# Memory Safety

## CS107 Additional Topics, 3/10/2023

Jerry Chen (with materials adapted from Will Crichton)

# What is memory safety?

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A ***memory safe*** program is one that has ***no memory errors***

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But you've taken CS107 and know how to find and prevent these errors!
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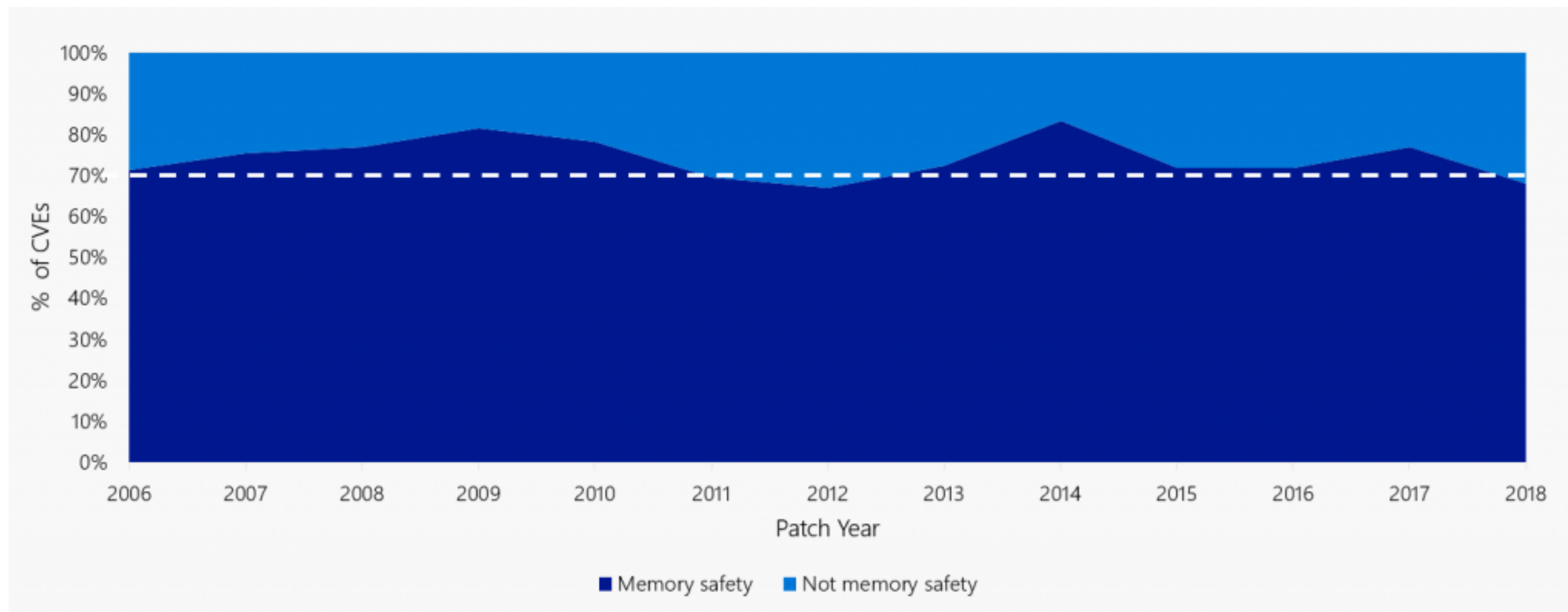
## 70% of all Microsoft vulnerabilities are memory errors




Microsoft Security Response Center. "A proactive approach to more secure code." 2019

