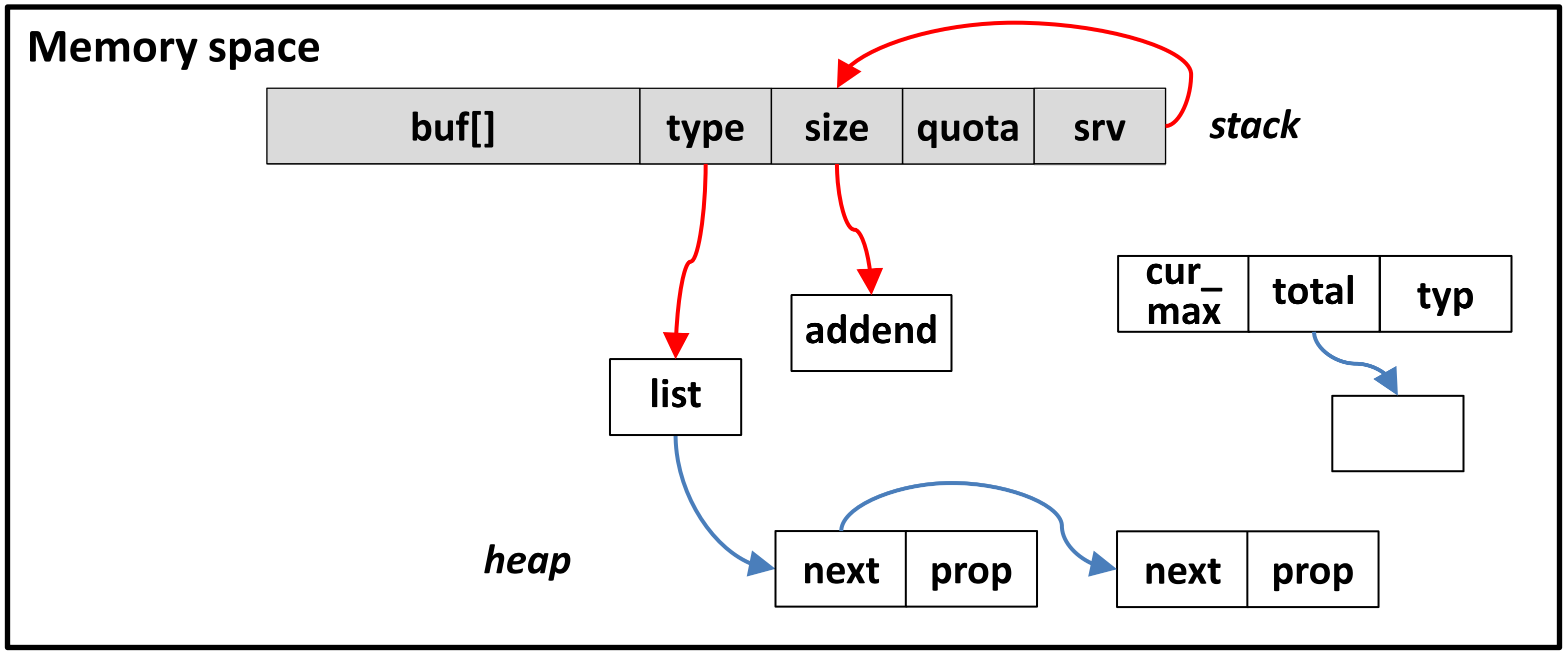

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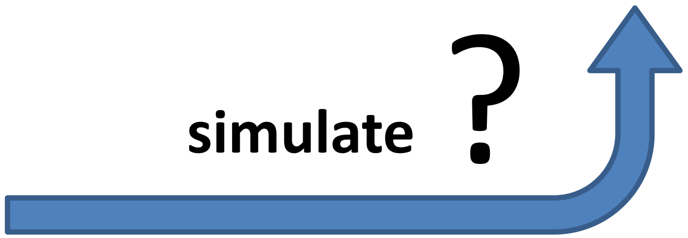

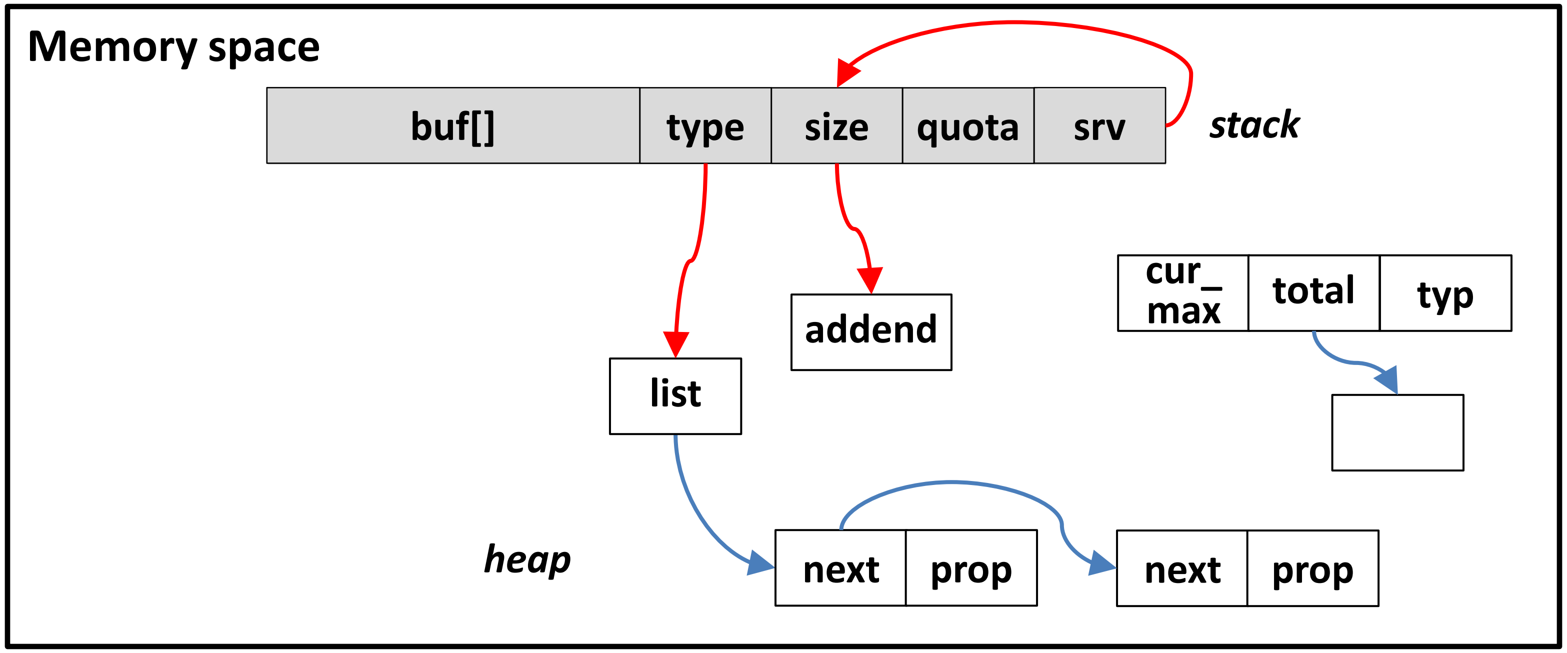

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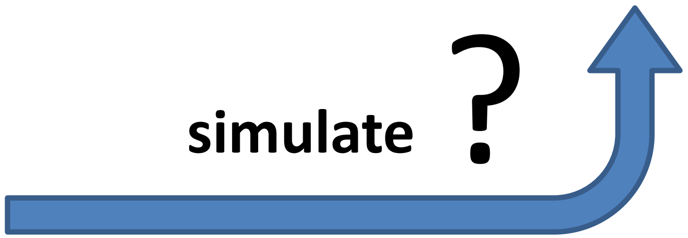

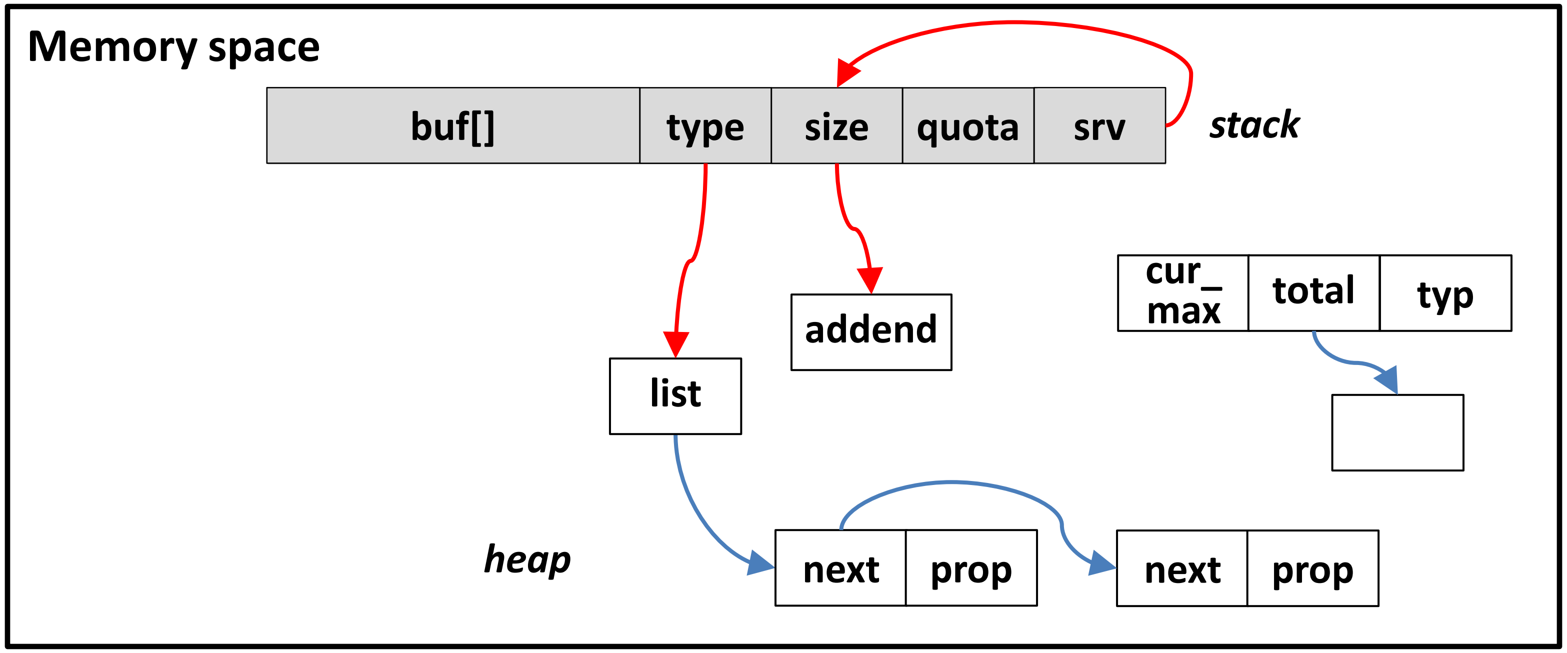

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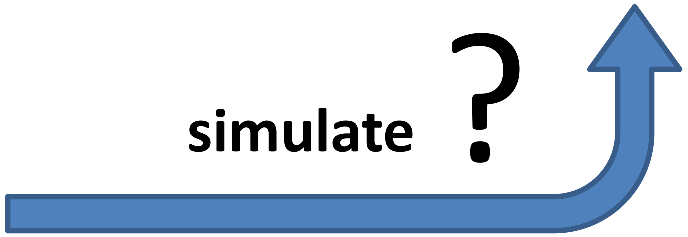

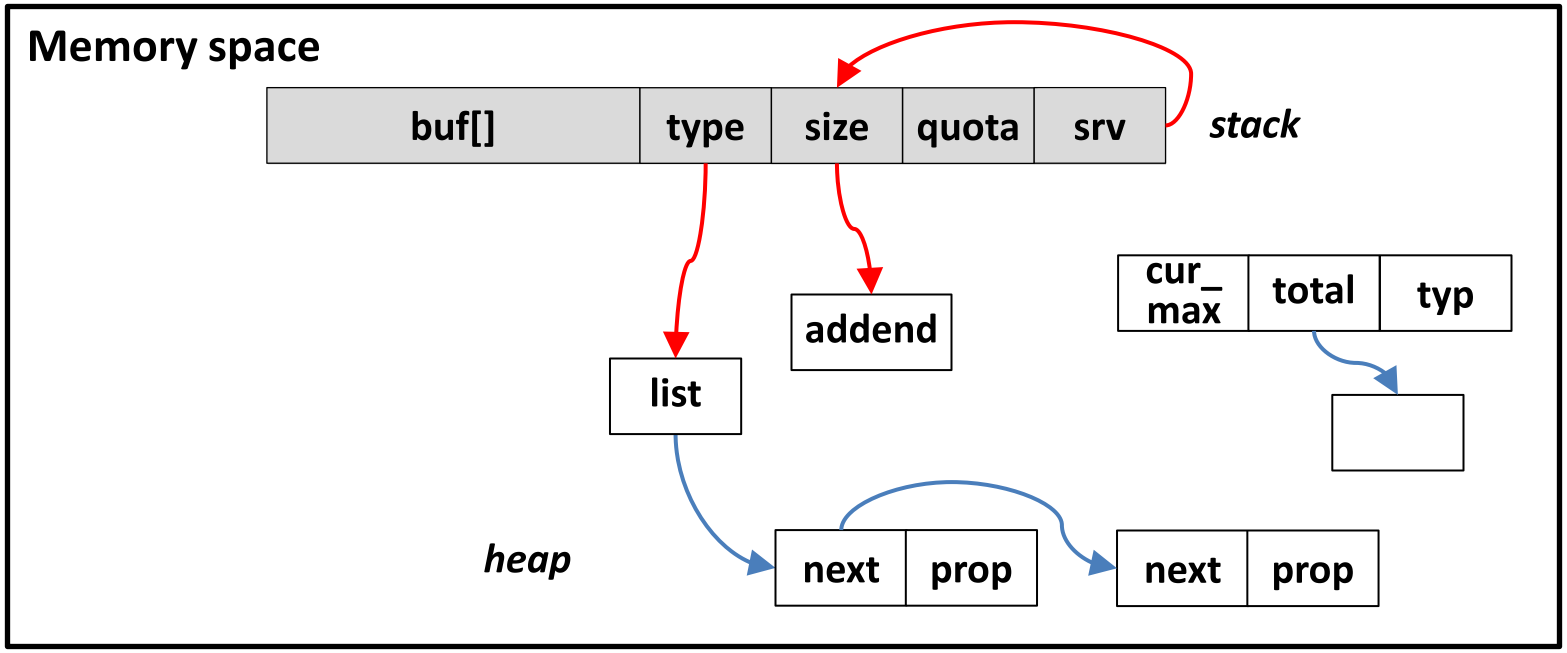

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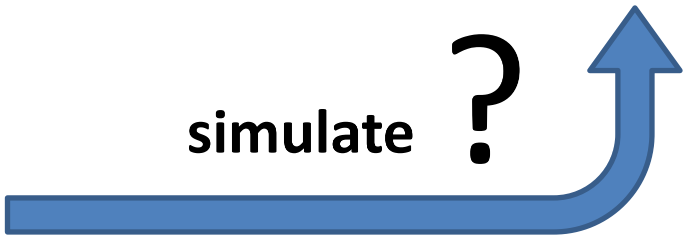

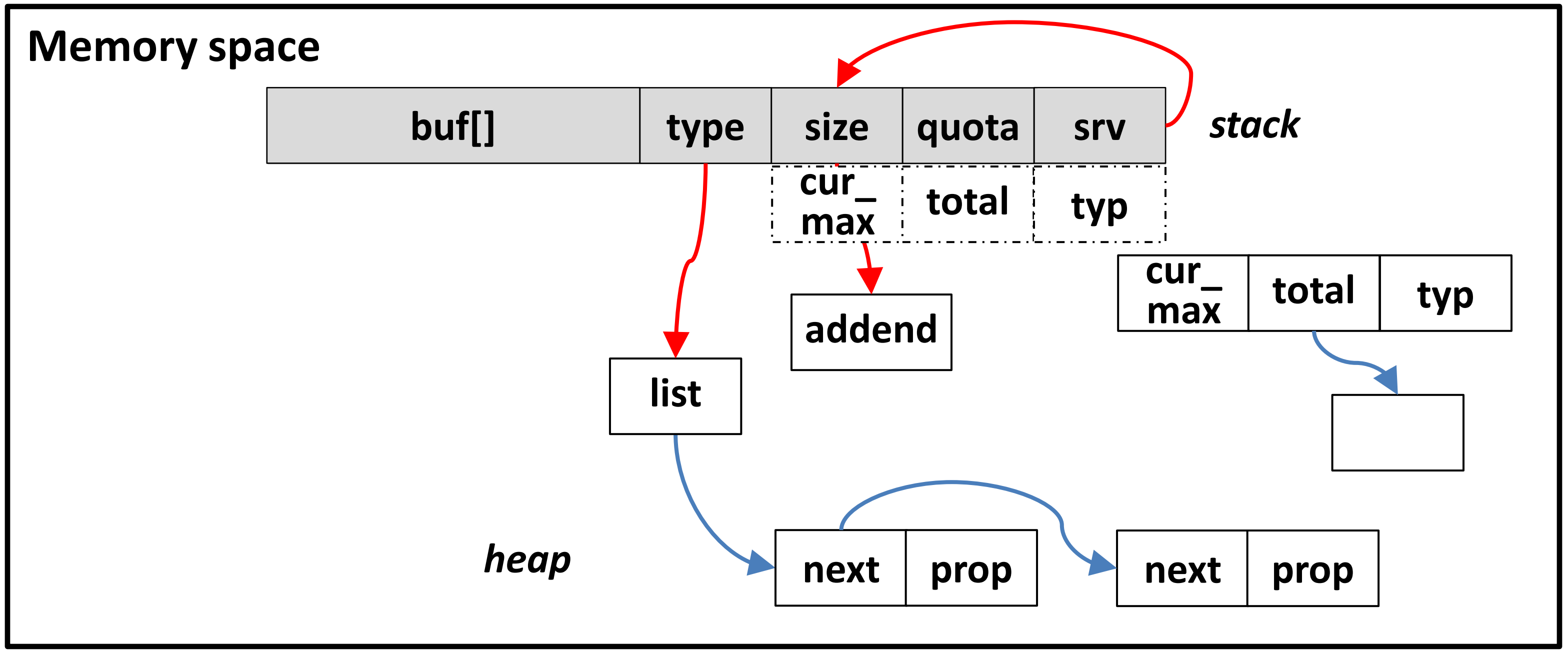

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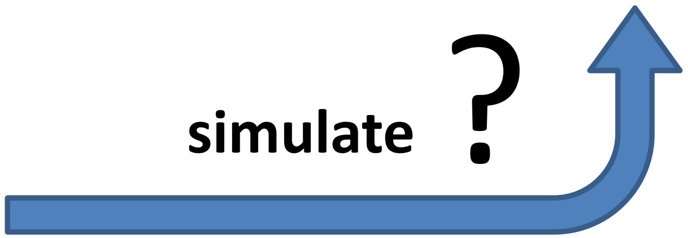

