On the Effectiveness of Type-based Control Flow Integrity

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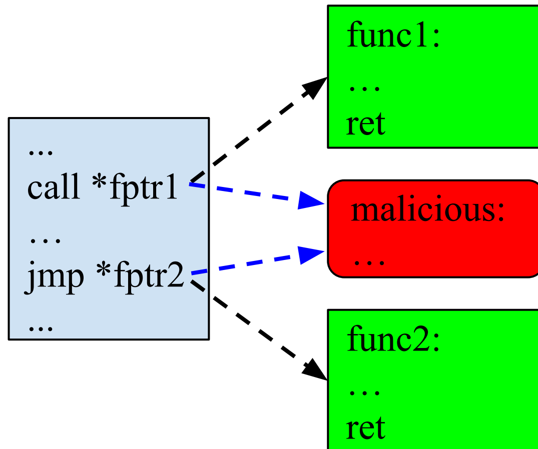
Outline

- Control Flow Hijacking
- Control Flow Integrity (CFI)
- Runtime Type Checking (RTC)
- Reuse Attack Protector (RAP)
- Typed ROP (TROP)
- PoC Exploit for Nginx
- Evaluation
- Conclusion

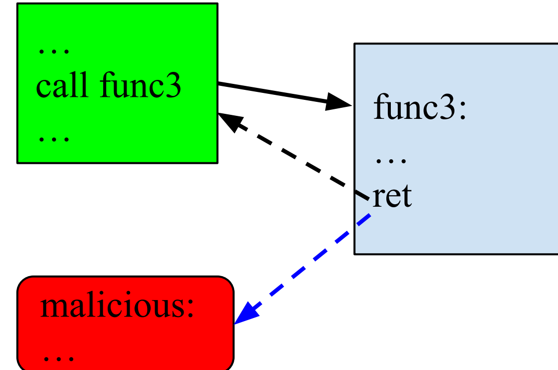
Control Flow Hijacking

- **Memory Corruption** can lead to violation of **Control Flow Graph (CFG)**

Forward Edges (calls, jumps)



Backward Edges (return addresses)



Control Flow Integrity (CFI)

- CFI prevents control flow hijacking by enforcing CFG at runtime
- CFG is usually generated ***statically*** using **Points-to Analysis**
  - **DSA**: Data Structure Analysis
  - **SVF**: Static Value-Flow (interprocedural analysis)
    - Support developing different analyses (flow-, field-sensitivity)
- Constructing **Sound** and **Precise** CFGs is **undecidable** and **impractical**

Runtime Type Checking (RTC)

- **Runtime Type Checking (RTC)** generates the CFG based on **Type Signature**
- RTC matches the type signature of each indirect control transfer with its target
- Forward edge
  - The type of function pointer and the target are checked at each control transfer
- Backward edge
  - The type of callee is checked during the function epilogue
- Implementations
  - Reuse Attack Protector (RAP), LLVM-CFI, KCFI (Kernel CFI), MCFI (Modular CFI), TypeArmor

Reuse Attack Protector (RAP)

RAP™ is here. Public demo in 4.5 test patch and commercially available today!

