Machine Programming

Lecture 18 – Programming Languages for Software Safety

Logistics – Week 10

- Oral Presentations
  - Emails are being sending out; plans established
  - Attendance will be noted down for oral presentation sessions!
- Final Projects
  - Final project proposal: 1 page PDF (due on Sunday)
  - Submit on GradeScope
  - Send email to the instructor questions

Effective Oral Presentation

- Title, Authors, and their Institutions stated clearly on first page
- Motivation
  - What is the problem? Why do people care about this problem? What is the goal? What is the real-world impact? Is there intellectual merit?
- Examples
  - (Without getting into the technical details) show an example of end-to-end input and output; show demo (images, videos, code snippets) if they are present.
- Methodology / Design / Experiments
  - Illustrate top-down: start from overview, pipeline, vision, overall statistics
  - Then go to the technical details: e.g., design decisions, formalism (code/theorem/math/algorithm), evaluation metrics, experimental design, dataset/benchmark selection
- Evaluations / Results
  - Figures, quantitative numbers, qualitative examples; connect the figures with findings and claims, e.g., “outperforms existing baselines on accuracy”, “is sample efficient”, “is more faithful”
- Critique
  - Your critique of the paper: What does it do well? What does it miss? Any potential future directions?

Effective Oral Presentation (Cont.)

- How to study the paper
  - Read paper thoroughly
  - Ask LLM to help you summarize the paper and answer your question
  - Ask LLM to help you find cited works that are relevant, which can strengthen your understanding
- How to make slides
  - Follow the guidelines (on the previous slide)
  - Find talks or presentations online, to study how they present the work
  - Find existing resource online (slides, websites, versions of papers, blog posts, repositories, etc.)
  - Take screenshots from the existing resources, don’t completely remake it
  - Ask LLM to help with storytelling (IMPORTANT!) and preciseness of language
- Notes
  - Be concise, you won’t have that much time (10-15 min); prepare at most 20 slides and no more
  - Always check LLM outputs, DO NOT TRUST everything LLM says

Module 3: Overview

Behavioral Specification
- What should the program do?

1. Syntax/Semantics/Functional correctness
2. **Comprehensive test coverage**
3. **Has no security flaw**
4. **Optimized for runtime speed**
5. **...**

Structural Specification
- What is the space of the programs?

General Purpose Programming Language
Python / Java / C / Rust / ...

Domain Specific Languages
SQL / LEAN / ROCQ / DATALOG / PDDL / ...

Synthesis Strategy
- How do we find such a program?

Enumeration: Bottom-up and Top-Down

Programming with Large Language Models
- Next token prediction, prompting, controlled decoding
- Iterative refinement, agentic frameworks and tool use
- Pre-training, fine-tuning, reinforcement learning