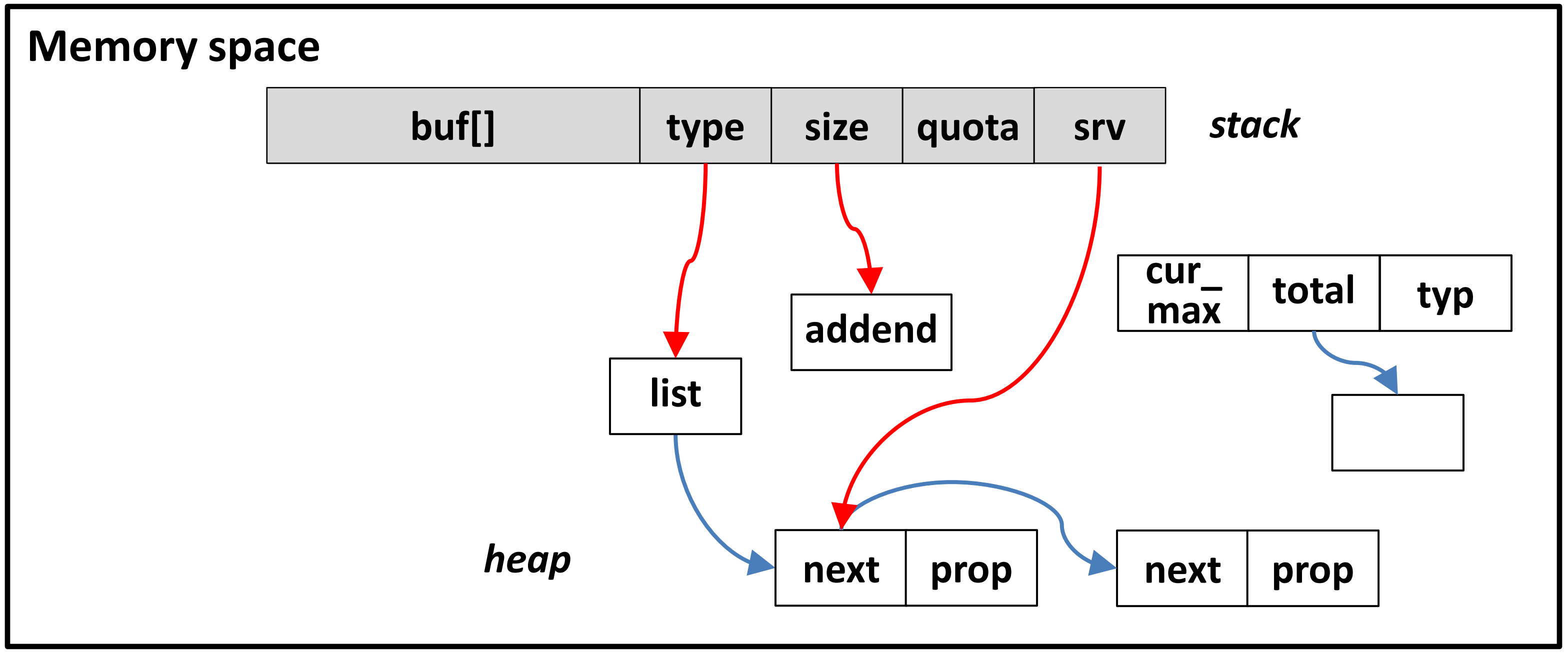

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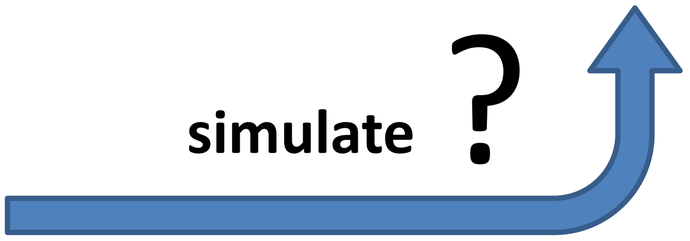

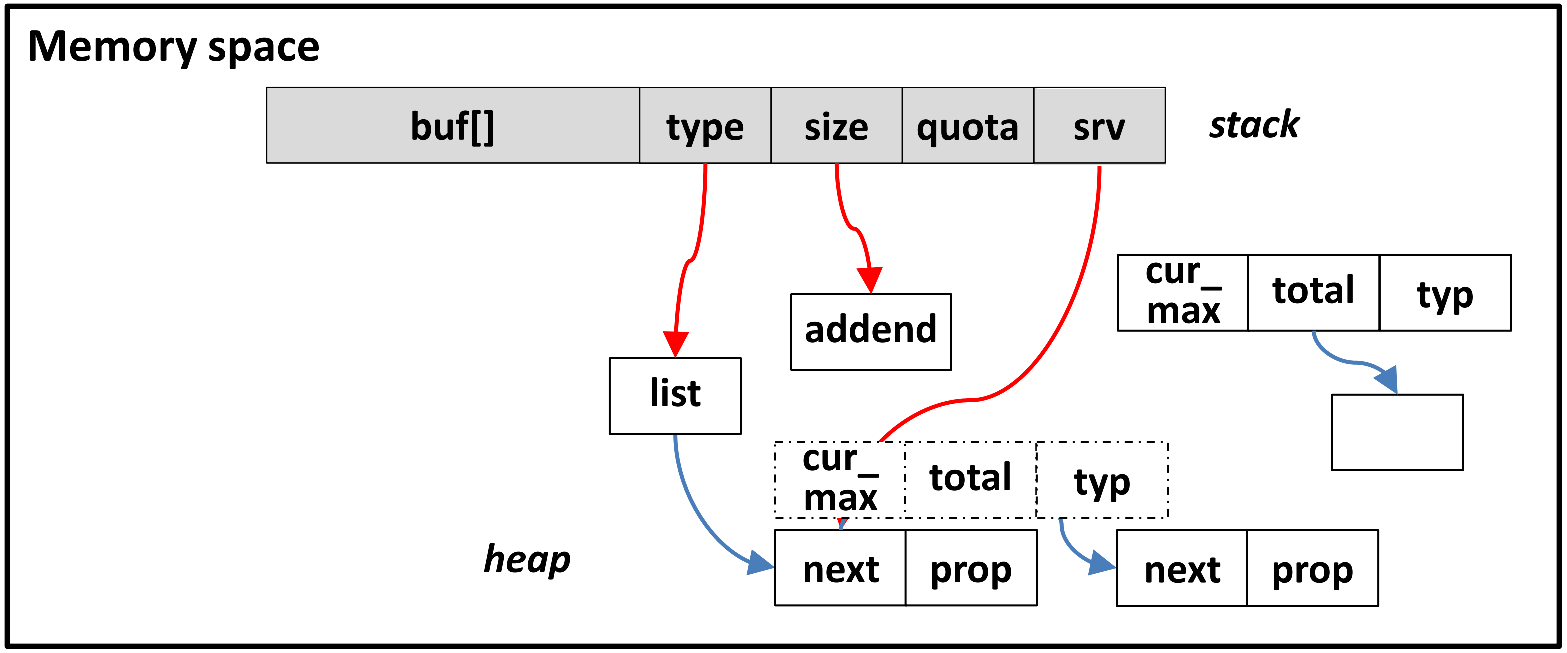

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      *size = *(srv->cur_max);
  else {
      srv->typ = *type;
      srv->total += *size;
  }
}
```

vulnerable program

```
for(; list != NULL; list = list->next)
    list->prop += addend;
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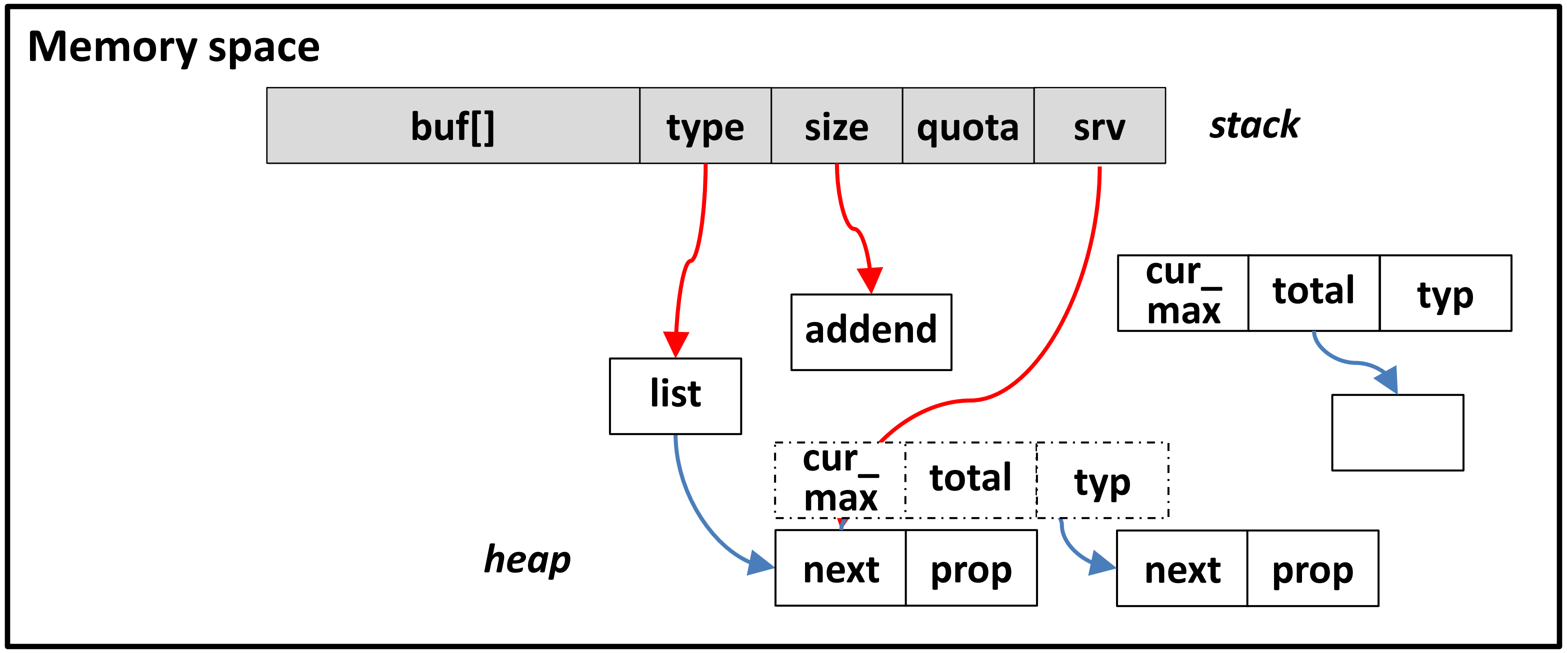
malicious computation

simulate ?



