Diversified Process Replicæ for Defeating Memory Error Exploits

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Memory Error

The Issue

Memory Error

A memory error occurs when an object accessed using a pointer expression is different from the one intended

- out-of-bounds access (e.g., buffer overflow)
- access using a corrupted pointers (e.g., buffer overflow, format bug)
- uninitialized pointer access;
- dangling pointers;
- ...

Memory Error

The Exploit

Memory Error Exploits

- well-known way to subvert/divert a legal process execution flow
- usually overwrite control-data with *absolute known* values:
  - saved return addresses
  - application-specific function pointers
  - “other” function pointers (e.g., `GOT`, `.dtors`, C++ vrt ptrs)

e.g., stack/data buffer overflow, format string bug, malloc chunk exploit, integer overflow

Artificial Diversity

State of the Art

Biological Diversity

Plays a crucial role for the survivability of every biological species

- a successful memory error exploit usually relies on using *well-known* absolute memory addresses

⇒ solution: make systems appear different!

- Address Space Layout Randomization
- Address Space Obfuscation
- Instruction Set Randomization

Artificial Diversity

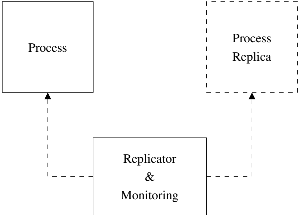
Limitations of the State of the Art

Usually diversity is applied on a process itself, but it:

- requires high entropy
- relies on keeping secrets:
  - . . . disclosed by information leakage attacks
  - . . . defeated by brute forcing attacks
- generally cannot defeat partial memory overwriting attacks (e.g., Impossible Path Executions)
- cannot defeat memory error exploits with *certainty*
- so far, offers a *probabilistic* protection mechanism

Our Approach: Diversified Process Replicæ

Framework



- T, the replicator & monitoring process, creates P_r, a replica of the protected process P
- T makes P and P_r to behave identically on benign input
- P and P_r are properly diversified to detect behavioral divergence caused by malicious input, i.e., memory error attacks

Our Approach: Diversified Process Replicæ

Process Replication

T synchronizes P and P_r for every system call invocation (*rendez-vouz* point), and:

- checks for system call consistency (e.g., system call arguments, system call number)
- *simulates* certain system calls (e.g., `read`, `write`, `recv`, `send`)
  - replicates input, correctly handles output on I/O system calls
  - performs system call "once"
  - returns consistent results to P and P_r
- lets P and P_r *execute* others system calls (e.g., `brk`, `signal`)
- carefully treats other system calls (e.g., `mmap2`, `shmat`, `shmget`)

Our Approach: Diversified Process Replicæ

Process Diversification

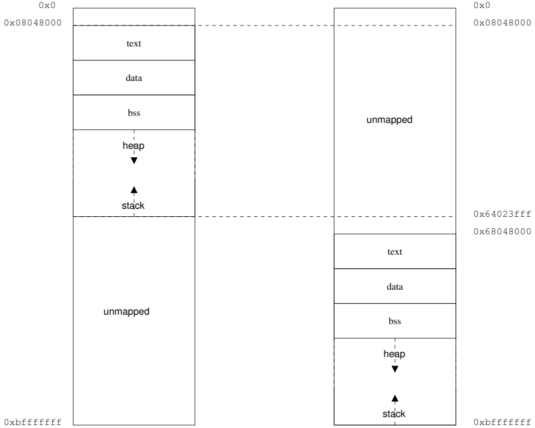
- non-overlapping address spaces to combat memory corruption attacks targeting absolute memory address
- address space shifting to combat partial overwriting memory corruption attacks

⇒ both address non relative control-data memory error exploits and some non-control data

- statically: custom linker script which takes care of the executable `.text`, `.data`, `.bss`, heap (next to `.bss`)
- dynamically: with a modified `ld-linux.so` which takes care of the executable stack and shared objects "relocation"

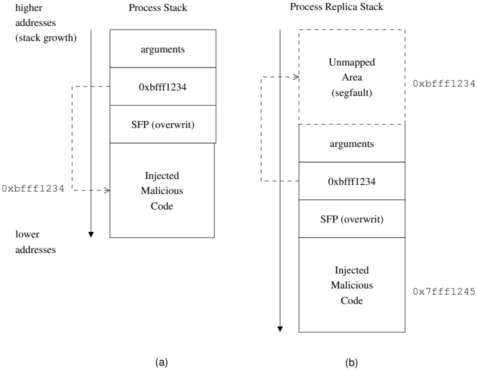
Our Approach: Diversified Process Replicæ

