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

```
1   int
2   im_vips2dz( IMAGE *in, const char *filename ){
3     char *p, *q;
4     char name[FILENAME_MAX];
5     char mode[FILENAME_MAX];
6     char buf[FILENAME_MAX];
7     ...
8
9     im_strncpy( name, filename, FILENAME_MAX );
10    if( (p = strchr( name, ':' )) ){
11      *p = '\0';
12      im_strncpy( mode, p + 1, FILENAME_MAX );
13    }
14
15    strcpy( buf, mode );
16    p = &buf[0];
17    ...
18  }
```

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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

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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

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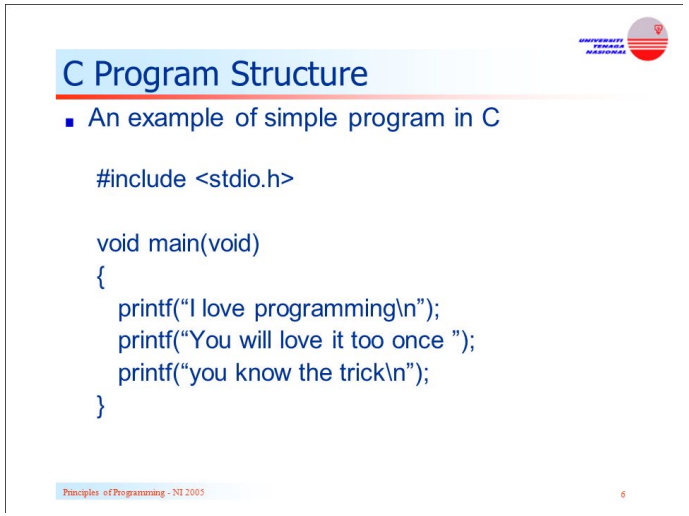
Example: C programming language

- **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

```
#include <stdio.h>

void main(void)
{
   printf("I love programming\n");
   printf("You will love it too once ");
   printf("you know the trick\n");
}
```

Principles of Programming - NI 2005 6

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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

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

- Here is what happens exactly

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

Pointer Arithmetic

- 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)

```
1  void example(int ct, char **buf) {
2     int lct = BUF_SIZE;
3     char lbuf[lct];
4     if (ct < lct){                  //(1) ct > buf's size
5       strlcpy(lbuf, *buf, (size_t) ct);     //(2) ct < 0
6     }
7     *buf = lbuf;                            //(3) temporal
8  }
```

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?

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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

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Example of Safe Stack

```
1  void example(int ct, char **buf) {
2      int lct = BUF_SIZE;
3      char safe_lbuf[lct];
4      char unsafe_lbuf[lct];
5      if (ct < lct){                                  //(1) ct > buf's size
6          strlcpy(unsafe_lbuf, *buf, (size_t) ct); //(2) ct < 0
7          ...                                         //Some safe operations on unsafe_lbuf
8          *buf = unsafe_lbuf;                         //(3) temporal
9      }
10     else{
11         strlcpy(safe_lbuf, *buf, lct-1);
12         ...                                         //Some safe operations on safe_lbuf
13         strcpy(*buf, safe_lbuf)
14     }
15 }
```

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

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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?

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Same Example Again…

```
1  void example(int ct, char **buf) {
2      int lct = BUF_SIZE;
3      char safe_lbuf[lct];
4      char unsafe_lbuf[lct];
5      if (ct < lct){                                  //(1) ct > buf's size
6          strlcpy(unsafe_lbuf, *buf, (size_t) ct); //(2) ct < 0
7          ...                                         //Some safe operations on unsafe_lbuf
8          *buf = unsafe_lbuf;                         //(3) temporal
9      }
10     else{
11         strlcpy(safe_lbuf, *buf, lct-1);
12         ...                                         //Some safe operations on safe_lbuf
13         strcpy(*buf, safe_lbuf)
14     }
15 }
```

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

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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**