Motivating Example (cont.)

```
while (quota--) {
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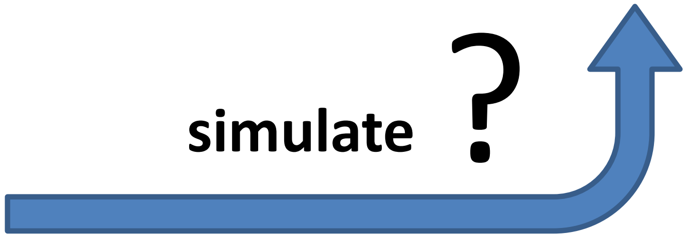

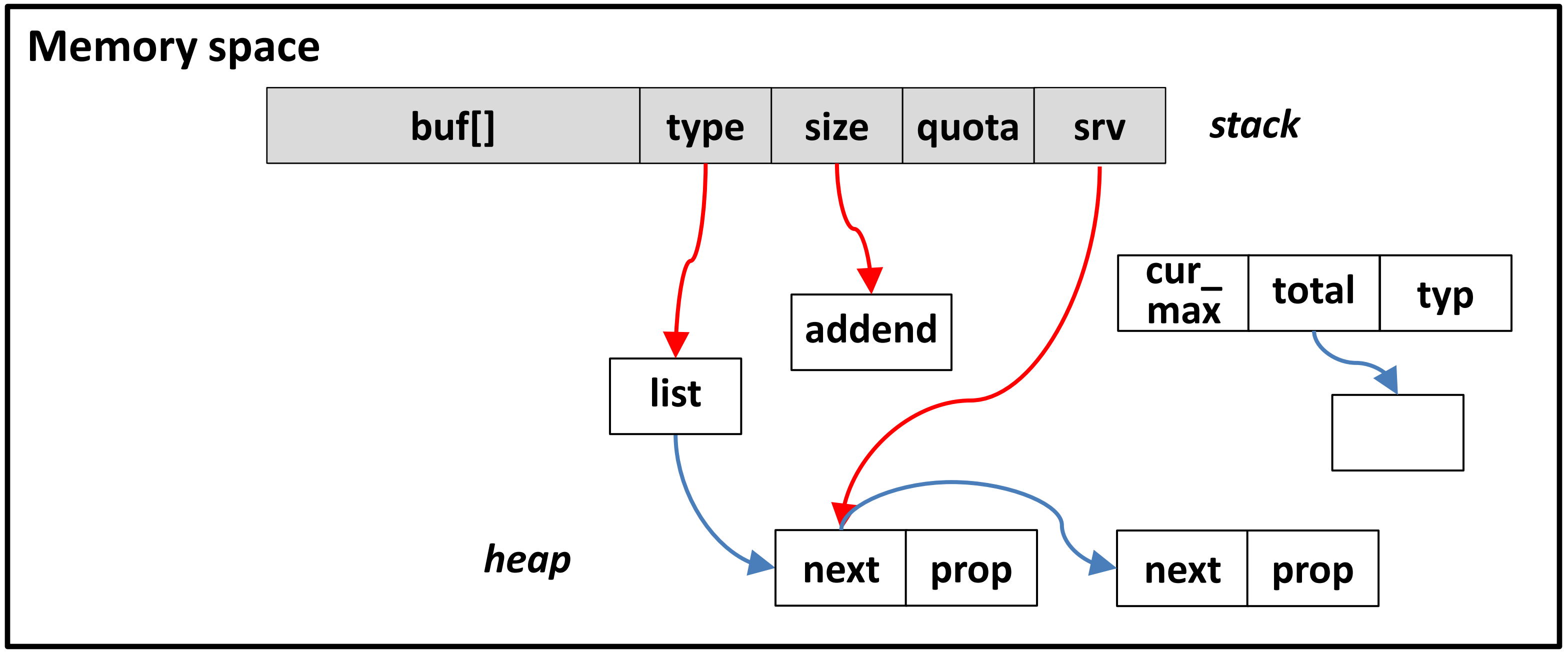

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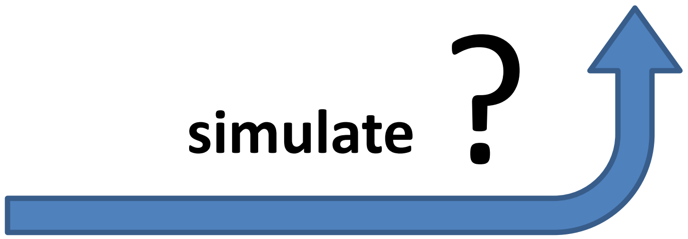

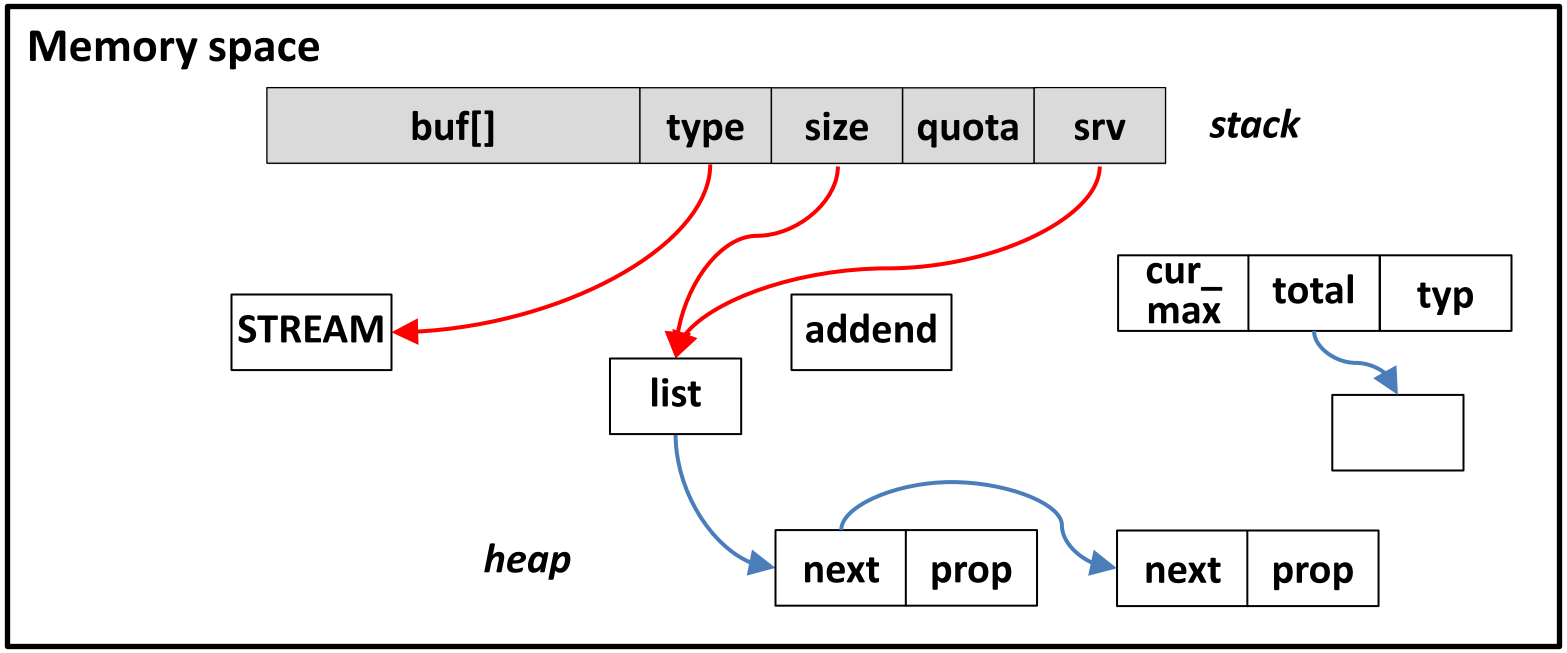

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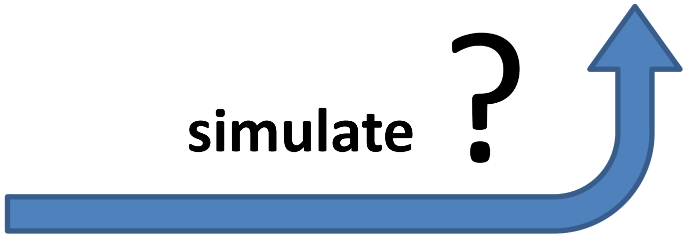

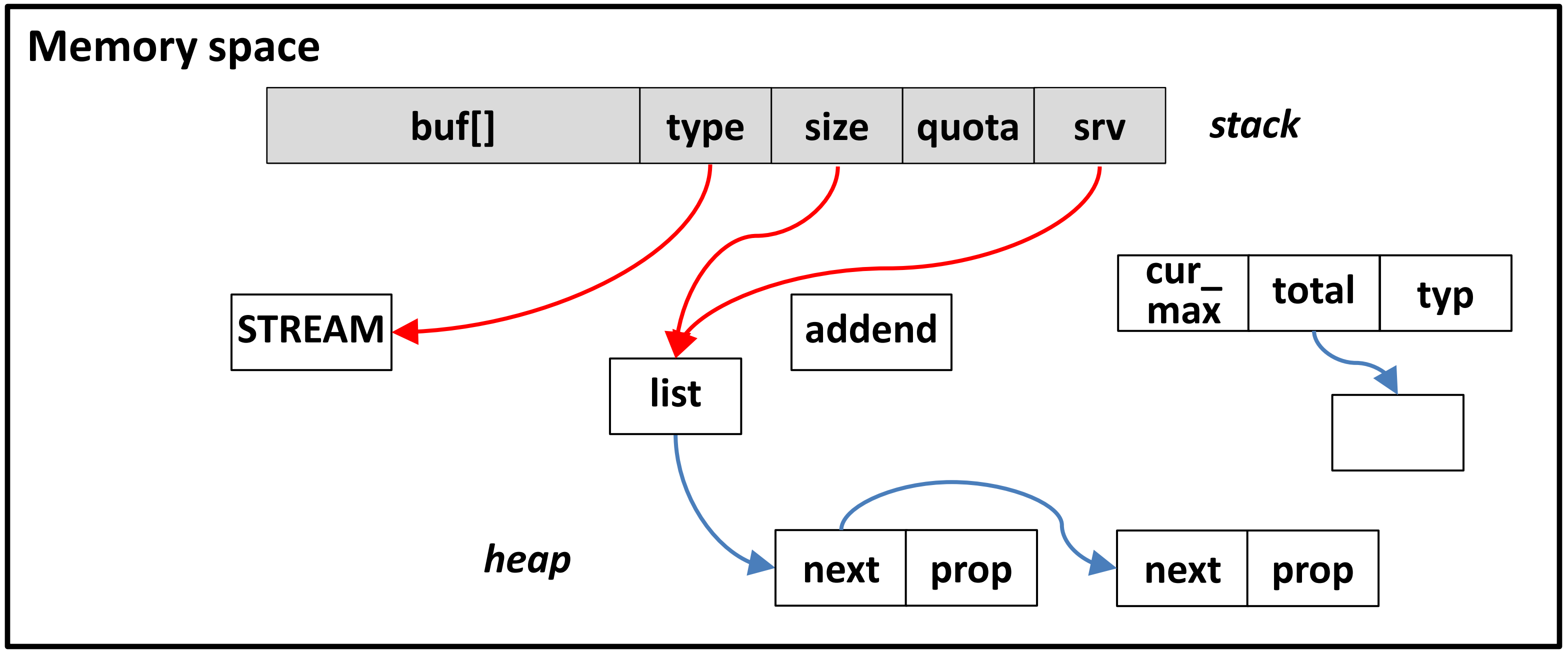

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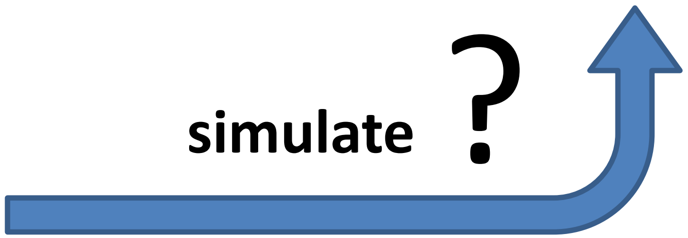

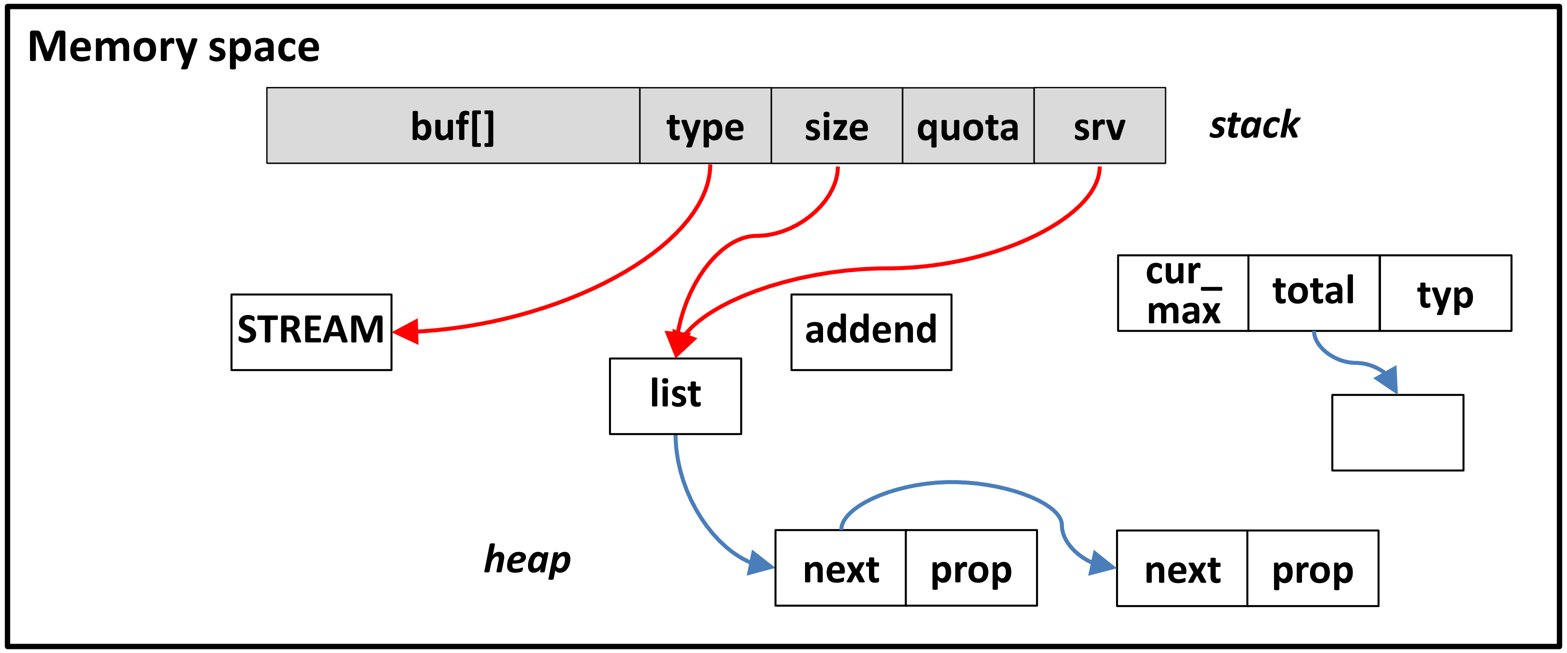

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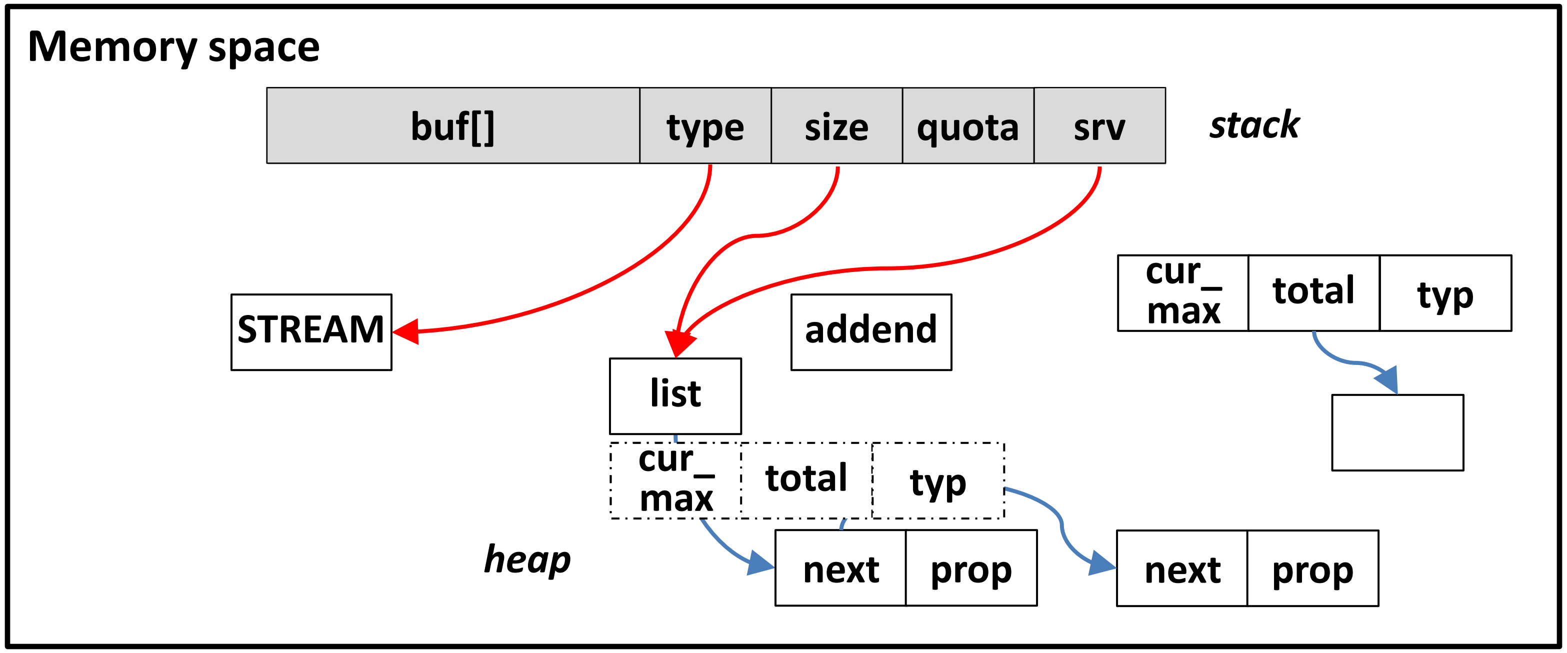

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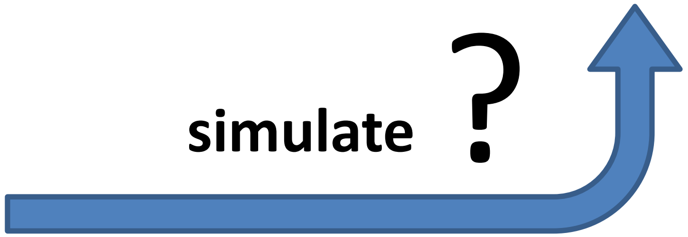

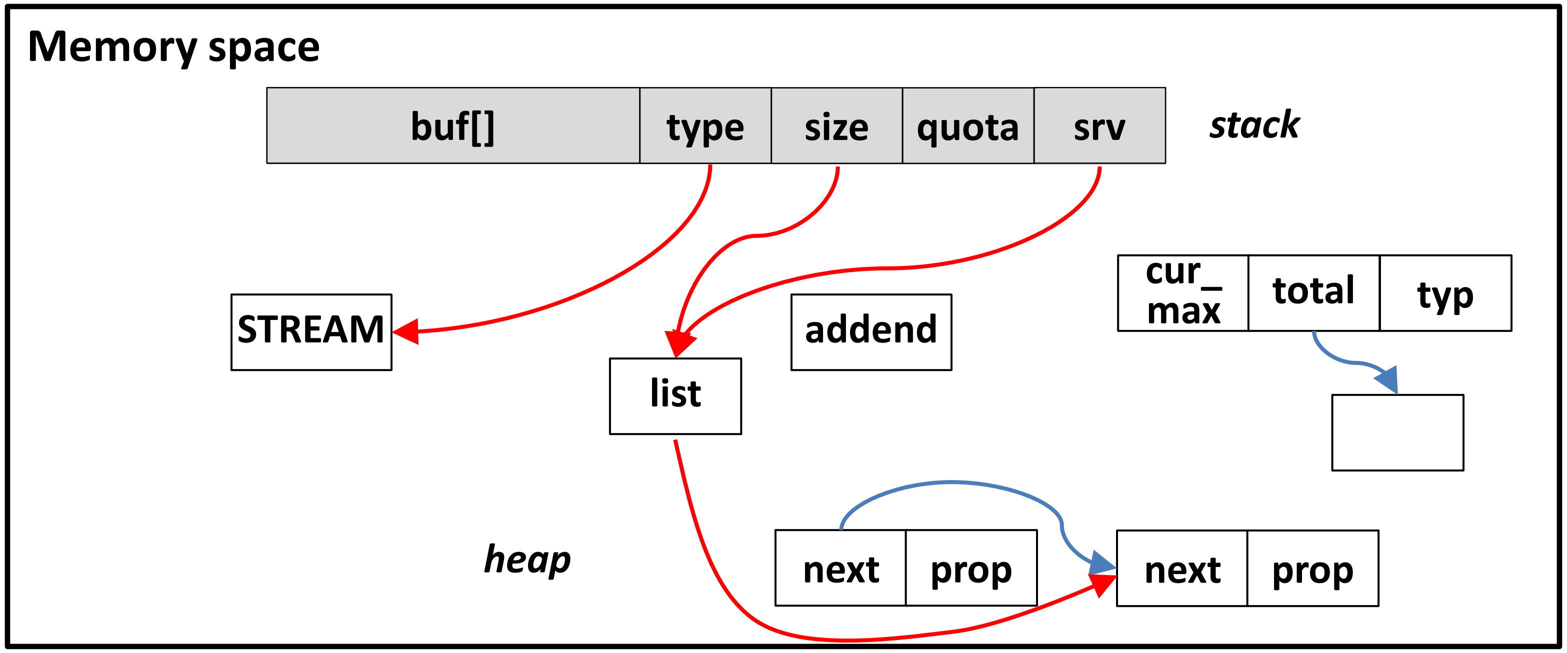

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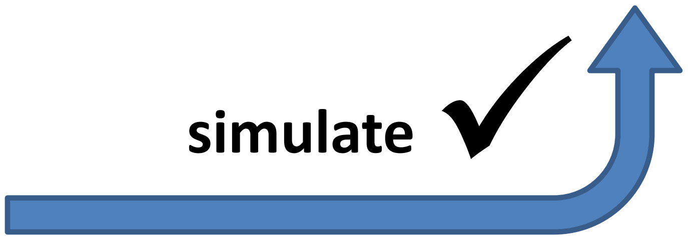

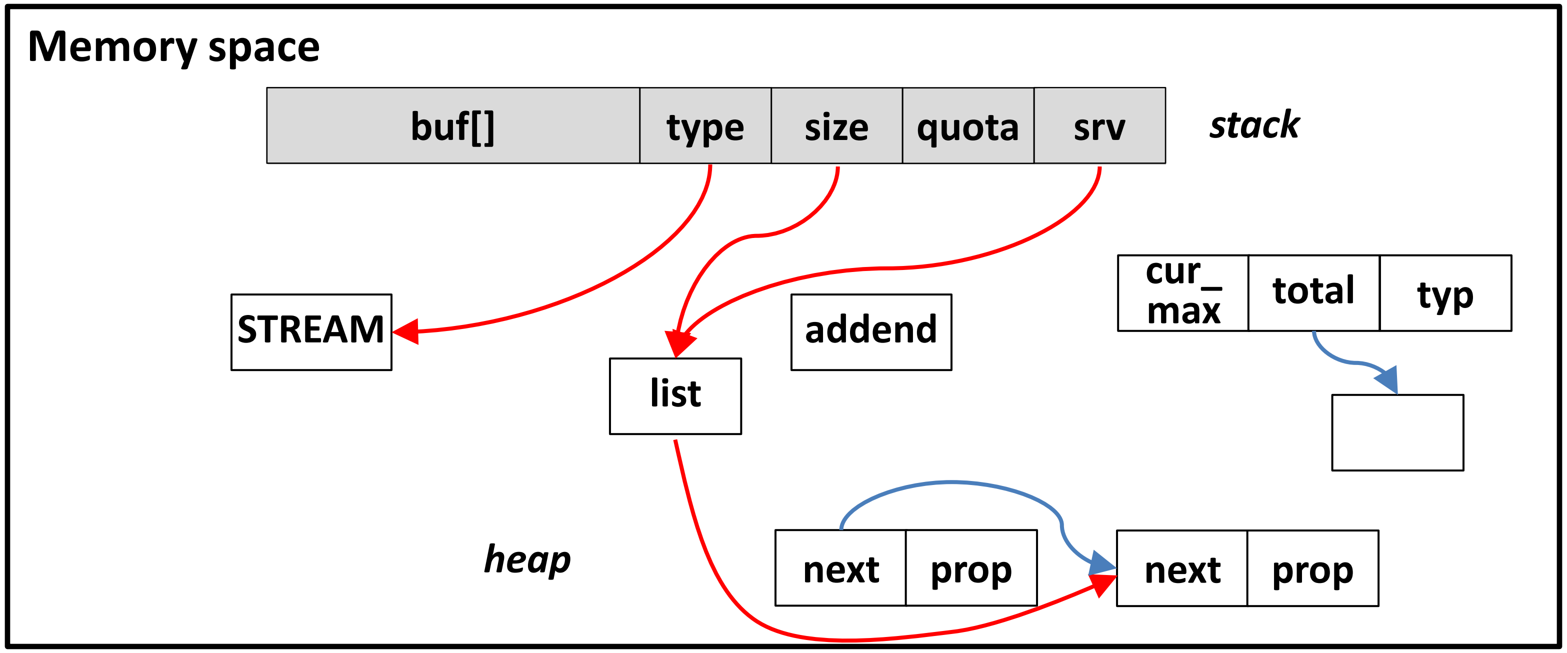

Data-Oriented Programming

A Generic Technique

Data-Oriented Programming (DOP)

- General construction
  - w/o dependency on specific data / functions

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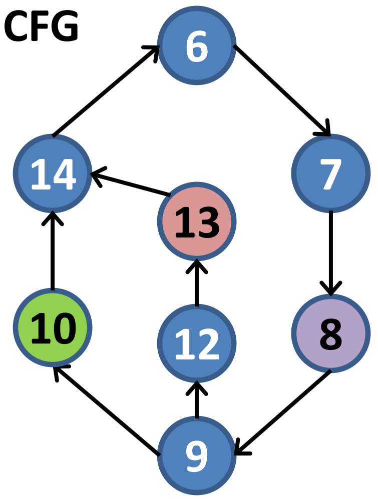
- Expressive attacks
  - towards Turing-complete computation
- Elements
  - data-oriented gadgets
  - gadget dispatchers

Data-Oriented Gadgets

- x86 instruction sequence
  - show in normal execution (CFI)

CFG


$$\begin{tikzcd}
 & 6 \arrow[dr] & \\
14 \arrow[ur] & 13 \arrow[l] & 7 \arrow[d] \\
10 \arrow[u] & 12 \arrow[u] & 8 \arrow[dl] \\
 & 9 \arrow[ul] \arrow[u] &
\end{tikzcd}$$

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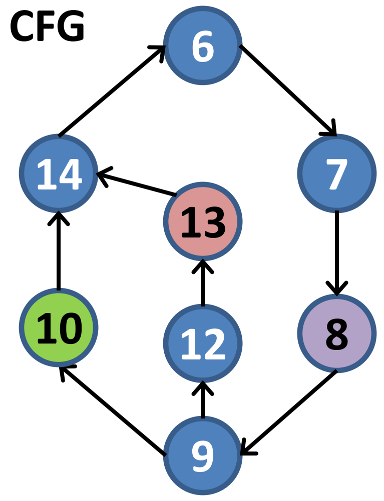

```
Addition: srv->total += *size;

1     mov (%esi), %ebx     //load micro-op
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3     add %ebx, %eax       //addition
4     mov %eax, (%edi)     //store micro-op
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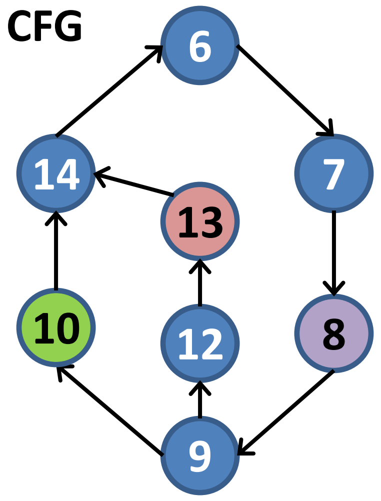
  - ***load*** *micro-op -->* ***semantics*** *micro-op -->* ***store*** *micro-op*



