The Taming of the Stack: Isolating Stack Data from Memory Errors

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Vulnerability – Memory Errors

• Still many vulnerabilities being discovered due to memory errors
  • Most famously – buffer overflows
  • Recent example → → → →
    • Bad coding style
    • Use of unsafe functions

• Allow adversary to write
  • Outside of allocated buffer (e.g., buf)
  • To write other objects (e.g., mode, *p)

• Other variants of memory errors

• Extensive problem
  • “Eternal War in Memory”
  • “The Neverending Story: Memory Corruption 30 Years Later”
  • Take full control over the system
  • Defeat all protection schemes

• Case Study: CVE-2020-20739

```c
int im_vips2dz( IMAGE *in, const char *filename ){
    char *p, *q;
    char name[MAXN];
    char mode[MAXN];
    char buf[MAXN];
    ...

    im_strncpy( name, filename, MAXN );
    if( ( p = strchr( name, ':' ) ) ){
        *p = '\0';
        im_strncpy( mode, p + 1, MAXN );
    }
    strcpy( buf, mode );
    p = &buf[0];
    ...
}
```
Security via Detecting Attacks

• But, detecting attacks is becoming more difficult
  • Adversaries are skilled and have systematic tools
  • Nation-state level attacks appear to be increasing
How did we get here?

- **Problem:** Systems often take risks (i.e., perform unsafe actions)
- **Internet:** enables parties worldwide to communicate
- **Firewalls:** must allow many unsafe communications
- **Access control:** cannot block any functional requirements
- **Software (part 1):** use of unsafe languages leads to memory errors
- **Software (part 2):** cannot validate information flows are safe in practice
Example: C programming language

- **Popular**: Still among the top-3 languages in preference in surveys
- **Lots of code**: Legacy code abounds
- **Useful**: Can write high performance code
- **Unsafe**: Makes no guarantees of memory safety

C Program Structure

An example of simple program in C

```c
#include <stdio.h>

void main(void)
{
    printf("I love programming!
");
    printf("You will love it too once ");
    printf("you know the trick
");
}
```
What Can Go Wrong?

• What are the 3 general categories of memory error?

• What operations are needed for triggering each memory error class?
Spatial Error – Pointer Arithmetic

• Think about how to access an element in a string

```c
char string[10];
string[3] = 'A';
```

• Here is what happens exactly

```c
char string[10];
char *p;
p = string;
//string[3] = 'A';
p = p + 3;
*p = 'A';
```

• Generally, there are 4 kinds of pointer arithmetic.
  • Increment/Decrement of a Pointer, e.g., p++
  • Addition of integer to a pointer, e.g., p+3
  • Subtraction of integer to a pointer, e.g., p-5
  • Subtracting two pointers of the same type, e.g., offset=p1-p2
What Can Go Wrong?

• **Memory safety errors** consist of three classes
  • **Spatial errors**: pointer accesses to an object may be outside its memory region (bounds) – unsafe pointer arithmetic operations.
  • **Type errors**: pointer accesses to an object may interpret the object using multiple types (casts) – unsafe type cast operations
  • **Temporal errors**: accesses to a pointer may occur before initialization (use-before-initialization or UBI) or after its target object is deallocated (use-after-free)

```c
void example(int ct, char ***buf) {
    int lct = BUF_SIZE;
    char lbuf[lct];
    if (ct < lct) { // (1) ct > buf's size
        strcpy(lbuf, *buf, (size_t) ct); // (2) ct < 0
    }
    *buf = lbuf; // (3) temporal
}
```

Fig. 1: Example function demonstrates: (1) bounds error that enables overread of `buf`; (2) type error due to casting of `ct` from signed to unsigned; and (3) temporal error as `*buf` references local variable `lbuf` after return.
Reality

- **For memory safety in C**: Still *only very limited protections*, even just when considering stack objects
  - E.g., stack canaries to protect return addresses

- In this work, we explore an *opportunity to leverage safety*
- Are we almost able to protect most objects from memory errors?
Stack Is Security-Critical

Stack saves important data.

- Control data – e.g., flag variable in conditional branch, return address.
- Non-control data – e.g., user-sensitive data.

Stack suffers from variety kinds of attacks.

- Control flow hijacking – return address, function pointers.
- Data-oriented attack – Direct data manipulation (DDM), DOP.
- Block-oriented programming.
- 500+ CVEs related to stack memory errors in recent 3 years.
Stack-Based Memory Bugs Still Exist

• 500+ CVEs related to stack memory errors in recent 3 years.

• OOB writes: writes data out of the range of the intended buffer.
  • 2021-28972, 2021-24276, 2021-25178.