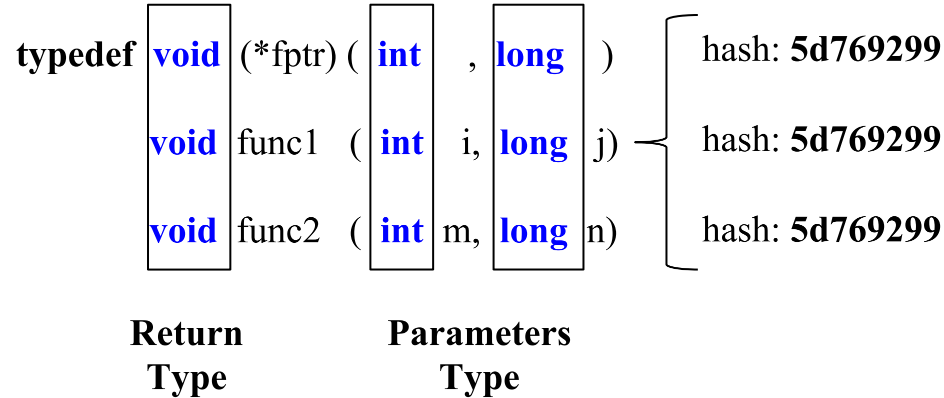
April 28, 2016

RAP™ Demonstrates World-First Fully CFI-Hardened OS Kernel

Type-based, high-performance, high-security, forward/backward-edge CFI

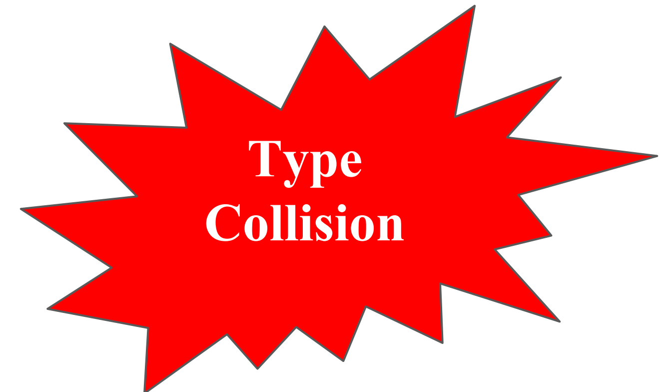
February 6, 2017

Reuse Attack Protector (RAP)



Reuse Attack Protector (RAP)

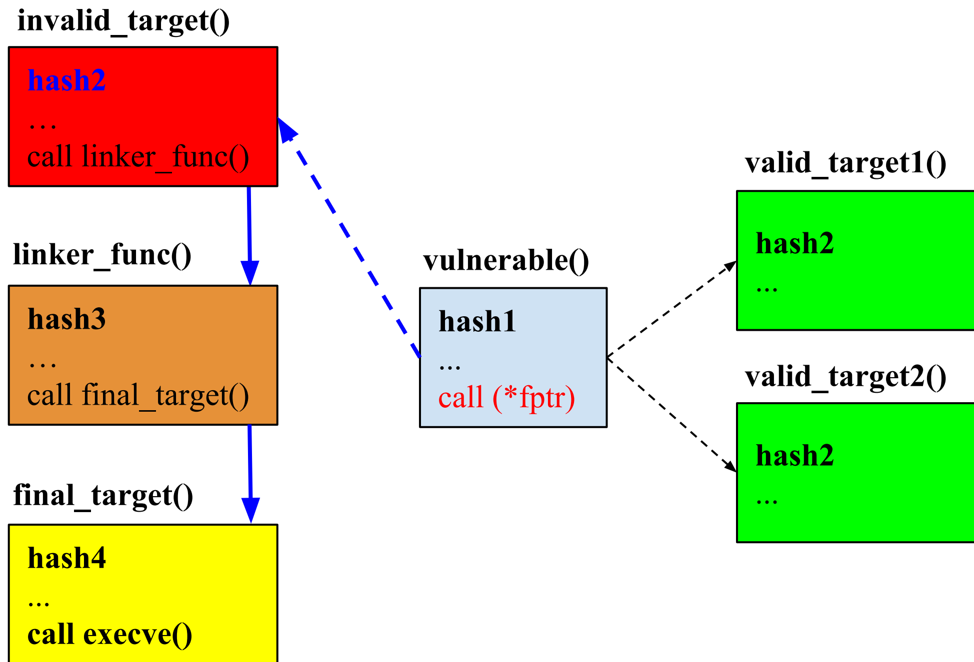
	Return Type		Parameters Type		Parameters Type		
typedef	**void**	(*fptr) (	**int**	,	**long**	)	hash: **5d769299**
	void	func1 (	**int**	i,	**long**	j)	hash: **5d769299**
	void	func2 (	**int**	m,	**long**	n)	hash: **5d769299**