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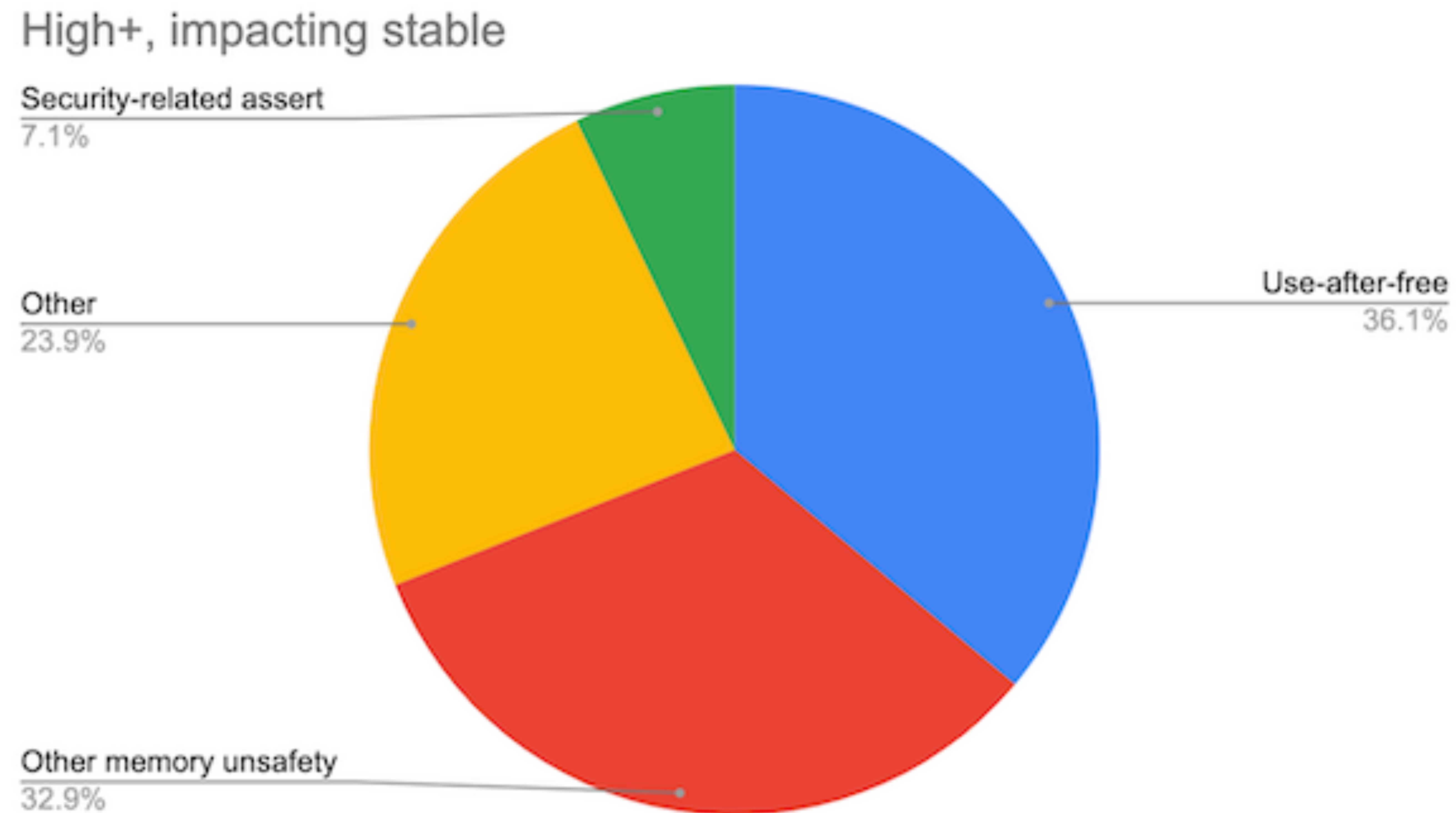