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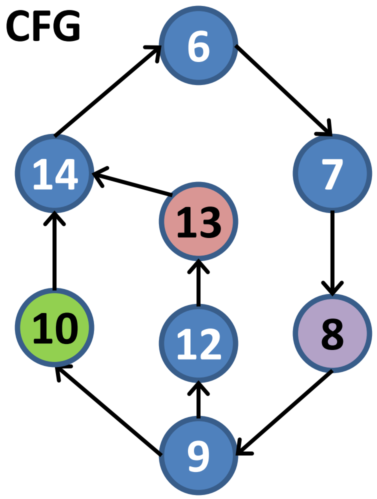

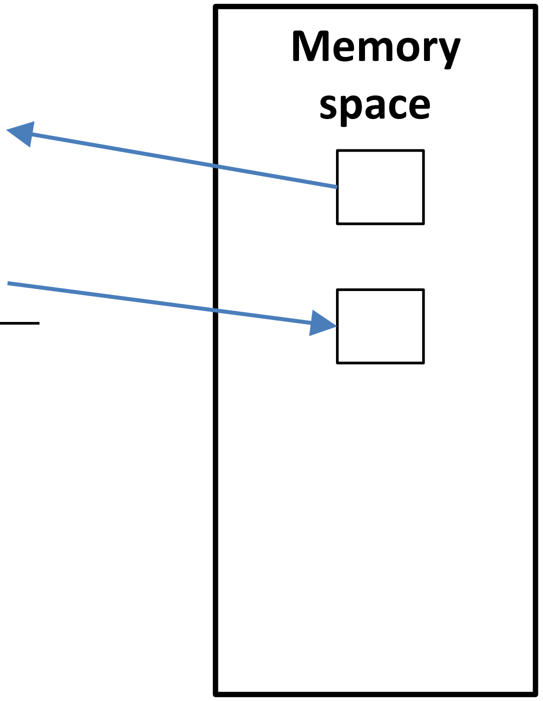

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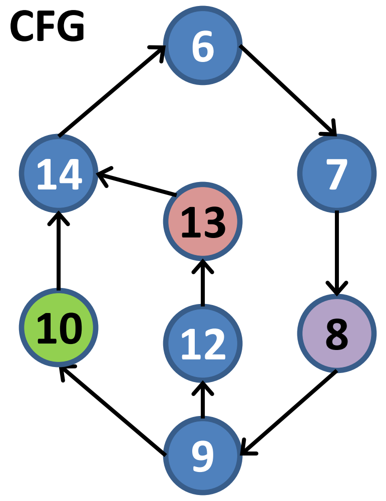

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Load: `*size = *(srv ->cur_max);`

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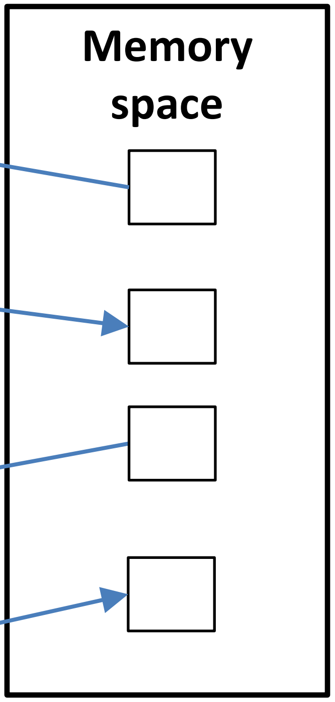

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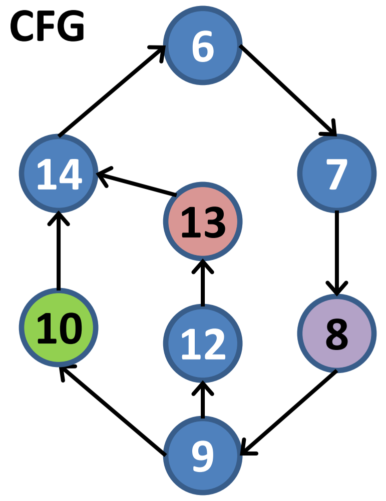

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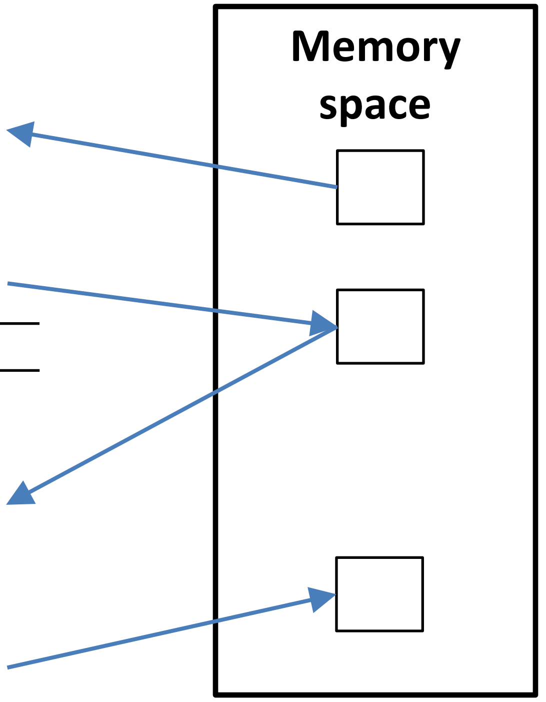
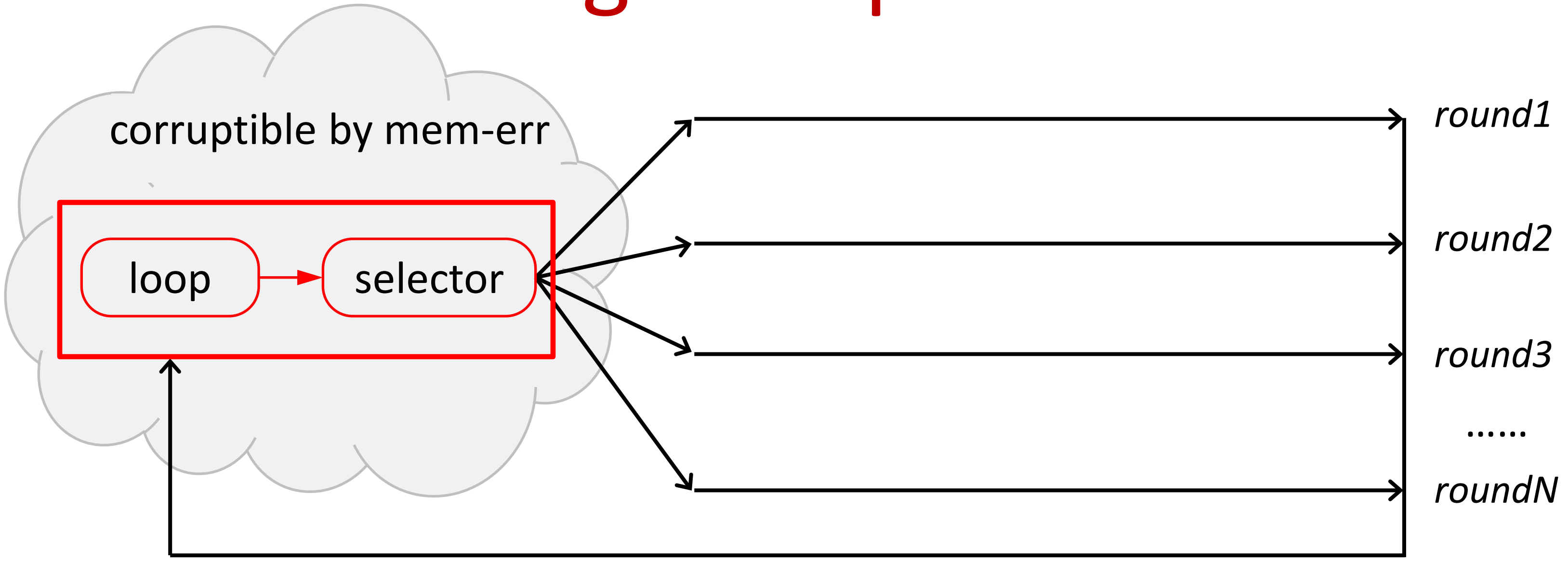


Gadget Dispatcher



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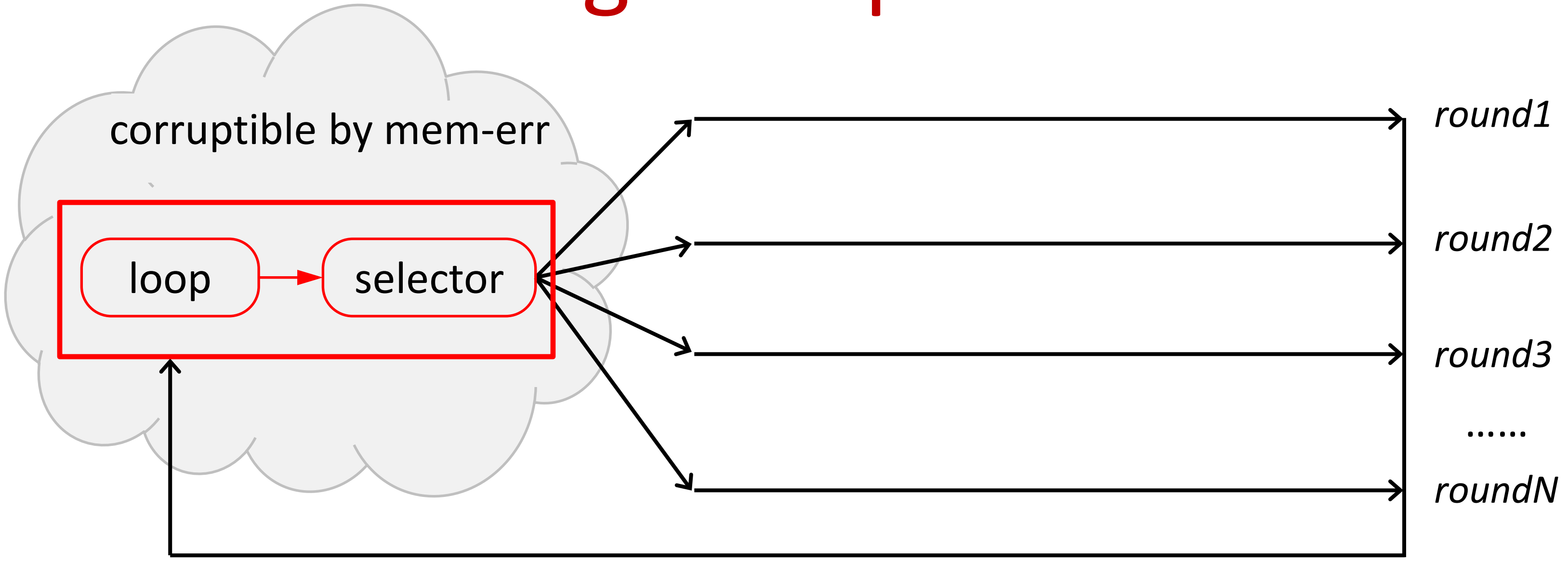

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  - **selector** ---> selectively activate gadgets

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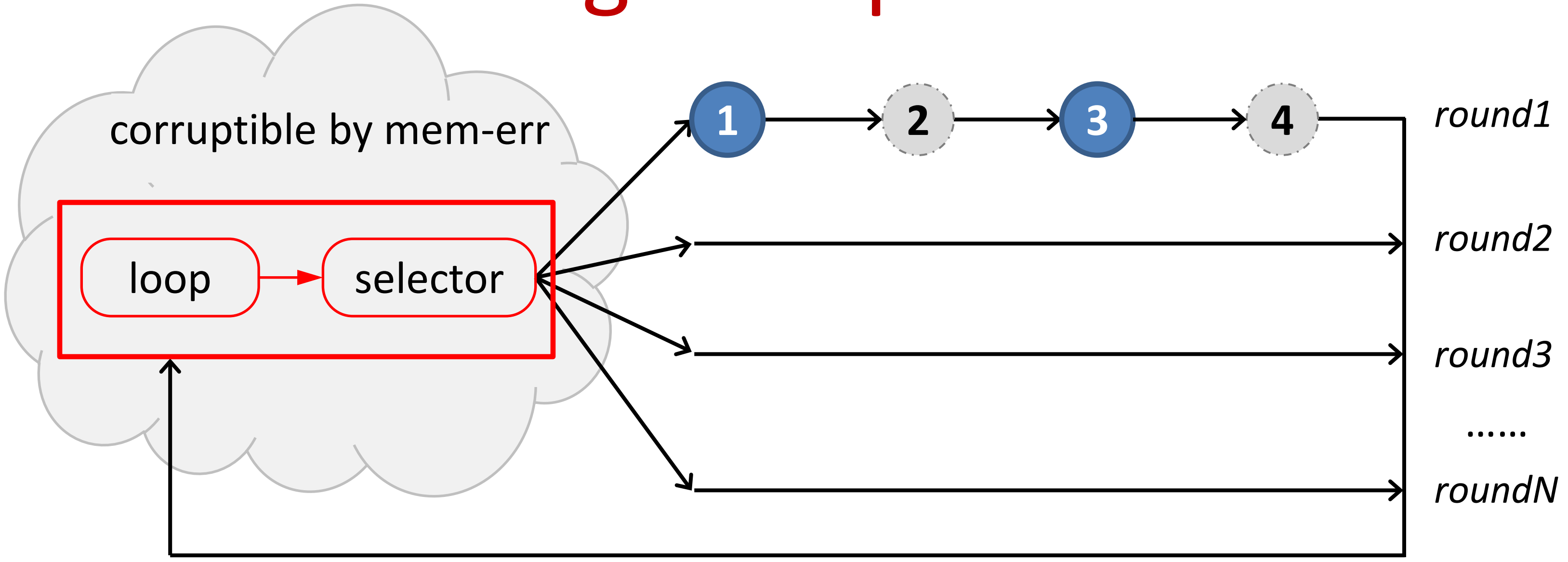

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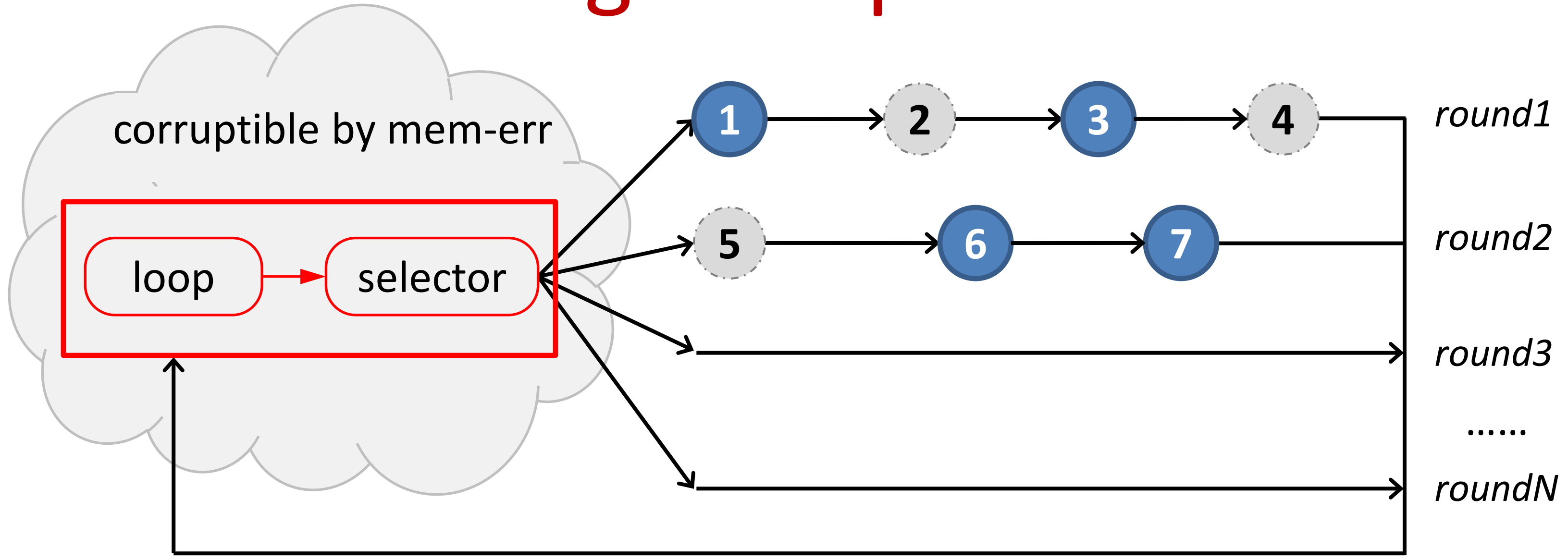

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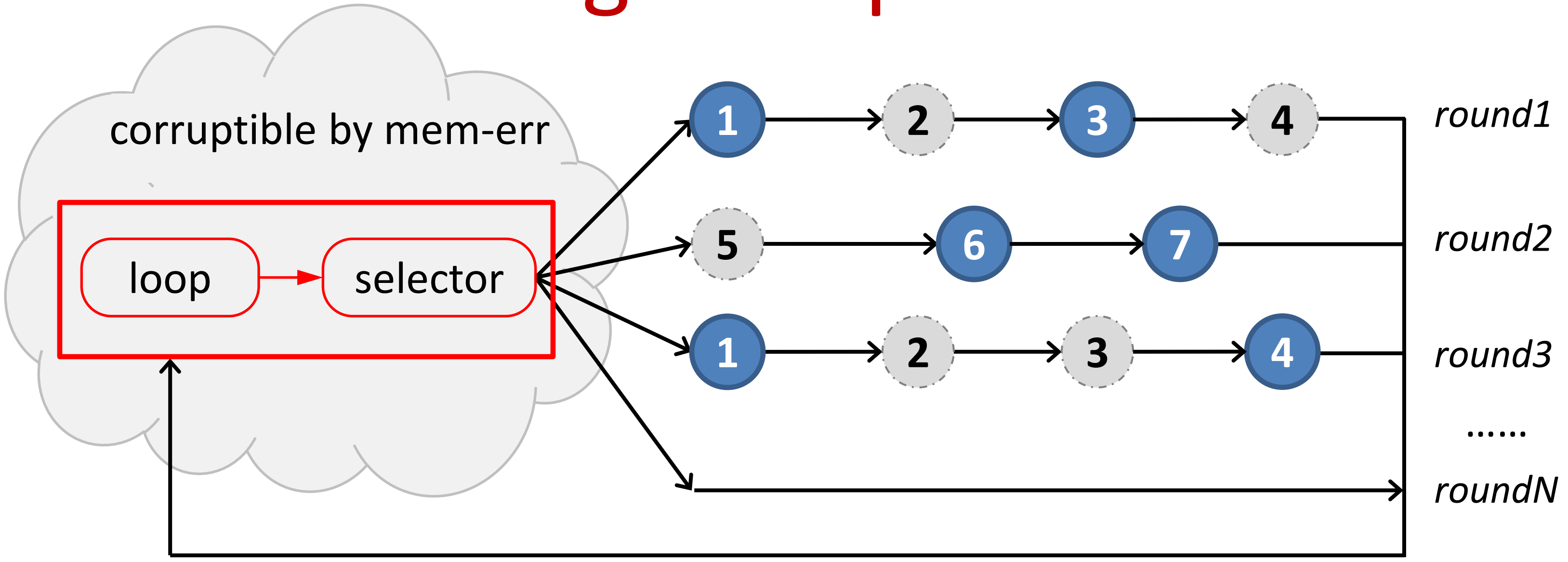