• OOB reads: disclose sensitive stack information.
  • 2021-3444, 2020-25624, 2020-16221.

• Type error: reference memory using different type semantics.
  • 2021-26825, 2020-15202, 2020-14147.

• Temporal error: reference memory using stale pointers.
  • 2020-25578, 2020-20739, 2020-13899.
Safe Stack Approach

Introduction

- Protects code pointers against stack buffer overflows
- Multistack with two distinct, isolated regions
  - Safe Stack: return addresses, function pointers, safe local variables
  - Unsafe Stack: everything else, e.g., buffers, address taken variables
- Isolating Safe Stack from Unsafe Stack
  - Ensure attack on unsafe stack object cannot corrupt Safe Stack.

Limitations

- Security depends on classification of safe objects
  - A safe stack object must not perform an operation that violates the security goal (i.e., no runtime checks on the safe stack)
- Safe Stack classification is incomplete for memory errors
  - Does not account for type errors and some temporal errors (e.g., UBI)
- Safe Stack classification is conservative
  - Some objects may be safe that are not placed on the safe stack
Example of Safe Stack

```c
void example(int ct, char **buf) {
    int lct = BUF_SIZE;
    char safe_lbuf[lct];
    char unsafe_lbuf[lct];
    if (ct < lct) {
        strncpy(unsafe_lbuf, *buf, (size_t) ct); // (1) ct > buf's size
        ...
        *buf = unsafe_lbuf;
        // Some safe operations on unsafe_lbuf
    } else {
        strncpy(safe_lbuf, *buf, lct-1);
        ...
        strcpy(*buf, safe_lbuf)
    }
}
```

- What are unsafe objects for Safe Stack?
  - *buf, unsafe_lbuf, safe_lbuf.

- What are real unsafe objects?
  - *buf, unsafe_lbuf, ct.
Inspiration

• **For memory safety in C**: **CCured system** enables checking of which pointers are used only in memory-safe ways
  • For buffers that can be overflowed, there must be pointer arithmetic operations
  • For type confusion error, there must be type cast operations
  • **Safe**: No pointer arithmetic or casting operations
  • **Results**: Estimated 90% of pointers are only used in safe operations
  • Are we almost able to protect most objects from memory errors?
### Same Example Again...

```c
void example(int ct, char **buf) {
    int lct = BUF_SIZE;
    char safe_lbuf[lct];
    char unsafe_lbuf[lct];
    if (ct < lct){
        strlcpy(unsafe_lbuf, *buf, (size_t) ct); // (1) ct > buf's size
        ...
        *buf = unsafe_lbuf; // Some safe operations on unsafe_lbuf
        // (3) temporal
    }
    else{
        strlcpy(safe_lbuf, *buf, lct-1);
        ...
        strcpy(*buf, safe_lbuf)
    }
}
```

- **What are unsafe objects for CCured?**
  - *buf, unsafe_lbuf, safe_lbuf, ct

- **What are real unsafe objects?**
  - *buf, unsafe_lbuf, ct.
Our Goals

• Validate the safety of stack objects against all types of memory errors
  • Spatial, type, and temporal errors
  • Remove all unsafe objects from the safe stack

• Maximize number of stack objects found that are safe from memory errors comprehensively.
  • Add as many safe objects to the safe stack as feasible

• Ensure no unsafe stack object is ever mistakenly classified as safe

• Remove runtime checks on safe stack objects by isolating their accesses from unsafe objects
  • Same as the “safe stack” runtime defense

• **Protect more stack objects from memory errors comprehensively without runtime checks** – ultimately, leading to **better performance**
Design
Our Approach - DataGuard

1. Step 1: Identify Error Classes for Stack Objects
   Section 5.1
   - Stack Objects
   - Per-Object Classes
   - Safe Stack Objects
     (No Classes)

2. Step 2: Collect Safety Constraints
   Section 5.2
   - Compute Safe Stack Objects
   - Unsafe Stack Objects
     (Constraint Failure)

3. Step 3: Verify Stack Object Safety
   Section 5.3
   - Safe Stack Objects
   - Unsafe Stack Objects
     (Validation Failure)

- Safe Stack Runtime Enforcement
- Runtime Enforcement

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Step 1 – Identifying Error Classes

• **Claim**: A stack object is safe unless it may be accessed by some pointer operation that may cause a memory error
  • May be cases where stack objects are trivially safe
  • Reduce validation effort where needed

• **Question**: Which classes of memory errors may be possible for each stack object?
Step 1 – Identifying Error Classes

• Find the classes of memory errors possible for each stack object
  • Based on the operations performed using its pointers

• Could a pointer operation cause a spatial error?
  • \textbf{CCured}: if used in pointer arithmetic operation

• Could a pointer operation cause a type error?
  • \textbf{CCured}: if used in type cast operation

• Could a pointer operation cause a temporal error?
  • \textbf{CCured}: does not address
    • \textbf{Escape analysis}: if used prior to initialization or if escape via call/return or heap/global

• 
\textbf{Pointers that are not used in any such operations are “safe”}

• Objects only aliased by safe pointers are ”safe”

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Step 2 – Collecting Safety Constraints

• **Question**: For pointers used in unsafe operations, under what conditions are those operations safe?