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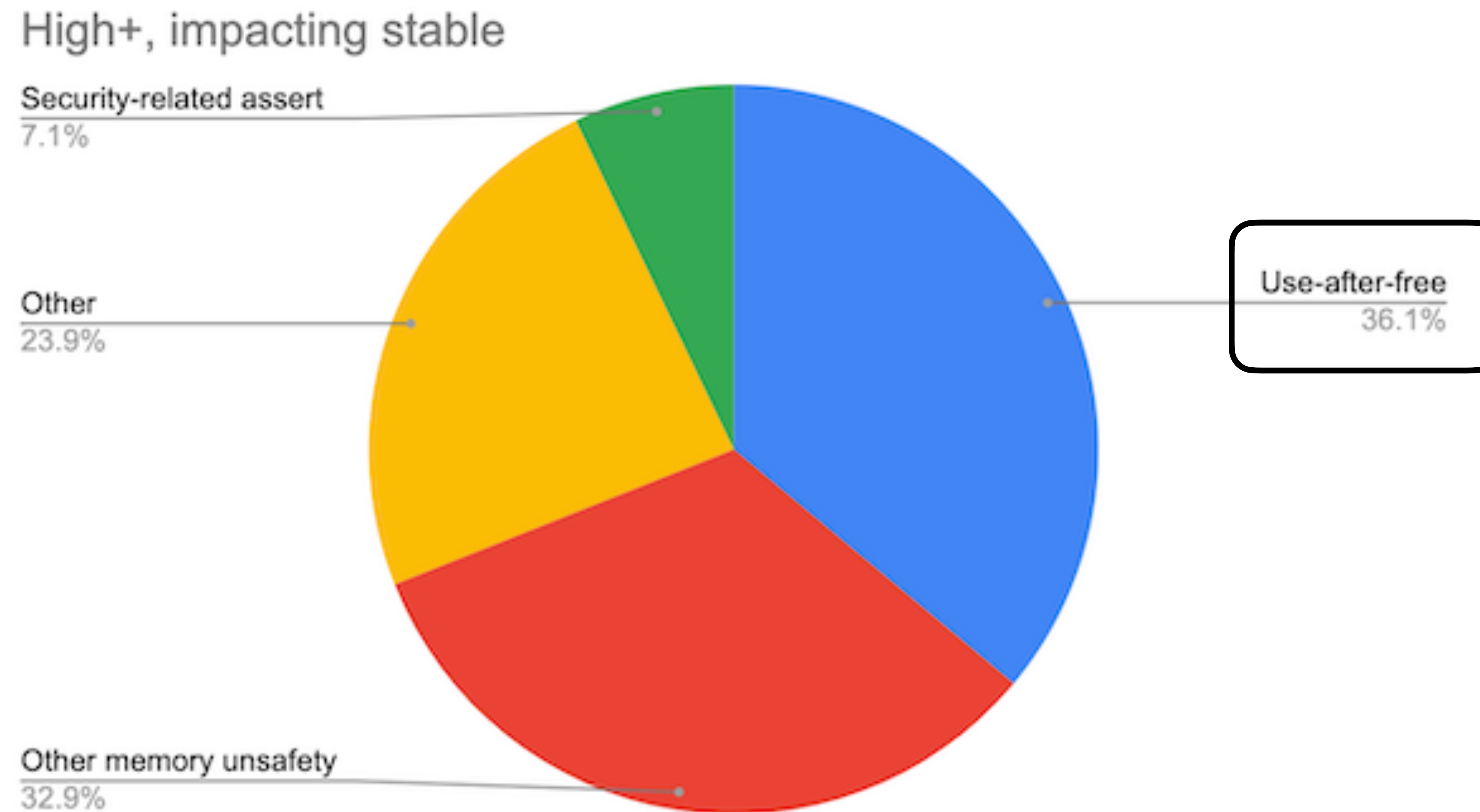


