Comprehensive Memory Error Protection via Diversity and Taint-Tracking

Dipartimento di Informatica e Comunicazione
Università degli Studi di Milano, Italy

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PhD Dissertation Defense

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- Research Goal

State of the Art
- Artificial Diversity
- Taint Analysis
- Anomaly Detection

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- Taint-enhanced Anomaly Detection

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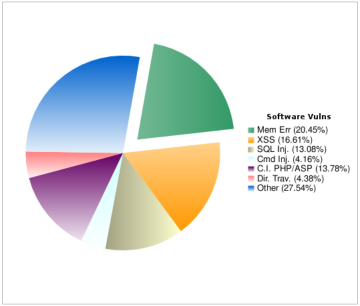
Breakdown of the NVD NIST Software Security Vulnerabilities (2006 – Q1-3 2007)



- Memory errors are still a relevant issue
- Most effective countermeasures are
  - Attack-specific
  - Mainly probabilistic
  - Vulnerable to alternative attacks

Our result:

- *Comprehensive* solutions
- Mainly *deterministic* protection
- *Resilient* to most evasions

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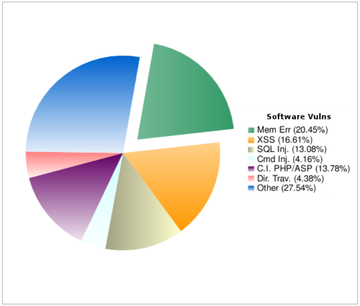

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Memory Error

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

- 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 exploitation generally relies on

- Data corruption
- Gathering information on memory location addresses

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Memory error exploitation generally relies on

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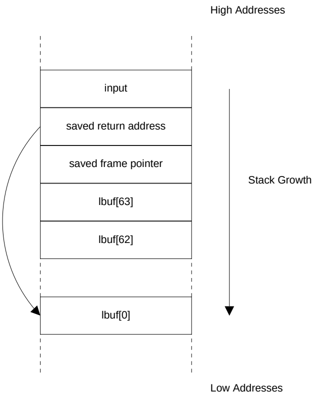
Memory Error I
Examples

Code pointer corruption

```
int foo(char *input) {
  char lbuf[64];
  int i;

  for (i = 0; i < strlen(input); i++)
    lbuf[i] = input[i];

  return 0;
```



Memory Error II

Examples

Data pointer corruption

```
FILE * getdatasock(char *arg1, ...) {
    char buf[128];
    ...
    seteuid(0);
    setsockopt(...);
    sprintf(buf, arg1);
    ...
    seteuid(pw->pw_uid);
}
```

Data corruption

```
void write_user_data(void) {
    FILE * fp ;
    char user_filename[256], user_data[256];

    gets(user_filename);

    if (privileged_file(user_filename)) {
      fprintf(stderr, "Illegal filename. Exiting.\n");
      exit(1);
    } else {
      gets(user_data); // overflow into user_filename
      fp = fopen(user_filename, "w");
      if (fp) {
        fprintf(fp, "%s", user_data);
        fclose(fp);
      }
    }
}
```

Research Goal

Program transformation techniques for memory error protection

- Comprehensive
- Mainly deterministic
- Vulnerability and attack-independent
- Resilient to different evasions

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Artificial Diversity

Biological Diversity

Plays a crucial role for the survivability of every biological species

- Memory error exploits rely on using *well-known* memory addresses

$\Rightarrow$ Make systems appear different!

- Address Space Layout Randomization (ASLR) [15]
- Fine-grained Address Space Randomization (ASR) [12, 11]
- Instruction Set Randomization (ISR) [3]

Artificial Diversity

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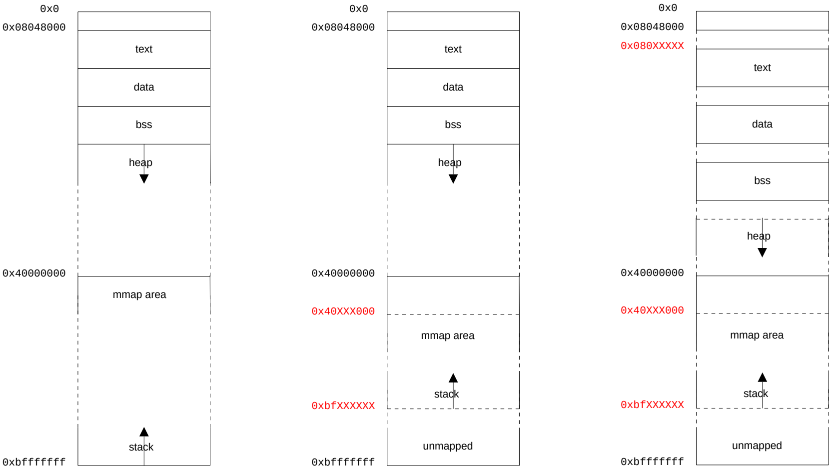
Artificial Diversity