• E.g., a pointer that is guaranteed to be used within bounds cannot cause a spatial memory error
Step 2 – Collecting Safety Constraints

- Safety Constraints
  - Spatial Constraints
  - Type Constraints
  - Temporal Constraints

- **Declaration**: The size from the object’s base must be declared as a constant value. The initial index is 0.

- **Definition**: When a pointer is defined to reference the object, the reference may be offset to change the index. This offset must be a constant value.

- **Use**: When a pointer is used in an operation, the pointer may be further offset to change the index. Each offset in a use must also be a constant value.

- **Validation**: For all uses, pointer $\text{index} < \text{size}$ and $\text{index} \geq 0$
Step 2 – Collecting Safety Constraints

• Define **safety validation requirements** for each memory error class
  • Spatial, type, and temporal

• Collect constraints for each stack object
  • E.g., Stack object size must be declared as a constant
  • Constraints may not be found for all stack objects

• Collect constraints for each pointer
  • E.g., All pointer arithmetic operations must use constants
  • Define constraints for pointer “definitions” and “uses”

• **If safety constraints cannot be derived for a stack object or any pointers that may alias it, then safety validation is not possible and the object is “unsafe”**
Step 3 - Verifying Stack Object Safety

• **Question**: w/o running program, can we tell if all executions satisfy safety constraints?
  - Static analysis and Symbolic execution
  - **Prior work** (Baggy Bounds) applied value-range analysis to reduce the number of pointer operations that would require bounds checks

• **Problem**: Static analyses that over-approximate program executions may find a pointer "unsafe" that could really be used on safely

• **Hypothesis**: A significant number of such cases exist (due to aliasing), so many stack objects may be found “unsafe” that can be proven “safe”
Step 3 - Verifying Stack Object Safety

- Apply the safety constraints to determine whether we can prove a stack object is only accessed via safe pointer operations

- Performed in two steps:
  - (1) Static analysis: Find all pointers that may-alias the stack object can only perform operations that comply with the safety constraints
    - Spatial: Value-range analysis
    - Type: Value-range analysis to validate that integer type casts never change value
    - Temporal: Live-range analysis to find that def and use of all aliases are within the live range

- A stack object is “safe” if all pointers that may-alias it are safe
  - I.e., all may-alias pointers are only used in safe operations relative to the safety constraints
Step 3 - Verifying Stack Object Safety

- Apply the safety constraints to determine whether we can prove a stack object is only accessed via safe pointer operations.

- Performed in **two steps**:
  1. **Concolic execution**: Determine whether a complete execution of all operations that access the stack object only consists of safe operations.
     - Only performed for stack objects with any aliases found to be “unsafe” from the static analysis.
  2. **Problem**: Path explosion of symbolic execution.
     - Utilize def-use chain already computed to guide symbolic execution.
     - Perform a limited symbolic execution for all stack objects not found safe via static analysis (e.g., limit the context depth).

- A stack object is “safe” if all operations that access it comply with safety constraints.
  - If a complete symbolic execution cannot be performed, the object is “unsafe.”
Soundness

- **Must ensure that** no stack object ever used in an unsafe operation may be classified as “safe”
  - Our analyses must overapproximate the program executions (i.e., be “sound”)

**Challenge:** DataGuard leverages a variety of static analyses [1,2]
- Some claim soundness, some prove soundness

- We show that DataGuard achieves *relative soundness*
  - DataGuard’s analysis is sound if all utilized analyses are sound

- By default, SE is a sound form of analysis because it follows all execution paths of a program [4]
  - However, for performance, SE analyses often make choices that render it unsound
  - DataGuard avoids such choices in SE, limiting [3]

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Evaluation
How Does DataGuard Impact the Security of Safe Stack Object Compared with Previous Work?