Fixed

Correct by Construction

Safe Programming Languages

Desirable Properties

Memory Safety

Side-channel Resistance

Termination

Injection-safety

Functional Assurance

Concurrency Safety

Type Safety

Capability Safety

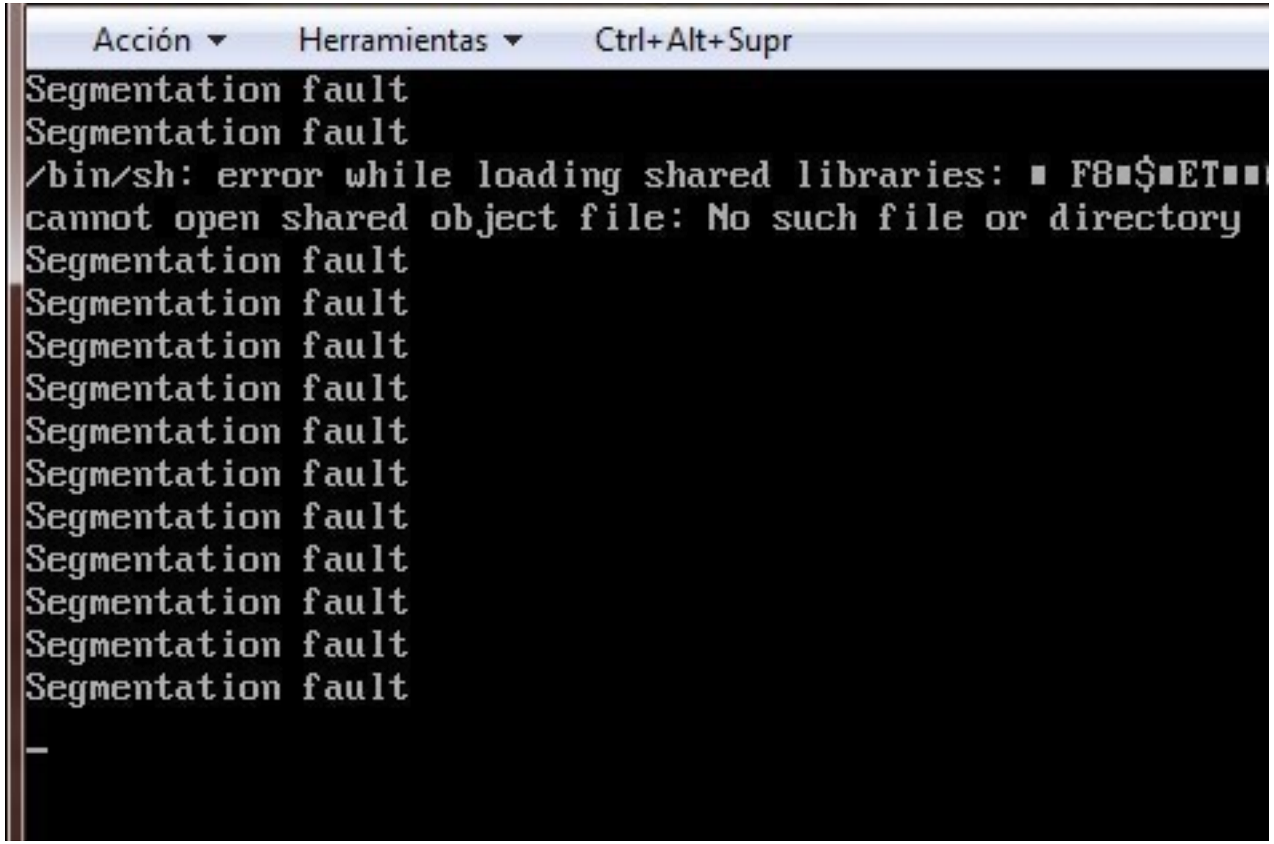
Smart-contract Safety

Control-flow Integrity

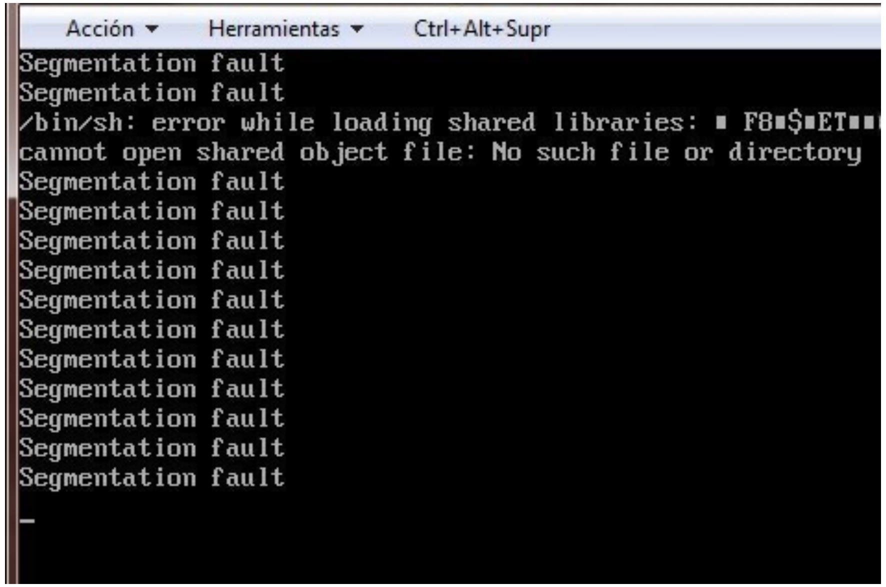
Resource Safety

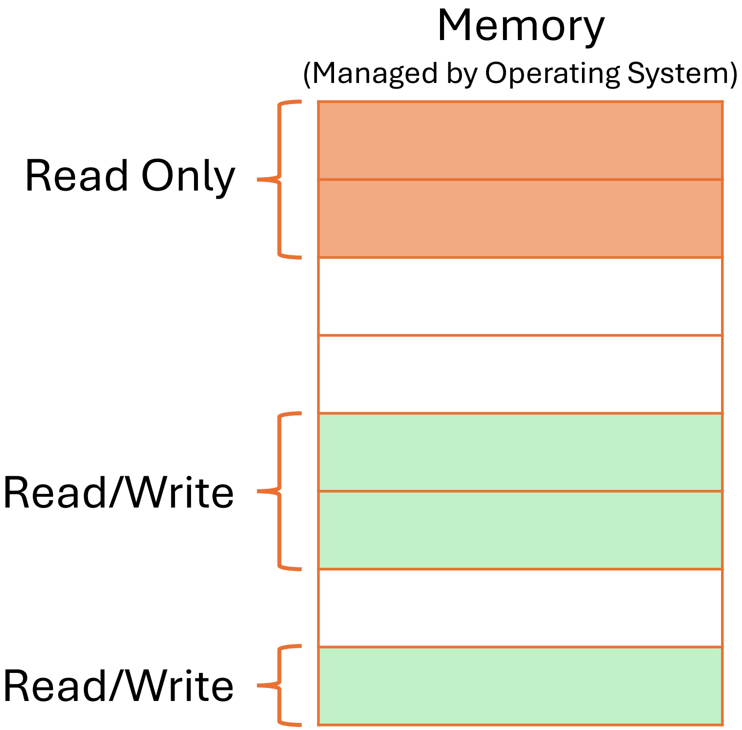
Data Integrity

Memory Safety

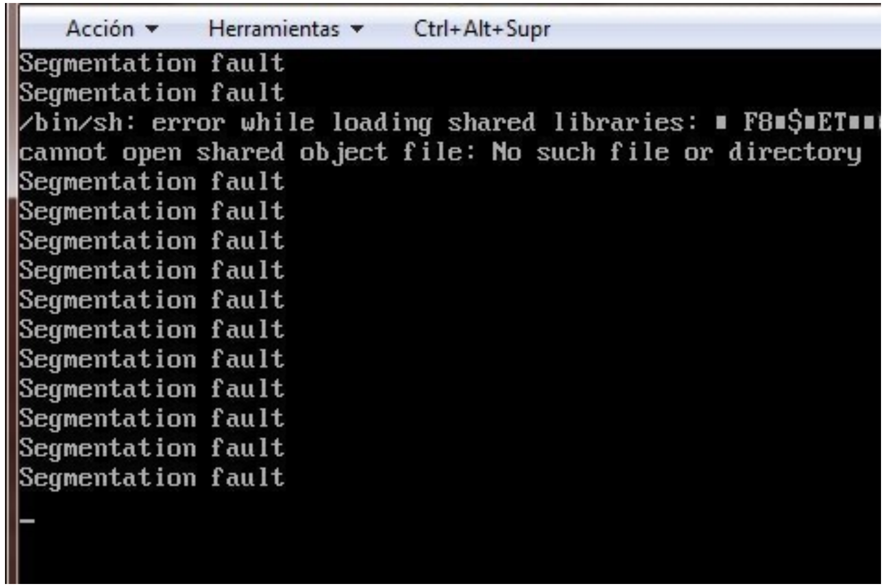


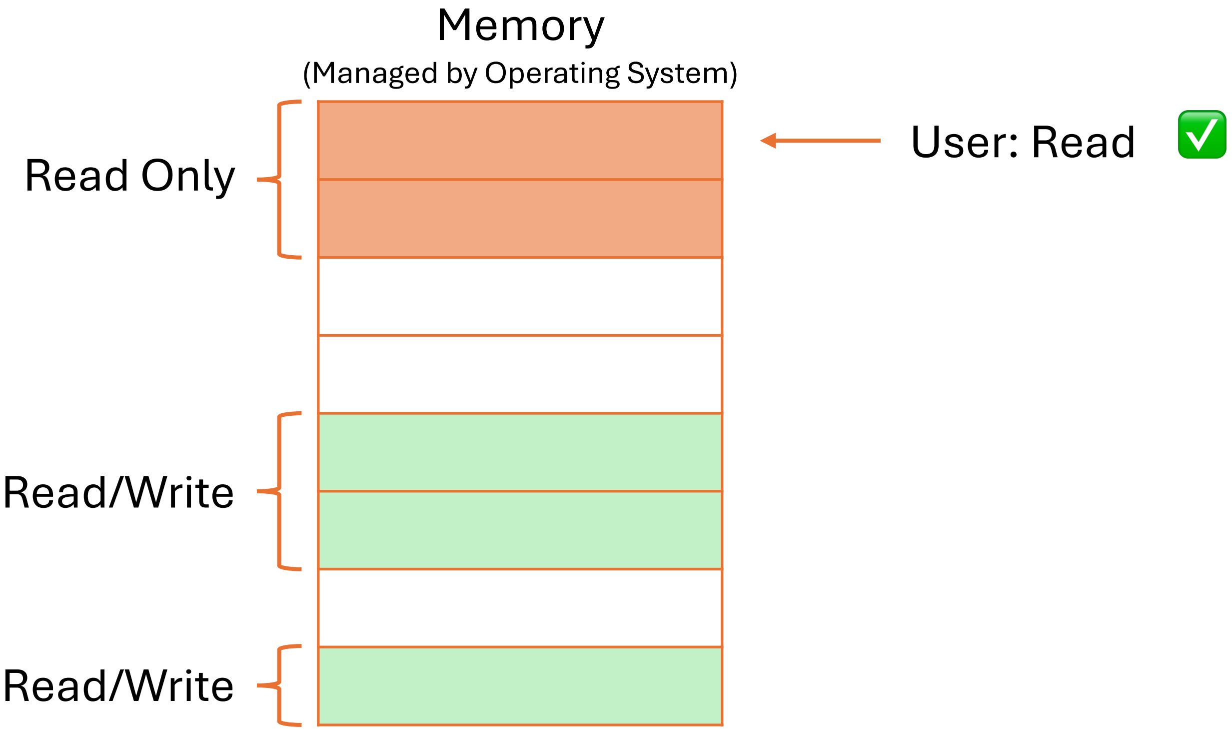
Memory Safety



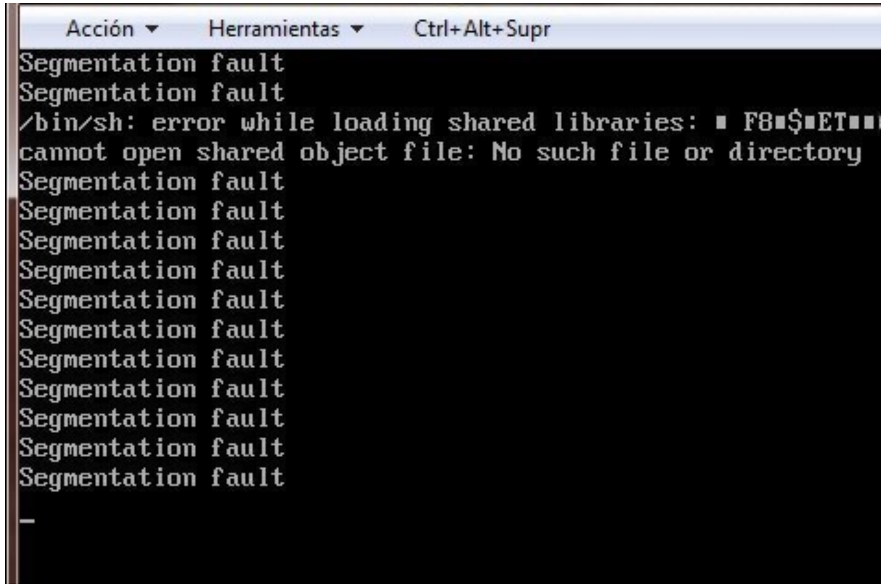


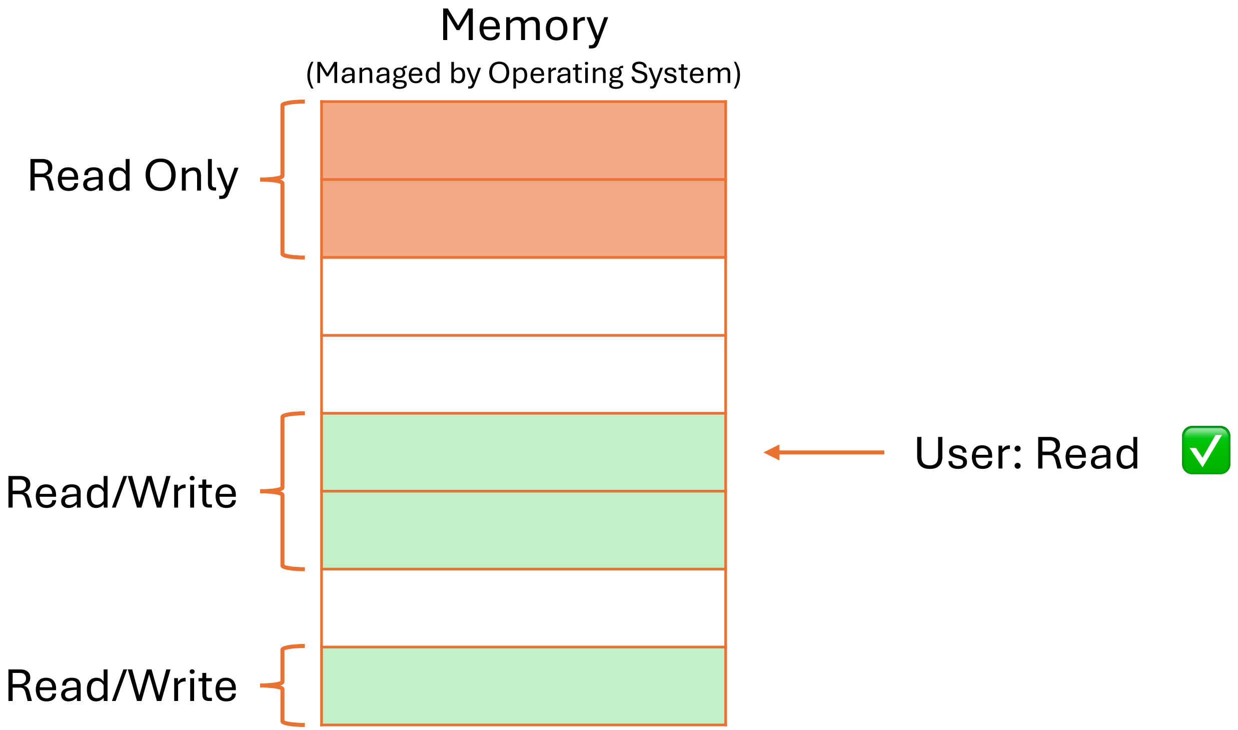
Memory Safety



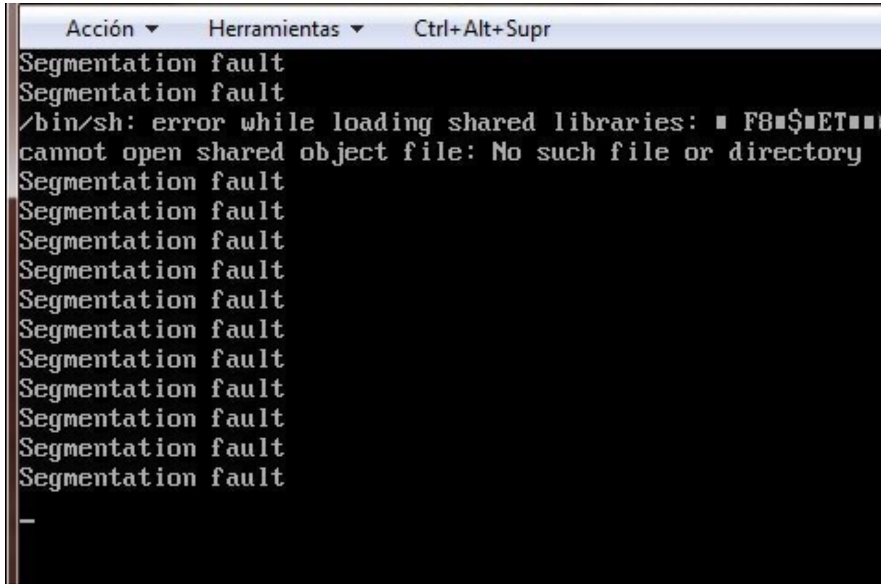


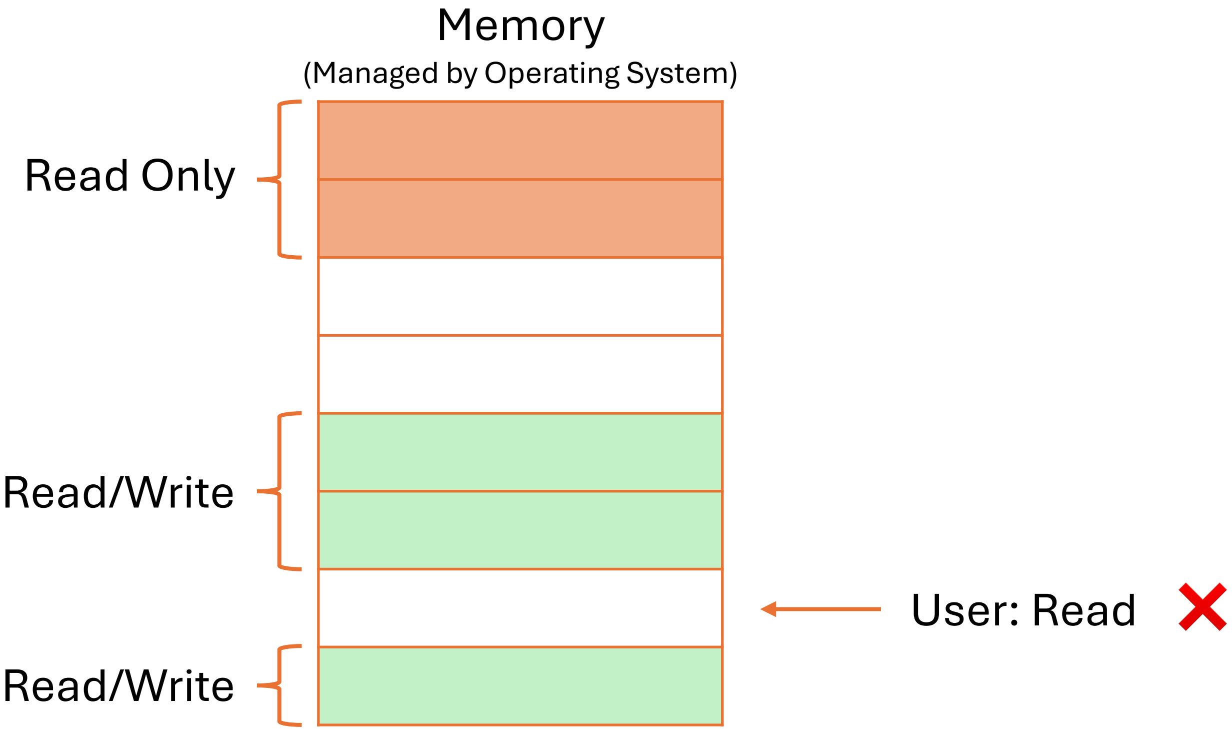
Memory Safety



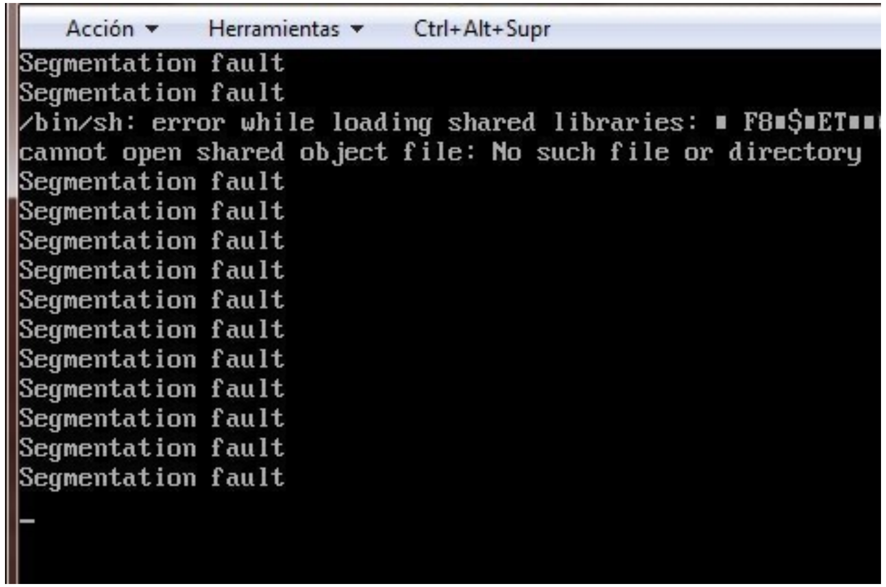


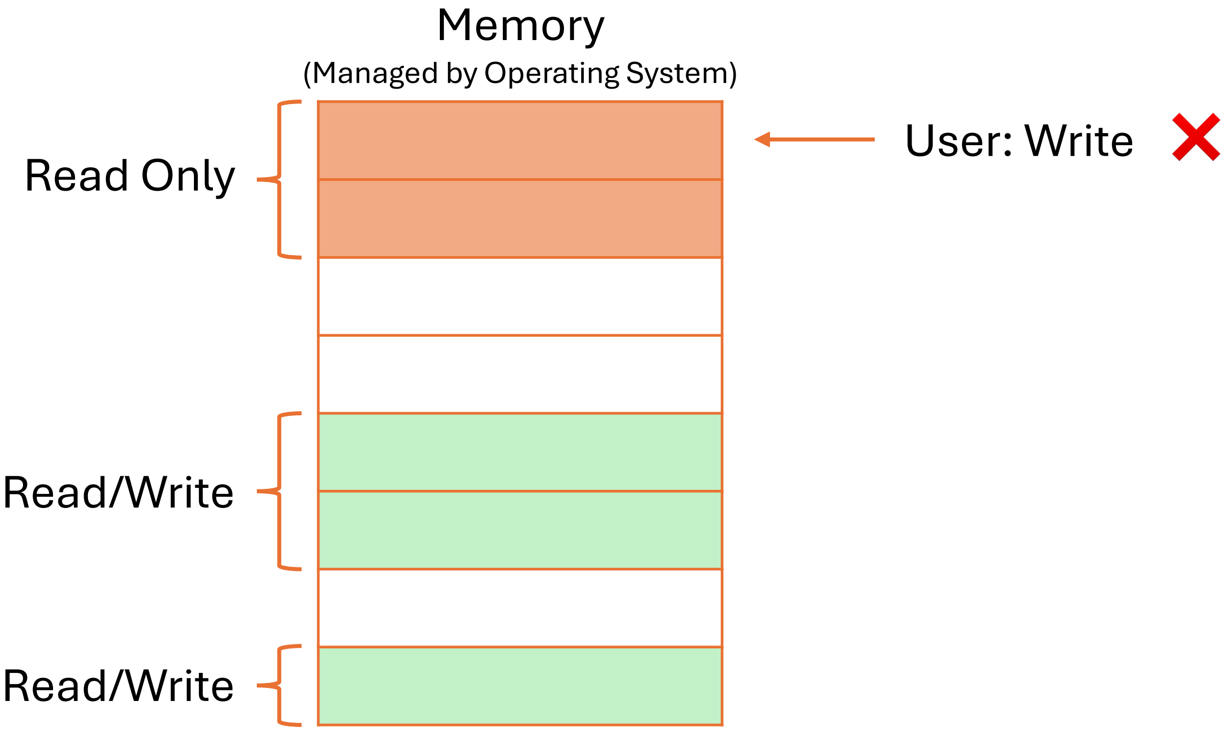
Memory Safety





Memory Safety





C Program that Breaks Memory Safety

```c
int main() {
  int *p = NULL;
  *p = 42;
}
```

C Program that Breaks Memory Safety

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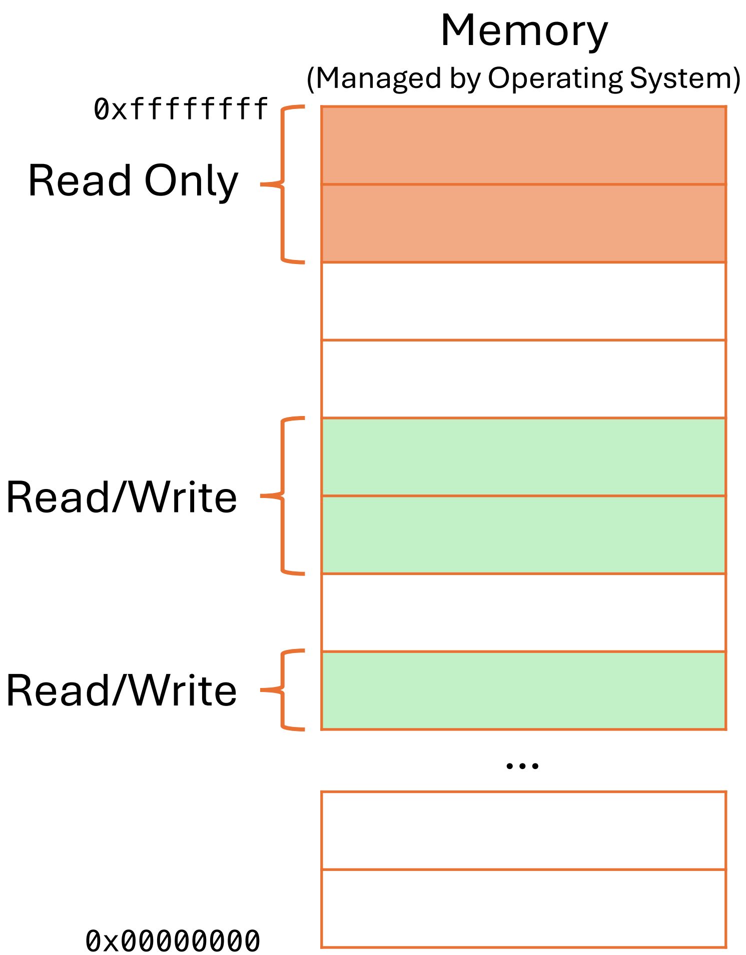

C Program that Breaks Memory Safety

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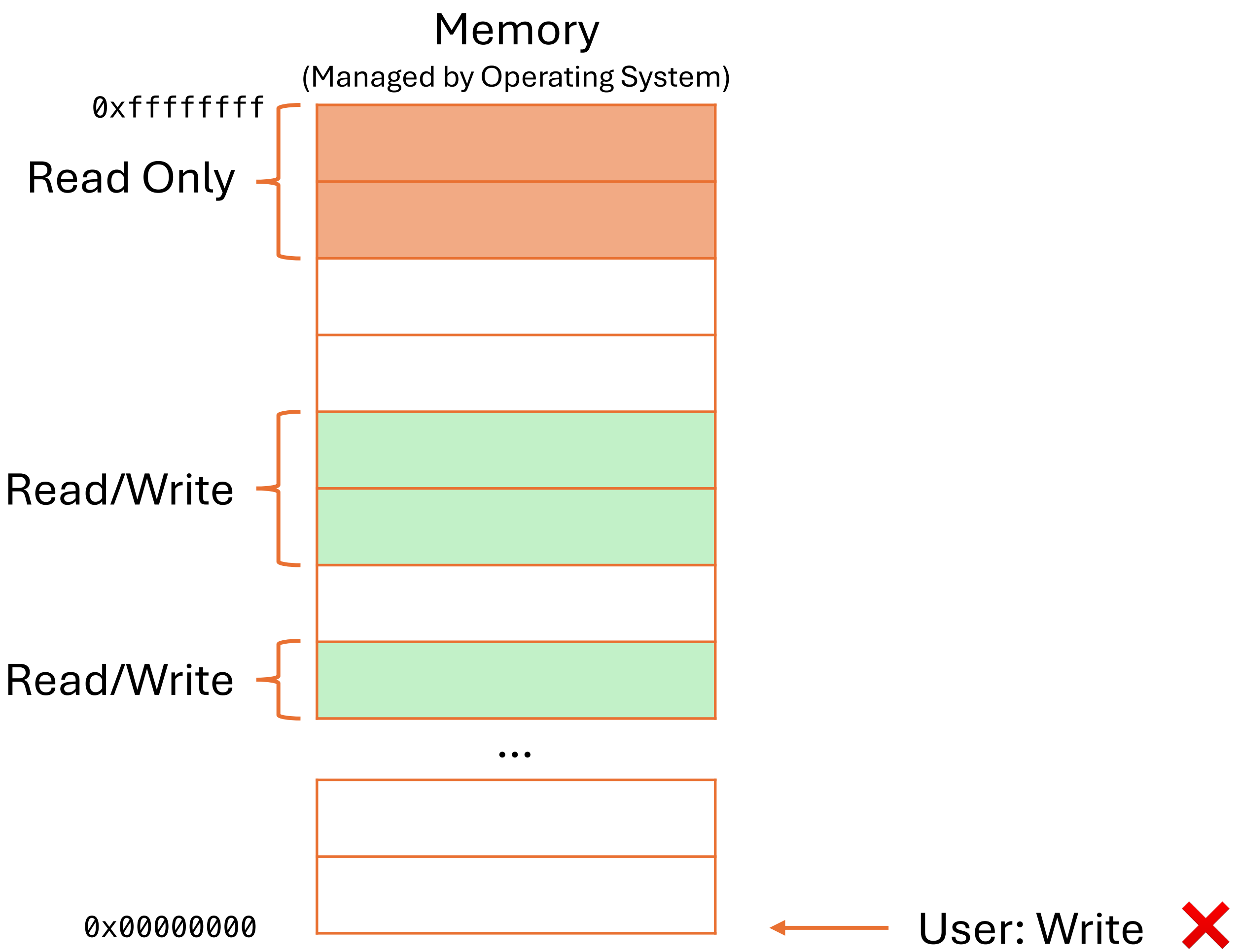
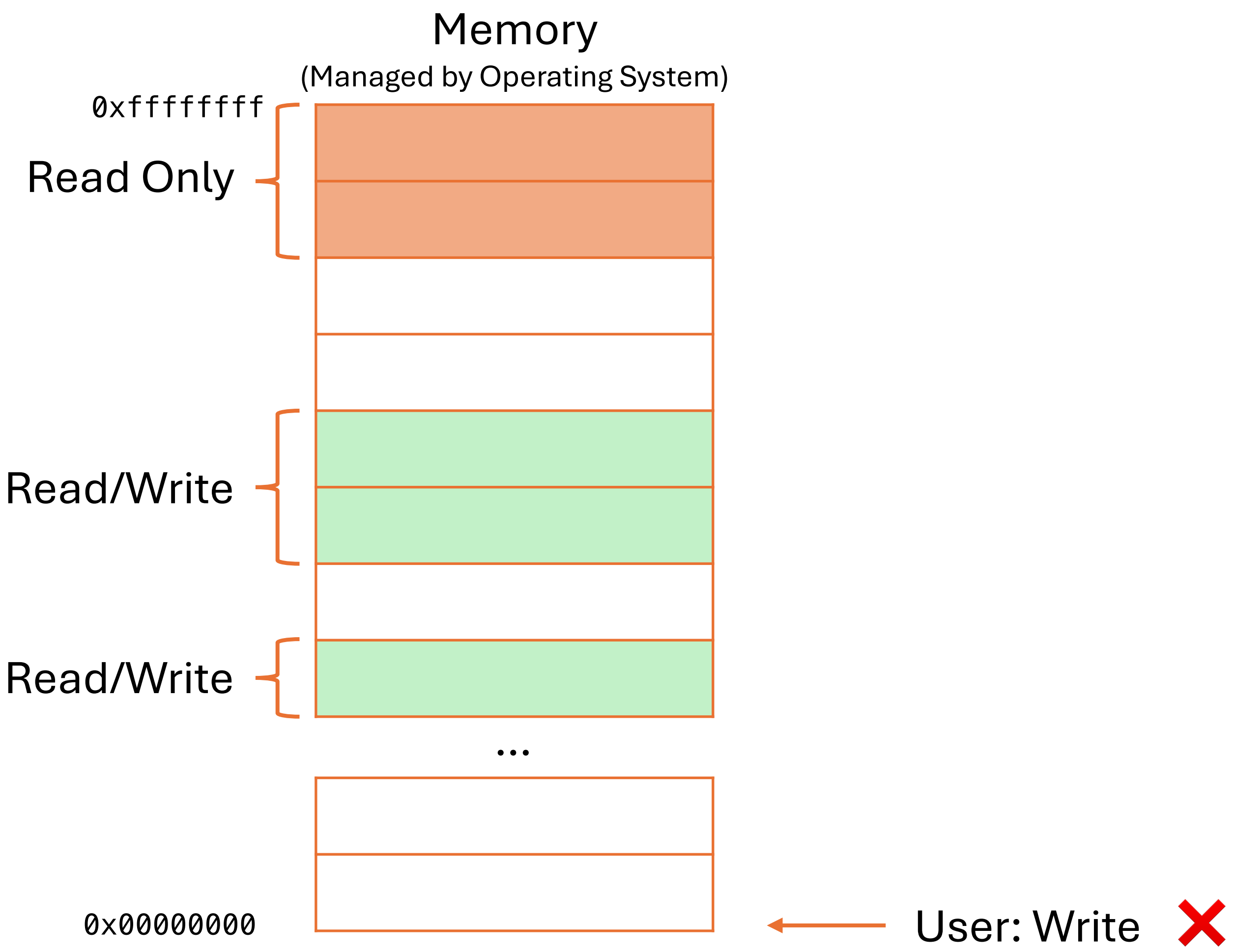
int main() {
  int *p = NULL;
  *p = 42;
}
```



C Program that Noticeably Breaks Memory Safety