Examples: ASLR [15] & Fine-grained ASR [12]



Artificial Diversity
Limitations

Diversity applied on a process itself

- Requires high entropy
- Relies on keeping secrets
  - ... Disclosed by information leakage attacks [13]
  - ... Defeated by brute forcing attacks [6]
- Hard to counteract
  - Partial memory overwriting attacks
  - Most arbitrary data corruption
- Provides *probabilistic* protection

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Taint Analysis

Determines whether the value of a variable x is influenced by the value of another variable y

- It tracks how a program *untrusted* data (input) *flow* into *sinks* (output), security sensitive points
  - $x := y$ (explicit data-dependent flow)
  - **if** $x = k$ **then** $y = k^{'}$ (explicit control-dependent flow)

↑ It enforces taint-enhanced security policies on sinks to detect improper usage of *tainted* data

- *Code pointer* memory error corruption

↓ Hard or impossible to manually specify policy for some (memory error) vulnerabilities (FPs/FNs)

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Anomaly Detection

Determines whether a process behavioral profile $\mathcal{M}'$ is *consistent* with the behavioral profile $\mathcal{M}$ learnt during a *learning* or *training* phase

- Deviation from $\mathcal{M}$ observed during a *detection* phase are considered anomalous
- Anomalous events are considered as attacks' manifestations

↑ It *automatically* infers policies of legitimate process behaviors

- It detects *unknown* attacks

↓ High false positives (FPs) rate

- Training *not exhaustive* flags some unseen — but legitimate — behaviors as anomalous

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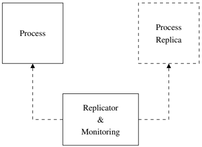
Diversified Process Replicæ

Framework

Idea

To couple the concept of *artificial diversity* and *process replication*

- T, the tracer, creates P_r, a *replica* of P
- T makes P and P_r to behave identically on benign input
- P and P_r are *artificially diversified*
  - $\Rightarrow$ Detect behavioral divergence caused by malicious input (i.e., memory error attacks)



Process Replication

Rendez-vouz

T synchronizes P and P_r at every system call invocation

- T checks for system call consistency (e.g., system call arguments, system call number)
- T *simulates* certain system calls (e.g., `read`, `send`)
  - It replicates input and handles output on I/O system calls
  - It performs the system call *once*
  - It returns consistent results to P and P_r
- T let P and P_r to *execute* other system calls (e.g., `brk`)
- T carefully handles other system calls (e.g., `mmap2`)

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Process Diversification

- *Non-overlapping* address spaces for absolute overwriting
- Address space *shifting* for partial overwriting

Result

Code and data pointer corruption are defeated

Statically: custom linker script for `.text`, `.data`, `.bss`, base of heap

Dynamically: modified `ld-linux.so` for the executable stack and shared objects mapping

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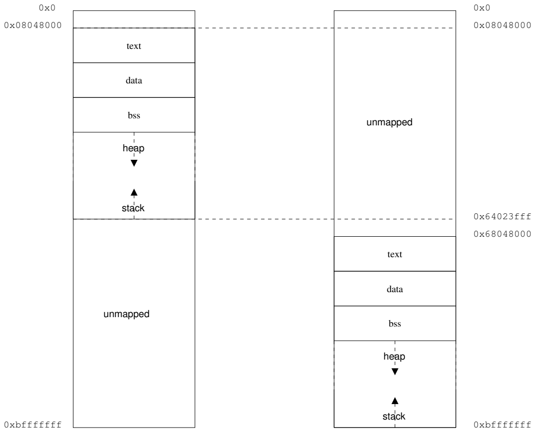
Address Space Partitioning