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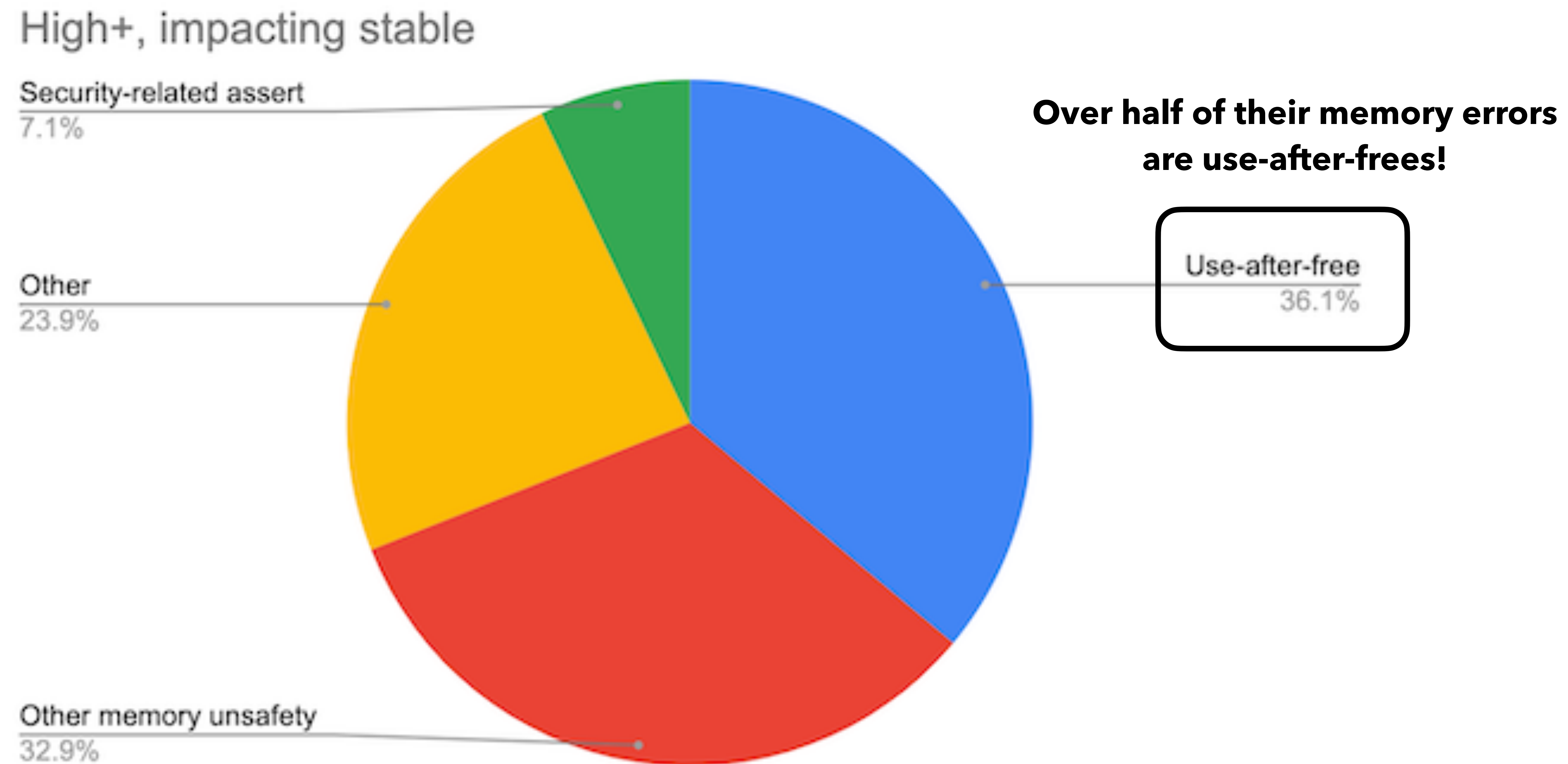


