Runtime Defenses against Memory Corruption

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Reading Assignment


◆ Dhurjati, Adve. “Backwards-compatible array bounds checking for C with very low overhead” (ICSE 2006).
Preventing Buffer Overflows

- Use safe programming languages, e.g., Java
  - Legacy C code? Native-code library implementations?
- Black-box testing with long strings
- Mark stack as non-executable
- Randomize memory layout or encrypt return address on stack by XORing with random string
  - Attacker won’t know what address to use in his string
- Run-time checking of array and buffer bounds
  - StackGuard, libsafe, many other tools
- Static analysis of source code to find overflows
Run-Time Checking: StackGuard

- Embed “canaries” (stack cookies) in stack frames and verify their integrity prior to function return
  - Any overflow of local variables will damage the canary

- Choose random canary string on program start
  - Attacker can’t guess what the value of canary will be

- Terminator canary: “\0”, newline, linefeed, EOF
  - String functions like strcpy won’t copy beyond “\0”
StackGuard Implementation

- StackGuard requires code recompilation
- Checking canary integrity prior to every function return causes a performance penalty
  - For example, 8% for Apache Web server
- StackGuard can be defeated
  - A single memory copy where the attacker controls both the source and the destination is sufficient
Defeating StackGuard

Suppose program contains `strcpy(dst,buf)` where attacker controls both dst and buf

- Example: dst is a local pointer variable

```
buf | dst | canary | sfp | RET

Return execution to this address

BadPointer, attack code | &RET | canary | sfp | RET

Overwrite destination of strcpy with RET position
strcpy will copy BadPointer here
```
ProPolice / SSP

Rerrange stack layout (requires compiler mod)

- args
- return address
- exception handler records
- SFP
- CANARY
- arrays
- local variables

No arrays or pointers

Cannot overwrite any pointers by overflowing an array

Ptrs, but no arrays

[IBM, used in gcc 3.4.1; also MS compilers]
What Can Still Be Overwritten?

- Other string buffers in the vulnerable function
- Exception handling records
- Any stack data in functions up the call stack

  - Example: call to a vulnerable member function passes as an argument `this` pointer to an object up the stack
  - Stack overflow can overwrite this object’s vtable pointer and make it point into an attacker-controlled area
  - When a virtual function is called (how?), control is transferred to attack code (why?)
  - Do canaries help in this case?
    - Hint: when is the integrity of the canary checked?
Litchfield’s Attack

- Microsoft Windows 2003 server implements several defenses against stack overflow
  - Random canary (with /GS option in the .NET compiler)
  - When canary is damaged, exception handler is called
  - Address of exception handler stored on stack above RET

- Litchfield’s attack (see paper)
  - Smashes the canary AND overwrites the pointer to the exception handler with the address of the attack code
    - Attack code must be on the heap and outside the module, or else Windows won’t execute the fake “handler”
  - Similar exploit used by CodeRed worm
Safe Exception Handling

- Exception handler record must be on the stack of the current thread (*why?*)
- Must point outside the stack (*why?*)
- Must point to a valid handler
  - Microsoft’s /SafeSEH linker option: header of the binary lists all valid handlers
- Exception handler records must form a linked list, terminating in FinalExceptionHandler
  - Windows Server 2008: SEH chain validation
  - Address of FinalExceptionHandler is randomized (*why?*)
When SafeSEH Is Incomplete

[Sotirov and Dowd]

◆ If DEP is disabled, handler is allowed to be on any non-image page except stack
  - Put attack code on the heap, overwrite exception handler record on the stack to point to it

◆ If any module is linked without /SafeSEH, handler is allowed to be anywhere in this module
  - Overwrite exception handler record on the stack to point to a suitable place in the module
  - Used to exploit Microsoft DNS RPC vulnerability in Windows Server 2003
PointGuard

◆ Attack: overflow a function pointer so that it points to attack code

◆ Idea: encrypt all pointers while in memory
  • Generate a random key when program is executed
  • Each pointer is XORed with this key when loaded from memory to registers or stored back into memory
    – Pointers cannot be overflowed while in registers

◆ Attacker cannot predict the target program’s key
  • Even if pointer is overwritten, after XORing with key it will dereference to a “random” memory address
Normal Pointer Dereference