Effectiveness I

Code pointer corruption

```
int foo(char *input) {
  char lbuf[64];
  int i;

  for (i = 0; i < strlen(input); i++)
    lbuf[i] = input[i];

  return 0;
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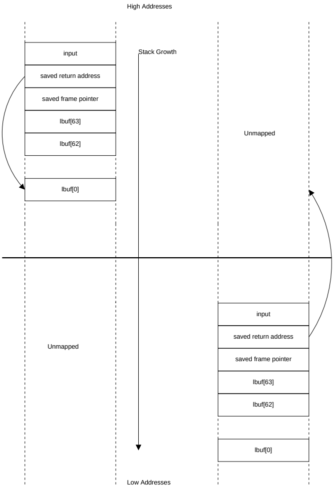

Effectiveness II

Limitations

It cannot thwart

- Arbitrary (non-pointer) data corruption
- Some information leakage

```
void write_user_data(void) {
    FILE *fp;
    char user_filename[256];
    char user_data[256];

    gets(user_filename);

    if (privileged_file(user_filename))
       exit(1);

    // overflow: corrupts user_filename

    gets(user_data);
    fp = fopen(user_filename, "w");
    if (fp) {
       fprintf(fp, "%s", user_data);
       fclose(fp);
    }
}
```

Experimental Results I
The Prototype

- User-space prototype developed on a Debian GNU/Linux system, 2.6.17 kernel, $5,700+$ LoC
- Modified run-time dynamic linker `ld-linux.so`
- Replication via `ptrace` implementation
- It supports
  - `clone`/`fork`/`vfork` support
  - Shared memory management
  - Signals management

Experimental Results
Throughput Penalties

100 conns, 4 sess/conn, 13 reqs/conn, $\sim$ 7.5MB web site

#	**Throughput**	**MB/s** (no DPR)	**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	$\sim$ 3.8%
4	`thttpd` (read-nocache)	12603.7	7086.3	$\sim$ 43.8%
5	`thttpd` (read-nocache-single)	9134.5	2838.1	$\sim$ 69%

Experimental Results
Latency Penalties

100 conns, 4 sess/conn, 13 reqs/conn, $\sim$ 7.5MB web site

#	**Latency**	**ms** (real system)	**ms** (DPR)	**slowdown**
1	`thttpd` (mmap)	3.5	4.6	31%
2	`thttpd` (mmap-nocache)	3.5	4.5	29%
3	`thttpd` (read)	3.5	5.3	51%
4	`thttpd` (read-nocache)	3.7	21.6	$\sim 6x$
5	`thttpd` (read-nocache-single)	166	646	$\sim 4x$

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Taint-enhanced Anomaly Detection

Idea

To couple *taint information* with learning-based *anomaly detection*

- Fine-grained taint analysis provides information about the ability of the attacker to *exercise* the vulnerability
- ↓ Hard to specify arbitrary security policies (FPs/FNs)
- Anomaly detection automatically learns application behaviors
- ↓ Learning approaches are *not exhaustive* (FPs/FNs)

$\Rightarrow$ Consider *tainted events* only

↑ False positives are decreased
↑ True positives are increased

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Fine-grained Taint Analysis

Source-to-source *program transformation* technique

- It marks incoming input as untrusted (i.e., *tainted*)
- It tracks data propagation
- It inserts callback functions for every *sink* (e.g., system call)
  - Learning phase
  - Detection phase
  - Null-behavior (taint-enhanced only)

Learning-based Approaches

$$\Sigma = \{sinks\}, s(a_1, \cdots, a_n) \in \Sigma, a_i \; sinks \; arguments, i \in \{1, \cdots, n\}$$

- Context-sensitive analysis
- Taint information (e.g., a_i taintedness), $\forall s \in \Sigma$
- An event $s \in \Sigma$ is tainted if it exists at least one tainted a_i

For tainted events

Untainted bytes

- Longest common prefix (LCP)
- Minimum length

Tainted bytes

- Structural inference
- Maximum length

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Tainted bytes

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Effectiveness I

- Coarse-grained taint information
- Maximum length
- Structural inference

```
void write_user_data(void) {
    FILE *fp;
    char user_filename[256];
    char user_data[256];

    gets(user_filename);
    if (privileged_file(user_filename)) { exit(1); }
    gets(user_data);
    fp = fopen(user_filename, "w");
    if (fp) { fprintf(fp, "%s", user_data); fclose(fp); }
}
```

learning:

`user_data` taintedness & length

detection:

`user_data` length is violated during attack

Effectiveness II

Fine-grained taint information