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Design

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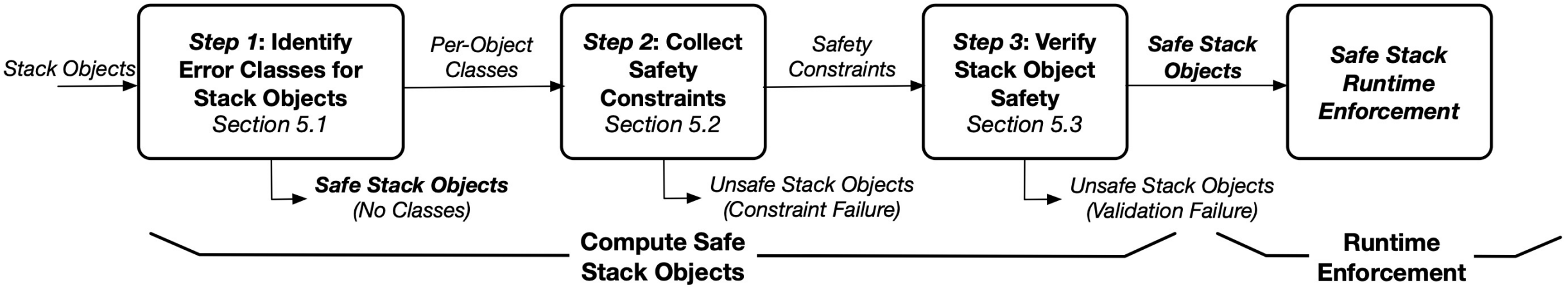
Our Approach - DataGuard



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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 to where needed
- **Question**: Which classes of memory errors may be possible for each stack object?

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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?
  - **CCured**: if used in pointer arithmetic operation
- Could a pointer operation cause a type error?
  - **CCured**: if used in type cast operation
- Could a pointer operation cause a temporal error?
  - **CCured**: does not address
  - **Escape analysis**: if used prior to initialization or if escape via call/return or heap/global
- **Pointers that are not used in any such operations are "safe"**
- **Objects only aliased by safe pointers are "safe"**

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

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Step 2 – Collecting Safety Constraints

- Safety Constraints
  - Spatial Constriants
  - 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 $index < size$ and $index \geq 0$

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”

```
1  char str[30];
2  int v1 = read_int();
3  int v2, v3, v4 = 0;
4  if (v1 > 10){
5      v2 = 10; //v2:[10,10]
6      v3 = 20; //v3:[20,20]
7  }
8  else{
9      v2 = 15; //v2:[15,15]
10     v3 = 15; //v3:[15,15]
11 }
12 v4 = v2+v3-1; //v4:[24,34]
13 read(0, str, v4);
```

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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**:
  - **(2) 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
  - **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]

[1] SVF: interprocedural static value-flow analysis in LLVM. Y. Sui et al, CC '06
[2] PtrSplit: Supporting general pointers in automatic program partitioning. S. Liu et al, CCS '17
[3] S2E: A Platform for In-vivo Multi-path Analysis of Software Systems, V. Chipounov et al, ASPLOS '11
[4] A Survey of Symbolic Execution Techniques. R. Baldoni et al, 2018.