```c
int main() {
  int p[42];
  *p = 42;
}
```

```
liby@mac ~/L/P/Demo> gcc demo.c
liby@mac ~/L/P/Demo> ./a.out
fish: Job 1, './a.out' terminated
by signal SIGSEGV (Address boundary
error)
```



C Program that Noticeably Breaks Memory Safety

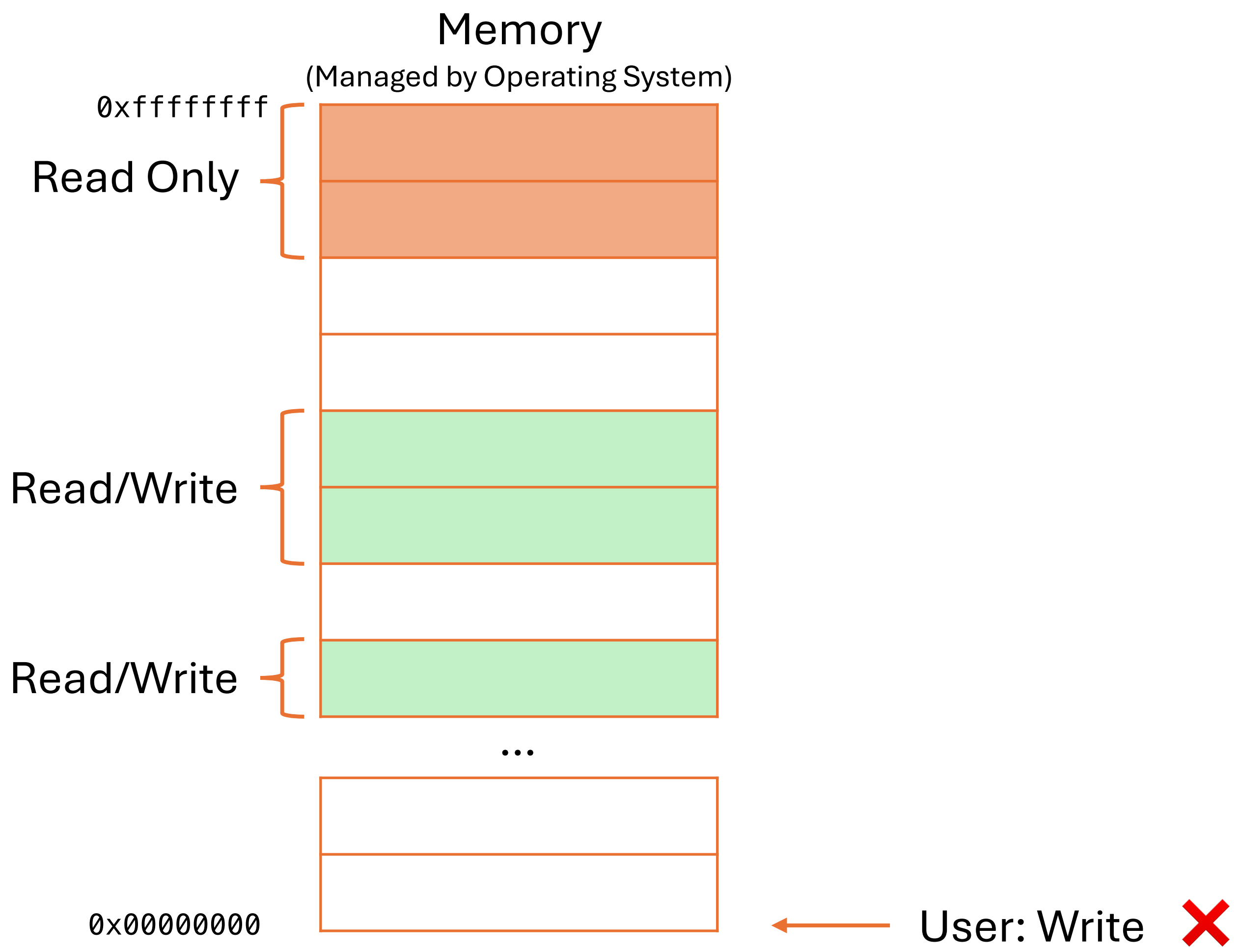
CWE-476: NULL Pointer Dereference

Weakness ID: 476
Vulnerability Mapping: ALLOWED
Abstraction: Base

NULL Pointer Dereference

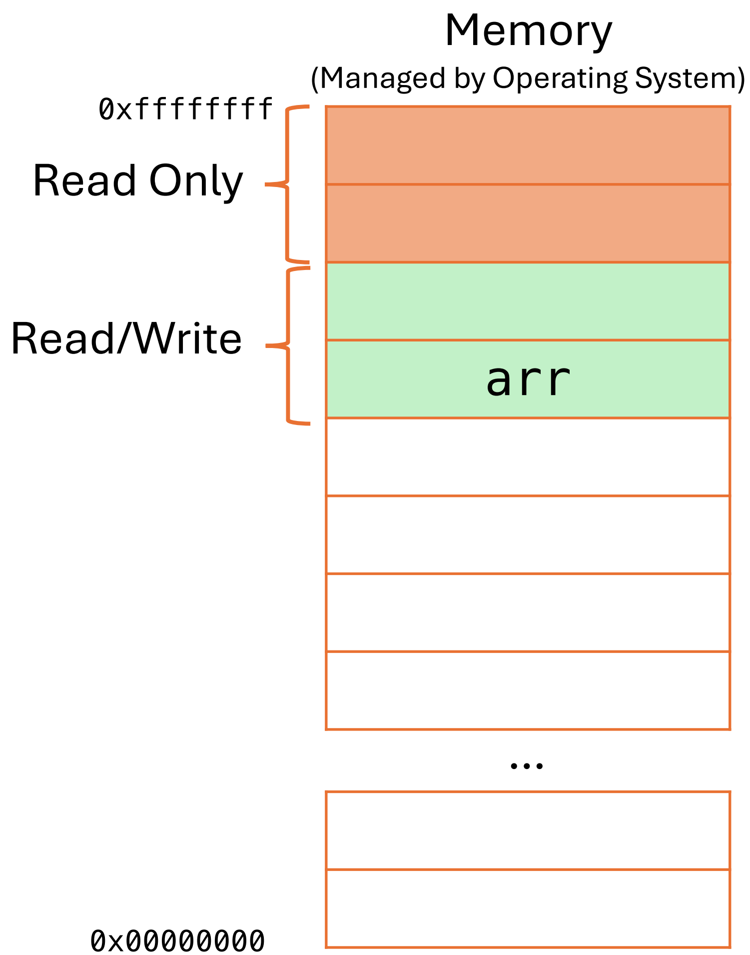
```c
t main() {
  int p[42];
  *p = 42;
}
```

```
liby@mac ~/L/P/Demo> gcc demo.c
liby@mac ~/L/P/Demo> ./a.out
fish: Job 1, './a.out' terminated
by signal SIGSEGV (Address boundary
error)
```



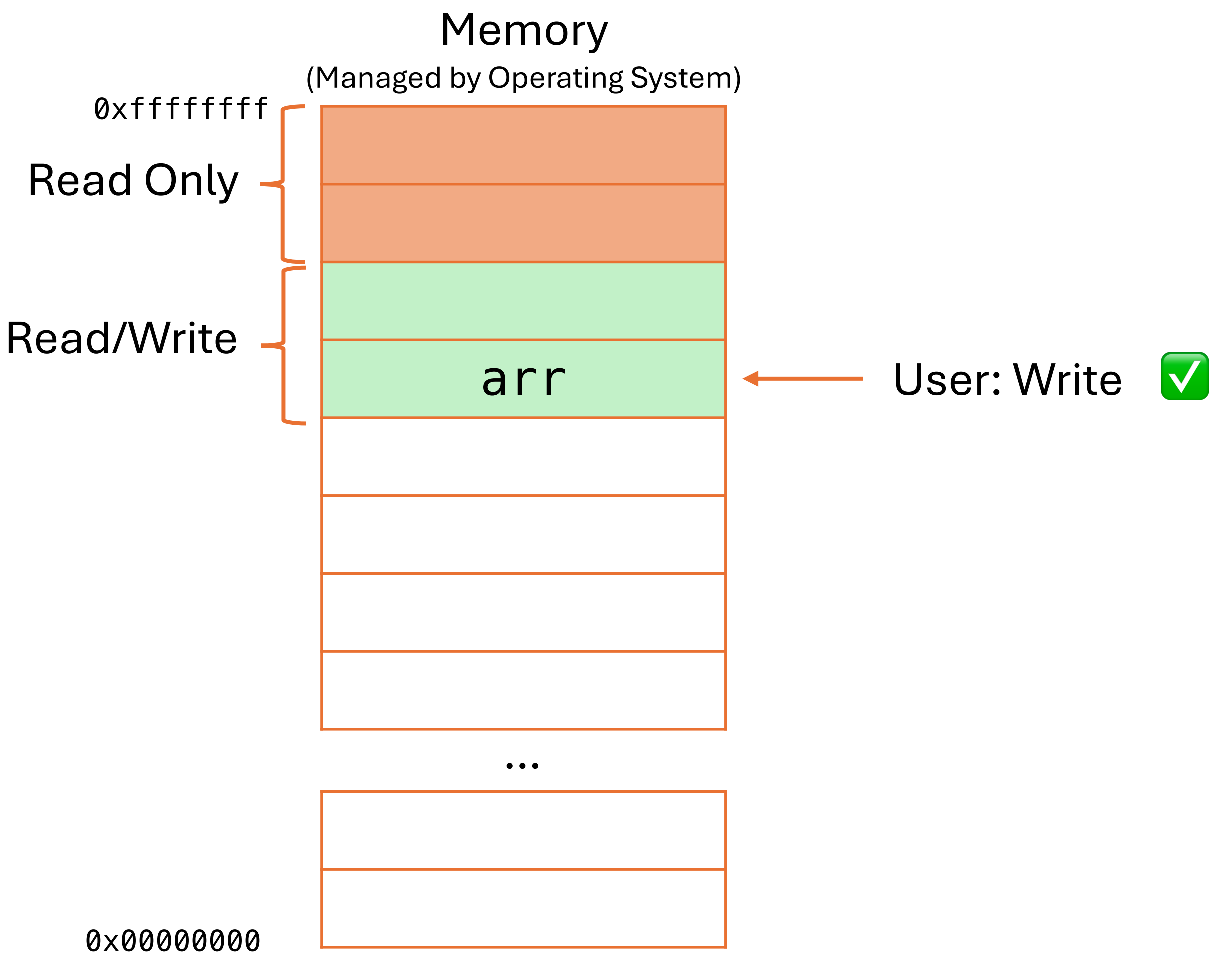
C Program that Silently Breaks Memory Safety

```c
int main() {
  int arr[100];
  arr[182] = 42;
}
```



C Program that Silently Breaks Memory Safety

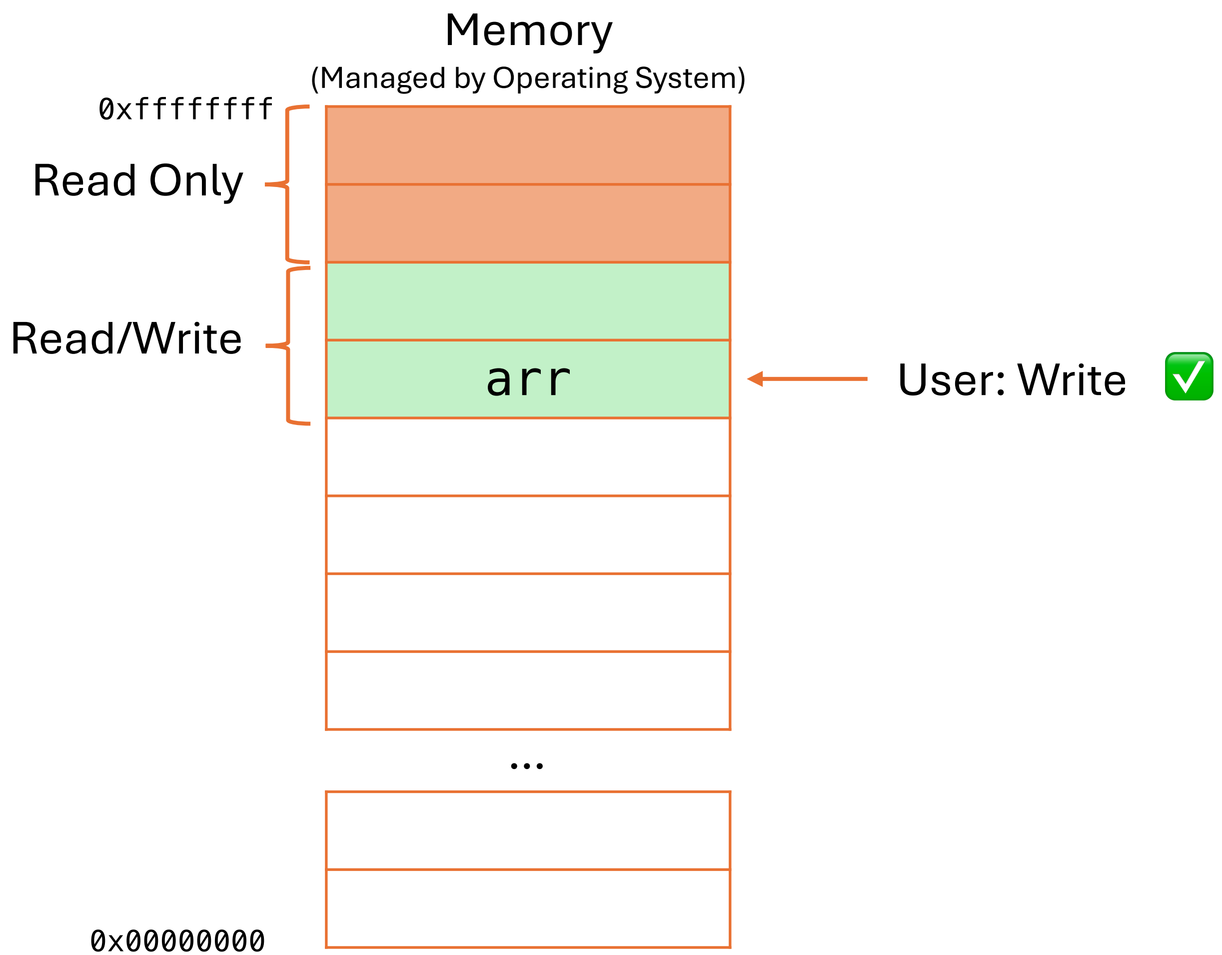
```c
int main() {
  int arr[100];
  arr[182] = 42;
}
```



C Program that Silently Breaks Memory Safety

```c
int main() {
  int arr[100];
  arr[182] = 42;
}
```

```
liby@mac ~/L/P/Demo> gcc demo.c
liby@mac ~/L/P/Demo> ./a.out
```



C Program that Silently Breaks Memory Safety

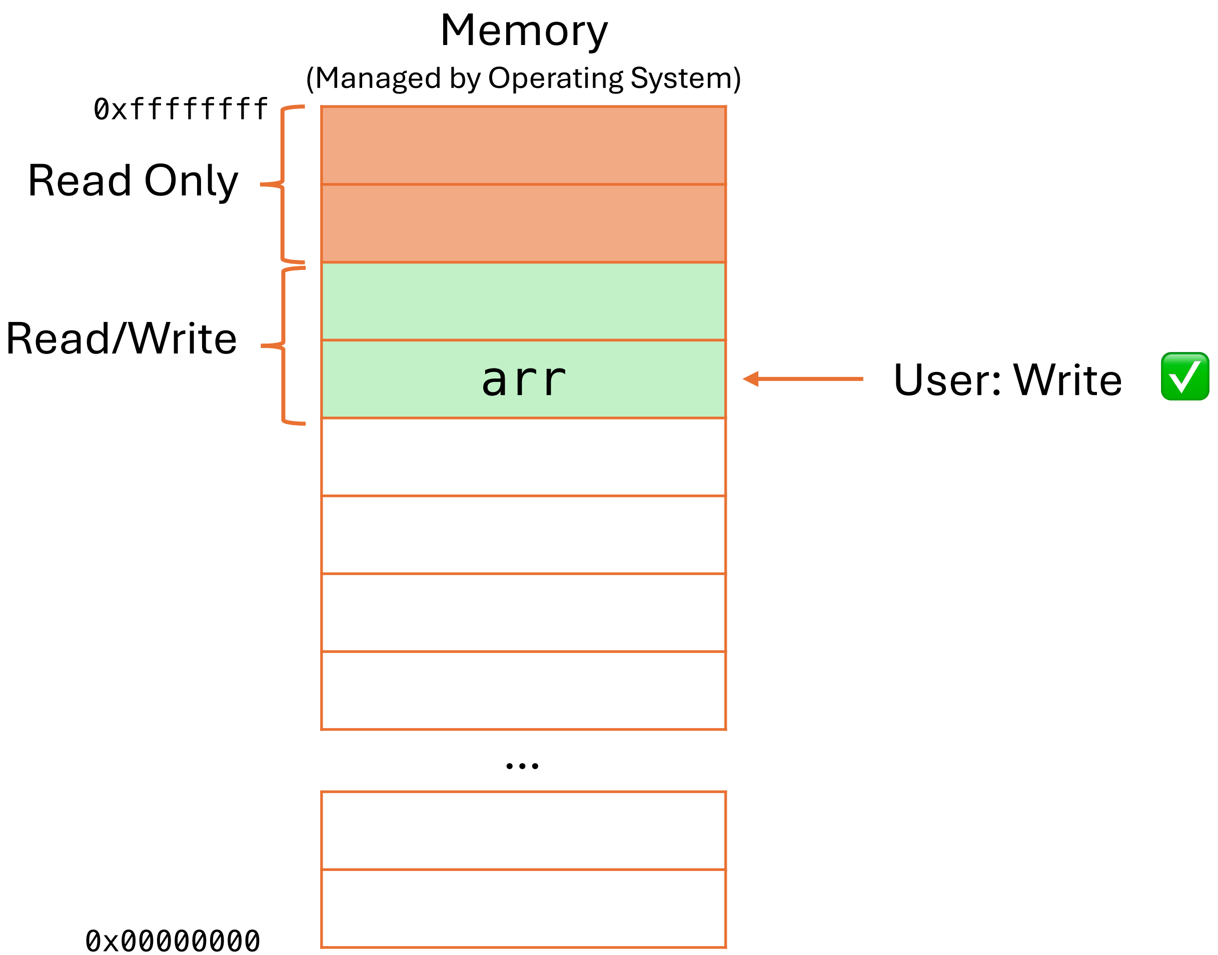
CWE-121: Stack-based Buffer Overflow

Weakness ID: 121
Vulnerability Mapping: ALLOWED
Abstraction: Variant

Buffer Overflow

```c
int main() {
  int arr[100];
  arr[182] = 42;
}
```

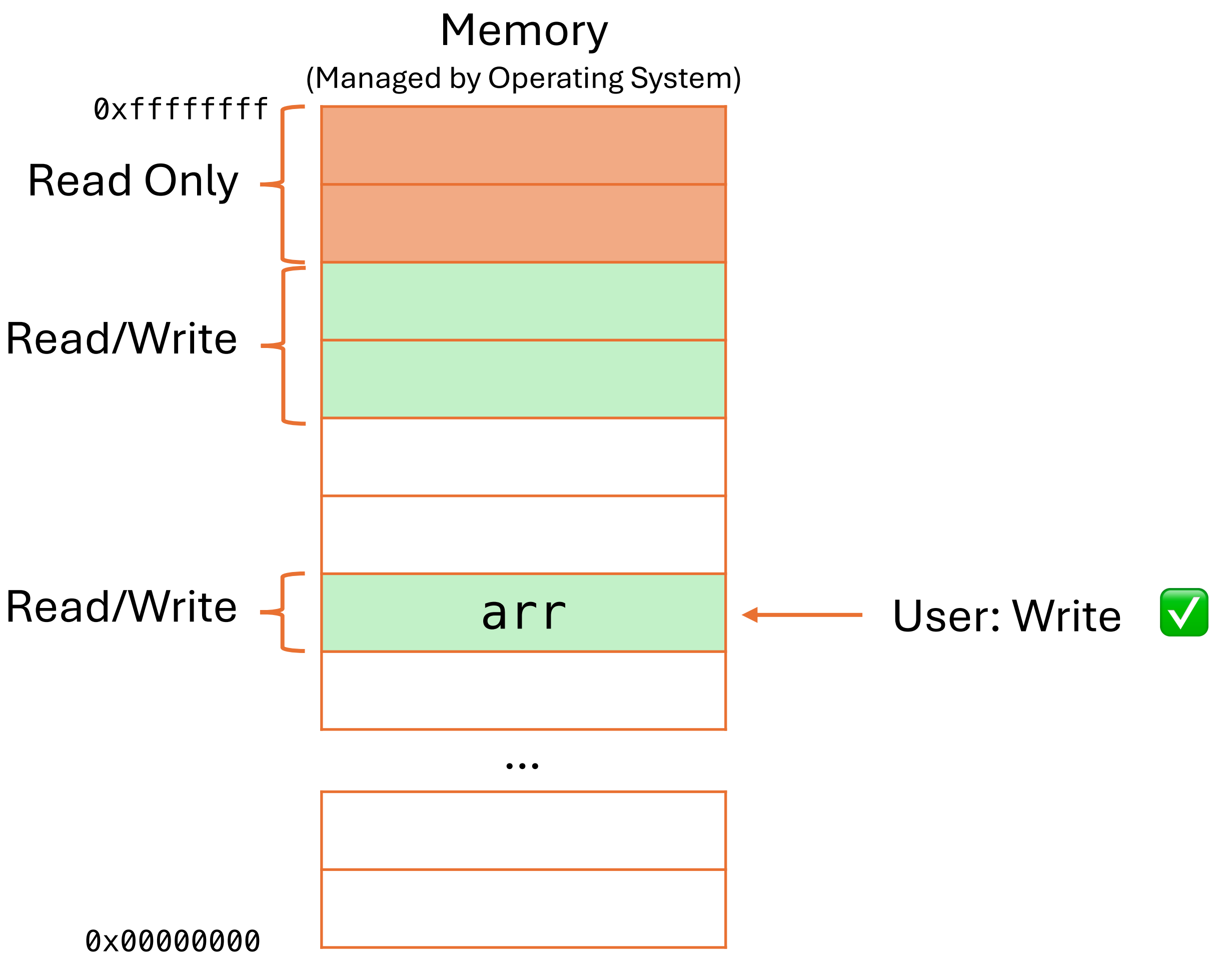
```
liby@mac ~/L/P/Demo> gcc demo.c
liby@mac ~/L/P/Demo> ./a.out
```



C Program that Silently Breaks Memory Safety

```c
int main() {
  int *arr = (int *)
    malloc(100 * sizeof(int));
  arr[182] = 42;
}
```