Address Space Partitioning



Effectiveness

Stack-based Buffer Overflow



Practical Issues

- shared memory management
- signals
- threads

Shared Memory

mmap-based and "classical" shared memory

mmap-based

1. non-anonymous
   - (a) private mapping (intra-process communication)
   - (b) shared mapping (*inter-process communication*)
2. anonymous (intra-process communication)

classical shared memory

(a) private mapping (intra-process communication)

(b) shared mapping (*inter-process communication*)

Shared Memory

Data inconsistency and Behavioral Divergence

- P and P_r create a readable and writable non-anonymous shared memory segment $\mathcal{M}$
- `ptr[0]` points to the beginning of $\mathcal{M}$

```
if (ptr[0] == 'A')
   ptr[0] = 'B';
else
   ptr[0] = 'C';
...
/*
 * process invokes system calls based on the
 * value held by ptr[0]
*/
```

Shared Memory

Related-only Processes

- let suppose that only P and P_r are sharing a resource R
- as seen before, P and P_r start an unwanted form of *inter-process communication* between them
- the direct consequence is that P and P_r might exhibit a different behavior and R might be inconsistent
- the solution is simple: let P_r create a *private* mapping, i.e., no IPC between P and P_r

Shared Memory

Unrelated Processes (1)

Assumption

"[...] What is normally required [when using shared memory], however, is some form of synchronization between the processes that are storing and fetching information to and from the shared memory region"

- the scenario with unrelated processes is more tricky
- creating a *private* mapping is *necessary* but it is *not sufficient*
- an external process E might modify the resource
    - P will see the modification (shared mapping)
    - P_r will not (private mapping)
- P_r must operate on an *up-to-dated* view of the shared resource R

Shared Memory

Unrelated Processes (2)

- the Assumption provides the following
  - it makes possible to decide *when* to perform the refresh operation (rendez-vouz point)
  - it permits to wait for P to "acquire a lock" for R: it grants data consistency during the *refresh* operation

Main point: *how* and *when* to update the memory regions where R is referenced at:

- to get "*when*" requires to analyze the synchronization mechanisms P can use
- knowing such mechanisms help to find the answer to the "*how*" ⇒ *Fault Interpretation*

Fault Interpretation

- T marks P and P_r shared mapping as read-only
- T exploits the CPU page fault exception to know whenever P is writing into a shared memory area
- T interprets the outcome of the synchronization adopted (might be tricky)
- T refreshes P_r shared memory mapping if P acquired the lock successfully

Signals and Non-Determinism

- signals are asynchronous events; they might cause P and P_r to behave differently if delivered asynchronously to them
    - signals can be delivered synchronously by postponing them at the next rendez-vouz point (in general)
- threads share the same issues raised by shared memory management, but their treatment could be more tricky
    - open issue if shared control-dependencies data might modify a thread's behavior
    - scheduling P and P_r threads in the same way might not be enough

Diversified Process Replicæ

Project Status & Experimental Results

- user space `ptrace` prototype on a Debian GNU/Linux system, 2.6.x kernel
- `clone`/`fork`/`vfork` support (still unreliable)
- *shared memory management* (preliminary idea)
- *signals management* (preliminary idea)
- preliminary experimental results (100 conns, 4 sess x conn, 13 reqs x conn, $\sim$ 7.5MB web site):

#	Throughput	MB/s (real)	MB/s (DPR)	slowdown
1	`thttpd` (mmap)	12386.9	12238.8	1.20%
2	`thttpd` (mmap-nocache)	12718.4	12496.5	1.75%
3	`thttpd` (read)	12599.5	12117.4	3.83%
4	`thttpd` (read-nocache)	12603.7	7086.3	43.78%
5	`thttpd` (read-nocache-single)	9134.5	2838.1	68.93%

Future Works

- full implementation of the prototype
- assess the viability and practicability of the shared memory solution
- improve protection from partial overwriting memory corruption attacks targeting control-data
- address relative addressing and, in general, non-control-data memory corruption attacks
- performance:
  - hybrid system call interposition implementation
  - (selective) file system replication (currently testing)
  - could SMP help out?

It seems to be an exciting research topic! :-)

Questions & Answers

Q & A?
Thank you! :-)