Evaluation

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

	CCured-default	*CCured-min*	*Safe Stack-default*	*Safe Stack-min*	*DataGuard*	*Total*
nginx	14,573 (79.52%)	14,496 (79.10%)	13,047 (71.20%)	12,375 (67.53%)	16,684 (91.05%)	18,324
httpd	61,915 (73.06%)	60,526 (71.42%)	49,523 (58.44%)	46,833 (55.27%)	78,266 (92.36%)	84,741
proftpd	14,521 (81.66%)	14,189 (79.79%)	12,837 (72.19%)	12.513 (70.37%)	16,190 (91.04%)	17,782
openvpn	48,379 (76.58%)	47,662 (75.45%)	40,627 (64.31%)	39,145 (61.97%)	57,693 (91.33%)	63,171
opensshd	20,238 (79.45%)	20,062 (78.75%)	18,176 (71.35%)	17,712 (69.53%)	23,871 (93.71%)	25,474
perlbench	52,738 (91.61%)	51,165 (88.57%)	42,398 (73.65%)	42,014 (72.98%)	52,324 (90.89%)	57,567
bzip2	1,293 (92.29%)	1,162 (82.94%)	1,057 (75.44%)	1,049 (74.87%)	1,238 (88.39%)	1,401
gcc	123,427 (73.34%)	120,856 (71.82%)	96,796 (57.52%)	91,344 (54.28%)	152,452 (90.59%)	168,283
mcf	580 (90.34%)	569 (88.63%)	441 (68.69%)	436 (67.91%)	602 (93.77%)	642
gobmk	34,376 (85.53%)	33,969 (84.52%)	26,229 (65.26%)	26,013 (64.72%)	38,552 (95.92%)	40,191
hmmer	20,133 (75.84%)	19,874 (74.87%)	13,873 (52.26%)	13,629 (51.34%)	25,674 (96.71%)	26,546
sjeng	3,461 (85.62%)	3,415 (84.49%)	2,798 (69.22%)	2,712 (67.10%)	3,741 (92.55%)	4,042
libquantum	2,576 (66.80%)	2,521 (65.38%)	2,036 (52.80%)	1,878 (48.70%)	3,214 (83.35%)	3,856
h264ref	19,525 (87.70%)	19,283 (86.61%)	14,418 (64.76%)	14,339 (64.40%)	20,177 (90.63%)	22,264
lbm	448 (82.96%)	442 (81.85%)	376 (69.63%)	369 (68.33%)	506 (93.70%)	540
sphinx3	2,744 (72.90%)	2,713 (72.10%)	2,058 (54.67%)	1,962 (52.13%)	3,398 (90.28%)	3,764
milc	4,325 (81.50%)	4,233 (79.76%)	3,887 (73.24%)	3,794 (71.49%)	4,680 (88.19%)	5,307
omnetpp	20,572 (83.44%)	20,264 (82.19%)	16,967 (68.82%)	16,283 (66.04%)	22,091 (89.60%)	24,655
soplex	14,253 (72.80%)	14,072 (71.87%)	11,044 (56.41%)	9,513 (50.12%)	16,368 (83.60%)	19,579
namd	21,676 (85.17%)	21,352 (83.90%)	18,389 (72.26%)	18,213 (78.34%)	23,249 (91.36%)	25,448
astar	4,016 (87.36%)	3,977 (86.51%)	3,606 (78.44%)	3,524 (76.66%)	4,206 (91.49%)	4,597

- 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.

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How Frequently are Pointers Used in Unsafe Operations for Each Error Class?

	Total	*Spatial*	*Type*	*Temporal*	*Safe*
nginx	11,679	1,555 (13.31%)	555 (4.75%)	1,401 (11.99%)	8,785 (75.22%)
httpd	58,572	12,116 (20.69%)	2,905 (4.96%)	16,232 (27.71%)	37,899 (64.70%)
proftpd	10,354	1,332 (12.86%)	488 (4.71%)	1,156 (11.16%)	8,155 (78.76%)
openvpn	38,065	7,061 (18.55%)	2,326 (6.11%)	8,734 (22.93%)	26,020 (68.36%)
opensshd	15,067	2,185 (14.50%)	479 (3.18%)	1,924 (12.77%)	11,798 (78.30%)
perlbench	33,241	2,255 (6.78%)	454 (1.37%)	5,571(16.76%)	27,345 (82.30%)
bzip2	778	52 (6.68%)	9 (1.16%)	146 (18.76%)	616 (79.17%)
gcc	103,285	22,661 (21.94%)	6,012 (5.82%)	19,476 (18.85%)	69,863 (67.64%)
mcf	384	28 (7.29%)	7 (1.82%)	57 (14.84%)	303 (78.90%)
gobmk	22,363	2,959 (13.23%)	170 (0.76%)	5,302 (23.71%)	15,522 (69.40%)
hmmer	16,257	3,759 (23.12%)	203 (1.25%)	2,803 (17.24%)	11,126 (68.43%)
sjeng	2,449	348 (14.20%)	74 (3.02%)	420 (17.14%)	1,768 (72.19%)
libquantum	2,182	524 (24.01%)	162 (7.42%)	343 (15.72%)	1,387 (63.57%)
h264ref	13,246	1,535 (11.59%)	91 (0.69%)	2,192 (16.55%)	10,109 (76.32%)
lbm	307	35 (11.40%)	8 (2.61%)	56 (18.24%)	226 (73.62%)
sphinx3	2,143	478 (22.30%)	135 (6.30%)	509 (23.75%)	1,320 (61.60%)
milc	2,943	338 (11.48%)	117 (3.98%)	314 (10.67%)	2,326 (79.03%)
omnetpp	13,780	1,247 (9.05%)	848 (6.15%)	1,832 (13.29%)	10,636 (77.18%)
soplex	11,941	1,910 (16.00%)	1,482 (12.41%)	2,453 (20.54%)	7,107 (59.51%)
namd	14,026	1,780 (12.69%)	154 (1.10%)	2,325 (16.58%)	10,852 (77.37%)
astar	2,571	193 (7.51%)	71 (2.76%)	414 (16.10%)	1,925 (74.87%)