1. Fetch pointer value
2. Access data referenced by pointer

1. Fetch pointer value
2. Access attack code referenced by corrupted pointer

[Cowan]
PointGuard Dereference

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1. Fetch pointer value

2. Access data referenced by pointer

CPU

Memory

Encrypted pointer

0x7239

Data

0x1234

Corrupted pointer

0x7239

0x1340

Data

0x1234

Attack code

0x1340

0x9786

[Source: Cowan]
PointGuard Issues

◆ Must be very fast
  • Pointer dereferences are very common

◆ Compiler issues
  • Must encrypt and decrypt only pointers
  • If compiler “spills” registers, unencrypted pointer values end up in memory and can be overwritten there

◆ Attacker should not be able to modify the key
  • Store key in its own non-writable memory page

◆ PG’d code doesn’t mix well with normal code
  • What if PG’d code needs to pass a pointer to OS kernel?
Run-Time Checking: Libsafe

- Dynamically loaded library
- Intercepts calls to `strcpy(dest,src)`
  - Checks if there is sufficient space in current stack frame
    \[|\text{frame-pointer} - \text{dest}| > \	ext{strlen(src)}\]
  - If yes, does `strcpy`; else terminates application

![Diagram showing stack frame with pointers and variables]

```
libsafe

main
```

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Limitations of Libsafe

- Protects frame pointer and return address from being overwritten by a stack overflow
- Does not prevent sensitive local variables below the buffer from being overwritten
- Does not prevent overflows on global and dynamically allocated buffers
TIED / LibsafePlus

◆ **TIED**: augments the executable with size information for global and automatic buffers
◆ **LibsafePlus**: intercepts calls to unsafe C library functions and performs more accurate and extensive bounds checking

[Avijit et al.]
Overall Approach

Executable compiled with -g option → TIED → Augmented executable

LibsafePlus.so

Preload → Run

Aborts if buffer overflow

Normal execution otherwise
TIED: The Binary Rewriter

- Extracts type information from the executable
  - Executable must be compiled with -g option
- Determines location and size for automatic and global character arrays
- Organizes the information as tables and puts it back into the binary as a loadable, read-only section
Type Information Data Structure

**Type info header pointer**

- No. of global variables
- Ptr to global var table
- No. of functions
- Ptr to function table

**Global Variable Table**

<table>
<thead>
<tr>
<th>Starting address</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Function Table**

<table>
<thead>
<tr>
<th>Starting address</th>
<th>End address</th>
<th>No. of vars</th>
<th>Ptr to var table</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</tr>
</tbody>
</table>

**Local Variable Table**

<table>
<thead>
<tr>
<th>Offset from frame pointer</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</tbody>
</table>

...
Rewriting ELF Executables

- **Constraint:** the virtual addresses of existing code and data should not change
- Extend the executable towards lower virtual addresses by a multiple of page size
- Serialize, relocate, and dump type information as a new loadable section in the gap created
- Provide a pointer to the new section as a symbol in the dynamic symbol table
**Before and After Rewriting**

- **.dynstr** is modified to hold the name of the symbolic pointer.
- **.hash** is modified to hold the hash value of the symbol added to **.dynsym**.
Bounds Checking by LibsafePlus

- Intercept unsafe C library functions
  - `strcpy`, `memcpy`, `gets` ...
- Determine the size of destination buffer
- Determine the size of source string
- If destination buffer is large enough, perform the operation using actual C library function
- Terminate the program otherwise
Estimating Stack Buffer Size

- Preliminary check: is the buffer address greater than the current stack pointer?
- Locate the encapsulating stack frame by traversing the saved frame pointers
- Find the function that defines the buffer
- Search for the buffer in the local variable table corresponding to the function
  - This table has been added to the binary by TIED
- Return the loose Libsafe bound if buffer is not present in the local variable table
Where Was The Buffer Defined?

- **Case 1:** buf may be a local variable of function f
  - or
- **Case 2:** buf may be an argument to the function g

Use return address into f to locate the local variable table of f, search it for a matching entry.