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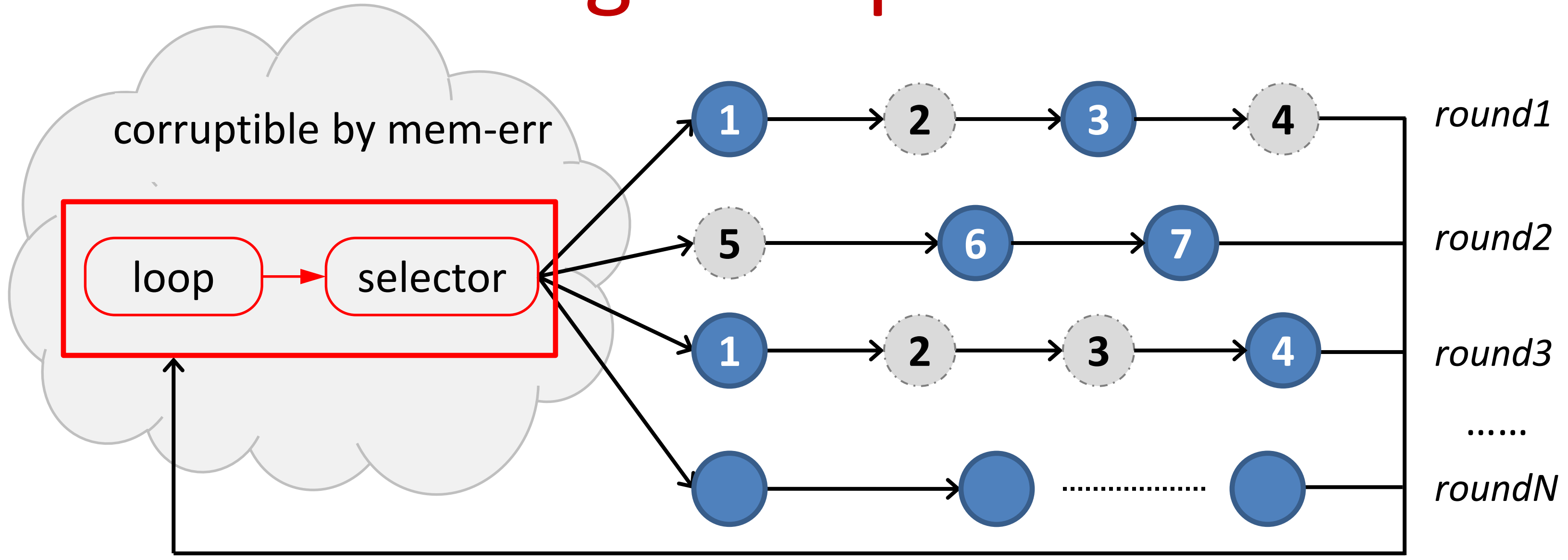

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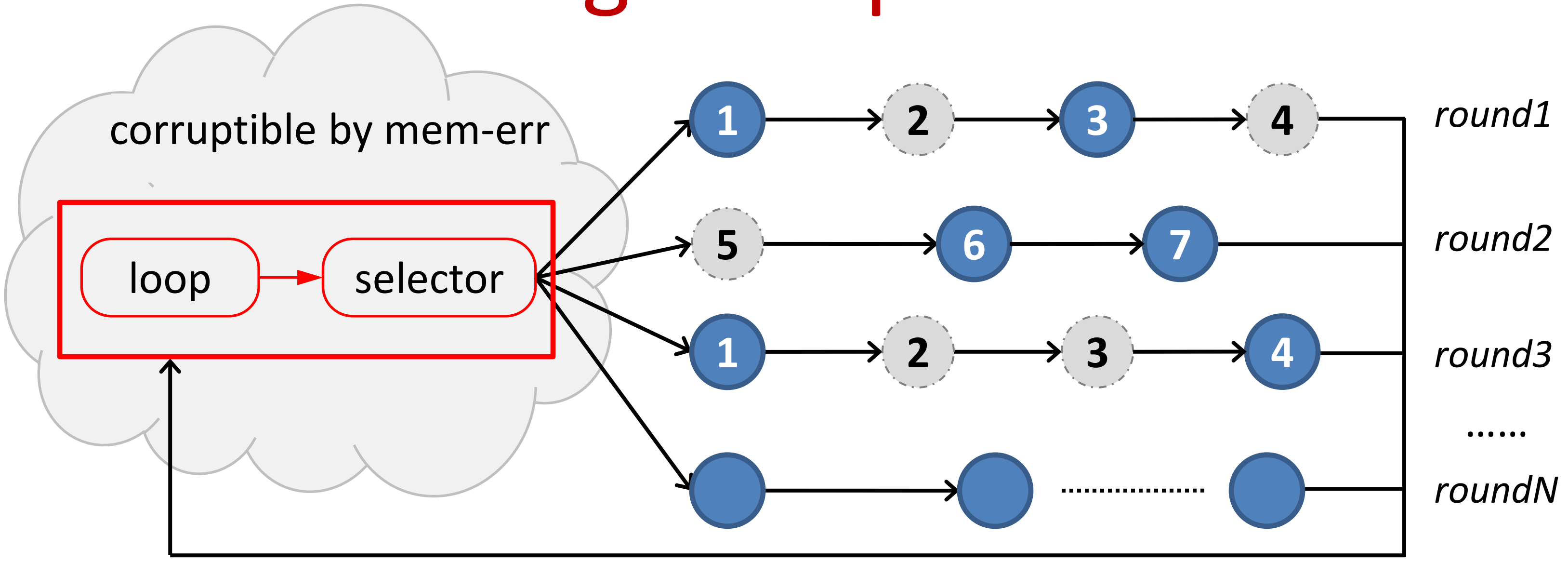

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  - **loop** ---> repeatedly invoke gadgets
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```
6  while (quota--) {                      // loop
7    readData(sockfd, buf);               // selector
8    if(*type == NONE ) break;
9    if(*type == STREAM) *size = *(srv->cur_max);
10    else{ srv->typ = *type;  srv->total += *size; }
14 }
```

Turing-completeness

- DOP emulates a minimal language *MINDOP*
  - *MINDOP* is Turing-complete

Semantics	Statements In C	Data-Oriented Gadgets in DOP
arithmetic / logical	a op b	*p op *q
assignment	a = b	*p = *q
load	a = *b	*p = **q
store	*a = b	**p = *q
jump	goto L	vpc = &input
conditional jump	if (a) goto L	vpc = &input if *p
p – &a; q – &b; op – any arithmetic / logical operation		

Attack Construction

```
while (quota--) {
  readData(sockfd, buf);
  if(*type == NONE ) break;
  if(*type == STREAM)
      *size = *(srv->cur_max);
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   } //...(code skipped)...
}
```

Attack Construction

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- Gadget identification
  - statically identify load-semantics-store chain from LLVM IR

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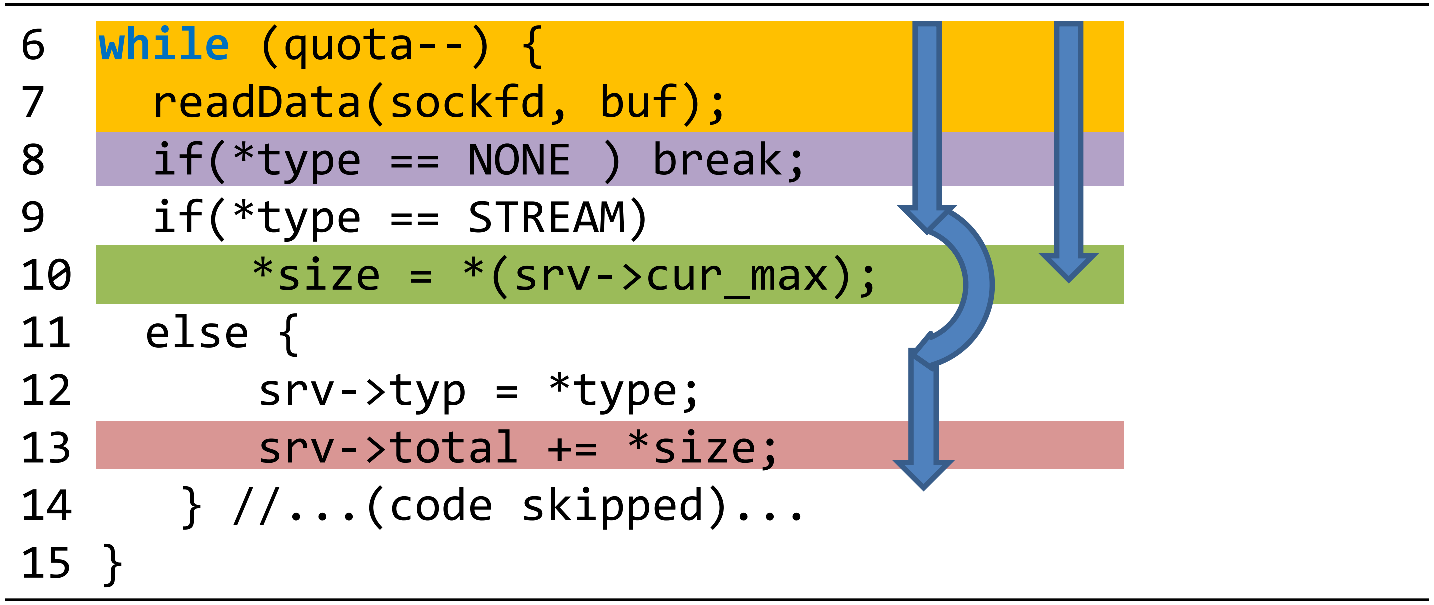
Attack Construction



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- Gadget identification
  - statically identify load-semantics-store chain from LLVM IR
- Dispatcher identification
  - static identify loops with gadgets from LLVM IR
- Gadget stitching
  - select gadgets and dispatchers (manual)
  - check stitchability (manual)

Evaluation

Evaluation – Feasibility

9 x86 programs with 9 vulnerabilities

- Nginx, ProFTPD, Wu-FTPD, sshd, Bitcoind,
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  - 8 programs can simulate all MINDOP operations
- x86 Dispatchers
  - 1443 in total, 110 reachable from selected CVEs

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- x86 Dispatchers
  - 1443 in total, 110 reachable from selected CVEs
- 2 programs can build Turing-complete attack
- 3 end-to-end attacks

Case Study: Bypassing Randomization

- Previous methods
  - information leakage to network
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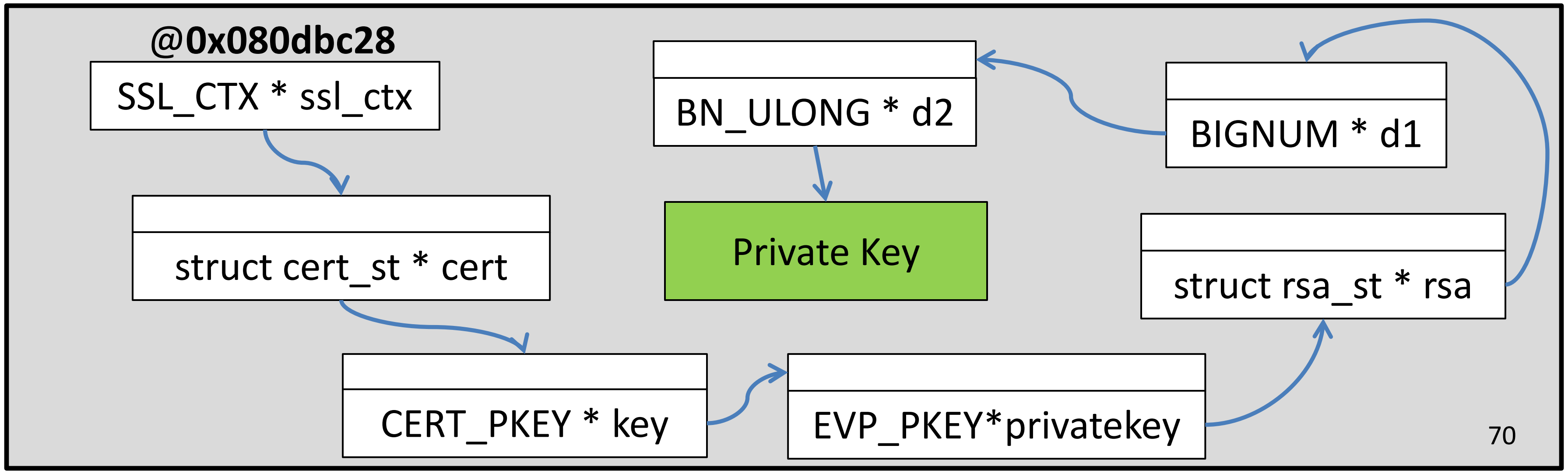

Case Study: Bypassing Randomization

- Gadgets

MOV	*p = *q
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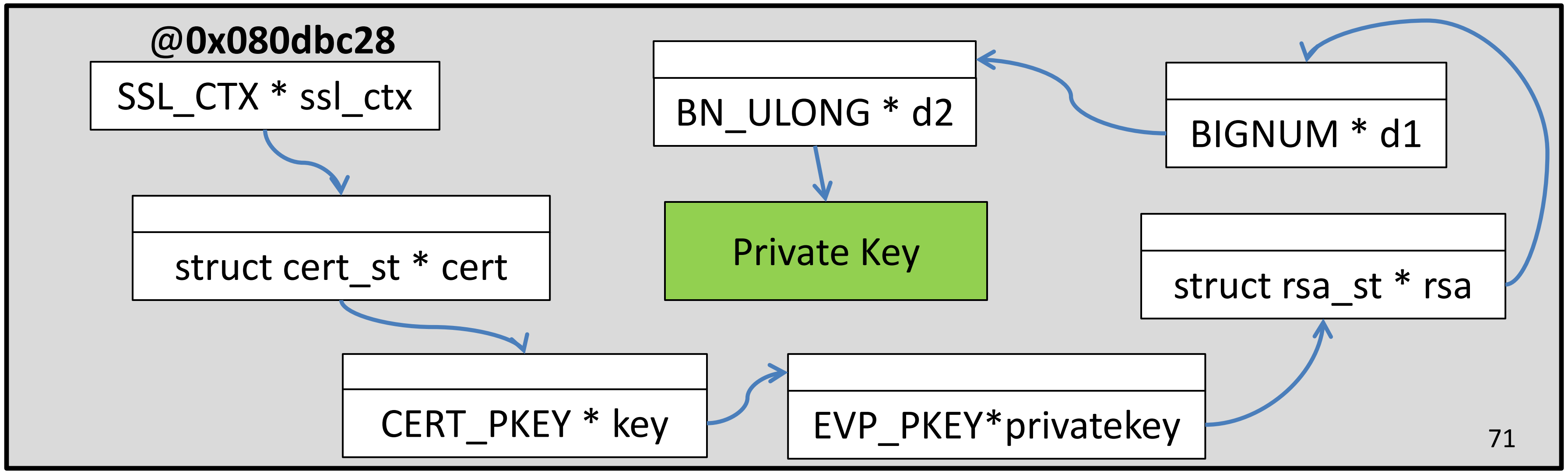
LOAD	*Z = **Y



Case Study: Bypassing Randomization

- Gadgets

MOV	*p = *q
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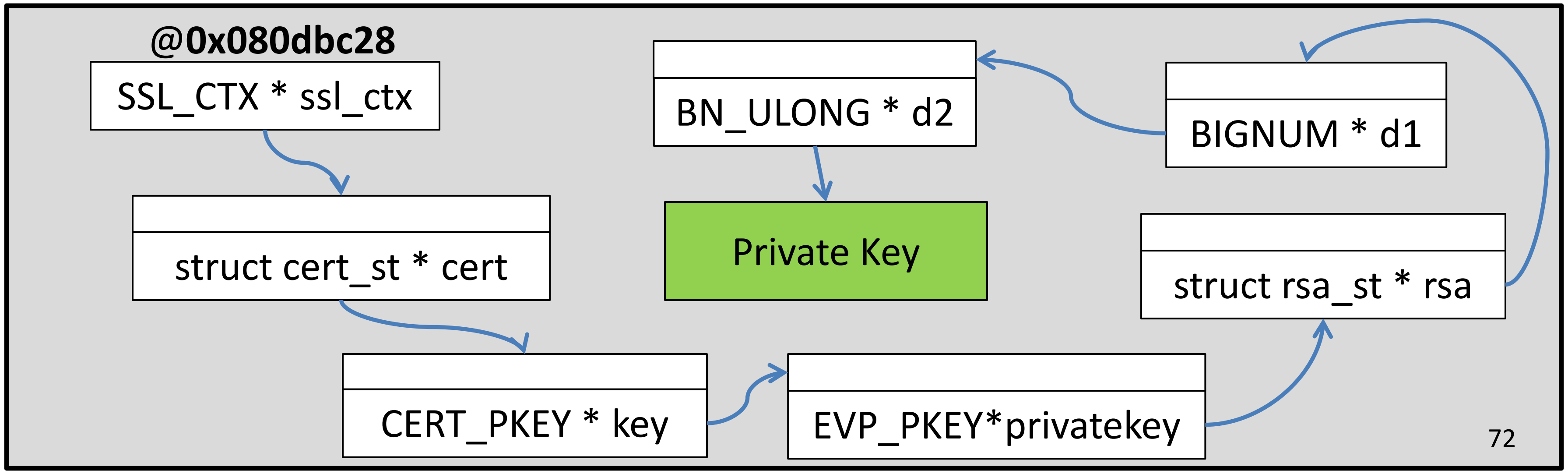
- Dispatcher

```
while (1) {
    user_request =
        get_user_request();
    dispatch(user_request);
}
```