```
liby@mac ~/L/P/Demo> gcc demo.c
liby@mac ~/L/P/Demo> ./a.out
```



C Program that Silently Breaks Memory Safety

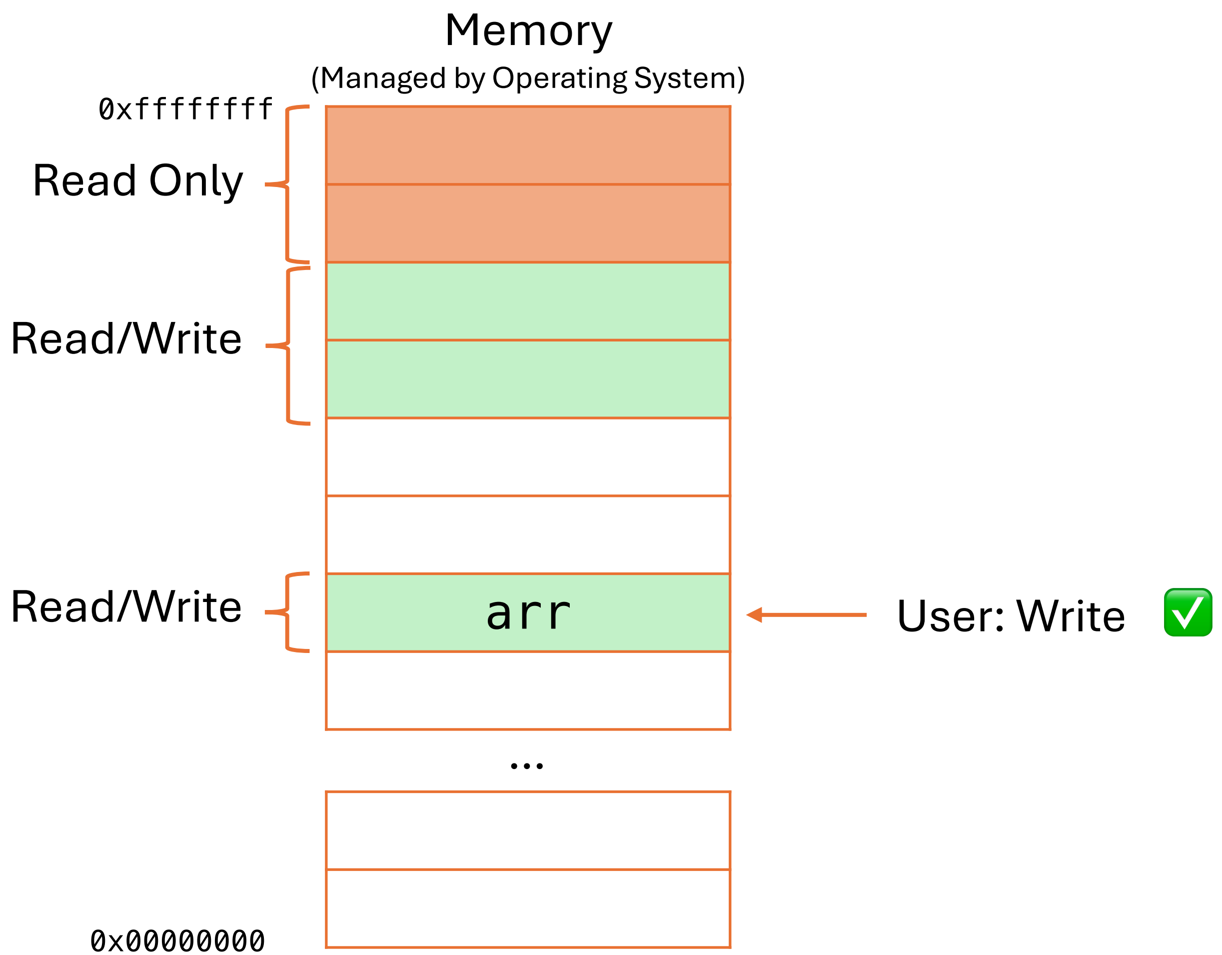
CWE-122: Heap-based Buffer Overflow

Weakness ID: 122
Vulnerability Mapping: **ALLOWED**
Abstraction: Variant

Buffer Overflow

```
int      () {
  int *arr = (int *)
    malloc(100 * sizeof(int));
  arr[182] = 42;
}
```

```
liby@mac ~/L/P/Demo> gcc demo.c
liby@mac ~/L/P/Demo> ./a.out
```

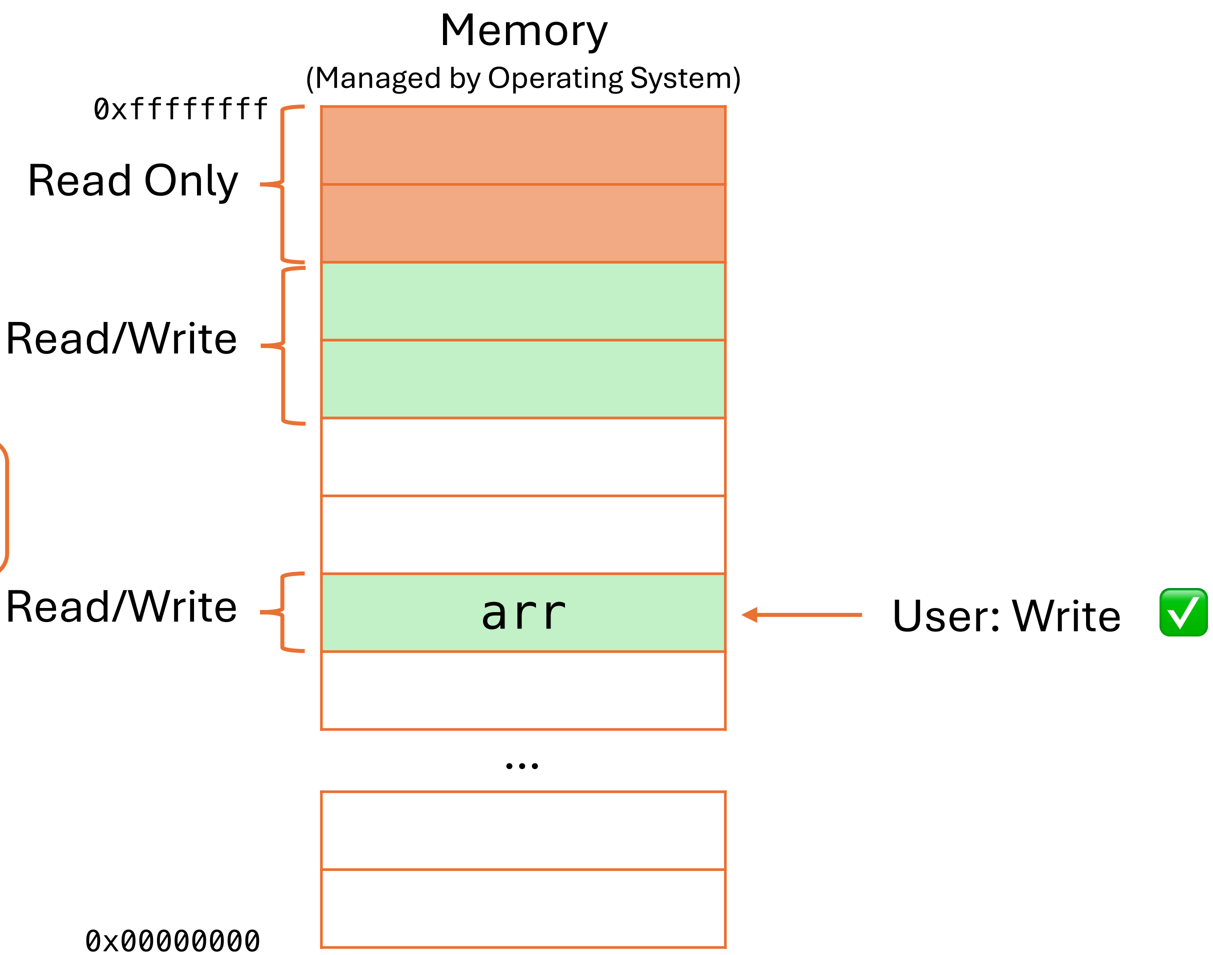


C Program that Silently Breaks Memory Safety

```c
int main() {
  int *arr = (int *)
    malloc(100 * sizeof(int));
  arr[182] = 42;
}
```

Another issue with "arr": Not free-ed

```
liby@mac ~/L/P/Demo> gcc demo.c
liby@mac ~/L/P/Demo> ./a.out
```



C Program that Silently Breaks Memory Safety

CWE-401: Missing Release of Memory after Effective Lifetime

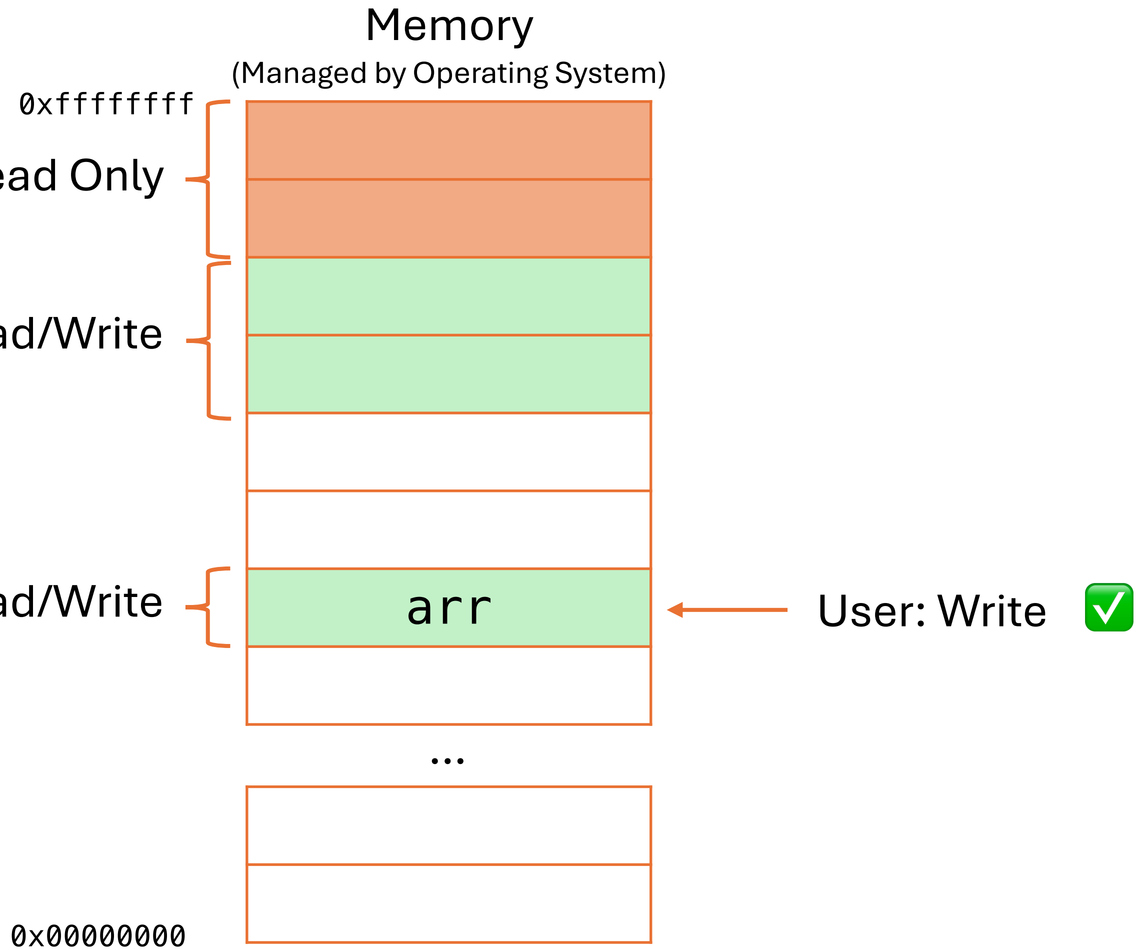
Weakness ID: 401
Vulnerability Mapping: ALLOWED
Abstraction: Variant

Memory Leak

```
int () {
  int *arr = (int *)
    malloc(100 * sizeof(int));
  arr[182] = 42;
}
```

Another issue with "`arr`": Not `free`-ed

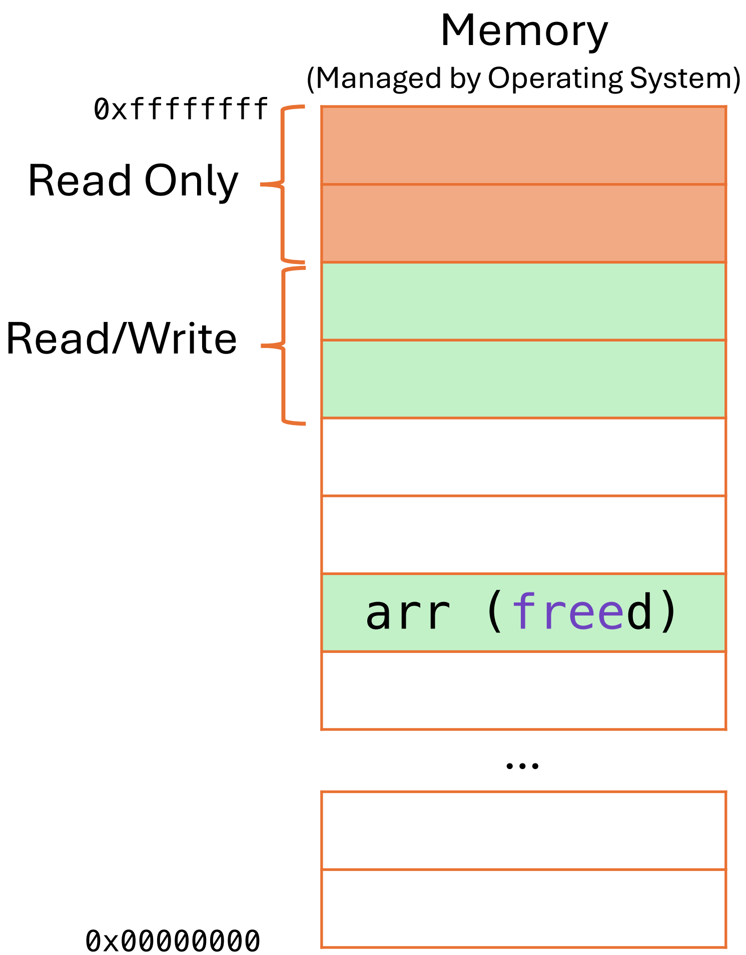
```
liby@mac ~/L/P/Demo> gcc demo.c
liby@mac ~/L/P/Demo> ./a.out
```



C Program that Silently Breaks Memory Safety

```
int main() {
  int *arr = (int *)
    malloc(100 * sizeof(int));
  arr[99] = 42;
+ free(arr);
}
```

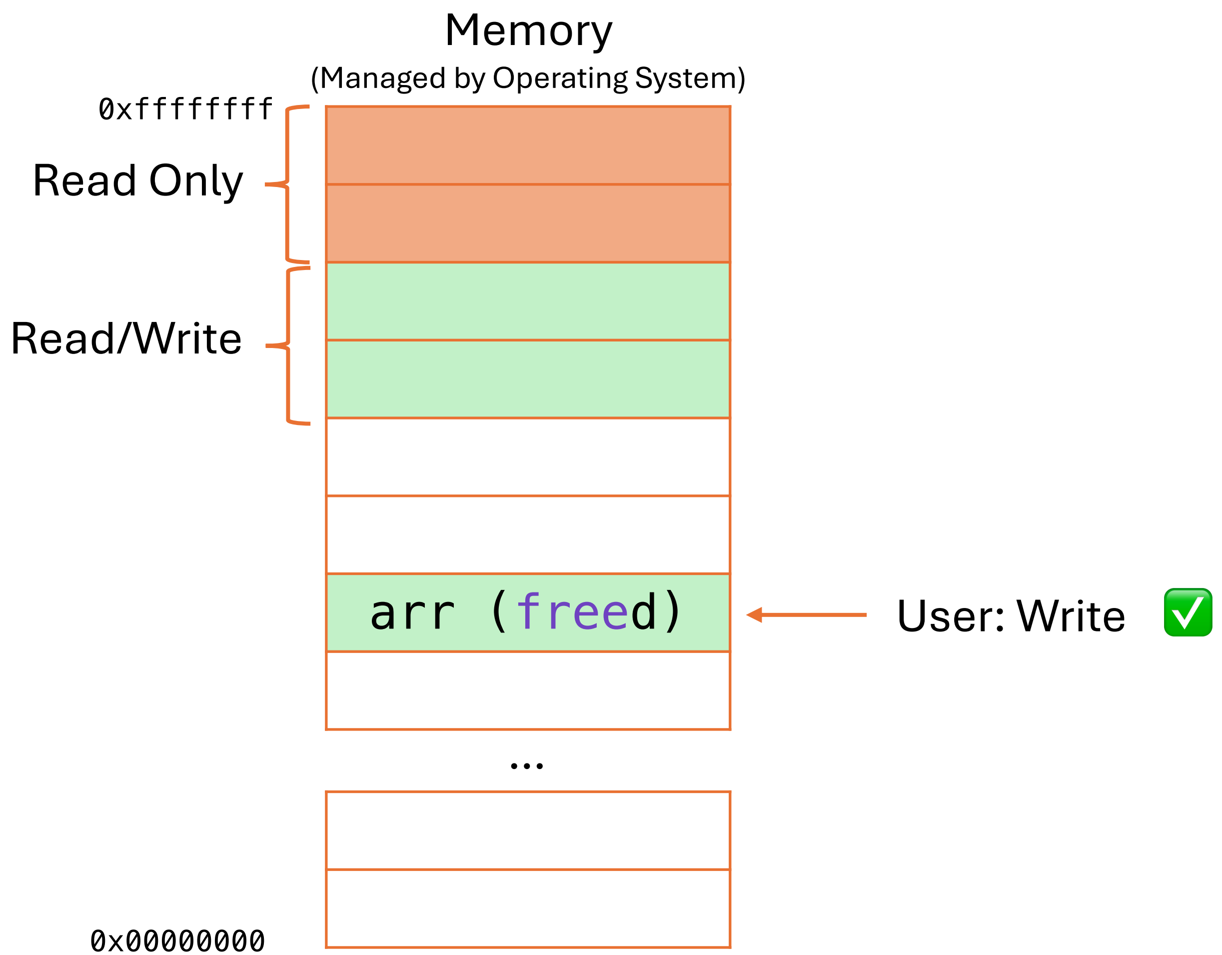
```
liby@mac ~/L/P/Demo> gcc demo.c
liby@mac ~/L/P/Demo> ./a.out
```



C Program that Silently Breaks Memory Safety

```
int main() {
  int *arr = (int *)
    malloc(100 * sizeof(int));
  arr[99] = 42;
  free(arr);
+ arr[3] = 27;
+ printf("%d\n", arr[3]);
}
```

```
liby@mac ~/L/P/Demo> gcc demo.c
liby@mac ~/L/P/Demo> ./a.out
27
```



C Program that Silently Breaks Memory Safety

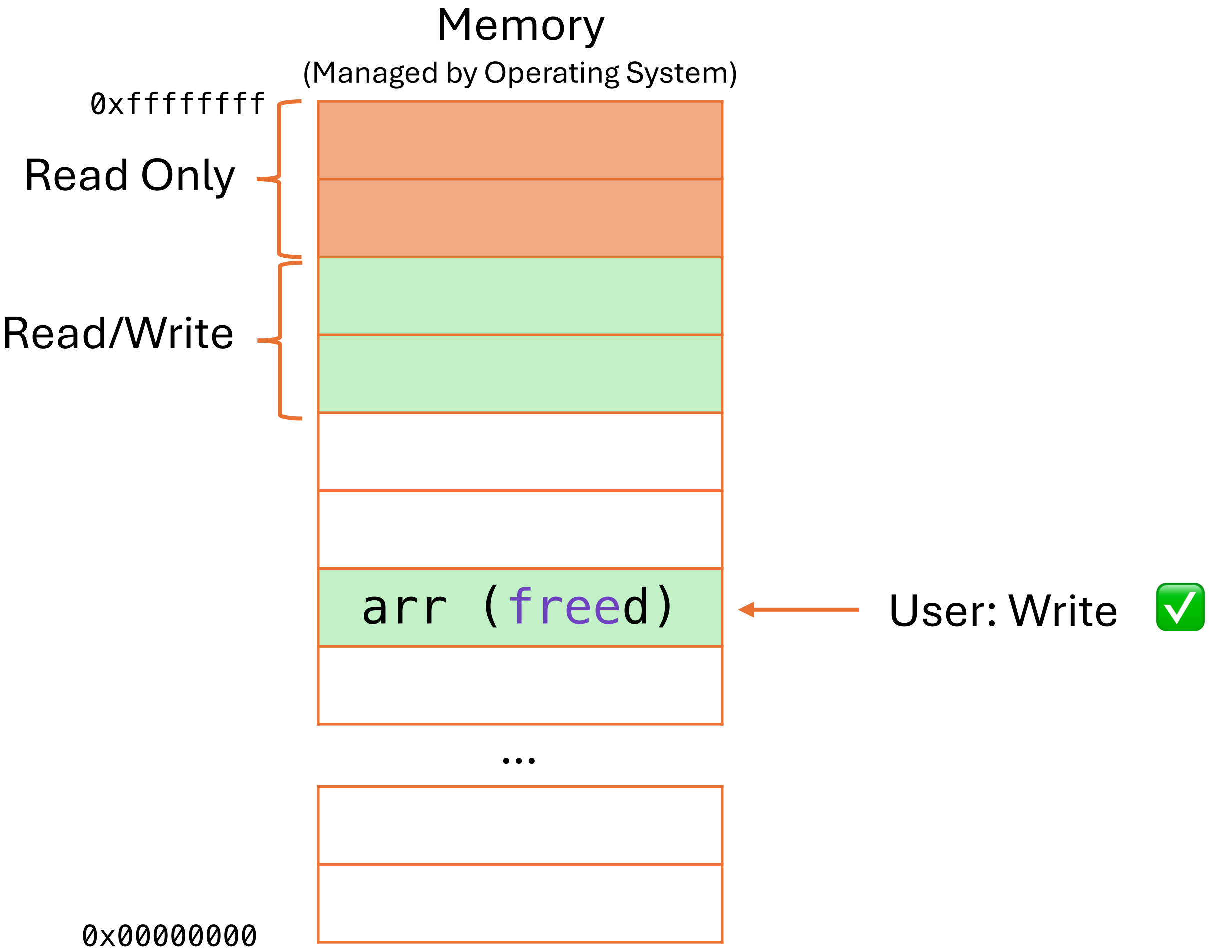
CWE-416: Use After Free

Weakness ID: 416
Vulnerability Mapping: ALLOWED
Abstraction: Variant