- 14.24% spatial, 3.92% type, 17.39% temporal.
- 72.70% of stack pointers are free from any class of memory errors.

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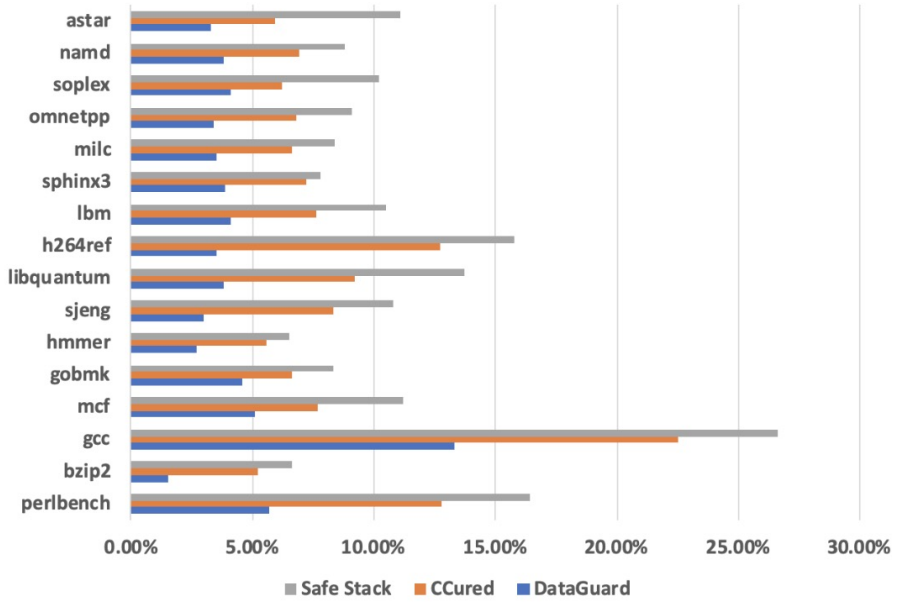
How Much Does the Two-Stage Validation Improve the Ability to Identify Safe Stack Objects over Prior Work?

	Safe Pointer	*Diff. from CCured*
CCured	10,124 (86.68%)	0 (00.00%)
Symbolic Exec (SE)	10,501 (89.91%)	377 (24.24%)
Value Range	11,085 (94.91%)	961 (61.80%)
Value Range+SE	11,498 (98.45%)	1,374 (88.36%)

	Safe Pointer	*Safe Address-Taken*
Safe Stack	10,278 (88.00%)	0 (00.00%)
Error Class (EC)	11,244 (96.27%)	966 (68.95%)
Liveness (LV) + EC	11,463 (98.15%)	1,185 (84.58%)
SE+LV+EC	11,586 (99.20%)	1,308 (93.36%)

- 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

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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

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

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

- Case Study: CVE-2020-20739

```
1   int
2   im_vips2dz( IMAGE *in, const char *filename ){
3     char *p, *q;
4     char name[FILENAME_MAX];
5     char mode[FILENAME_MAX];
6     char buf[FILENAME_MAX];
7     ...
8
9     im_strncpy( name, filename, FILENAME_MAX );
10    if( (p = strchr( name, ':' )) ){
11      *p = '\0';
12      im_strncpy( mode, p + 1, FILENAME_MAX );
13    }
14
15    strcpy( buf, mode );
16    p = &buf[0];
17    ...
18  }
```

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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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