Sample Vulnerable Program

```
1  typedef void (*FunctionPointer)(void);
2  int flag = 0;
3  char *cmd;
4  void valid_target1(void) {
5      printf("Valid Target 1\n");
6  }
7  void valid_target2(void) {
8      printf("Valid Target 2\n");
9  }
10
11 int final_target(char *cmd) {
12     system(cmd);
13 }
14 int linker_func(void) {
15     if (flag ==1)
16         final_target(cmd);
17 }
18 void invalid_target(void) {
19     linker_func();
20 }
21 void vulnerable(char * input) {
22     FunctionPointer corruptible_fptr;
23     char buf[20];
24     if (strcmp(input, "1") == 0)
25         corruptible_fptr = &valid_target1;
26     else
27         corruptible_fptr = &valid_target2;
28     printf(input);
29     strcpy(buf, input);
30     corruptible_fptr();
31 }
```

constraint



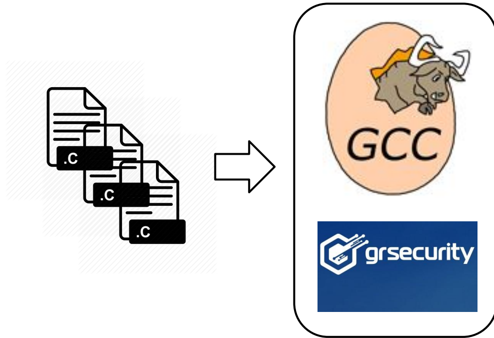
Research Questions

- Can RTC be practically bypassed using **type collisions**?
- Are there enough intermediate functions with satisfiable constraints in real-world applications?
- How prevalent are these constructs in real-world applications?

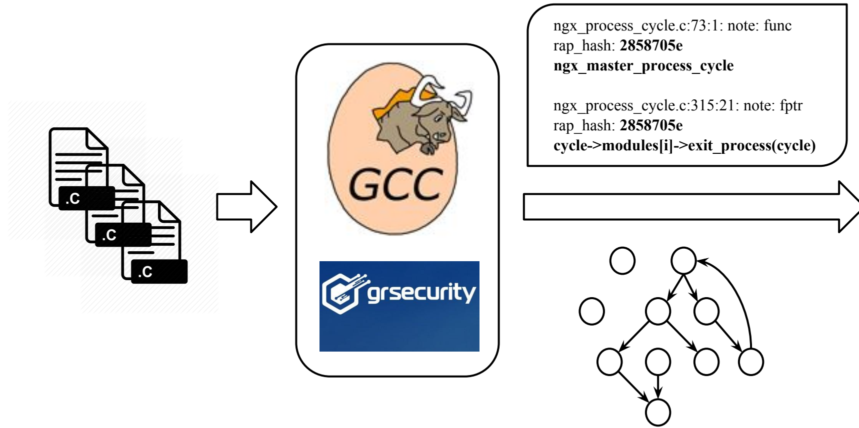
Threat Model

- The attacker has arbitrary **read** and **write** primitives to the memory
- The application contains **one strong** or **multiple limited** memory corruption vulnerabilities
- DEP and ASLR are enabled
- RAP is in place

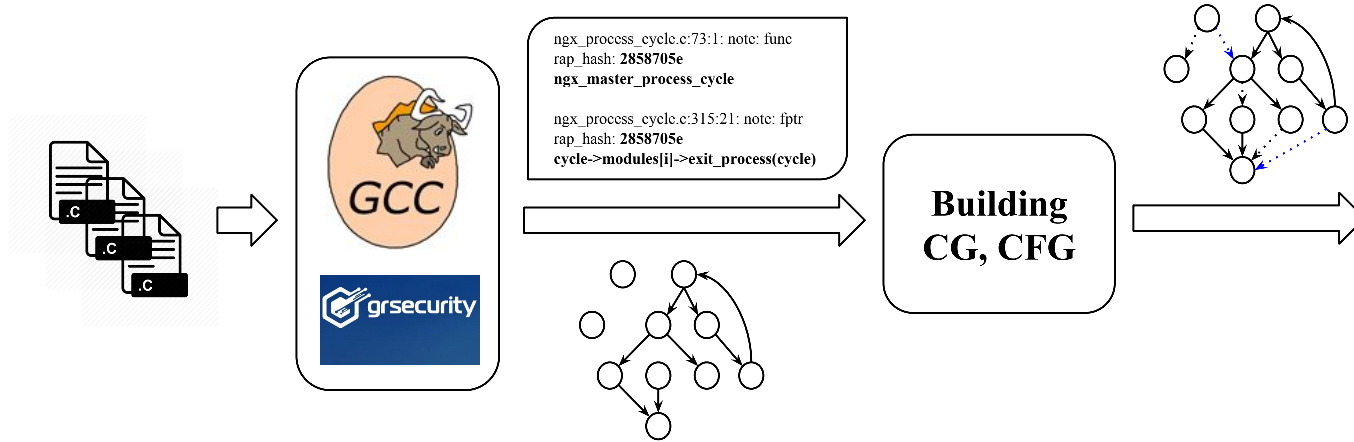
Typed ROP (TROP)