```
  int *arr = (int *)
                          (int));
  free(arr);
+ arr[3] = 27;
+ printf("%d\n", arr[3]);
}
```

Use After Free

```
liby@mac ~/L/P/Demo> gcc demo.c
liby@mac ~/L/P/Demo> ./a.out
27
```



Takeaway

- C language does NOT have memory safety by-construct
- The responsibility of keeping memory safe is on the developers
  - If we ask LLMs to write C code, the responsibility is on the LLMs
- The unsafe memory operations may not be always noticeable
  - Silent undefined behavior is hard to catch
- Need extra tools to help catching silent issues
  - E.g., most memory related issues can be caught by valgrind

(Memory) Safe by Construct: Python

C/C++ Program

```c
int main() {
  int *arr = (int *)
    malloc(100 * sizeof(int));
  arr[182] = 42;
  free(arr);
  arr[3] = 27;
  printf("%d\n", arr[3]);
}
```

Python Program

```python
def main():
  arr = [()] * 100
  arr[182] = 42
```

```
 File "demo.py", line 3, in main
    arr[182] = 42
    ~~~^^^^^
IndexError: list assignment index
out of range
```

(Memory) Safe by Construct: Python

C/C++ Program

```c
int main() {
  int *arr = (int *)
    malloc(100 * sizeof(int));
  arr[182] = 42;
  free(arr);
  arr[3] = 27;
  printf("%d\n", arr[3]);
}
```

Python Program

```python
def main():
  arr = [()] * 100
+ if 182 > len(arr):
+   raise Exception(...)
  arr[182] = 42
```

```
 File "demo.py", line 3, in main
    arr[182] = 42
    ~~~^^^^^
IndexError: list assignment index
out of range
```

(Memory) Safe by Construct: Python

C/C++ Program

```
int main() {
  int *arr = (int *)
    malloc(100 * sizeof(int));
  arr[99] = 42;
  free(arr);
  arr[3] = 27;
  printf("%d\n", arr[3]);
}
```

Python Program

```
def main():
  arr = [()] * 100
  arr[99] = 42
```

(Memory) Safe by Construct: Python

C/C++ Program

```c
int main() {
  int *arr = (int *)
    malloc(100 * sizeof(int));
  arr[99] = 42;
  free(arr);
  arr[3] = 27;
  printf("%d\n", arr[3]);
}
```

In Python, this is done implicitly by memory management system

Python Program

```python
def main():
  arr = [()] * 100
  arr[99] = 42
```

(Memory) Safe by Construct: Python

C/C++ Program

```
int main() {
  int *arr1 = (int *)
    malloc(100 * sizeof(int));
  int *arr2 = arr1;
  free(arr1);
  arr2[3] = 27;
  printf("%d\n", arr2[3]);
}
```

Python Program

```
def main():
  arr1 = [()] * 100
  arr2 = arr1
  del arr1
  arr2[3] = 27
  print(arr2[3])
```

(Memory) Safe by Construct: Python

C/C++ Program

```c
int main() {
  int *arr1 = (int *)
    malloc(100 * sizeof(int));
  int *arr2 = arr1;
  free(arr1);
  arr2[3] = 27;
  printf("%d\n", arr2[3]);
}
```

Python Program

```python
def main():
  arr1 = [()] * 100
  arr2 = arr1
  del arr1
  arr2[3] = 27
  print(arr2[3])
```

(Memory) Safe by Construct: Python

C/C++ Program

```
int main() {
  int *arr1 = (int *)
    malloc(100 * sizeof(int));
  int *arr2 = arr1;
  free(arr1);
  arr2[3] = 27;
  printf("%d\n", arr2[3]);
}
```

Python Program

```
def main():
  arr1 = [()] * 100
  arr2 = arr1
  del arr1
  arr2[3] = 27
  print(arr2[3])
```

()	()	()	()	...	()

Reference Count: 1

(Memory) Safe by Construct: Python

C/C++ Program

```c
int main() {
  int *arr1 = (int *)
    malloc(100 * sizeof(int));
  int *arr2 = arr1;
  free(arr1);
  arr2[3] = 27;
  printf("%d\n", arr2[3]);
}
```

Python Program

```python
def main():
  arr1 = [()] * 100
  arr2 = arr1
  del arr1
  arr2[3] = 27
  print(arr2[3])
```

()	()	()	()	…	()

Reference Count: 2 (+1)

(Memory) Safe by Construct: Python

C/C++ Program

```c
int main() {
  int *arr1 = (int *)
    malloc(100 * sizeof(int));
  int *arr2 = arr1;
  free(arr1);
  arr2[3] = 27;
  printf("%d\n", arr2[3]);
}
```

Python Program

```python
def main():
  arr1 = [()] * 100
  arr2 = arr1
  del arr1
  arr2[3] = 27
  print(arr2[3])
```

()	()	()	()	…	()

Reference Count: 1 (-1)

(Memory) Safe by Construct: Python

C/C++ Program

```c
int main() {
  int *arr1 = (int *)
    malloc(100 * sizeof(int));
  int *arr2 = arr1;
  free(arr1);
  arr2[3] = 27;
  printf("%d\n", arr2[3]);
}
```

Python Program

```python
def main():
  arr1 = [()] * 100
  arr2 = arr1
  del arr1
  arr2[3] = 27
  print(arr2[3])
```

()	()	()	27	…	()

Reference Count: 1

(Memory) Safe by Construct: Python

C/C++ Program

```
int main() {
  int *arr1 = (int *)
    malloc(100 * sizeof(int));
  int *arr2 = arr1;
  free(arr1);
  arr2[3] = 27;
  printf("%d\n", arr2[3]);
}
```

Python Program

```
def main():
  arr1 = [()] * 100
  arr2 = arr1
  del arr1
  arr2[3] = 27
  print(arr2[3])
```

()	()	()	27	…	()

Reference Count: 1

Garbage collection & “free”ing only happens when reference count (RC) of an object goes to 0

(Memory) Safe by Construct: Rust

C/C++ Program

```c
int main() {
  int *arr1 = (int *)
    malloc(100 * sizeof(int));
  int *arr2 = arr1;
  free(arr1);
  arr2[3] = 27;
  printf("%d\n", arr2[3]);
}
```

Rust Program

test1.rs 1

```rust
fn main() {
  let mut arr1 = vec![0; 100];
  let mut arr2 = arr1;
  arr2[3] = 27;
  arr1[1] = 3;
```

```
borrow of moved value: `arr1`
value borrowed here after move rustc(Click for full compiler diagnostic)

test1.rs(3, 18): value moved here

test1.rs(2, 7): move occurs because `arr1` has type `Vec<i32>`, which does not
implement the `Copy` trait

test1.rs(3, 22): consider cloning the value if the performance cost is
acceptable: `.clone()`

let mut arr1: Vec<i32>
```

(Memory) Safe by Construct: Rust

Rust Program

test1.rs 1

```
1  fn main() {
2    let mut arr1 = vec![0; 100];
3    let mut arr2 = arr1;
4    arr2[3] = 27;
5    arr1[1] = 3;
```

```
borrow of moved value: `arr1`
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test1.rs(3, 18): value moved here

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test1.rs(3, 22): consider cloning the value if the performance cost is acceptable: `.clone()`

let mut arr1: Vec<i32>
```
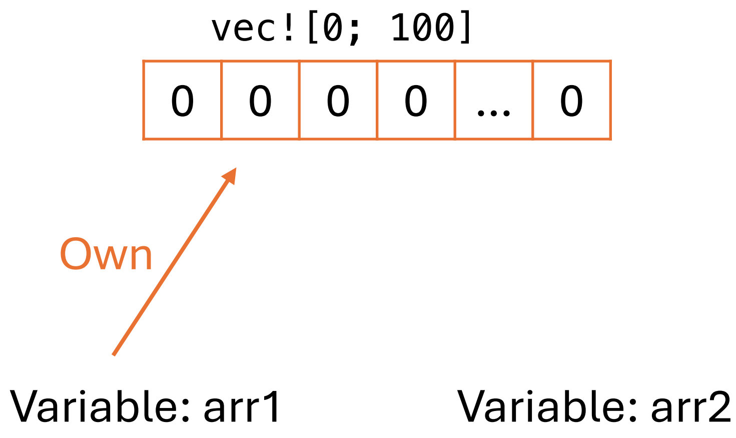

Single Ownership



(Memory) Safe by Construct: Rust

Rust Program

test1.rs 1

```rust
1  fn main() {
2    let mut arr1 = vec![0; 100];
3    let mut arr2 = arr1;
4    arr2[3] = 27;
5    arr1[1] = 3;
```

```
borrow of moved value: `arr1`
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```
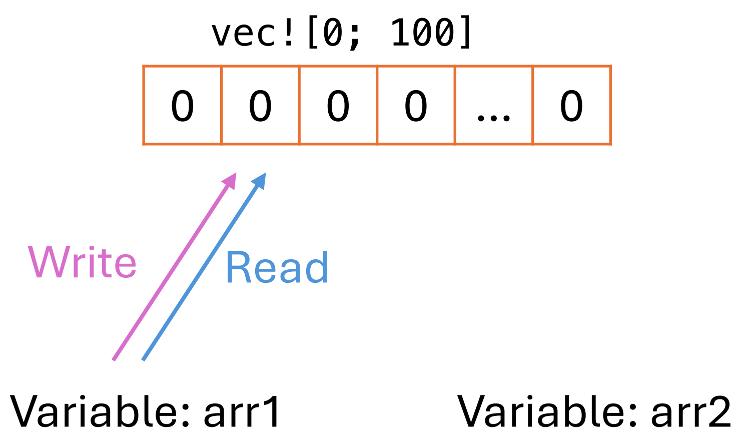

Single Ownership



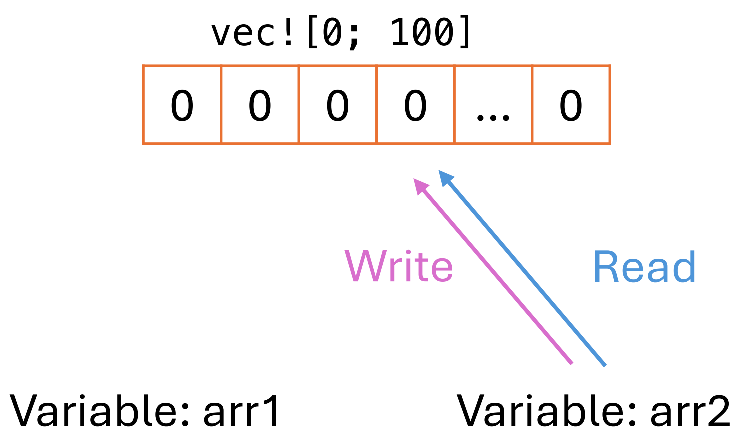
(Memory) Safe by Construct: Rust

Rust Program

```
test1.rs 1

1 fn main() {
2   let mut arr1 = vec![0; 100];
3   let mut arr2 = arr1;
4   arr2[3] = 27;
5   arr1[1] = 3;
```

```
borrow of moved value: `arr1`
value borrowed here after move rustc(Click for full compiler diagnostic)

test1.rs(3, 18): value moved here

test1.rs(2, 7): move occurs because `arr1` has type `Vec<i32>`, which does not
implement the `Copy` trait

test1.rs(3, 22): consider cloning the value if the performance cost is
acceptable: `.clone()`

let mut arr1: Vec<i32>
```

Single Ownership



(Memory) Safe by Construct: Rust

Rust Program

test1.rs 1

```
1  fn main() {
2    let mut arr1 = vec![0; 100];
3    let mut arr2 = arr1;
4    arr2[3] = 27;
5    arr1[1] = 3;
```

```
borrow of moved value: `arr1`
value borrowed here after move rustc(Click for full compiler diagnostic)

test1.rs(3, 18): value moved here

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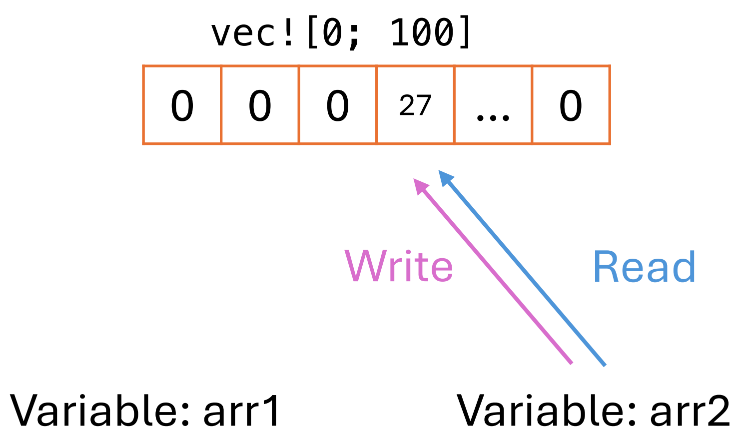

(Memory) Safe by Construct: Rust

Rust Program

test1.rs 1

```
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2   let mut arr1 = vec![0; 100];
3   let mut arr2 = arr1;
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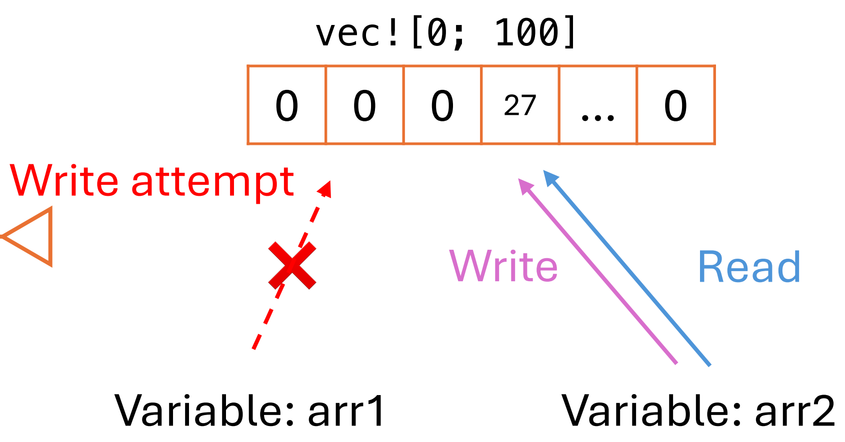
Single Ownership



(Memory) Safe by Construct: Rust

Rust Program

```
fn main() {
  let mut arr1 = vec![0; 100];
  let arr2 = &mut arr1;
  arr2[3] = 27;
  arr1[2] = 30;
}
```

Single Ownership

`vec![0; 100]`

0	0	0	0	...	0

Variable: arr1

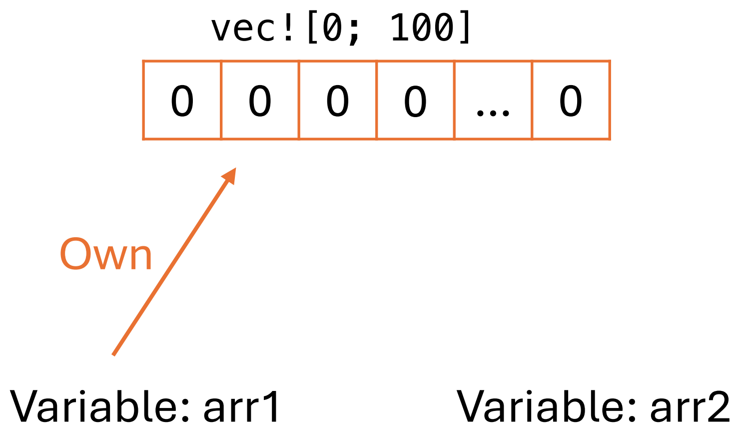
Variable: arr2

(Memory) Safe by Construct: Rust

Rust Program

```
fn main() {
  let mut arr1 = vec![0; 100];
  let arr2 = &mut arr1;
  arr2[3] = 27;
  arr1[2] = 30;
}
```

Single Ownership

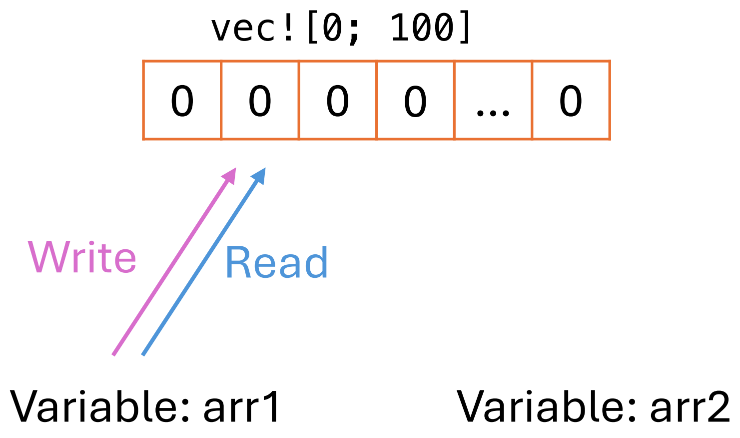


(Memory) Safe by Construct: Rust

Rust Program

```rust
fn main() {
  let mut arr1 = vec![0; 100];
  let arr2 = &mut arr1;
  arr2[3] = 27;
  arr1[2] = 30;
}
```

Single Ownership



(Memory) Safe by Construct: Rust

Rust Program

```
fn main() {
  let mut arr1 = vec![0; 100];
  let arr2 = &mut arr1;
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  arr1[2] = 30;
}
```
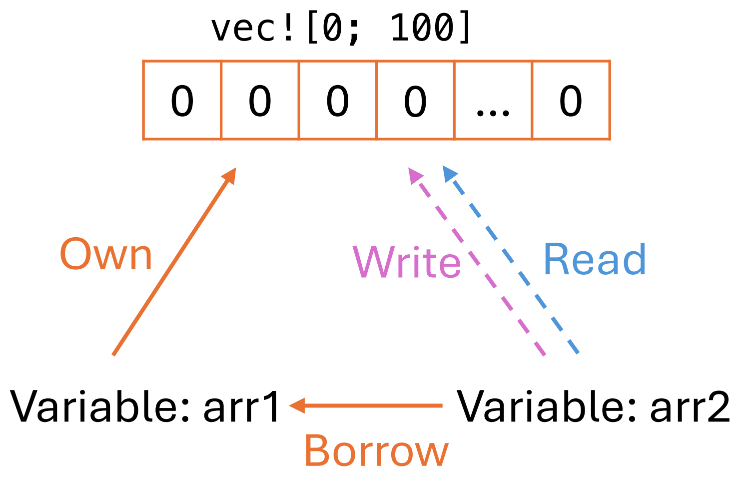

Single Ownership

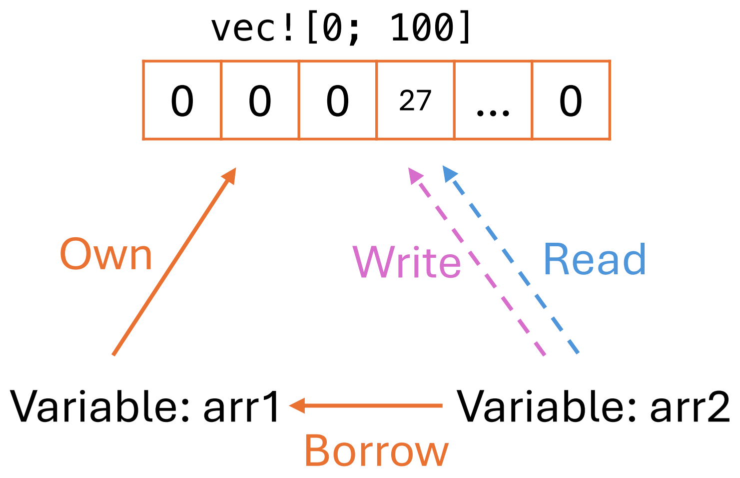


(Memory) Safe by Construct: Rust

Rust Program

```
fn main() {
  let mut arr1 = vec![0; 100];
  let arr2 = &mut arr1;
  arr2[3] = 27;
  arr1[2] = 30;
}
```

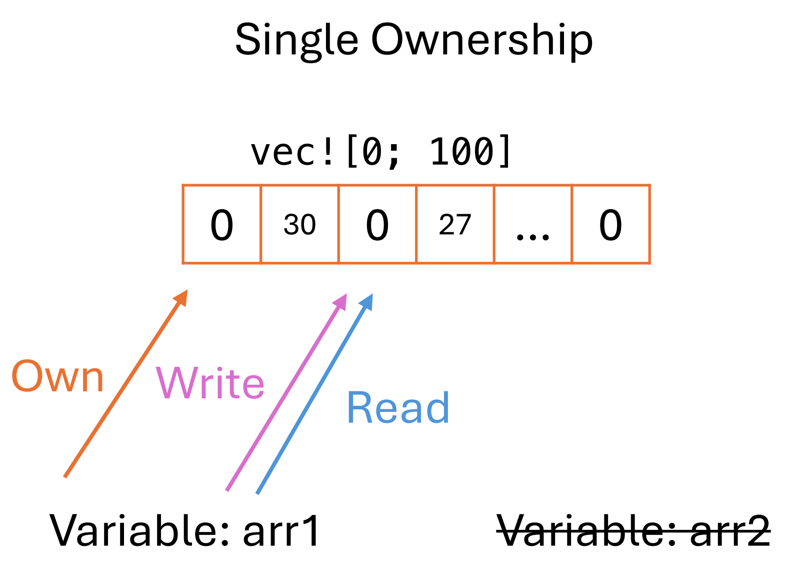
Single Ownership



(Memory) Safe by Construct: Rust

Rust Program

```rust
fn main() {
    let mut arr1 = vec![0; 100];
    let arr2 = &mut arr1;
    arr2[3] = 27;
    arr1[2] = 30;
}
```



Key Takeaway: Who is responsible for safety?