If no match is found, repeat the step using return address into g.
Protecting Heap Variables

- LibsafePlus also provides protection for variables allocated by malloc family of functions
- Intercepts calls to malloc family of functions
- Records sizes and addresses of all dynamically allocated chunks in a red-black tree.
  - Used to find sizes of dynamically allocated buffers
- Insertion, deletion and searching in $O(\log(n))$
Estimating Heap Buffer Size

- Maintain the smallest starting address $M$ returned by malloc family of functions
- Preliminary check: if the buffer is not on the stack, is its address greater than $M$?
- If yes, search in the red-black tree to get the size
- If buffer is neither on stack, nor on heap, search in the global variable table of the type information data structure
Limitations of TIED / LibsafePlus

- Does not handle overflows due to erroneous pointer arithmetic
- Imprecise bounds for automatic variable-sized arrays and alloca()’ed buffers
- Applications that mmap() to fixed addresses may not work
- Type information about buffers inside shared libraries is not available
  - Addressed in a later version
Runtime Bounds Checking

Referent object = buffer to which pointer points
- Actual size is available at runtime!

1. Modified pointer representation
- Pointer keeps information about its referent object
- Incompatible with external code, libraries, etc. 😞

2. Special table maps pointers to referent objects
- Check referent object on every dereference
- What if a pointer is modified by external code? 😞

3. Keep track of address range of each object
- For every pointer arithmetic operation, check that the result points to the same referent object
Jones-Kelly

[In Automated & Algorithmic Debugging, 1997]

- Pad each object by 1 byte
  - C permits a pointer to point to the byte right after an allocated memory object
- Maintain a runtime tree of allocated objects
- Backwards-compatible pointer representation
- Replace all out-of-bounds addresses with special ILLEGAL value (if dereferenced, program crashes)
- Problem: what if a pointer to an out-of-bounds address is used to compute an in-bounds address
  - Result: false alarm
Example of a False Alarm

```c
char *p, *q, *r, *s;
p = malloc(4);
q = p+1;
s = p+5;
r = s-3;
```

Note: this code works even though it’s technically illegal in standard C
Ruwase-Lam

- Catch out-of-bounds pointers at runtime
  - Requires instrumentation of malloc() and a special runtime environment
- Instead of ILLEGAL, make each out-of-bounds pointer point to a special OOB object
  - Stores the original out-of-bounds value
  - Stores a pointer to the original referent object
- Pointer arithmetic on out-of-bounds pointers
  - Simply use the actual value stored in the OOB object
- If a pointer is dereferenced, check if it points to an actual object. If not, halt the program!
Example of an OOB Object

```c
{  
    char *p, *q, *r, *s;
    p = malloc(4);
    q = p+1;
    s = p+5;
    r = s-3;
}
```

Note: this code works even though it’s technically illegal in standard C
Performance

- Checking the referent object table on every pointer arithmetic operation is very expensive
- Jones-Kelly: 5x-6x slowdown
  - Tree of allocated objects grows very big
- Ruwase-Lam: 11x-12x slowdown if enforcing bounds on all objects, up to 2x if only strings
- Unusable in production code!
Dhurjati-Adve

◆ Split memory into disjoint pools
  • Use aliasing information
  • Target pool for each pointer known at compile-time
  • Can check if allocation contains a single element (why does this help?)

◆ Separate tree of allocated objects for each pool
  • Smaller tree ⇒ much faster lookup; also caching

◆ Instead of returning a pointer to an OOB, return an address from the kernel address space
  • Separate table maps this address to the OOB
  • Don’t need checks on every dereference (why?)
OOB Pointers: Ruwase-Lam

\[
p = \text{malloc}(10 \times \text{sizeof(int)});
q = p + 20;
\]

\[
r = q - 15;
\]

*\(r = \ldots\); // no bounds overflow

*\(q = \ldots\); // overflow

q = OOB(p+20,p)
Put OOB(p+20,p) into a map

r = p + 5

Check if \(r\) is out of bounds

Check if \(q\) is out of bounds:
Runtime error

Check on every dereference
p = malloc(10 * sizeof(int));
q = p + 20;
r = q - 15;

*r = ... ; //no bounds overflow
*q = ... ; // overflow

q = 0xCCCCCCCCCC
Put (0xCCCCCCCCCC, OOB(p+20,p)) into a map

r = p + 5

No software check necessary!
No software check necessary!
Runtime error

Average overhead: 12% on a set of benchmarks