Typed ROP (TROP)



Typed ROP (TROP)



Typed ROP (TROP)

.c
.c
.c

GCC

grsecurity

ngx_process_cycle.c:73:1: note: func
rap_hash: **2858705e**
ngx_master_process_cycle

ngx_process_cycle.c:315:21: note: fptr
rap_hash: **2858705e**
cycle->modules[i]->exit_process(cycle)

Building CG, CFG

Finding Gadgets

Gadgets

Typed ROP (TROP)

.c
.c
.c

GCC
grsecurity

ngx_process_cycle.c:73:1: note: func rap_hash: **2858705e** **ngx_master_process_cycle**

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Building CG, CFG

Finding Gadgets

Detecting Candidate Paths

Typed ROP (TROP)

GCC

grsecurity

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Building CG, CFG

Finding Gadgets

Detecting Candidate Paths

Constraint Solving

Exploits

PoC Exploits (Nginx)

ngx_worker_process_exit

ngx_conf_flush_files

ngx_master_process_cycle

ngx_exec_new_binary

ngx_start_worker_processes

ngx_reap_children

ngx_execute

ngx_spawn_process

ngx_execute_proc

ngx_start_cache_manager_cycle

ngx_worker_process_cycle

execve

PoC Exploits (Nginx)

ngx_worker_process_exit

...
check **2858705e** hash
call (*exit_process)

ngx_conf_flush_files()

hash **2858705e**
...

```
static void
ngx_worker_process_exit(ngx_cycle_t *cycle) {
   ngx_uint_t i;
   ngx_connection_t *c;

   for (i = 0; cycle->modules[i]; i++) {
      if (cycle->modules[i]->exit_process) {
         cycle->modules[i]->exit_process(cycle);
      }
   }
   …
}
```

PoC Exploits (Nginx)

ngx_worker_process_exit

...
check **2858705e** hash
call (*exit_process)

ngx_master_process_cycle()

hash **2858705e**
call ngx_reap_children()
...

C-Gadget

ngx_conf_flush_files()

hash **2858705e**
...

```
void
ngx_master_process_cycle(ngx_cycle_t * cycle) {
   …
   /* By setting this condition to true, the attacker can
    * reach to the next gadget which is ngx_reap_children()
    */
   if (ngx_reap) {
      ngx_reap = 0;
      ngx_log_debug0(NGX_LOG_DEBUG_EVENT,
                     cycle, log, 0, "reap children");
      live = ngx_reap_children(cycle);
    …
    …
}
```