```
func1() { memory_error; MOV;}
func2() { ADD; }
func3() { LOAD; }
```



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MOV	*X = *0x080dbc28 (**ssl_ctx**)
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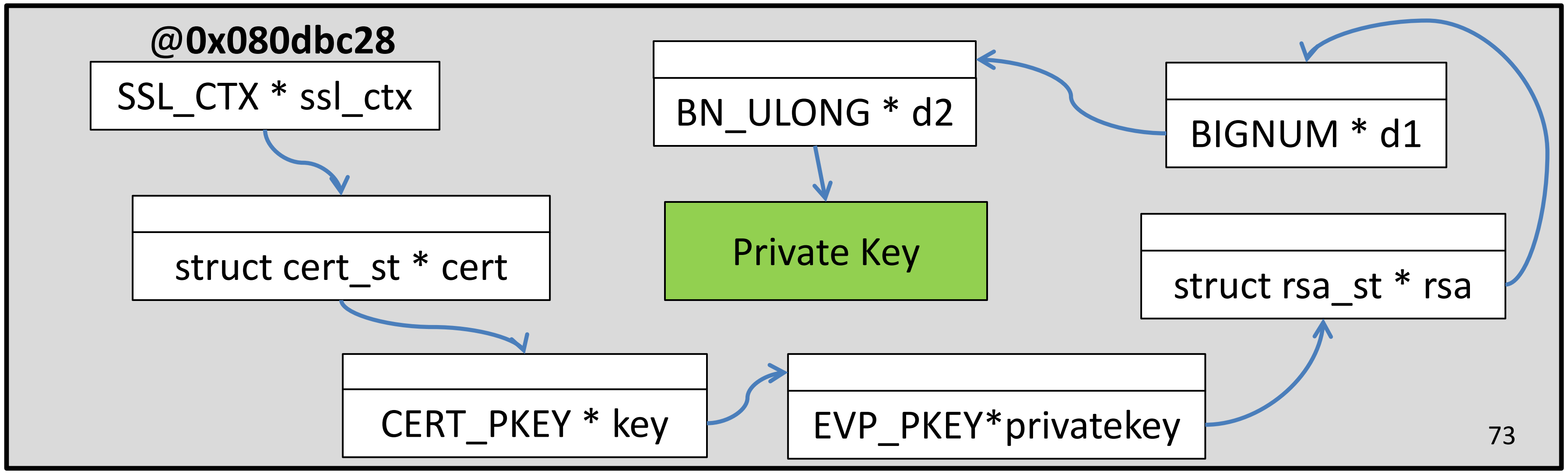

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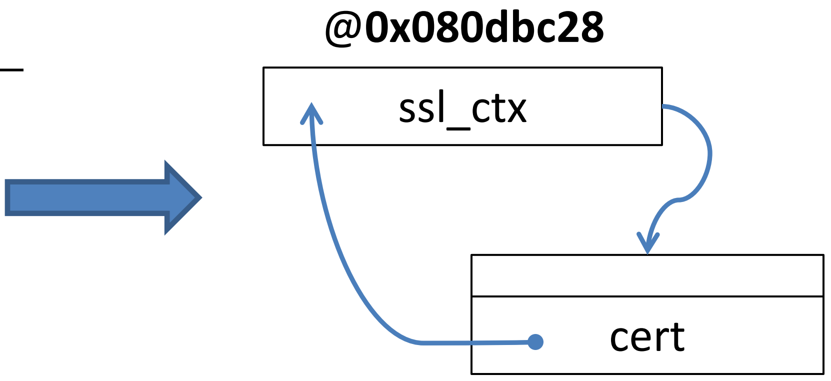

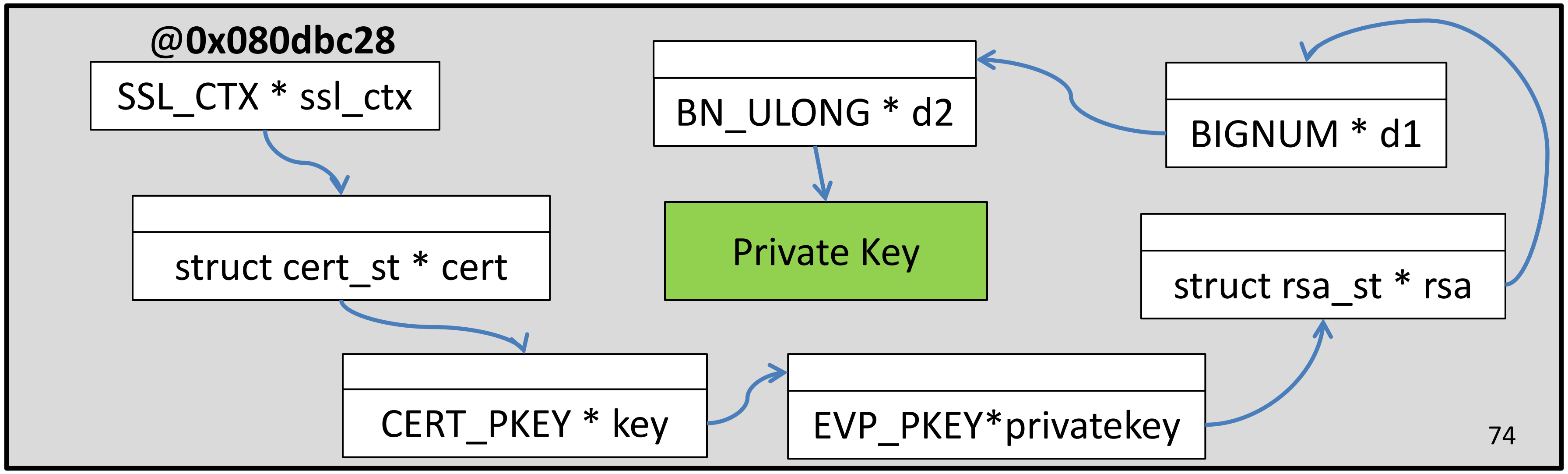

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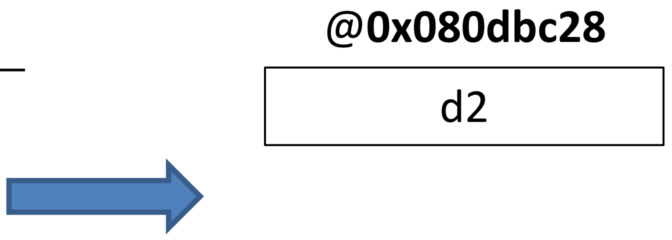

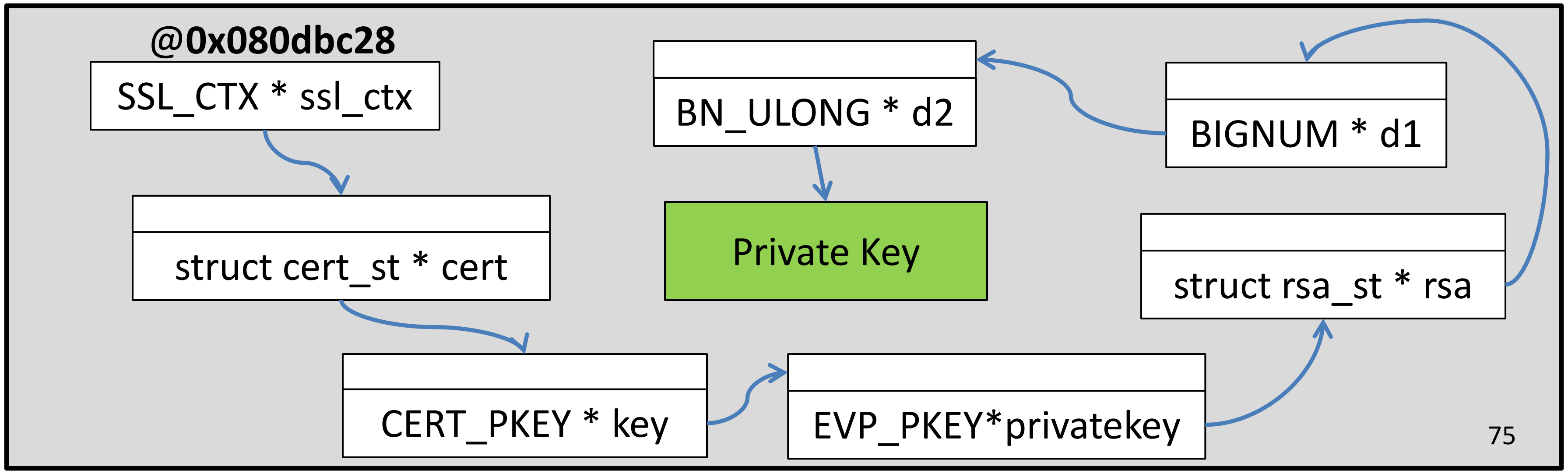

Case Study: Bypassing Randomization

MOV	*X = *0x080dbc28 (**ssl_ctx**)
ADD	*X = *X + offset1
MOV	*Y = *X
LOAD	*Z = **Y
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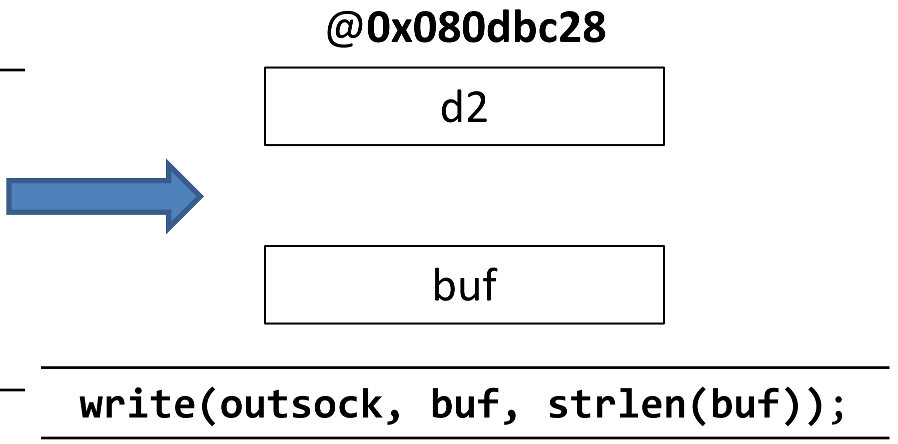
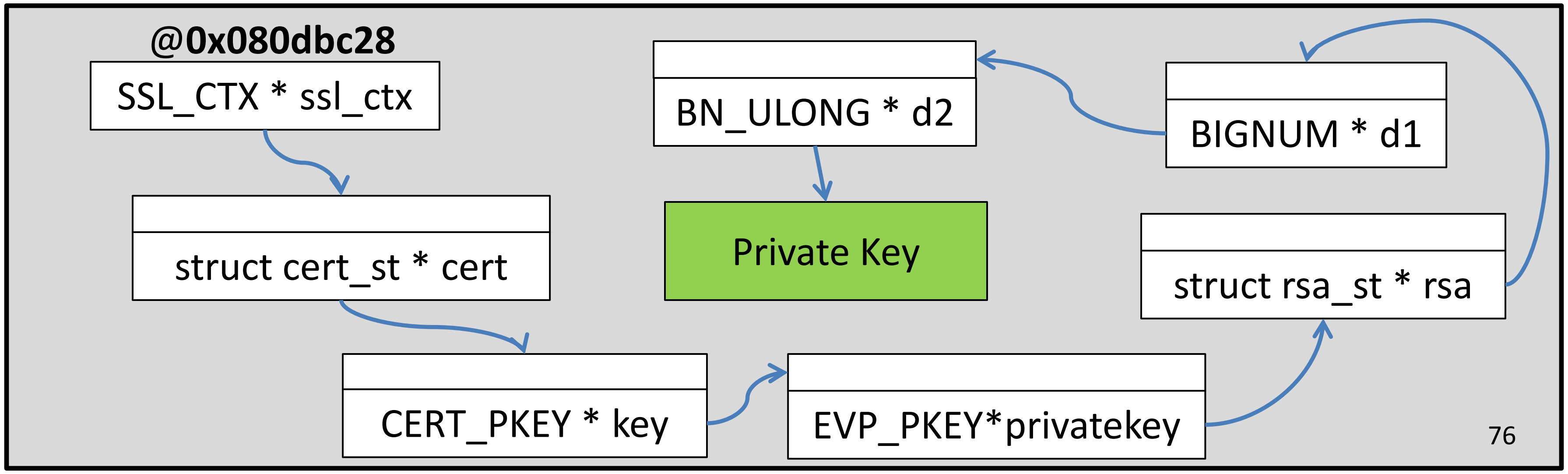