C/C++ Program

```c
int main() {
  int *arr1 = (int *)
    malloc(100 * sizeof(int));
  int *arr2 = arr1;
  free(arr1);
  arr2[3] = 27;
  printf("%d\n", arr2[3]);
}
```

Developer / LLM

Python Program

```python
def main():
  arr1 = [()] * 100
  arr2 = arr1
  del arr1
  arr2[3] = 27
  print(arr2[3])
```

Python Runtime

Memory Management

Reference Counting

Garbage Collection

Rust Program

```rust
fn main() {
  let mut arr1 = vec![0; 100];
  let arr2 = &mut arr1;
  arr2[3] = 27;
  arr1[2] = 30;
}
```

Rust Compiler

Linear type system

Ownership & borrow checker

Life-time resolver

Key Takeaway: Who can be trusted?

C/C++ Program

```
int main() {
  int *arr1 = (int *)
    malloc(100 * sizeof(int));
  int *arr2 = arr1;
  free(arr1);
  arr2[3] = 27;
  printf("%d\n", arr2[3]);
}
```

Developer / LLM

NO

Python Program

```
def main():
  arr1 = [()] * 100
  arr2 = arr1
  del arr1
  arr2[3] = 27
  print(arr2[3])
```

Python Runtime

Memory Management
Reference Counting
Garbage Collection

Maybe yes

Rust Program

```
fn main() {
  let mut arr1 = vec![0; 100];
  let arr2 = &mut arr1;
  arr2[3] = 27;
  arr1[2] = 30;
}
```

Rust Compiler

Linear type system
Ownership & borrow checker
Life-time resolver

Maybe yes

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TRACTOR: Translating All C to Rust

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TRACTOR:

Summary

After more than two decades of grappling with memory safety issues in C and C++, the software engineering community has reached a consensus. It's not enough to rely on bug-finding tools.

The preferred approach is to use "safe" programming languages that can reject unsafe programs at compile time, thereby preventing the emergence of memory safety issues.

The TRACTOR program aims to automate the translation of legacy C code to Rust. The goal is to achieve the same quality and style that a skilled Rust developer would produce, thereby eliminating the entire class of memory safety security vulnerabilities present in C programs.

This program may involve novel combinations of software analysis, such as static analysis and dynamic analysis, and machine learning techniques like large language models.

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TRA

Summary

After more than two decades of grappling with memory safety issues in C and C++, the software enginee
finding tools.

The preferred ap
programs at com

The TRACTOR pr
to achieve the sa
eliminating the e

This program ma
and dynamic ana

Type-migrating C-to-Rust translation using a large language model

Jaemin Hong[1] · Sukyoung Ryu[1]

Accepted: 10 October 2024 / Published online: 17 October 2024

Towards Translating Real-World Code with LLMs: A Study of Translating to Rust

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Maria Christakis
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Joey Dodds
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Context-aware Code Segmentation for C-to-Rust Translation using Large Language Models

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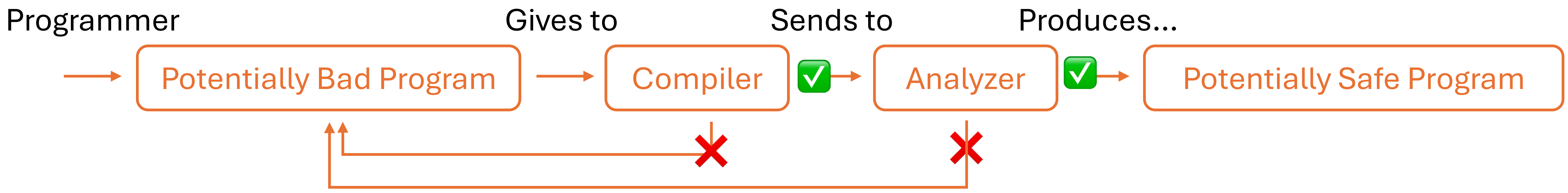
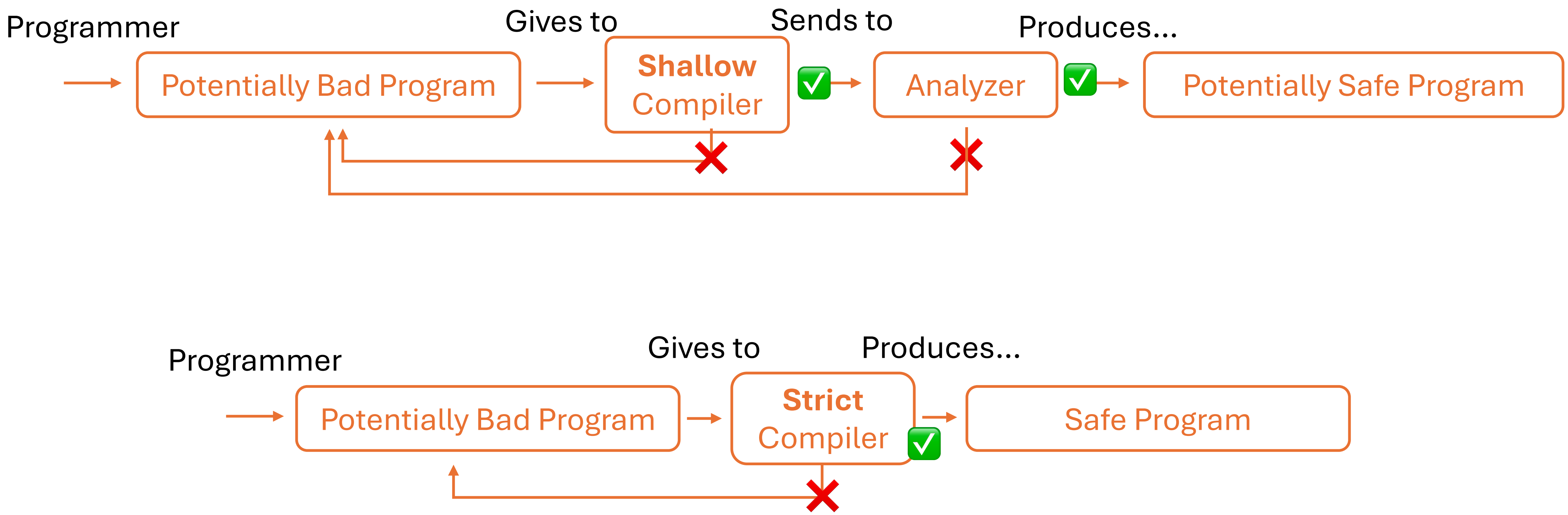
LLM-Driven Multi-step Translation from C to Rust using Static Analysis

Tianyang Zhou[*, 1], **Haowen Lin**[†, 1], **Somesh Jha**[‡, 2], **Mihai Christodorescu**[§, 3], **Kirill Levchenko**[¶, 1], **and Varun Chandrasekaran**[‖, 1]
[1]University of Illinois Urbana-Champaign
[2]University of Wisconsin–Madison
[3]Google


Programmer
Gives to
Sends to
Produces...
Potentially Bad Program
Compiler
Analyzer
Potentially Safe Program



Programmer
Potentially Bad Program
Gives to
Shallow
Compiler
Sends to
Analyzer
Produces...
Potentially Safe Program
Programmer
Potentially Bad Program
Gives to
Strict
Compiler
Produces...
Safe Program

Desirable Properties

Memory Safety

Side-channel Resistance

Termination

Injection-safety

Functional Assurance

Concurrency Safety

Type Safety

Capability Safety

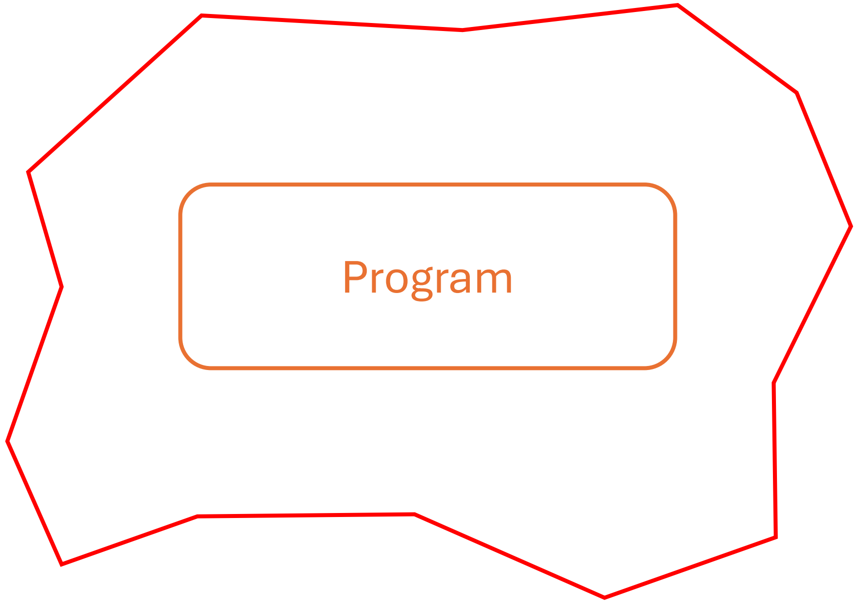
Smart-contract Safety

Control-flow Integrity

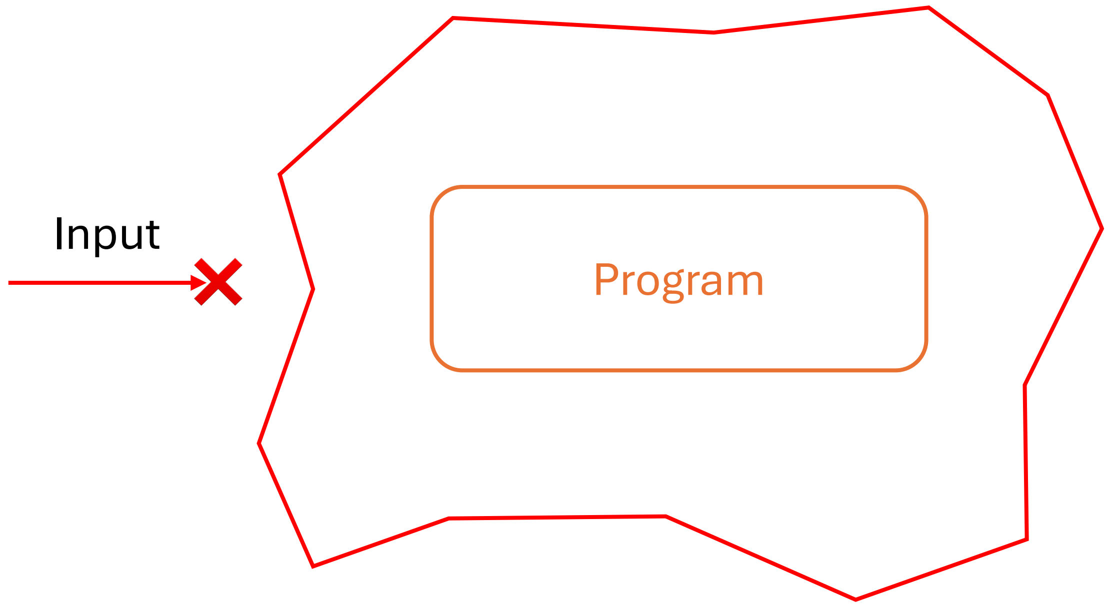
Resource Safety

Data Integrity

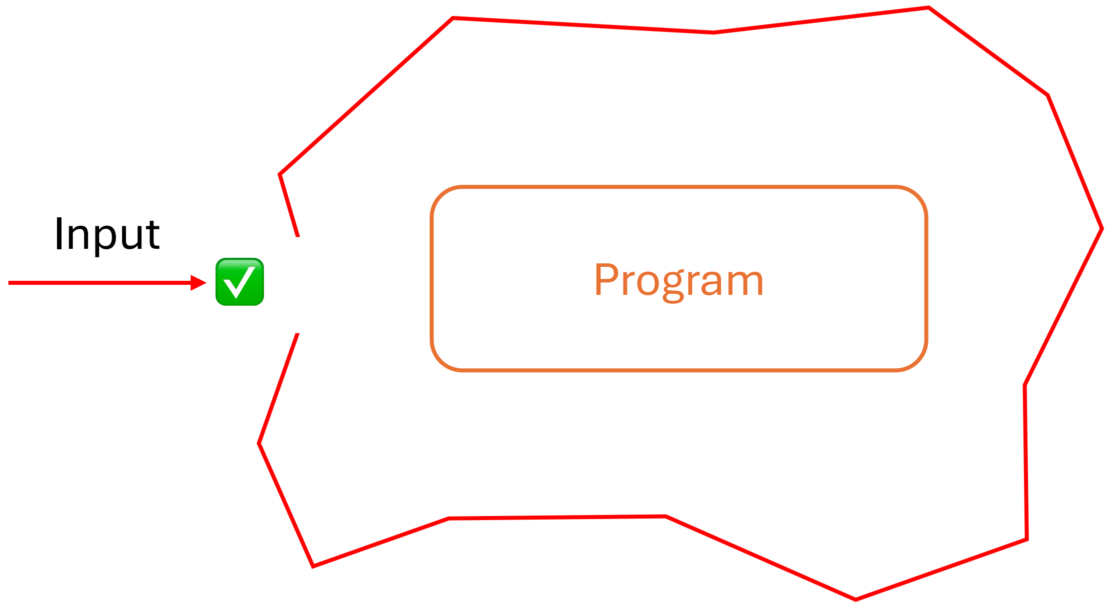
Safe (?) Program



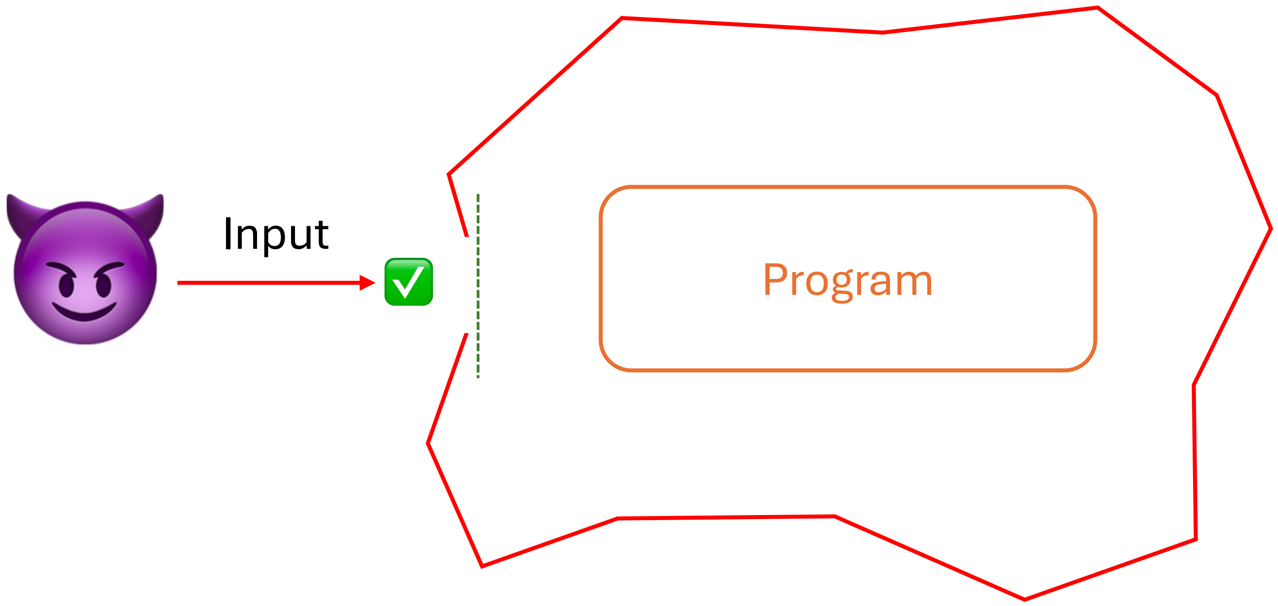
Safe Program is not interesting



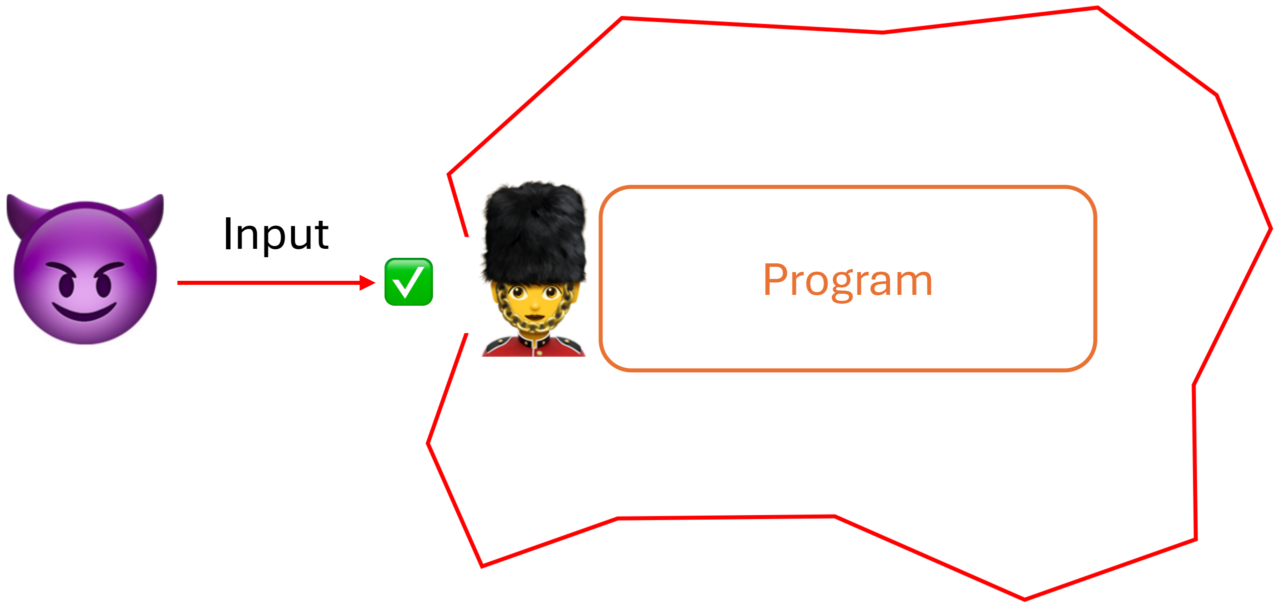
Programs Take Input...