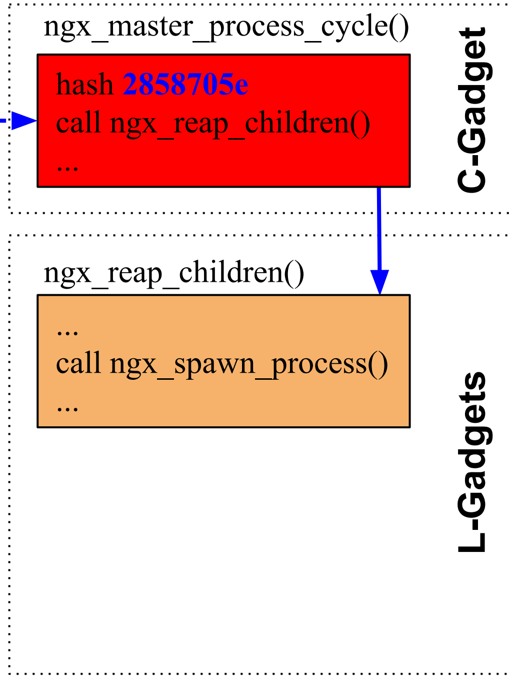
PoC Exploits (Nginx)

ngx_worker_process_exit

...
check **2858705e** hash
call (*exit_process)

ngx_conf_flush_files()

hash **2858705e**
...




```
static ngx_uint_t
ngx_reap_children(ngx_cycle_t * cycle) {
  …
  for (i = 0; i < ngx_last_process; i++) {
    …
    if (ngx_processes[i].respawn &&
        !ngx_processes[i].exiting &&
        !ngx_terminate &&
        !ngx_quit) {
      if (ngx_spawn_process(cycle,
          ngx_processes[i].proc,
          ngx_processes[i].data,
          ngx_processes[i].name, i)
          == NGX_INVALID_PID) {
          …
```

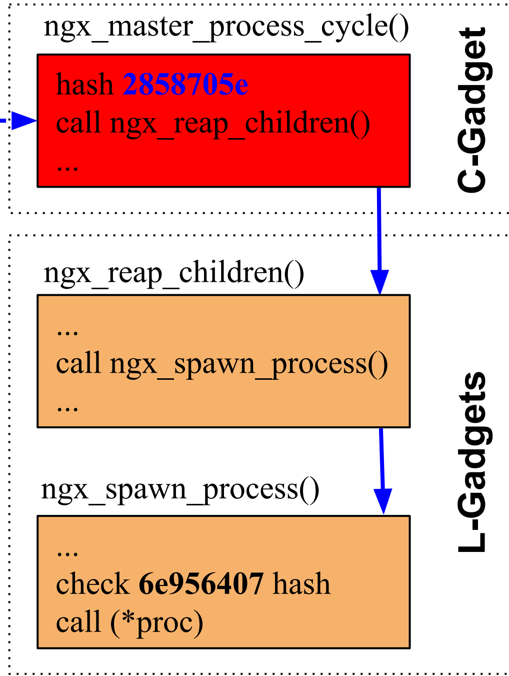
PoC Exploits (Nginx)

ngx_worker_process_exit

```
…
check 2858705e hash
call (*exit_process)
```

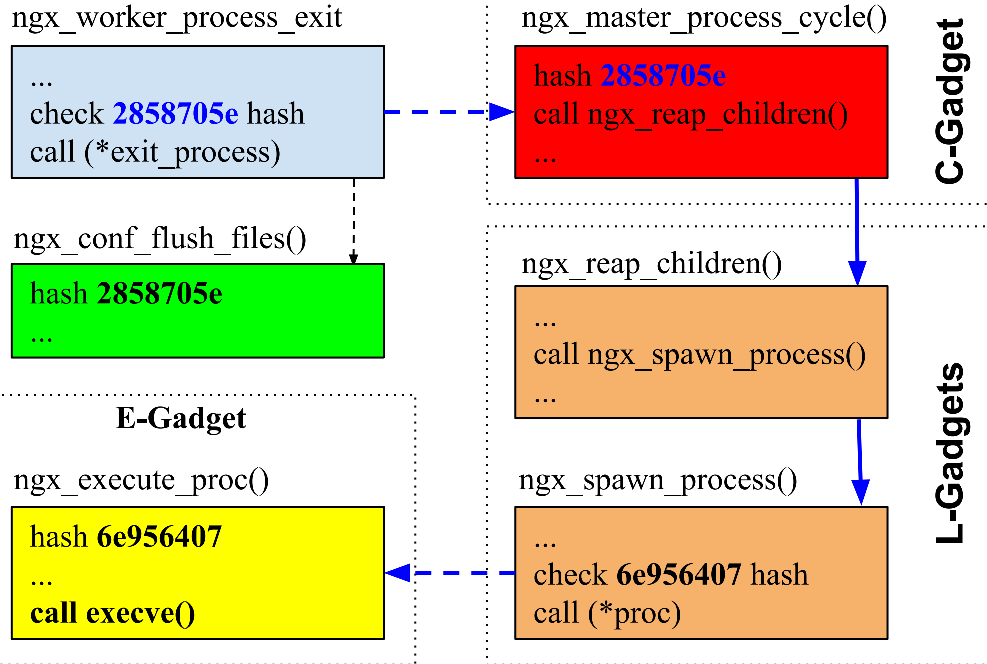
ngx_conf_flush_files()

```
hash 2858705e
…
```




```
ngx_pid_t ngx_spawn_process(ngx_cycle_t *cycle,
        ngx_spawn_proc_pt proc, void *data, char *name,
        ngx_int_t respawn) {
    …
    switch (pid) {
        case -1:
            …
        case 0:
            ngx_pid = ngx_getpid();
            proc(cycle, data);
            …
}
```