**Over half of their memory errors are use-after-frees!**

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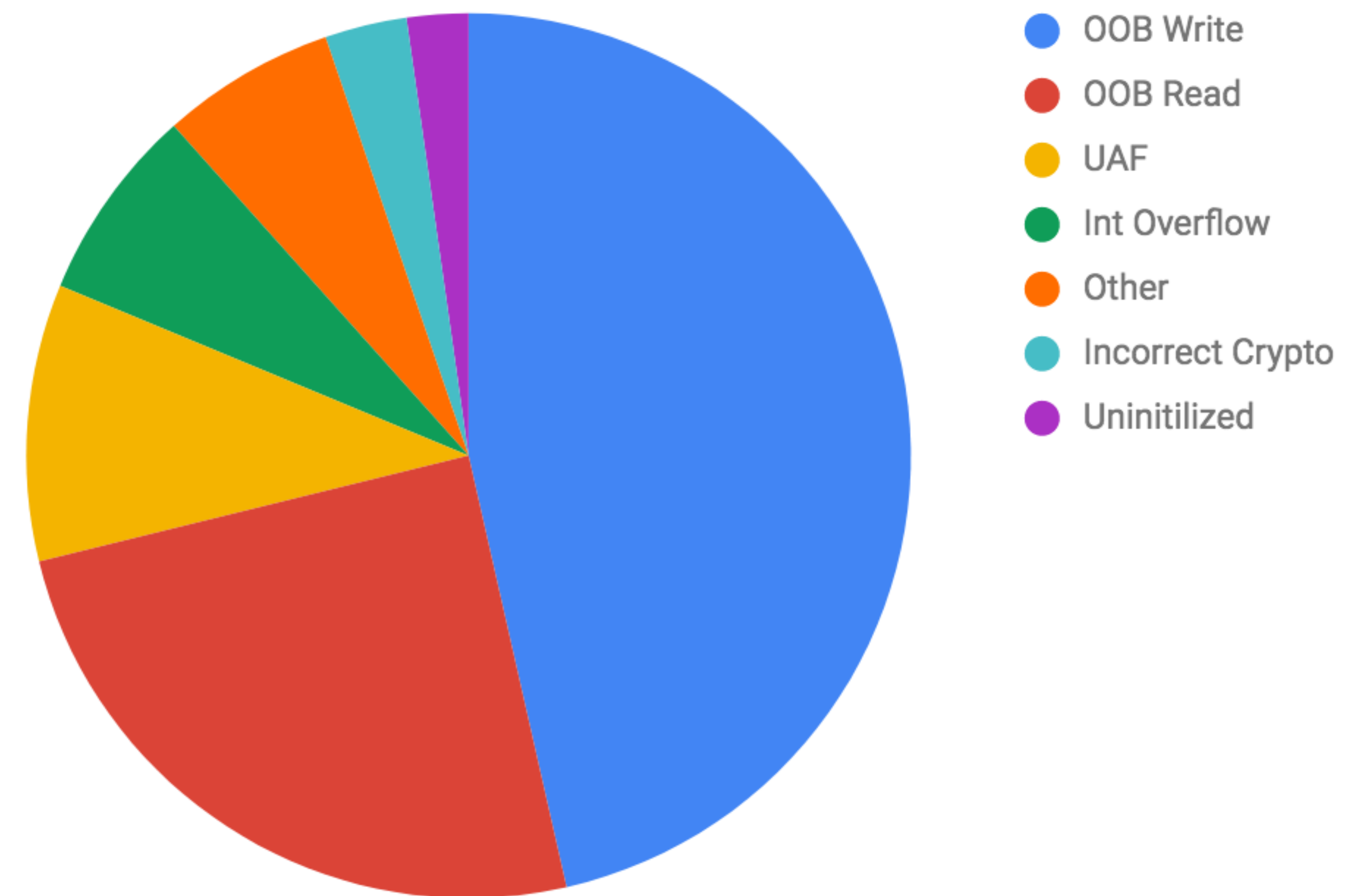