- 91.45% of stack objects are shown to be safe soundly by DataGuard w.r.t. spatial, type and temporal errors.
- 79.54% and 64.48% of stack objects classified as safe by CCured and Safe Stack, respectively.
- 50% and 70% unsafe stack objects by CCured and Safe Stack are found safe by DataGuard.
- 3% and 6.3% safe stack objects by CCured and Safe Stack are found unsafe by DataGuard.
How Frequently are Pointers Used in Unsafe Operations for Each Error Class?

<table>
<thead>
<tr>
<th></th>
<th>Total</th>
<th>Spatial</th>
<th>Type</th>
<th>Temporal</th>
<th>Safe</th>
</tr>
</thead>
<tbody>
<tr>
<td>nginx</td>
<td>11,679</td>
<td>1,555 (13.31%)</td>
<td>555 (4.75%)</td>
<td>1,401 (11.99%)</td>
<td>8,785 (75.22%)</td>
</tr>
<tr>
<td>httpd</td>
<td>58,572</td>
<td>12,116 (20.69%)</td>
<td>2,905 (4.96%)</td>
<td>16,232 (27.71%)</td>
<td>37,899 (64.70%)</td>
</tr>
<tr>
<td>profpmd</td>
<td>10,354</td>
<td>2,332 (12.86%)</td>
<td>488 (4.71%)</td>
<td>1,156 (11.16%)</td>
<td>8,155 (78.76%)</td>
</tr>
<tr>
<td>openvpn</td>
<td>38,065</td>
<td>7,061 (18.55%)</td>
<td>2,326 (6.11%)</td>
<td>8,734 (22.93%)</td>
<td>26,020 (68.36%)</td>
</tr>
<tr>
<td>opensshd</td>
<td>15,067</td>
<td>2,185 (14.50%)</td>
<td>479 (3.18%)</td>
<td>1,924 (12.77%)</td>
<td>11,798 (78.30%)</td>
</tr>
<tr>
<td>perlbench</td>
<td>33,241</td>
<td>2,255 (6.78%)</td>
<td>454 (1.37%)</td>
<td>5,571 (16.76%)</td>
<td>27,345 (82.30%)</td>
</tr>
<tr>
<td>bzrp2</td>
<td>778</td>
<td>52 (6.68%)</td>
<td>9 (1.16%)</td>
<td>146 (18.76%)</td>
<td>616 (79.17%)</td>
</tr>
<tr>
<td>gcc</td>
<td>103,285</td>
<td>22,661 (21.94%)</td>
<td>6,012 (5.82%)</td>
<td>19,476 (18.85%)</td>
<td>69,863 (67.64%)</td>
</tr>
<tr>
<td>mcf</td>
<td>384</td>
<td>28 (7.29%)</td>
<td>7 (1.82%)</td>
<td>57 (14.84%)</td>
<td>303 (78.90%)</td>
</tr>
<tr>
<td>gobmk</td>
<td>22,363</td>
<td>2,959 (13.23%)</td>
<td>170 (0.76%)</td>
<td>5,302 (23.71%)</td>
<td>15,522 (69.40%)</td>
</tr>
<tr>
<td>hmmer</td>
<td>16,257</td>
<td>3,759 (23.12%)</td>
<td>203 (1.25%)</td>
<td>2,803 (17.24%)</td>
<td>11,126 (68.43%)</td>
</tr>
<tr>
<td>sjeng</td>
<td>2,449</td>
<td>348 (14.20%)</td>
<td>74 (3.02%)</td>
<td>420 (17.14%)</td>
<td>1,768 (72.19%)</td>
</tr>
<tr>
<td>libquantum</td>
<td>2,182</td>
<td>524 (24.01%)</td>
<td>162 (7.42%)</td>
<td>343 (15.72%)</td>
<td>1,387 (63.57%)</td>
</tr>
<tr>
<td>h264ref</td>
<td>13,246</td>
<td>1,535 (11.59%)</td>
<td>91 (0.69%)</td>
<td>1,292 (16.55%)</td>
<td>10,109 (76.32%)</td>
</tr>
<tr>
<td>lhm</td>
<td>205</td>
<td>35 (14.40%)</td>
<td>8 (2.61%)</td>
<td>56 (18.24%)</td>
<td>226 (73.62%)</td>
</tr>
<tr>
<td>sphinx3</td>
<td>2,143</td>
<td>478 (22.30%)</td>
<td>135 (6.30%)</td>
<td>509 (23.75%)</td>
<td>1,320 (61.60%)</td>
</tr>
<tr>
<td>milc</td>
<td>2,943</td>
<td>338 (11.48%)</td>
<td>117 (3.98%)</td>
<td>314 (10.67%)</td>
<td>2,326 (79.03%)</td>
</tr>
<tr>
<td>omnetpp</td>
<td>13,780</td>
<td>1,247 (9.05%)</td>
<td>848 (6.15%)</td>
<td>1,832 (13.29%)</td>
<td>10,636 (77.18%)</td>
</tr>
<tr>
<td>soplex</td>
<td>11,941</td>
<td>1,910 (16.00%)</td>
<td>1,482 (12.41%)</td>
<td>2,453 (20.54%)</td>
<td>7,107 (59.51%)</td>
</tr>
<tr>
<td>namd</td>
<td>14,026</td>
<td>1,780 (12.69%)</td>
<td>154 (1.10%)</td>
<td>2,325 (16.58%)</td>
<td>10,852 (77.37%)</td>
</tr>
<tr>
<td>astart</td>
<td>2,571</td>
<td>193 (7.51%)</td>
<td>71 (2.76%)</td>
<td>414 (16.10%)</td>
<td>1,925 (74.87%)</td>
</tr>
</tbody>
</table>