PoC Exploits (Nginx)




```
static void
ngx_execute_proc(ngx_cycle_t *cycle, void *data) {
   ngx_exec_ctx_t * ctx = data;

   if (execve(ctx->path, ctx->argv, ctx->envp) == -1) {
      ngx_log_error(NGX_LOG_ALERT,
            cycle -> log,
            ngx_errno,
            "execve() failed while executing %s\"%s\"",
             ctx -> name, ctx -> path);
   }

   exit(1);
}
```

Evaluation

- Type Collisions
- Gadget Distribution
- Libc
- Type Checking vs. Points-to Analysis
- Type Diversification
- Practical Challenges

Type Collisions

App	Version	Function Pointer	Call Sites	Functions	Functions w/ Hash	Function Targets		Indirect Calls	
						All	Invalid	All	Invalid
base-passwd	3.5.39	6	6	45	45 (100.0%)	0	0	0	0 (0.0%)
coreutils	8.2	42	80	1,789	682 (38.1%)	116	43	416	110 (26.4%)
e2fsprogs	1.42.13	97	264	1,964	1,243 (63.3%)	251	176	1,383	400 (28.9%)
exim	4.89	43	93	968	607 (62.7%)	88	121	359	165 (46.0%)
findutils	4.6.0	28	52	821	554 (67.5%)	200	89	326	65 (19.9%)
grep	2.25	19	28	460	264 (57.4%)	38	19	113	52 (46.0%)
httpd	2.4.25	248	546	2,800	2,338 (83.5%)	1,332	483	3,915	794 (20.3%)
lighttpd	1.4.45	27	108	899	524 (58.3%)	228	40	830	221 (26.6%)
ncurses	6.0	46	77	1,835	1,045 (56.9%)	156	273	969	397 (41.0%)
nginx	1.10.1	84	290	1,299	977 (75.2%)	610	319	5,977	3,512 (58.8%)
sed	4.2.2	1	1	213	140 (65.7%)	2	0	2	0 (0.0%)
tar	1.28	46	86	1,166	730 (62.6%)	141	166	1,008	754 (74.8%)
util-linux	2.27.1	53	75	3,143	1,681 (53.5%)	211	177	1,060	643 (60.7%)
zlib	1.2.8	5	14	152	108 (71.1%)	5	0	13	0 (0.0%)

Gadget Distribution

App	Version	C-GADGET	L-GADGET	E-GADGET
nginx	1.10.1	8	6	1
httpd	2.4.25	40	19	5
lighttpd	1.4.45	8	29	6
exim	4.90	16	32	7

Libc (Targets)

Libc (Edges)

Without Libc
With Libc

Programs

base-passwd
coreutils
e2fsprogs
exim
findutils
grep
httpd
lighttpd
ncurses
nginx
sed
tar
util-linux
zlib