```
FILE * getdatasock(char *arg1, ...) {
    char buf[128];
    ...
    seteuid(0);
    setsockopt(...);
// fmt bug overwrites current user cred
    sprintf(buf, arg1);
    ...
    seteuid(pw->pw_uid);
}
```

learning:

untainted `seteuid` argument

detection:

taintedness violation for `seteuid` argument `pw->pw_uid` during attack

Experimental Results
The Prototype

- Fine-grained taint analysis
  - CIL & OCaml for the program transformation ($\sim 5,000$ LoC)
  - C for the taint propagation strategy and callback insertion
- Learning-based anomaly detection approach
  - C/C++ for learning, detection and original behavior phase ($15,000+$ LoC)
  - Python for automatic code generation

Experimental Results I

#	App	# Traces (Learning)	# Traces (Detection)	FP	Overall FPs
1	`proftpd`	$68,851$	$983,740$	200	2.0×10^{-4}
2	`apache`	$58,868$	$688,100$	2000	2.9×10^{-3}

Table: Overall False Positives.

#	App	Taint	LCP	Min	Struct Inf.	T. Max	Overall FPs
1	`proftpd`	3.0×10^{-5}	3.0×10^{-5}	0	1.4×10^{-4}	0	2.0×10^{-4}
2	`apache`	0	4.3×10^{-4}	0	2.4×10^{-3}	0	2.9×10^{-3}

Table: False Positives Breakdown.

Experimental Results II

#	App	Unkn. untaint. traces	Taint. of sinks args	FPs (taint inf.)
1	`proftpd`	2.1×10^{-4}	3.0×10^{-5}	2.4×10^{-4}
2	`apache`	4.3×10^{-4}	0	4.3×10^{-4}

Table: Unknown/Untainted Traces.

#	App	slowdown (taint)	slowdown (taint-learn)	slowdown (taint-detect)
1	`proftpd`	3.1%	5.9%	9.3%
2	`apache`	5.7%	10.3%	18.5%

Table: Throughput Slowdown.

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- Artificial diversity [11, 12, 15]
- Taint analysis [2, 7, 10, 16]
- Learning-based anomaly detection techniques
  - system call sequences [5]
  - FSA [14]
  - call stack information [4]
  - statistical multi-model (e.g., bytes frequency, token presence, structural inference) [8, 9]
  - data-flow relationship [1]

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Diversified Process Replicæ

Optimizations
- Do not simulate FS-related system calls that operate on a FS-objects $\mathcal{O}$ unless $\mathcal{O}$ is shared
- SMP

Dynamic Binary Translation (QEMU)
- ↑ Does not require program recompilation
- Faster then a `ptrace` implementation
- Partial overwrite protection is lost

Program Transformation
- Insert non-overlapping gaps between buffer-like variables of P and P_r to thwart some data corruption (probabilistic protection)

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Taint-enhanced Anomaly Detection

- Apply the same technique to a broader class of vulnerabilities (e.g., web application vulnerabilities)
- Preliminary results
  - Context-sensitive analysis on a taint-enhanced PHP interpreter
  - Learning policy for SQL injection attacks deals with
    - 2^{nd} order SQL injection on tainted query
    - Dynamic construction of SQL query (e.g., fuzzy advanced search)
  - Leverage on the learning-based approach to learn safe attack pattern usage

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- State of the art approaches have drawbacks
  - Mostly *probabilistic* protection
  - Hard to deal with data and data pointer corruption
  - Vulnerable to evasions (e.g., brute forcing, mimicry)
- Diversified process replicæ
  - ↑ Comprehensive & deterministic code/data pointer protection
  - ↓ No arbitrary data corruption protection
- Taint-enhanced anomaly detection
  - ↑ Comprehensive memory error protection
  - ↑ Deterministic code pointer protection
  - ↑ Probabilistic data and data pointer protection
  - ↑ Low false positives rate
  - ↓ It requires a learning-phase

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Q&A

Thank You!
Q&A?

Backup Material

Backup Material

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
- sync at `mmap` or `msync` time

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
- either P or P_r has to modify the resource R
- they must operate on an *up-to-dated* view of the shared resource R

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 let P to execute a single instruction that accesses the shared area
  - if P has mutual access to R, this is reflected to R and P AS
- T replicates the effect made by P into P_r AS

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