- 14.24% spatial, 3.92% type, 17.39% temporal.
- 72.70% of stack pointers are free from any class of memory errors.
How Much Does the Two-Stage Validation Improve the Ability to Identify Safe Stack Objects over Prior Work?

• For Nginx
  • 88.36% of pointers classified as unsafe for spatial errors by CCured are found as safe by DataGuard.
    • DataGuard’s use of “Value range+SE” finds more (413) safe pointers than “SE alone” (377).
  • 93.36% of pointers classified as unsafe for temporal errors by Safe Stack are found as safe by DataGuard.
How Does the Increase in Safe Stack Objects Impact Performance?

- DataGuard finds 76.12% of functions have only safe stack objects, whereas CCured and Safe Stack find 41.52% and 31.33% respectively.

- Runtime performance: 4.3% for DataGuard, 8.6% for CCured, 11.3% for Safe Stack.
  - All using the same safe stack defense implementation
Does DataGuard Enhance the Security of Programs and Prevents Real-World Exploits?

- **Attack Mitigation**
  - Exploit objects are classified as unsafe.
  - Target object are classified as safe.

- **CGC Binaries**
  - 87 binaries have stack-related memory bugs.
  - Directly mitigates 95 of 118 exploits.
  - Successfully classifies all targets objects of the steppingstone objects for the remaining 23.

- **Impact on Control Data**

<table>
<thead>
<tr>
<th></th>
<th>Control Data</th>
<th>Safe-Stack-Safe</th>
<th>DataGuard-Safe</th>
</tr>
</thead>
<tbody>
<tr>
<td>nginx</td>
<td>1,023</td>
<td>632 (61.78%)</td>
<td>946 (92.47%)</td>
</tr>
<tr>
<td>httpd</td>
<td>2,276</td>
<td>1,431 (62.87%)</td>
<td>2,108 (92.62%)</td>
</tr>
<tr>
<td>proftpd</td>
<td>1,214</td>
<td>576 (47.45%)</td>
<td>1,128 (92.92%)</td>
</tr>
<tr>
<td>openvpn</td>
<td>3,482</td>
<td>1,965 (56.43%)</td>
<td>3,289 (94.46%)</td>
</tr>
<tr>
<td>opensshd</td>
<td>1,458</td>
<td>862 (59.12%)</td>
<td>1,326 (90.95%)</td>
</tr>
</tbody>
</table>

  - 92.68% of control data on stack are safe.
  - Much more than Safe Stack approach.

- **Case Study: CVE-2020-20739**

  ```
  int im_vips2dz( IMAGE *in, const char *filename ){
      char *p, *q;
      char name[FILENAME_MAX];
      char mode[FILENAME_MAX];
      char buf[FILENAME_MAX];
      ...
      im_strncpy( name, filename, FILENAME_MAX );
      if( (p = strchr( name, ':' )) ){
          *p = '\0';
          im_strncpy( mode, p + 1, FILENAME_MAX );
      }
      strcpy( buf, mode );
      p = &buf[0];
      ...
  }
  ```
Conclusion

• Hypothesis
  • We can improve security enforcement if we focus on validating safety accurately

• DataGuard
  • Validated >90% of stack objects are from safe spatial, type and temporal errors
  • More complete definition of memory safety than prior work, improving security
  • More accurate analysis finds as safe 70% of the objects classified as unsafe by Safe Stack
  • Average overhead reduced from 11.3% to 4.3% for SPEC 2006 benchmarks.
  • Applicable to real-world programs and prevents real exploits.
  • Will be available open source soon

• DataGuard shows that a comprehensive and accurate analysis can both increase the scope of stack data protection and reduce overheads.
  • Safety validation gets us more security for lower cost!

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