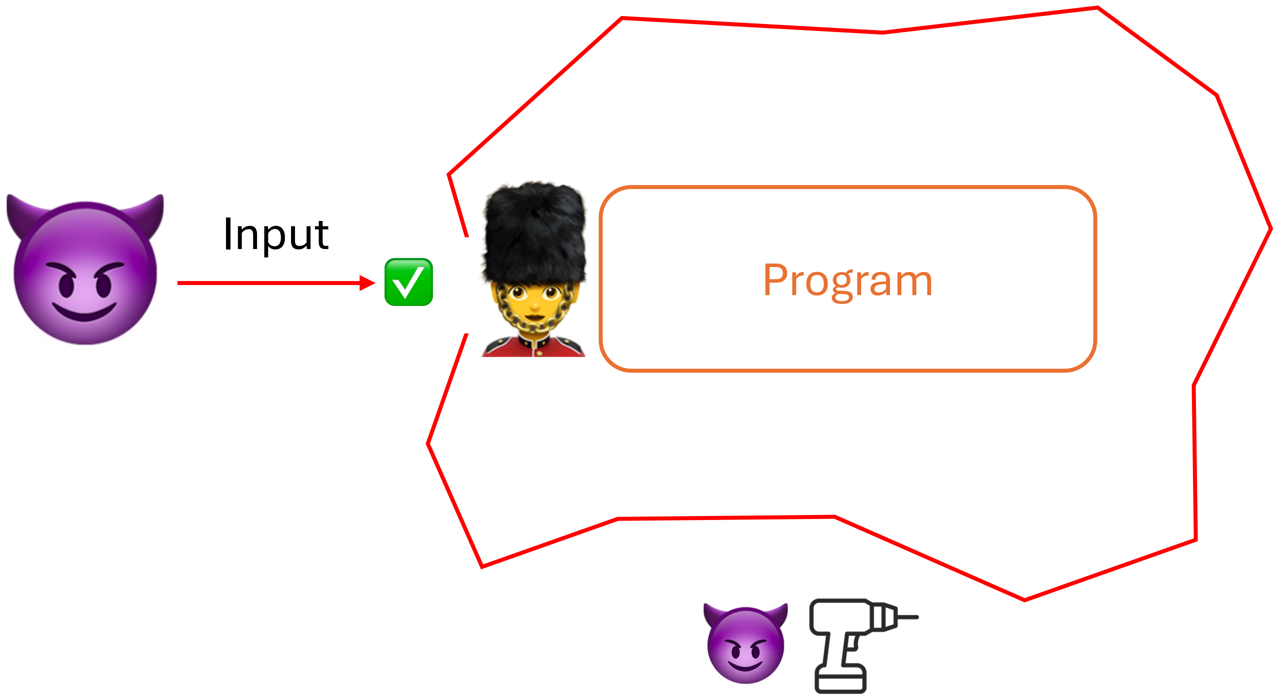
Attack Surface is Exposed...



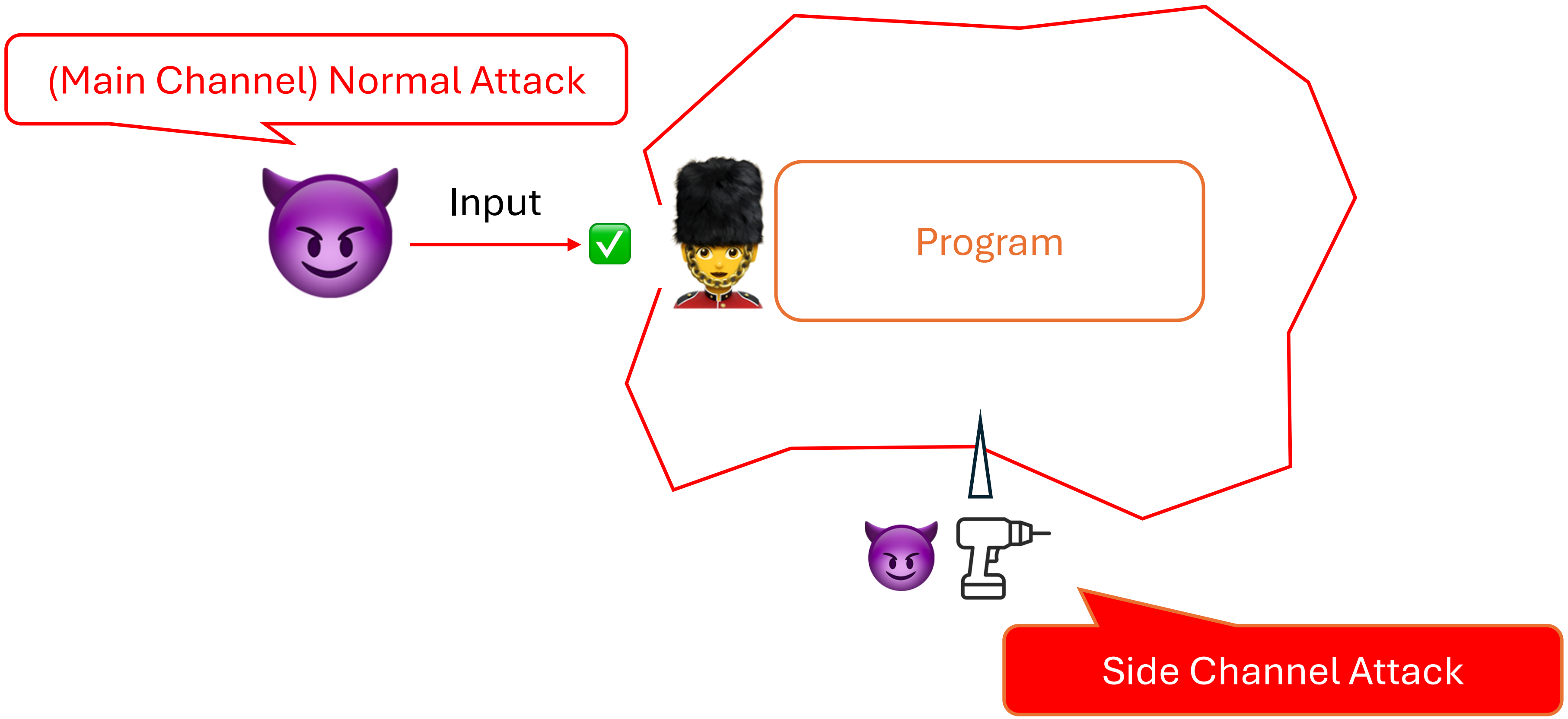
Defense is Setup...

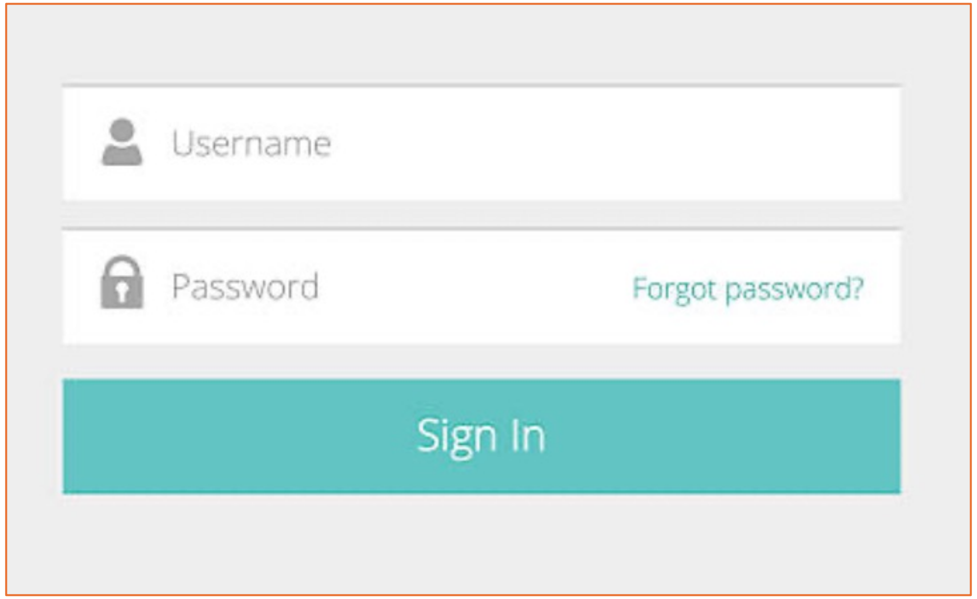


Defense is Setup, But



Defense is Setup, But...




Username
Password
Forgot password?
Sign In

```python
def check_password(expected_password, provided_password):
  if len(expected_password) != len(provided_password):
    return False
  for (expected_char, provided_char) in zip(expected_password, provided_password):
    if expected_char != provided_char:
      return False
  return True
```

```python
def check_password(expected_password, provided_password):
  if len(expected_password) != len(provided_password):
    return False
  for (expected_char, provided_char) in zip(expected_password, provided_password):
    if expected_char != provided_char:
      return False
  return True
```

Expected Password: 12345678

Attempt 1: 13579 ✗

Attempt 2: 02468 ✗

Attempt 3: 12345 ✗

```python
def check_password(expected_password, provided_password):
  if len(expected_password) != len(provided_password):
    return False
  for (expected_char, provided_char) in zip(expected_password, provided_password):
    if expected_char != provided_char:
      return False
  return True
```

Expected Password: 12345678

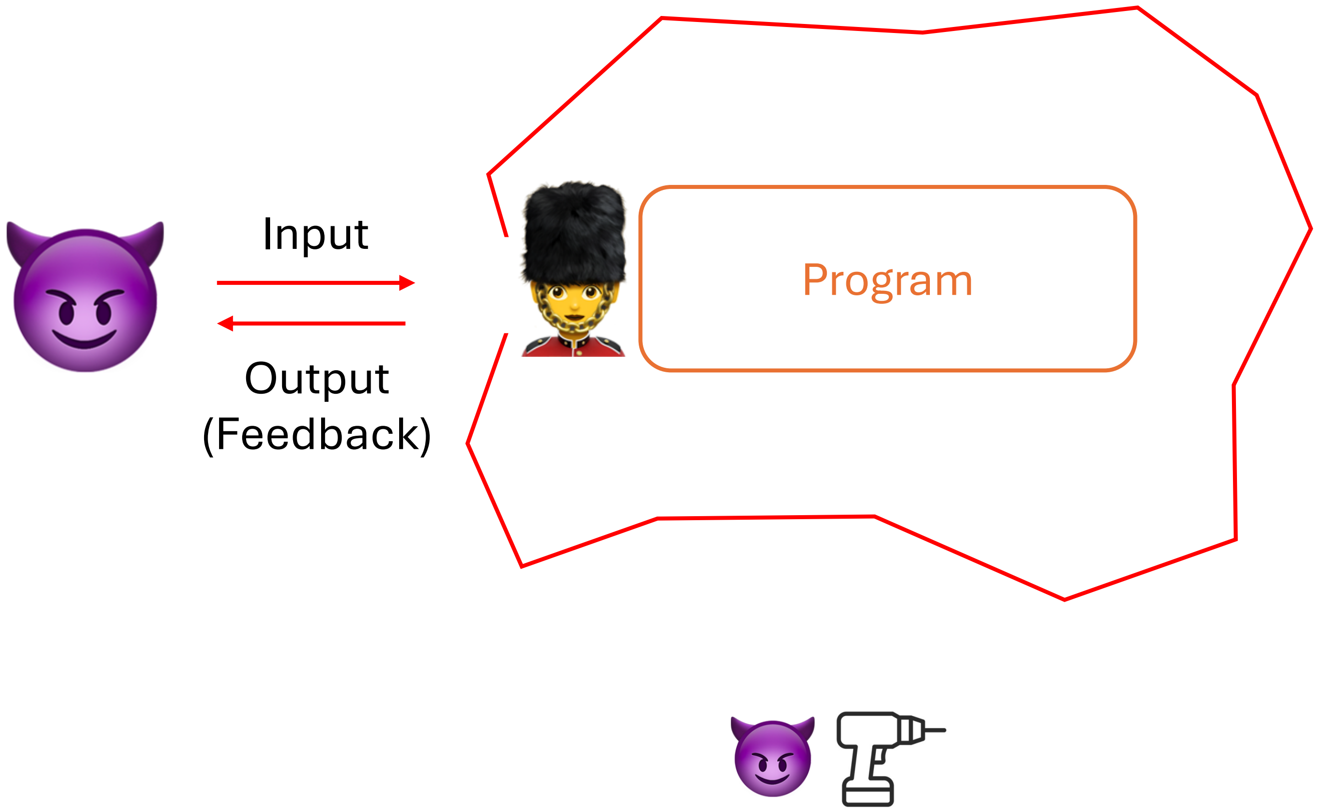
Attempt 1: 13579	Attempt 2: 02468	Attempt 3: 12345
Finishes in 4 CPU cycles	Finishes in 2 CPU cycles	Finishes in 12 CPU cycles
Estimation: 1 char match	Estimation: 0 char match	Estimation: 5 char match

```python
# --- Victim (vulnerable) ---
SECRET = "s3cr3t!"  # real secret (attacker doesn't know)

def check_password(expected_password: str, user_supplied_password: str) -> bool:
    if len(expected_password) != len(user_supplied_password):
        return False
    for a, b in zip(expected_password, user_supplied_password):
        dummy_operation_that_takes_time()
        if a != b:
            return False
    dummy_operation_that_takes_time()
    return True

def dummy_operation_that_takes_time():
    for i in range(10000):
        i += i

# A wrapper that an attacker times (simulate server handling)
def victim_check(attempt: str) -> bool:
    # In a real server there is processing overhead and network jitter.
    # We keep it simple here.
    return check_password(SECRET, attempt)
```

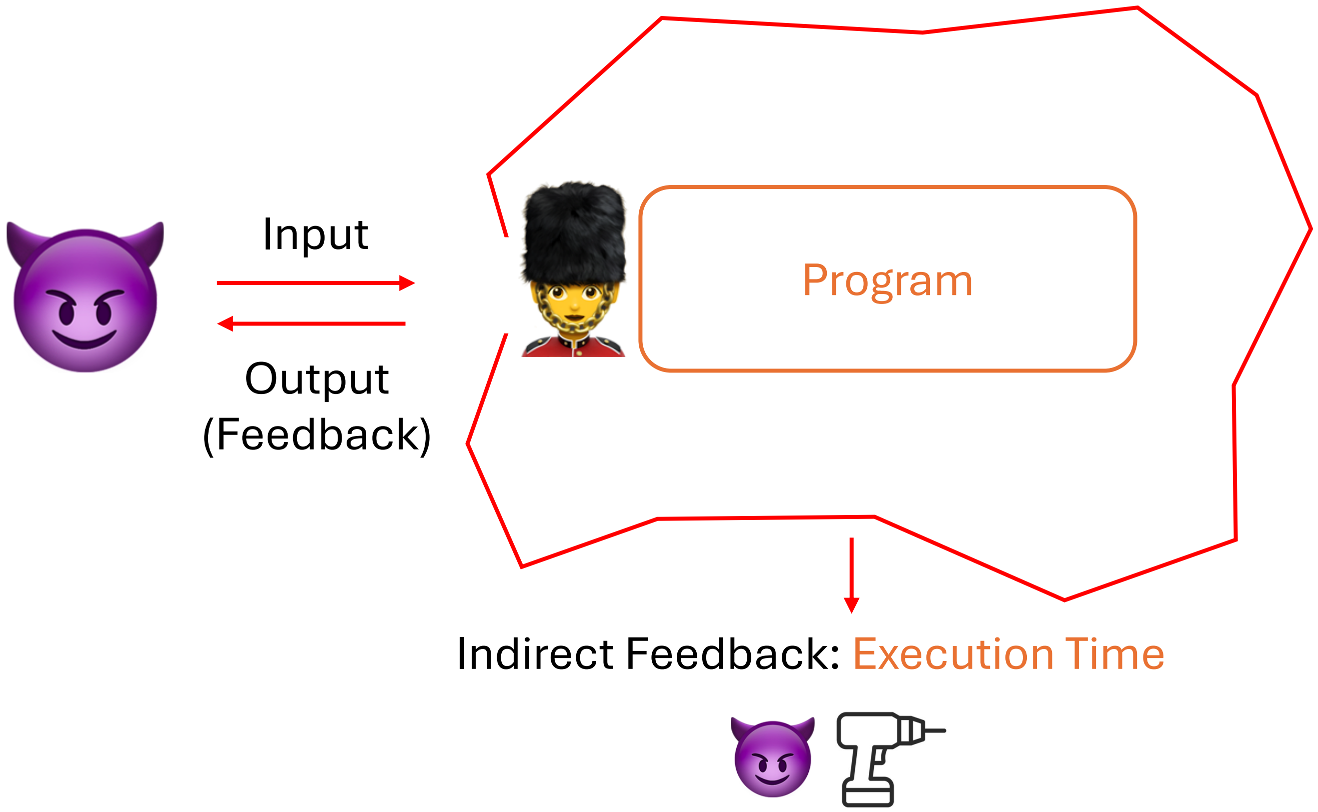
```
me@computer ~/demo> python3 side-channel.py
Discovering length...
Length guessed: 7
Recovering characters by timing...
pos 0: picked 's' (median time=0.000492s) -> 's'
pos 1: picked '3' (median time=0.000741s) -> 's3'
pos 2: picked 'c' (median time=0.000998s) -> 's3c'
pos 3: picked 'r' (median time=0.001228s) -> 's3cr'
pos 4: picked '3' (median time=0.001474s) -> 's3cr3'
pos 5: picked 't' (median time=0.001722s) -> 's3cr3t'
pos 6: picked '!' (median time=0.002012s) -> 's3cr3t!'
Guessed secret: s3cr3t!
```

```python
# --- Attacker ---
CHARSET = string.ascii_letters + string.digits + string.punctuation  # search space
SAMPLES_PER_TRY = 30

def discover_length(max_len=32):
    """Discover password length by trying lengths 1..max_len"""
    timings = []
    for L in range(1, max_len + 1):
        attempt = "A" * L
        elapsed = time_call(victim_check, attempt)
        timings.append((L, elapsed))
    # choose length with (largest?) — here length equality to secret will often take longer
    best = max(timings, key=lambda x: x[1])
    return best[0], timings

def recover_by_timing(known_len):
    recovered = ""
    for pos in range(known_len):
        best_char = None
        best_time = -1.0
        for ch in CHARSET:
            attempt = (recovered + ch).ljust(known_len, "A")  # fill remaining with dummy chars
            elapsed = time_call(victim_check, attempt)
            if elapsed > best_time:
                best_time = elapsed
                best_char = ch
        recovered += best_char
        print(f"pos {pos}: picked '{best_char}' (median time={best_time:.6f}s) -> {recovered!r}")
    return recovered
```

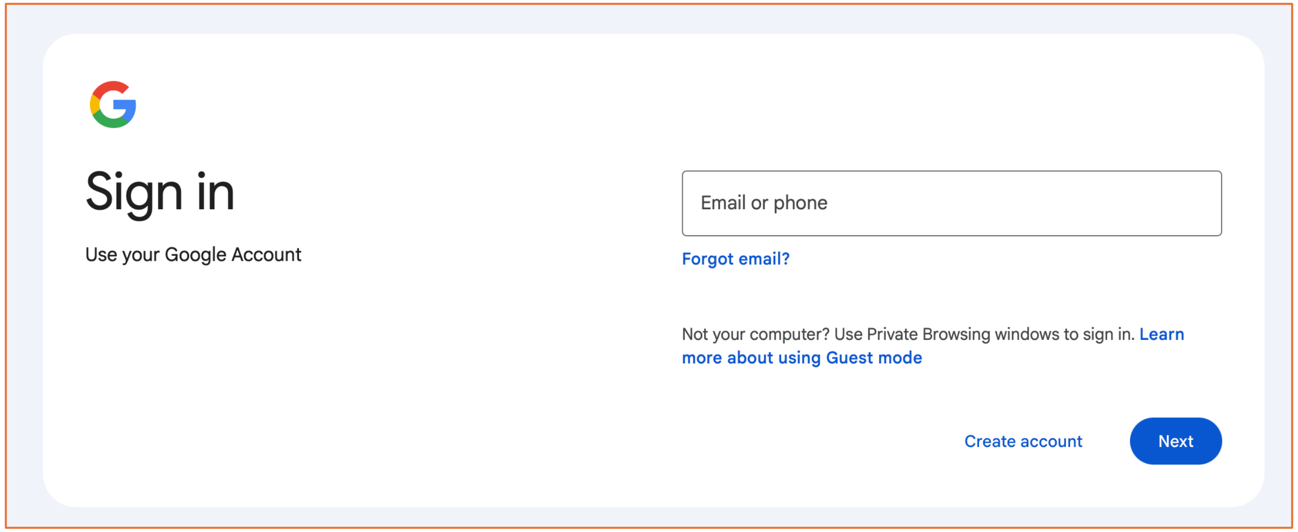
Side-Channel Attack: Non-Constant Time Op