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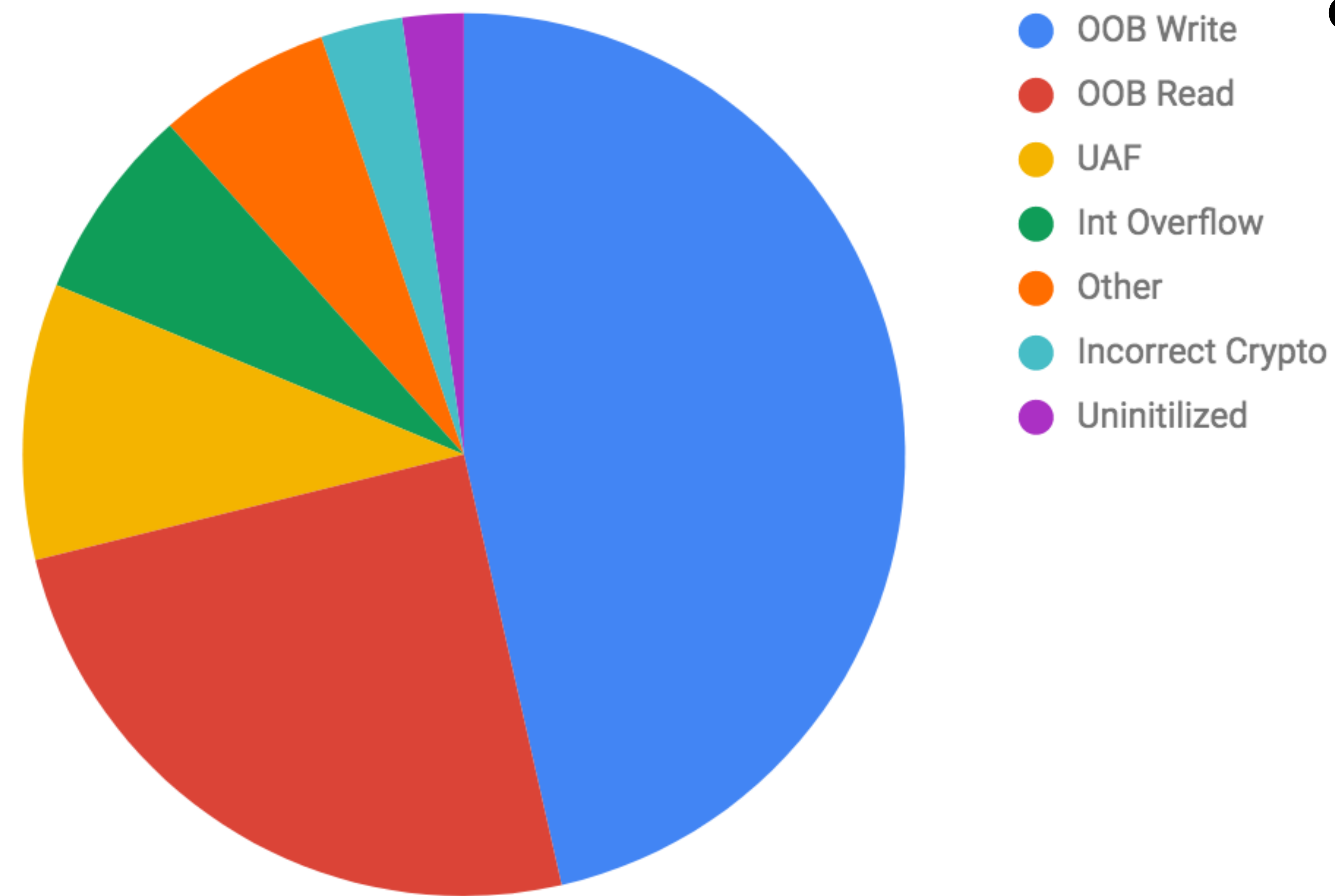