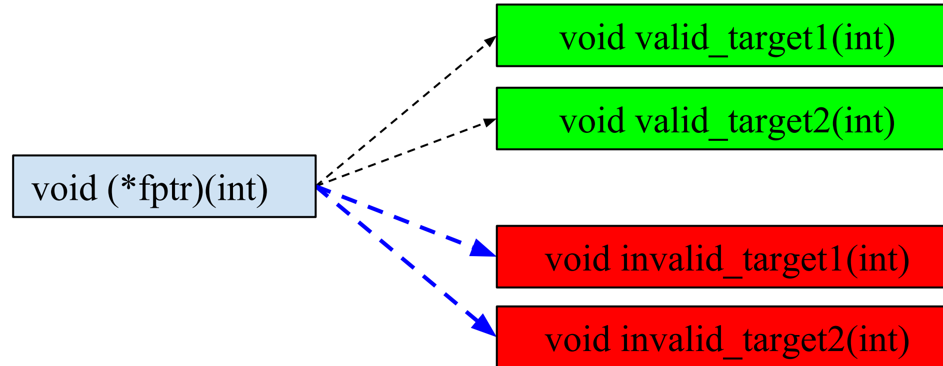
0 500 1000 1500 2000 2500 3000 3500 4000

No. of Edges

Type Checking vs. Points-to Analysis

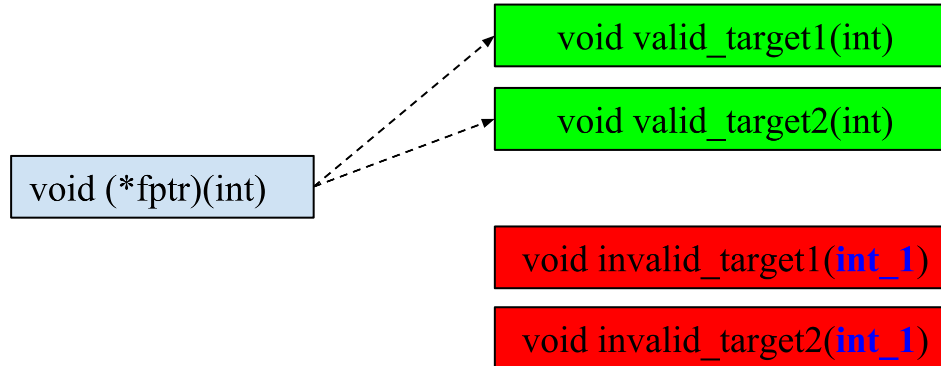
App	Base	Type Checking		Points-to Analysis	
		Total	Invalid	Total	Invalid
base-passwd	0	0	0 (0.0%)	0	0 (0.0%)
coreutils	213	291	78 (26.8%)	308	198 (64.3%)
e2fsprogs	557	861	304 (35.3%)	42	15 (35.7%)
exim	107	212	105 (49.5%)	169	99 (58.6%)
findutils	237	279	42 (15.1%)	448	231 (51.6%)
grep	54	105	51 (48.6%)	108	60 (55.6%)
httpd	2,126	2,870	744 (25.9%)	-	-
lighttpd	327	442	115 (26.0%)	1,096	938 (85.6%)
ncurses	291	558	267 (47.8%)	507	238 (46.9%)
nginx	1,276	2,287	1,011 (44.2%)	-	-
sed	2	2	0 (0.0%)	2	0 (0.0%)
tar	208	664	456 (68.7%)	360	167 (46.4%)
util-linux	311	943	632 (67.0%)	596	465 (78.0%)
zlib	10	10	0 (0.0%)	10	4 (40.0%)

Type Diversification



Type Diversification

- Complicates separate compilation



Practical Challenges

- Mismatch Types
  - **void** * can point to any pointer (e.g., **int** *)
- Support for Assembly Code

Conclusion

- Evaluated RTC from security and practicality perspectives
- Type collisions between function pointers and E-Gadgets are rare
- TROP showed collisions with other functions in a nested fashion can be exploited
- Gadgets for mounting TROP are **abundant** in real-world applications
- RTC is a practical defense but **not sufficient** to prevent control flow hijacking

Questions?

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