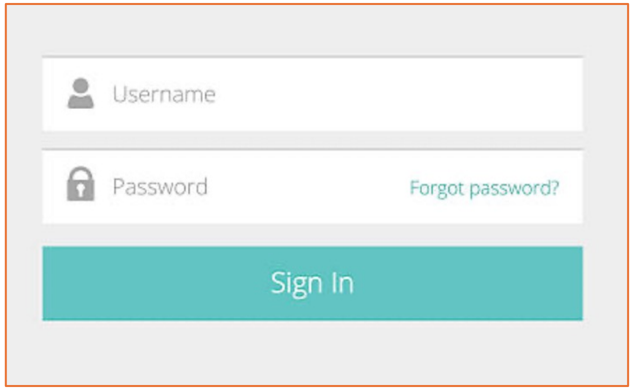
Side-Channel Attack: Non-Constant Time Op



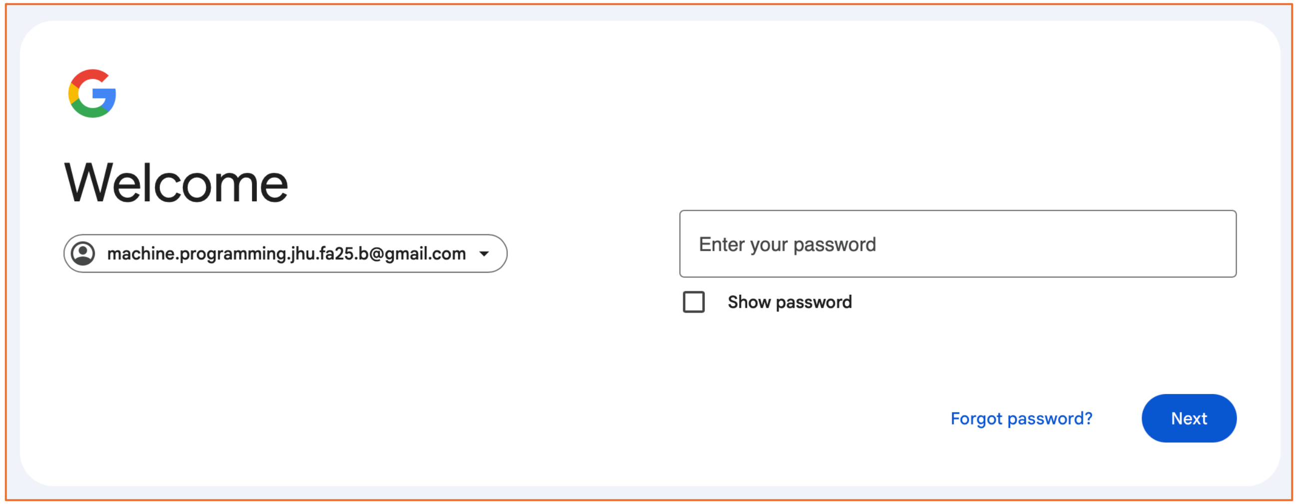
Two Stage Login: Step 1



Single Step Login



Two Stage Login: Step 2



Mitigation: Constant-Time Operations

Non-Constant Time

C Program

```
if (secret) x = e
```

Constant Time

C Program

```
x = (-secret & e) | (secret - 1) & x
```

FaCT: A DSL for Timing-Sensitive Computation, Cauligi et. al., PLDI 2019

Mitigation: Constant-Time Operations

Non-Constant Time

C Program

```
for (j = 0; j < md_block_size; j++, k++) {
  if (is_past_c) {
    b = 0x80;
  } else {
    b = data[k - header_length];
  }
  if (is_past_cp1 || (is_block_b && !is_block_a)) {
    b = 0;
  }
  block[j] = b;
}
```

Constant Time

C Program

```
for (j = 0; j < md_block_size; j++, k++) {
  b  = data[k - header_length];
  b  = constant_time_select_8(is_past_c, 0x80, b);
  b  = b & ~is_past_cp1;
  b &= ~is_block_b | is_block_a;
  block[j] = b;
}
```

FaCT: A DSL for Timing-Sensitive Computation, Cauligi et. al., PLDI 2019

Mitigation: Constant-Time Operations

Non-Constant Time

C Program

```c
for (j = 0; j < md_block_size; j++, k++) {
  if (is_past_c) {
    b = 0x80;
  } else {
    b = data[k - header_length];
  }
  if (is_past_cp1 || (is_block_b && !is_block_a)) {
    b = 0;
  }
  block[j] = b;
```

Are we trusting Human/LLM to write this correctly?

Constant Time

C Program

```c
for (j = 0; j < md_block_size; j++, k++) {
  b  = data[k - header_length];
  b  = constant_time_select_8(is_past_c, 0x80, b);
  b  = b & ~is_past_cp1;
  b &= ~is_block_b | is_block_a;
  block[j] = b;
}
```

FaCT: A DSL for Timing-Sensitive Computation, Cauligi et. al., PLDI 2019

Mitigation: Constant-Time Operations

C Program

```
for (j = 0; j < md_block_size; j++, k++) {
  if (is_past_c) {
    b = 0x80;
ock_a)) {
block[j] = b;
```

CWE-208: Observable Timing Discrepancy

Weakness ID: 208
Vulnerability Mapping: ALLOWED
Abstraction: Base

Are we trusting Human/LLM to write this correctly?

C Program

Constant Time

```
for (j = 0; j < md_block_size; j++, k++) {
  b  = data[k - header_length];
  b  = constant_time_select_8(is_past_c, 0x80, b);
  b  = b & ~is_past_cp1;
  b &= ~is_block_b | is_block_a;
  block[j] = b;
}
```

FaCT: A DSL for Timing-Sensitive Computation, Cauligi et. al., PLDI 2019

Mitigation: Constant-Time Operations

C Program

```
for (j = 0; j < md_block_size; j++, k++) {
```

CVE-2024-31074 Detail

AWAITING ANALYSIS

This CVE record has been marked for NVD enrichment efforts.

Description

Observable timing discrepancy in some Intel(R) QAT Engine for OpenSSL software before version v1.6.1 may allow information disclosure via network access.

Constant Time

```
  b  = data[k - header_length];
  b  = constant_time_select_8(is_past_c, 0x80, b);
  b  = b & ~is_past_cp1;
  b &= ~is_block_b | is_block_a;
  block[j] = b;
}
```

FaCT: A DSL for Timing-Sensitive Computation, Cauligi et. al., PLDI 2019

FaCT: A DSL for Timing-Sensitive Computation

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FaCT: A DSL for Timing-Sensitive Computation, Cauligi et. al., PLDI 2019

Fa **omputation**

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UC San Diego, USA

Be
INRIA

PROCEDURE DEFINITIONS

fdef ::=

|	$f(\vec{x} : \vec{\beta})\ \{\ S\ \} : \beta$	internal procedure
|	$\texttt{export}\ f(\vec{x} : \vec{\beta})\ \{\ S\ \} : \beta$	exported procedure
|	$\texttt{extern}\ f(\vec{x} : \vec{\beta}) : \beta$	external procedure

STATEMENTS

S ::=

|	$S; S$	sequence
|	$\beta\ x = e$	variable declaration
|	$\beta\ x = f(\vec{e})$	procedure call
|	$e := e$	assignment
|	$\texttt{if}\ (e)\ \{\ S\ \}\ \texttt{else}\ \{\ S\ \}$	conditional
|	$\texttt{for}\ (x\ \texttt{from}\ e\ \texttt{to}\ e)\ \{\ S\ \}$	range-for
|	$\texttt{return}\ e$	return

EXPRESSIONS

e ::=

|	$\texttt{true} \mid \texttt{false}$	boolean literal
|	n	numeric literal
|	x	variable
|	$\ominus\ e$	unary op
|	$e \oplus e$	binary op
|	$e[e]$	array get
|	$\texttt{len}\ e$	array length
|	$\texttt{zeros}(\beta, e)$	zero array
|	$\texttt{clone}(e)$	array clone
|	$\texttt{view}(e, e, e)$	array view
|	$\texttt{declassify}(e)$	declassify
|	$\texttt{assume}(e)$	assume
|	$\texttt{ref}\ e$	reference
|	$\texttt{deref}\ e$	dereference
|	$\texttt{ctselect}(e, e, e)$	constant-time selection

Figure 1. (Subset of) FaCT grammar.

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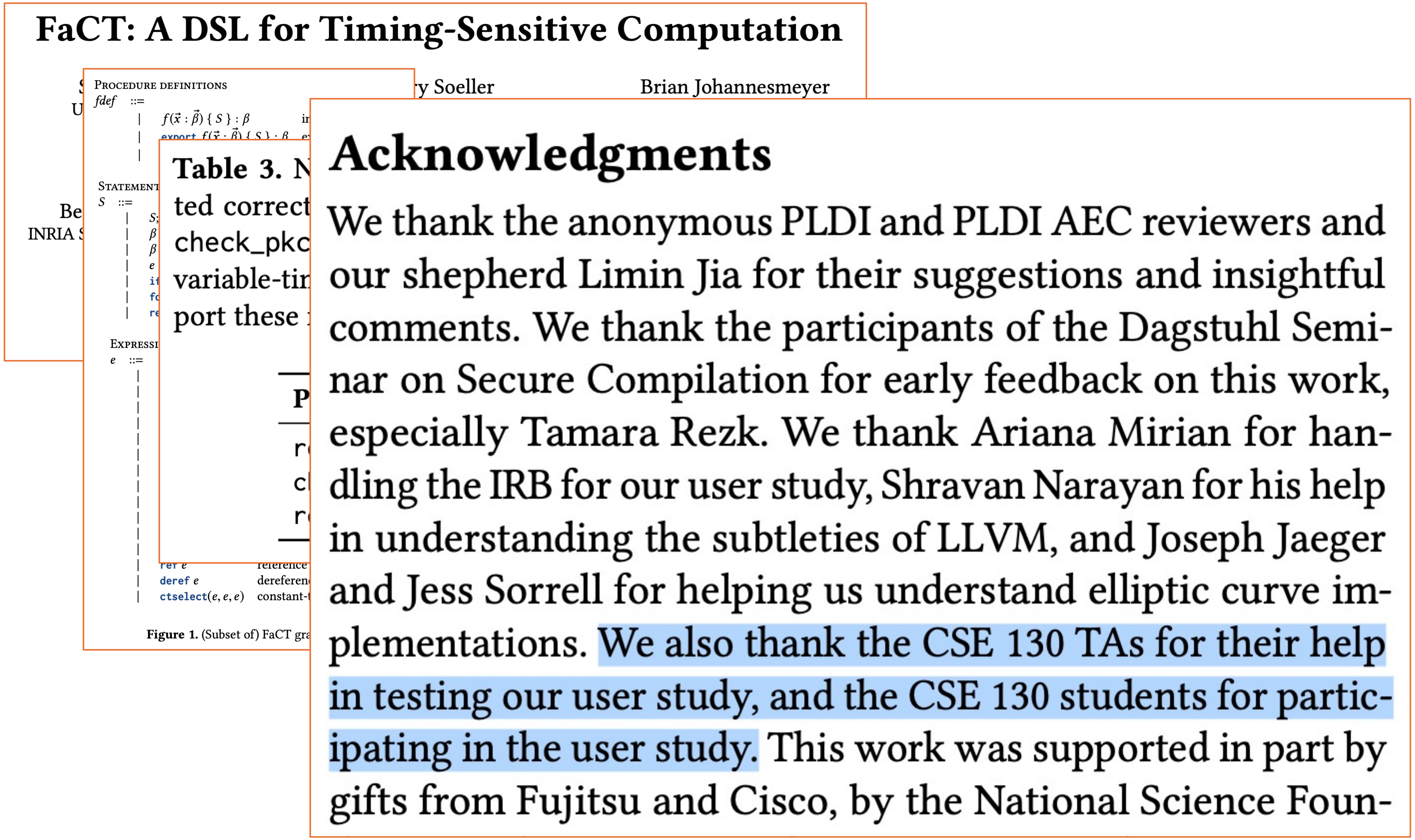
FaCT: A DSL for Timing-Sensitive Computation

Brian Johannesmeyer
UC San Diego, USA

John Renner

Table 3. Number of participants (out of 77) that submitted correct and constant-time solution for each task. The `check_pkcs7_padding` task was misconfigured, and marked variable-time code as constant-time (16 submissions); we report these numbers for completeness (§5.2.2).

Programming task	FaCT	C
`remove_secret_padding`	62	49
`check_pkcs7_padding`	35	32 (16)
`remove_pkcs7_padding`	34	24



FaCT: A DSL for Timing-Sensitive Computation

Acknowledgments

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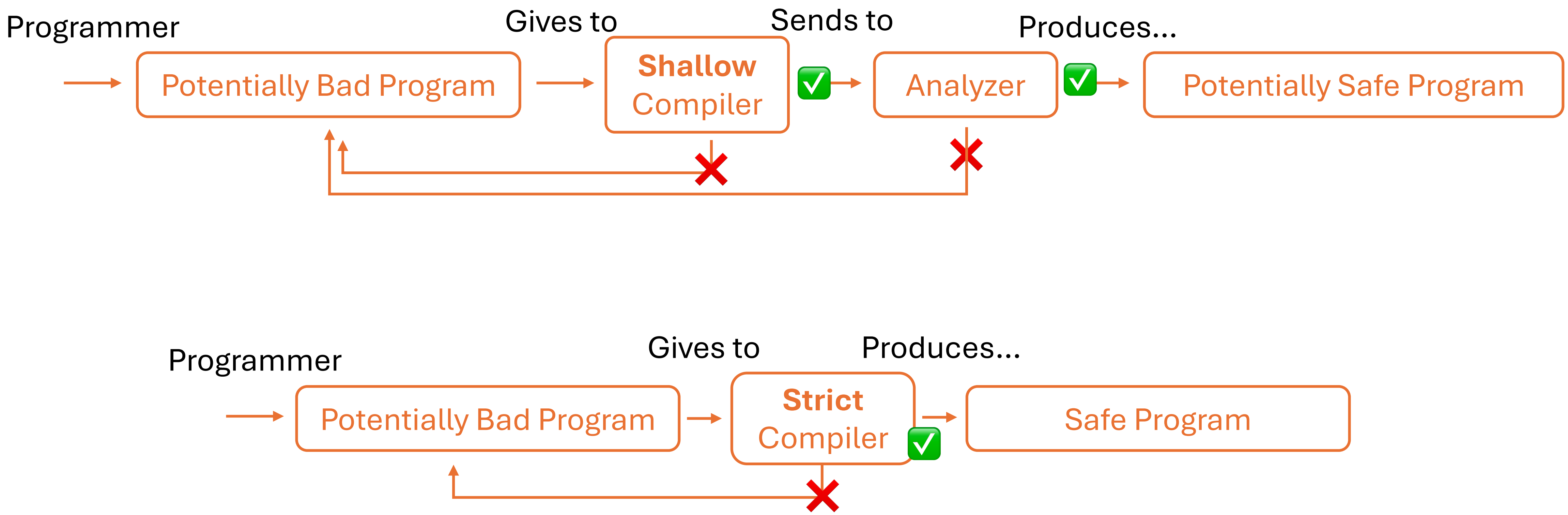
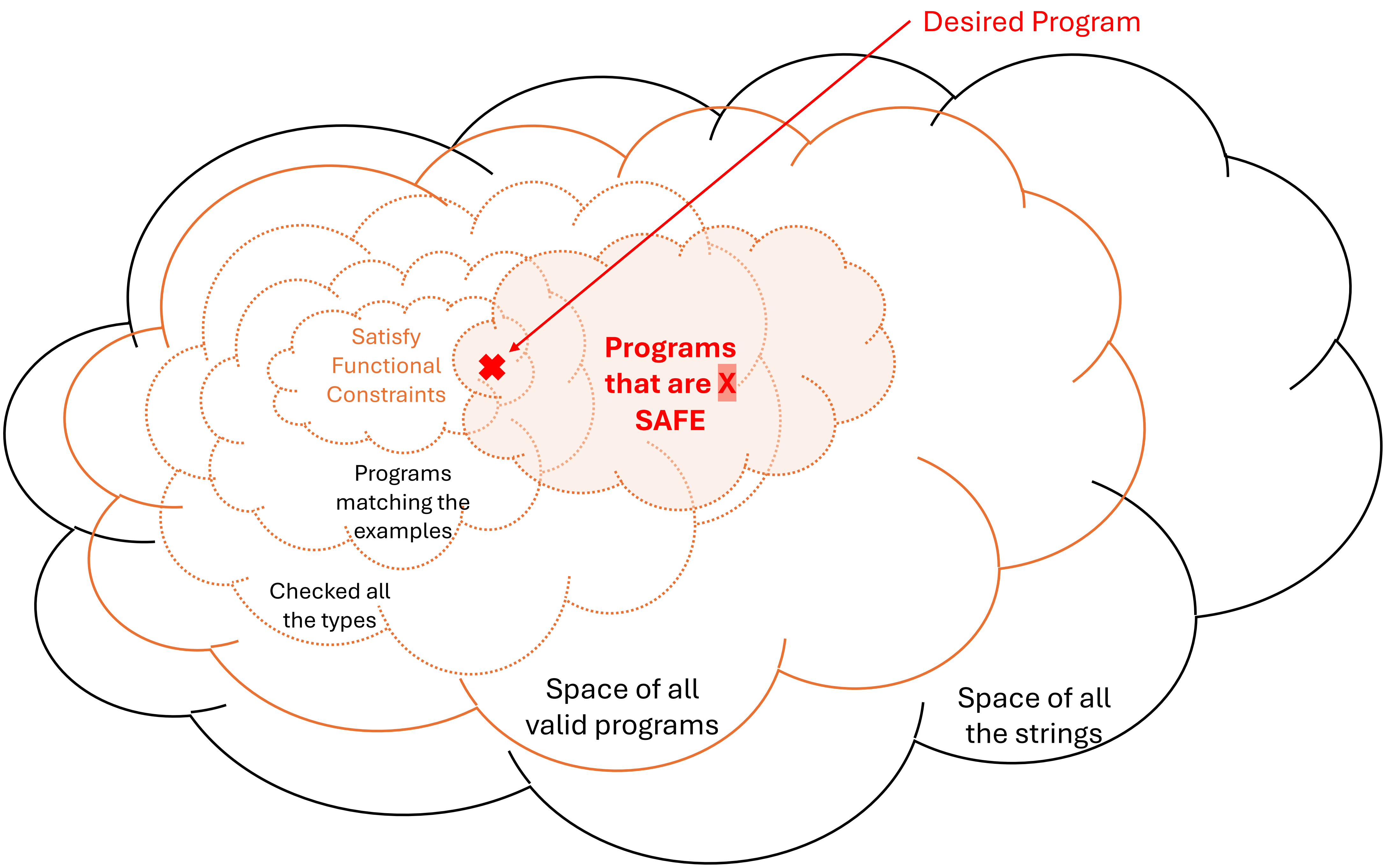

Programmer
Potentially Bad Program
Gives to
Shallow
Compiler
Sends to
Analyzer
Produces...
Potentially Safe Program
Programmer
Potentially Bad Program
Gives to
Strict
Compiler
Produces...
Safe Program

Takeaway

- There are many generally used languages with different safety features: memory safety, concurrency safety, smart-contract safety, …
- Instead of writing buggy code and use analysis tools to detect and fix them afterwards, we may prefer employing a better language that is safe-by-construct
    - The language may be more limiting, but is safer
    - A good safe language mitigates the limitations well and is fast
- We want to ask LLM to write programs in safer languages
    - It maybe harder to get the compiler to compile the program, but the compiled program already has good and provable safety properties
    - E.g., Generate Rust > C
    - E.g., Generate TypeScript > JavaScript


Desired Program
Satisfy Functional Constraints
Programs that are X SAFE
Programs matching the examples
Checked all the types
Space of all valid programs
Space of all the strings

Logistics – Week 10

- Oral Presentations
  - Emails are being sending out; plans established
  - Attendance will be noted down for oral presentation sessions!
- Final Projects
  - Final project proposal: 1 page PDF (due on Sunday)
  - Submit on GradeScope
  - Send email to the instructor questions