```
write(outsock, buf, strlen(buf));
```



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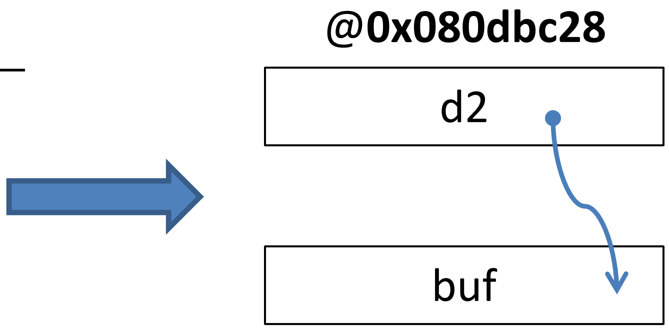

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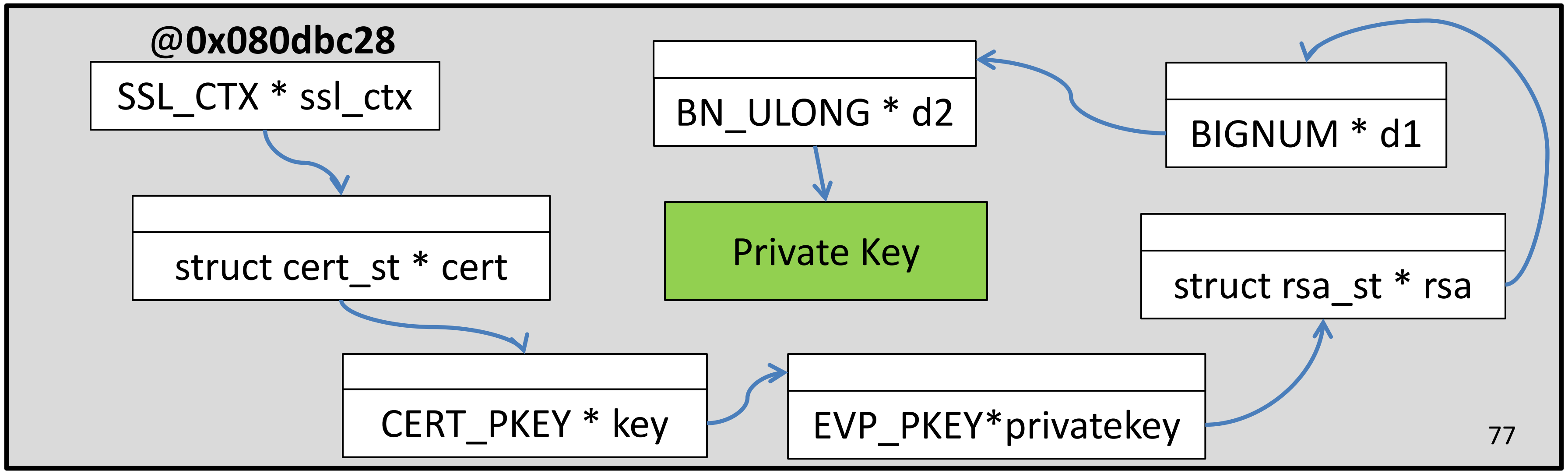

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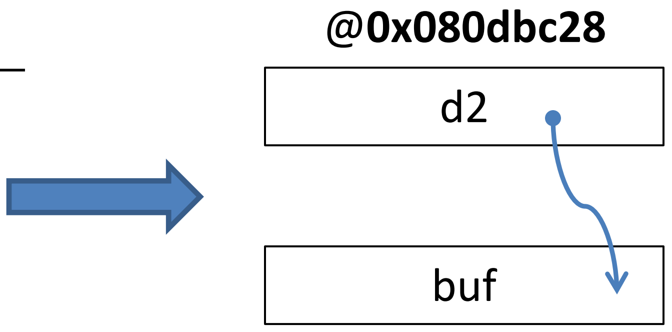

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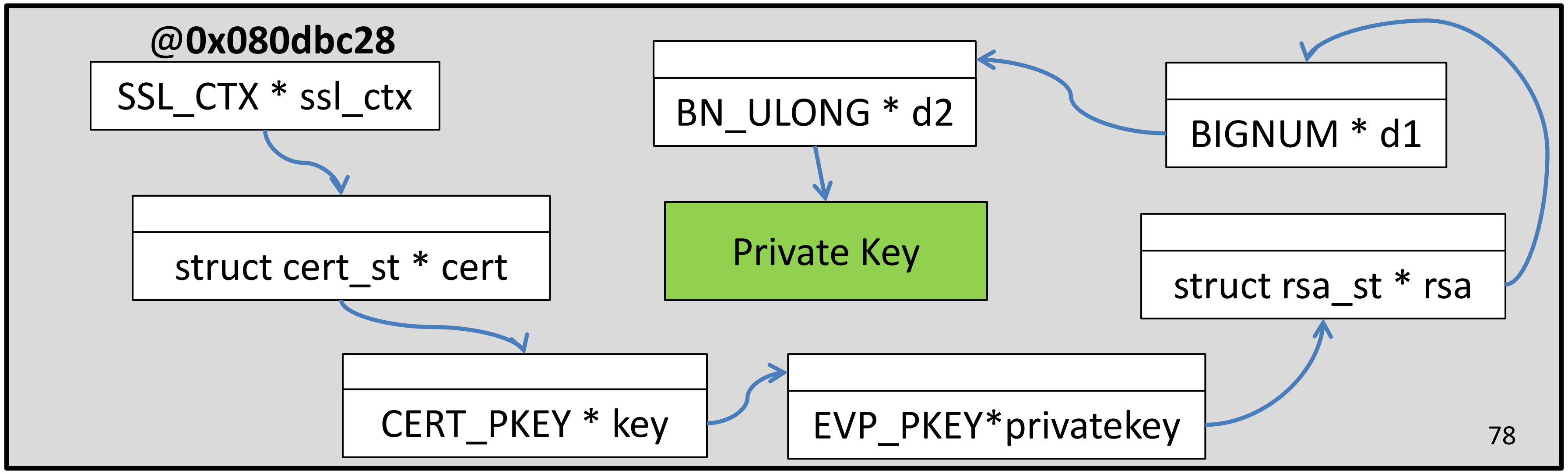
leak private key to network



dlopen() – Dynamic Linking Interface

- Load the dynamic library into memory space
  - resolve symbols based on binary metadata
  - patch program due to relocation
  - like *LoadLibrary*() on Windows

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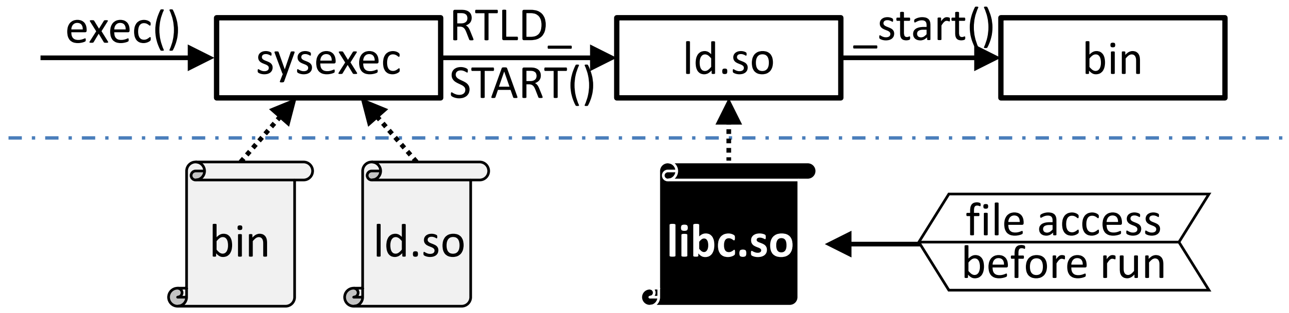

* R. Shapiro, S. Bratus, and S. W. Smith, ""Weird Machines" in ELF: A Spotlight on the Underappreciated Metadata," in WOOT 2013.

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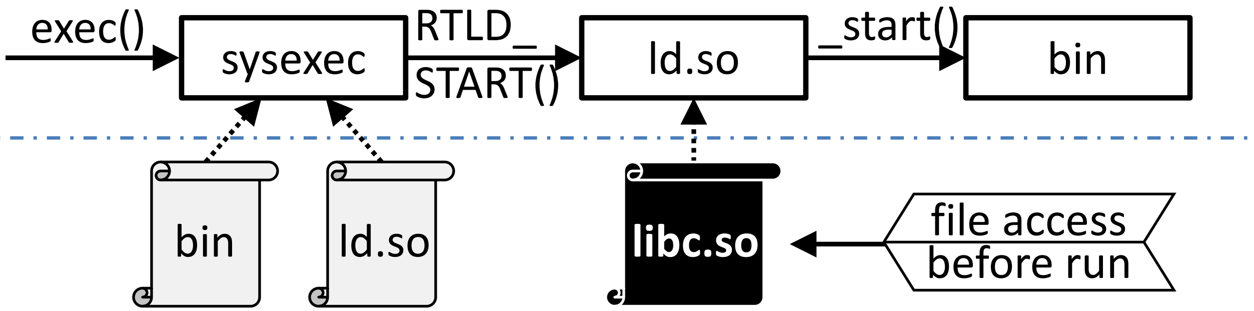

- The same to *dlopen*()

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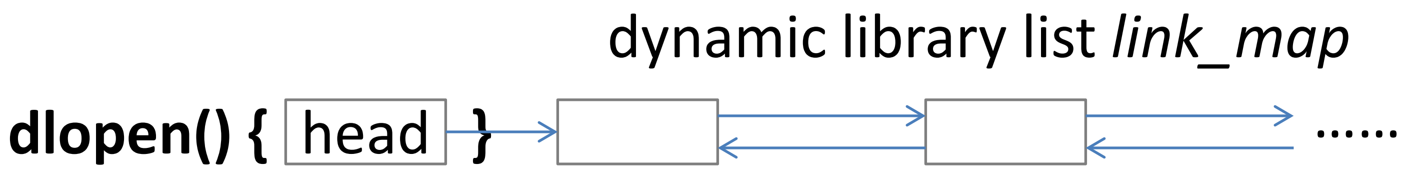
Case Study: Simulating A Network Bot

- Attacks with *dlopen*



Case Study: Simulating A Network Bot

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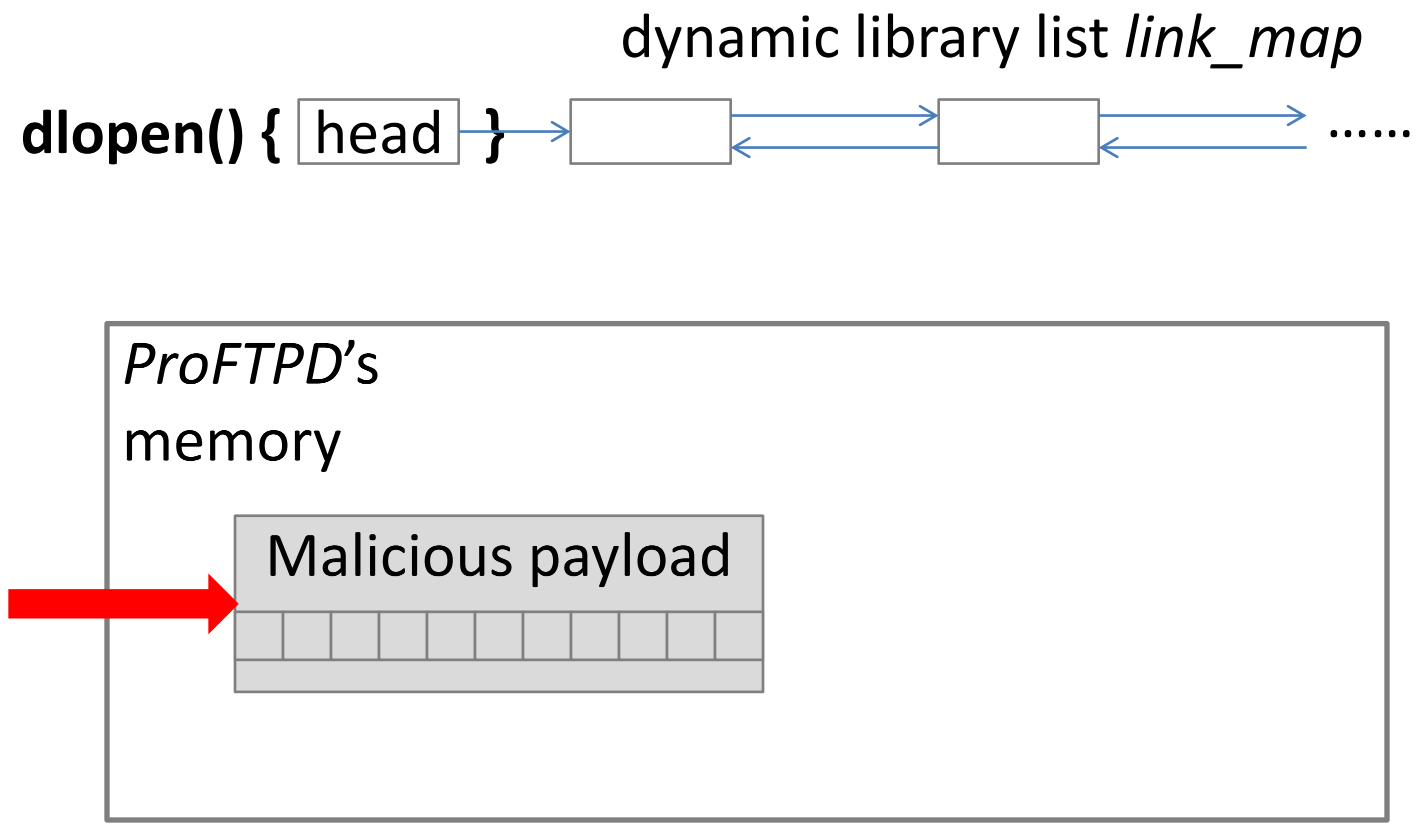

Case Study: Simulating A Network Bot

- Attacks with *dlopen*
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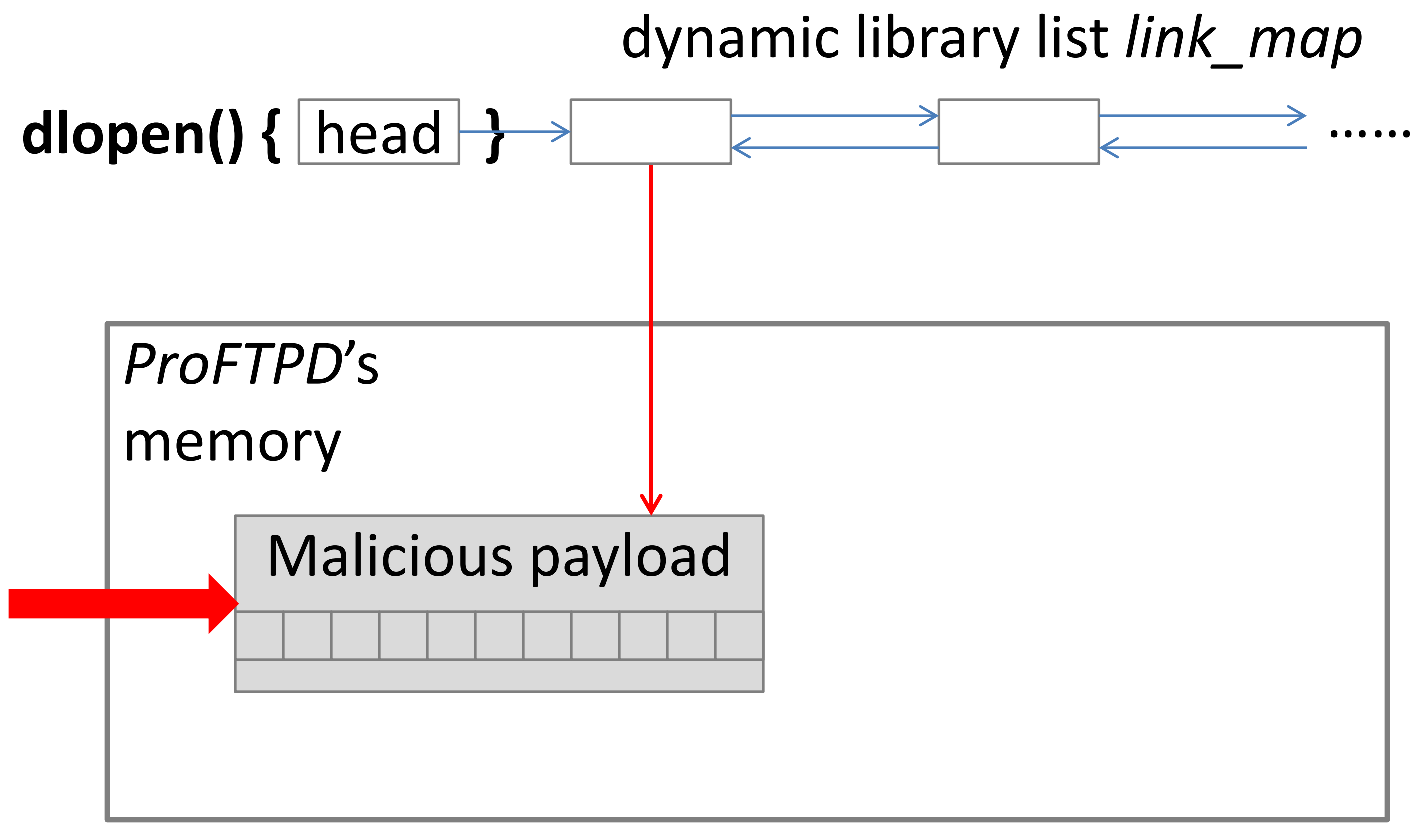
  - corrupt link list & call *dlopen*



Case Study: Simulating A Network Bot

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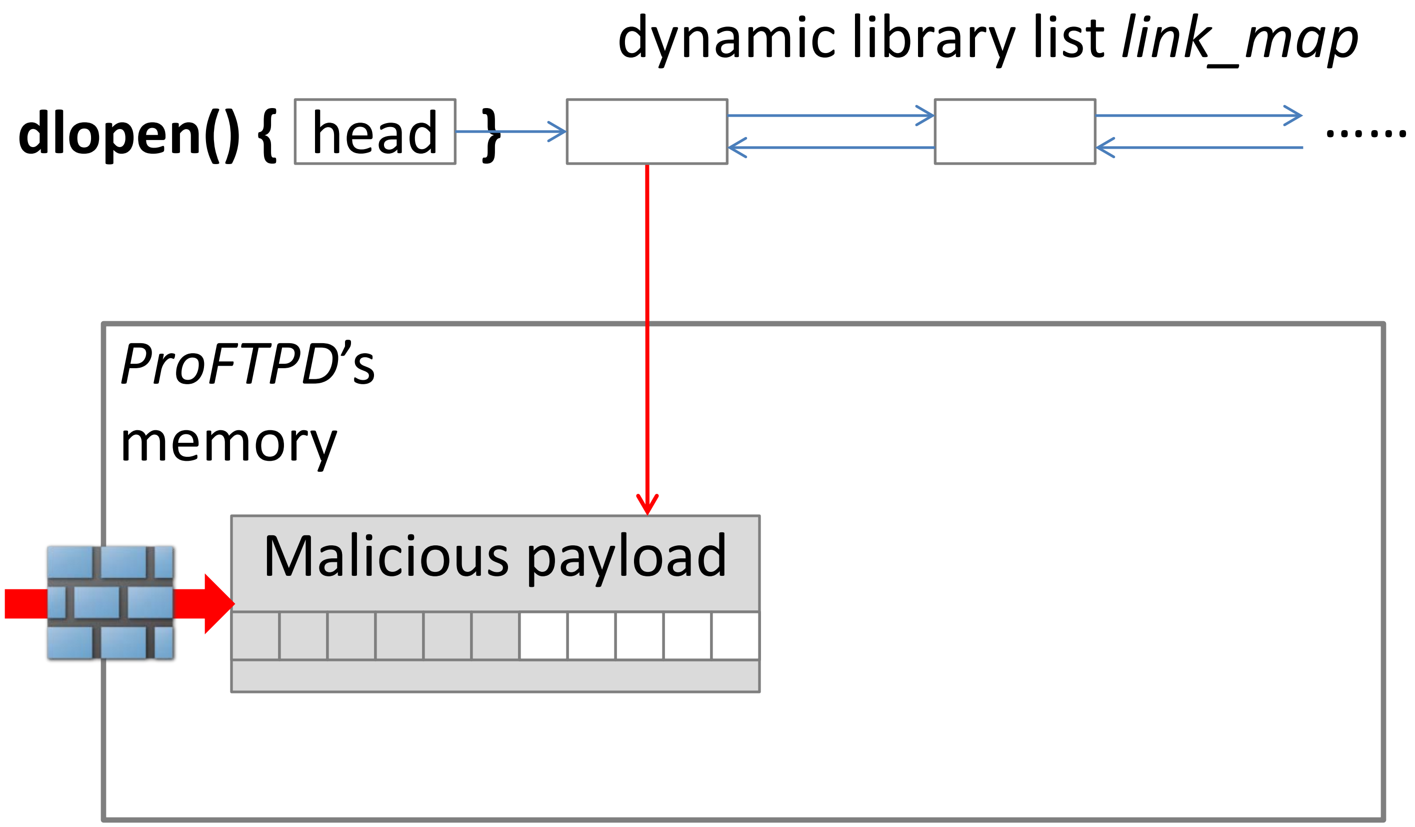

Case Study: Simulating A Network Bot

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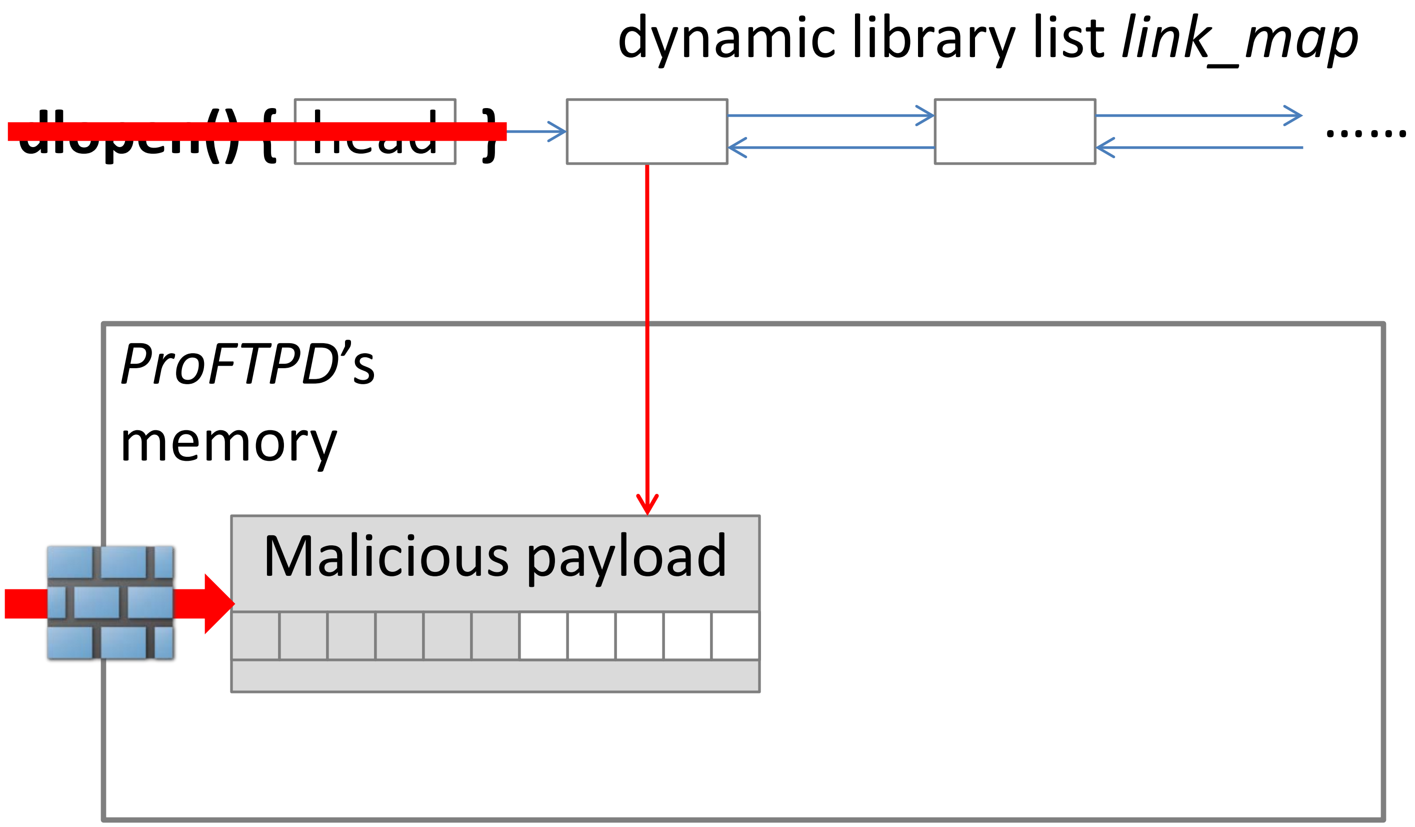

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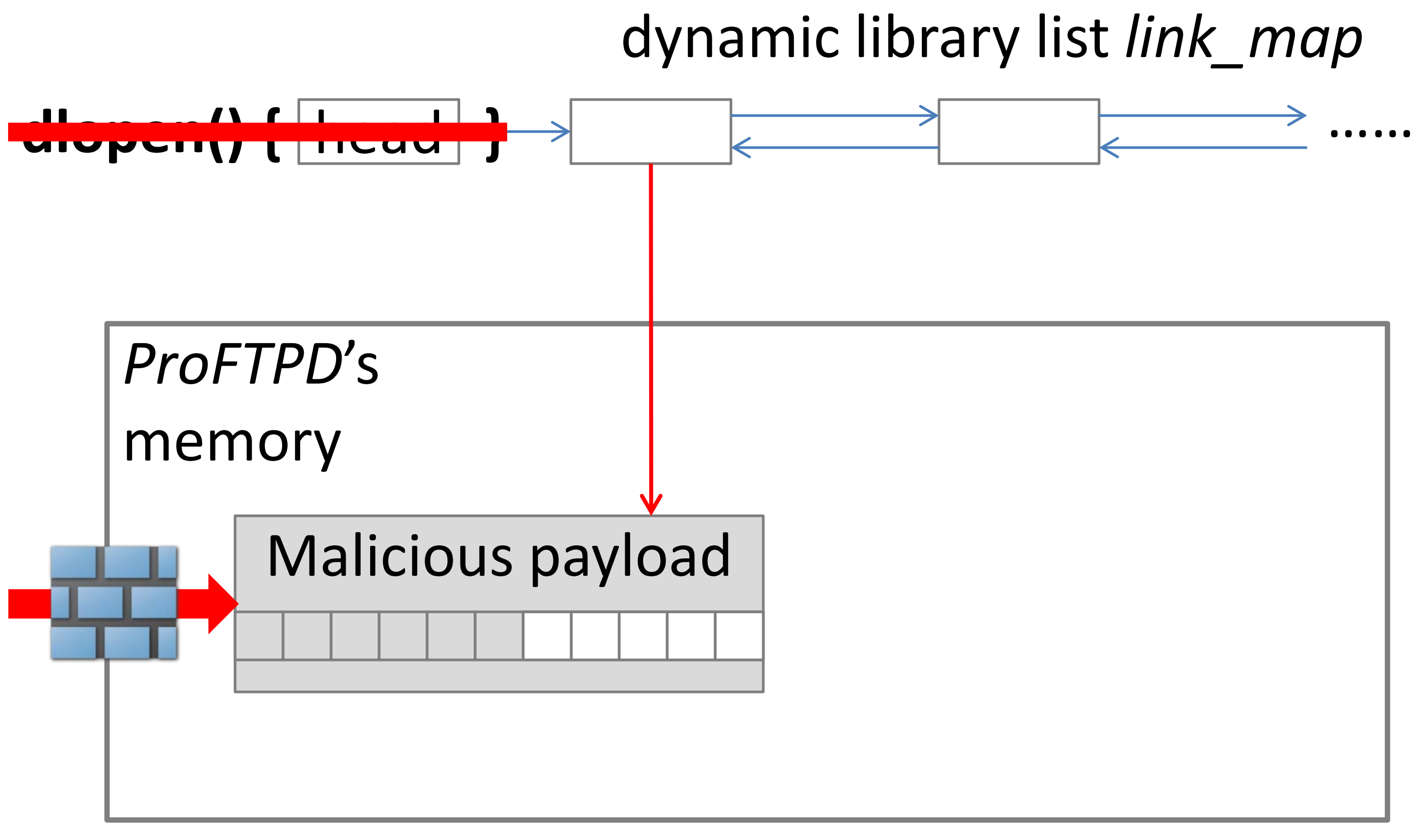

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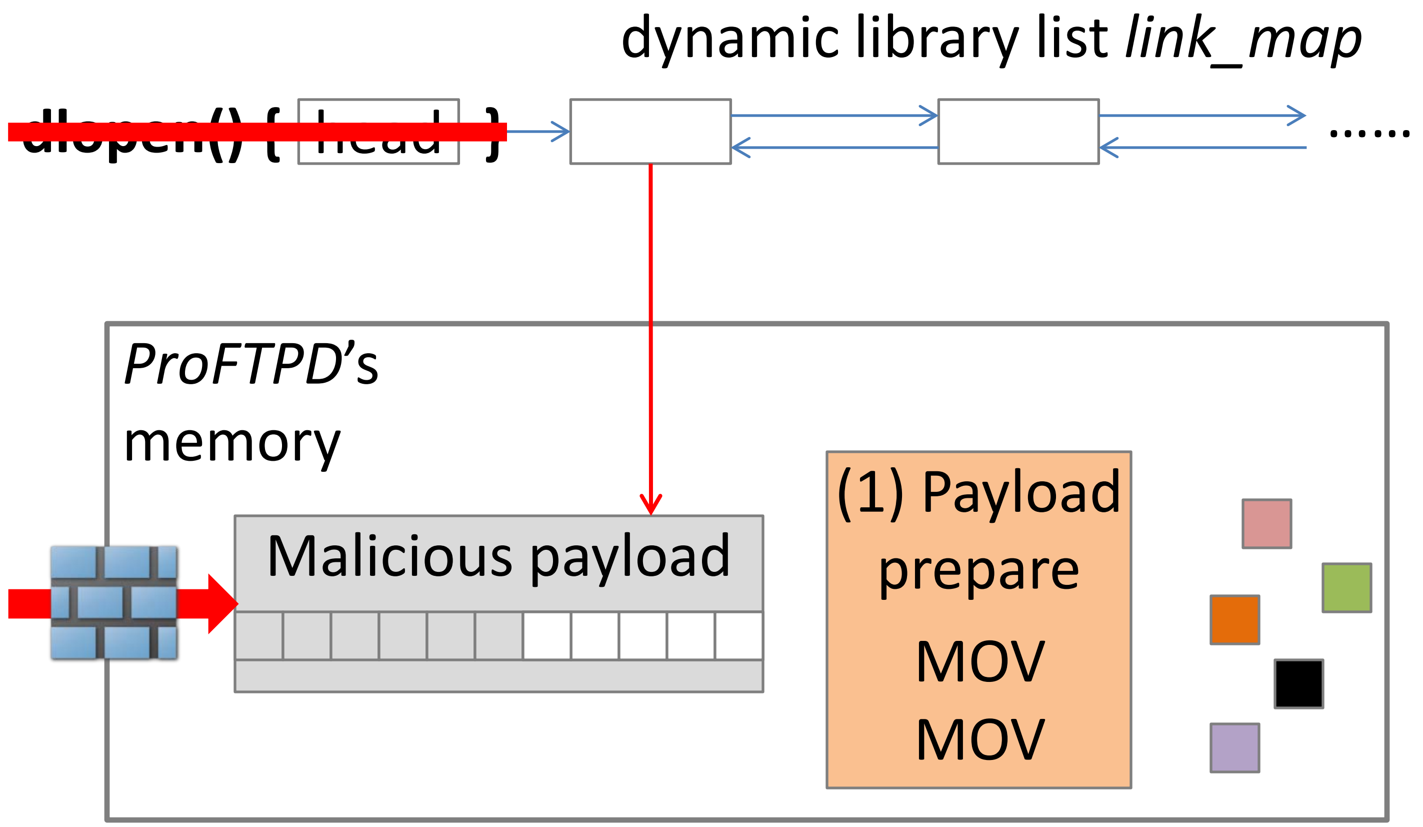

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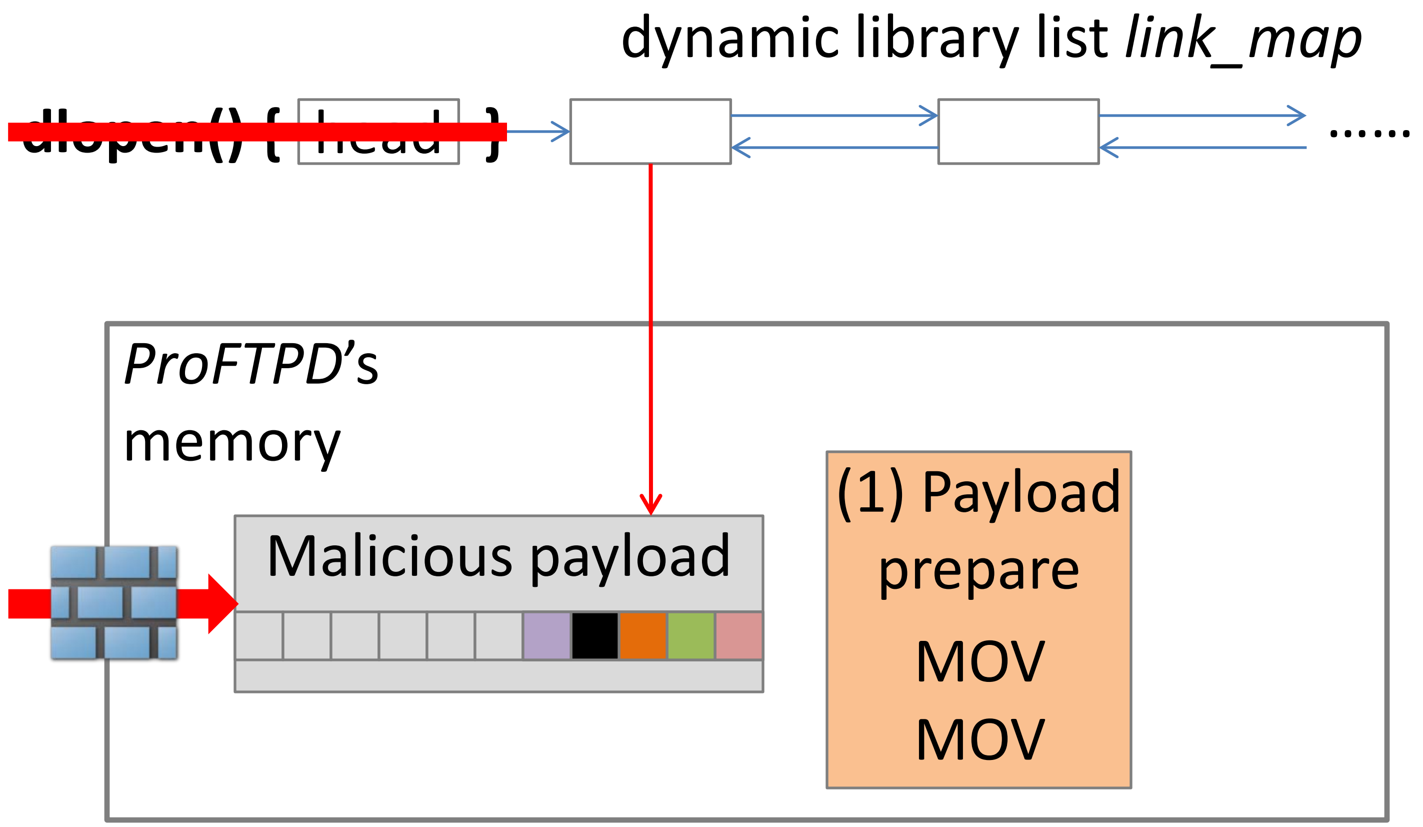

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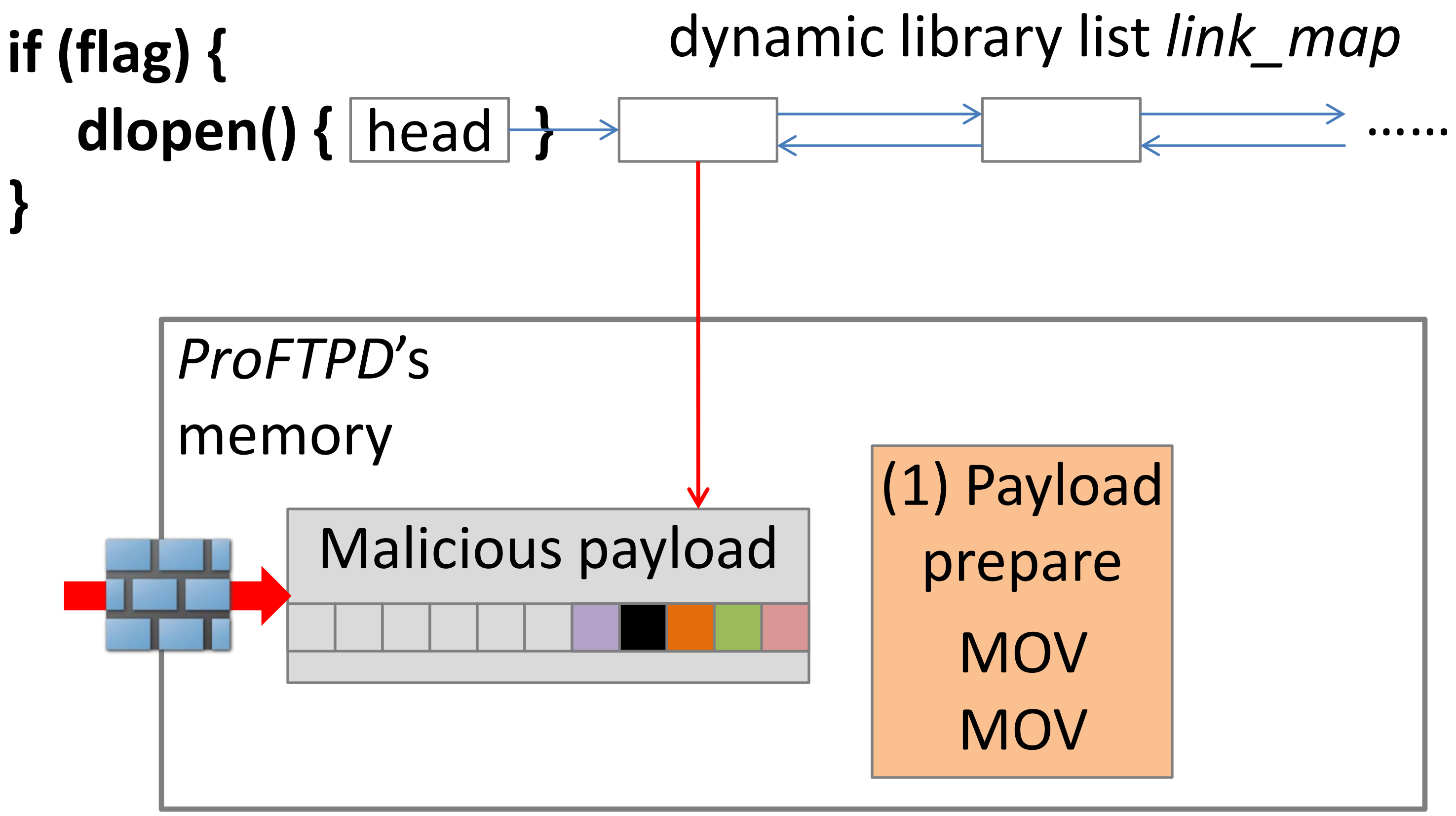

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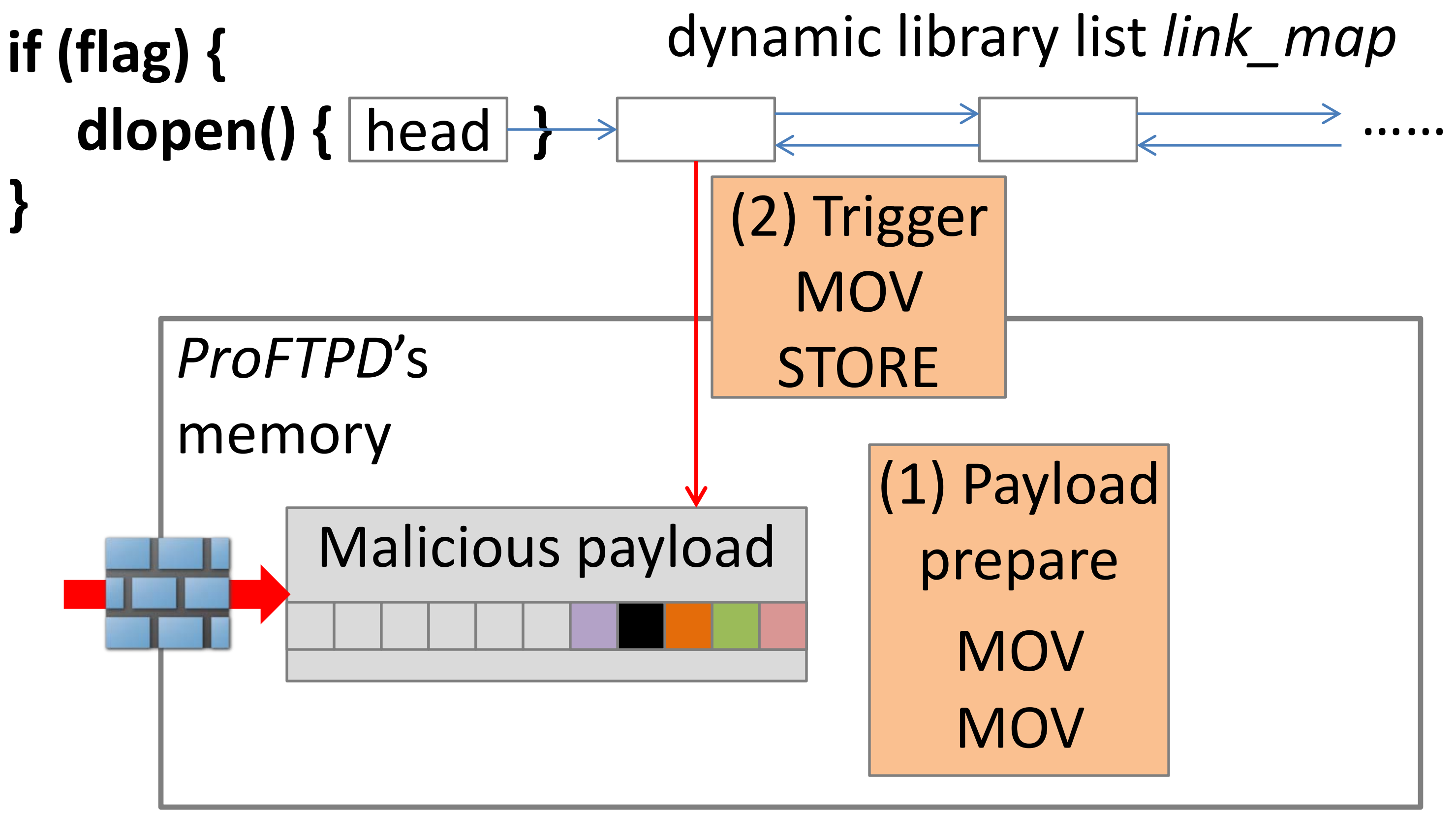

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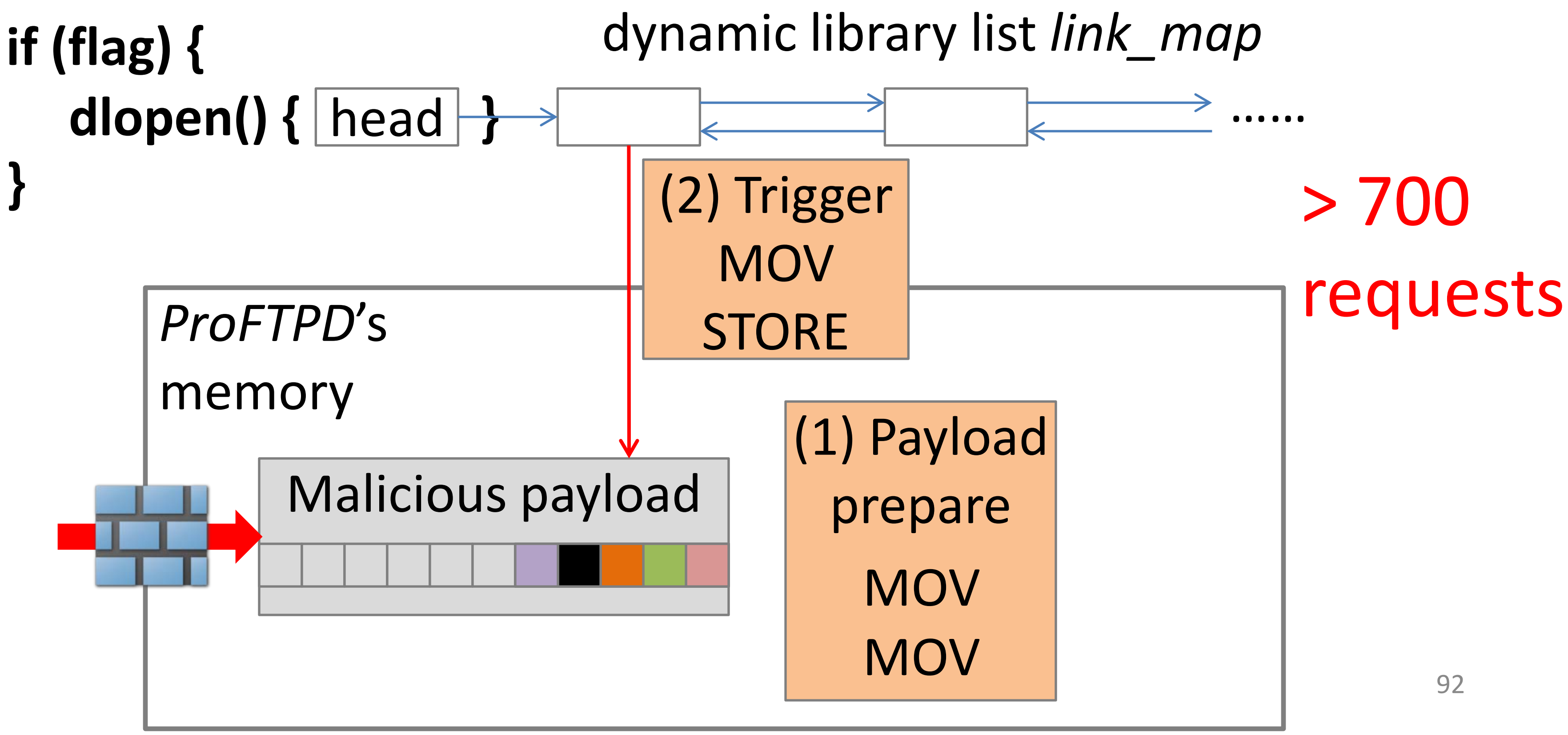

Case Study: Altering Memory Permissions

- Defenses based on memory permissions
  - DEP: non-writable code
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- DOP attacks
  - *dlopen*(code_addr, shellcode)
- Code injection is back!

Related Work

Techniques	Turing Complete?	Preserve CFI?	Independent of specific data / funcs?
Non-control Data Attacks (Chen *et al.* 2005)		✓	
COOP (Schuster *et al.* 2015)	✓		✓
FlowStitch (Hu *et al.* 2015)		✓	
Printf-Oriented Programming (Carlini *et al.* 2015)	✓	✓	
Control Jujustu (Evans *et al.* 2015)		✓	
Data-Oriented Programming	✓	✓	✓

Potential Defenses

- Memory Safety
  - e.g., Cyclone (Jim *et al.* 2002), CCured (Necula *et al.* 2002) , SoftBounds+CETS (Nagarakatte *et al.* 2009, 2010)
  - high performance overhead (> 100%)
- Data-flow Integrity
  - e.g, DFI (Castro *et al.* 2006) , kernel DFI (Song *et al.* 2016)
- Fined-grained randomization in data space
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No practical defenses yet !

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- Data-Oriented Programming (DOP)
  - build expressive non-control data attacks
  - independent of specific data / functions
- In real-world programs, DOP can build attacks
  - bypass ASLR w/o address leakage
  - simulate a network bot
  - enable code injection

Thanks!

Hong Hu

huhong@comp.nus.edu.sg

http://www.comp.nus.edu.sg/~huhong

Non-control data attacks are available

http://huhong-nus.github.io/advanced-DOP/