**Out-of-bound writes comprise nearly half of all Android security bugs!**

Google Security Blog. "Queue the Hardening Enhancements." 2019

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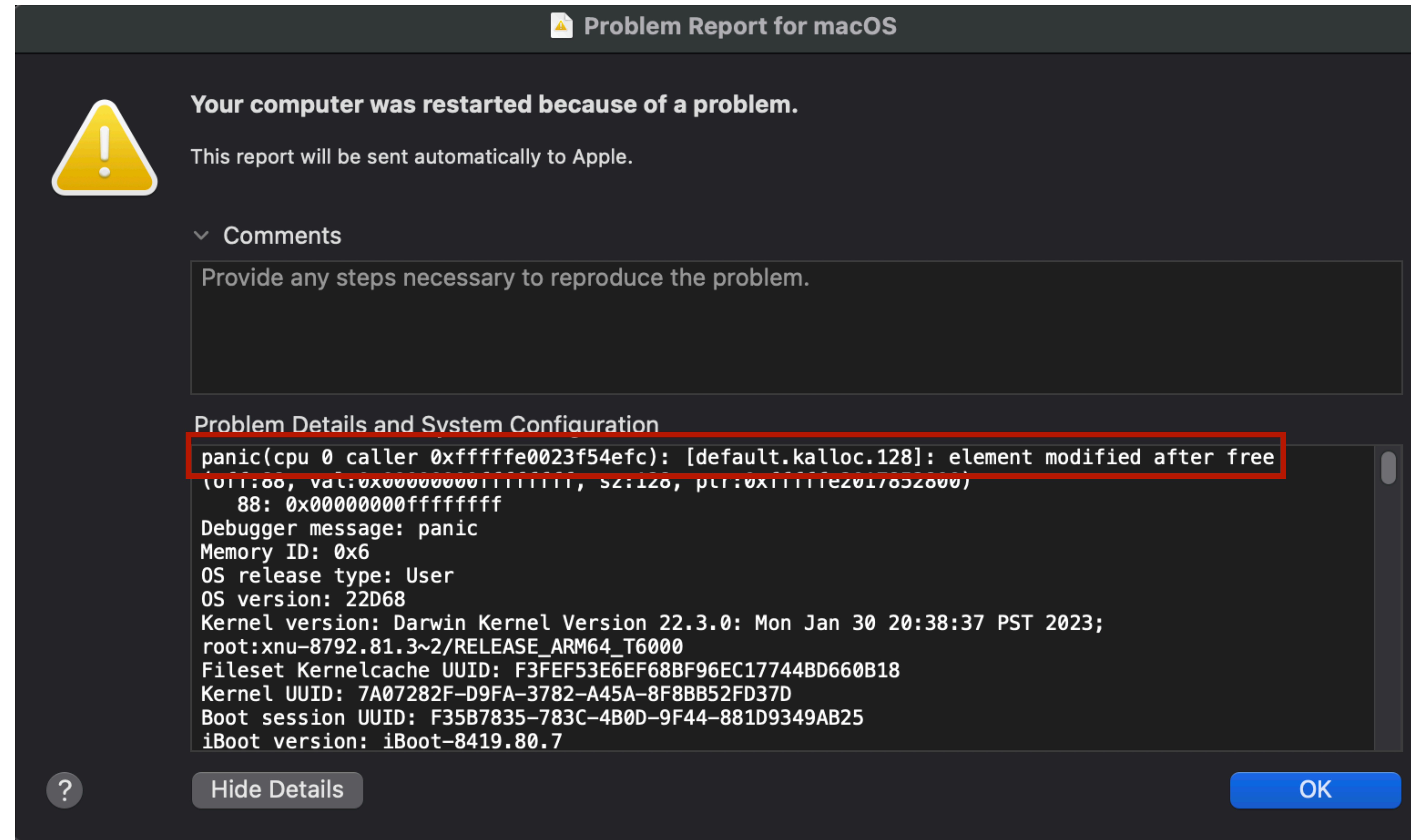

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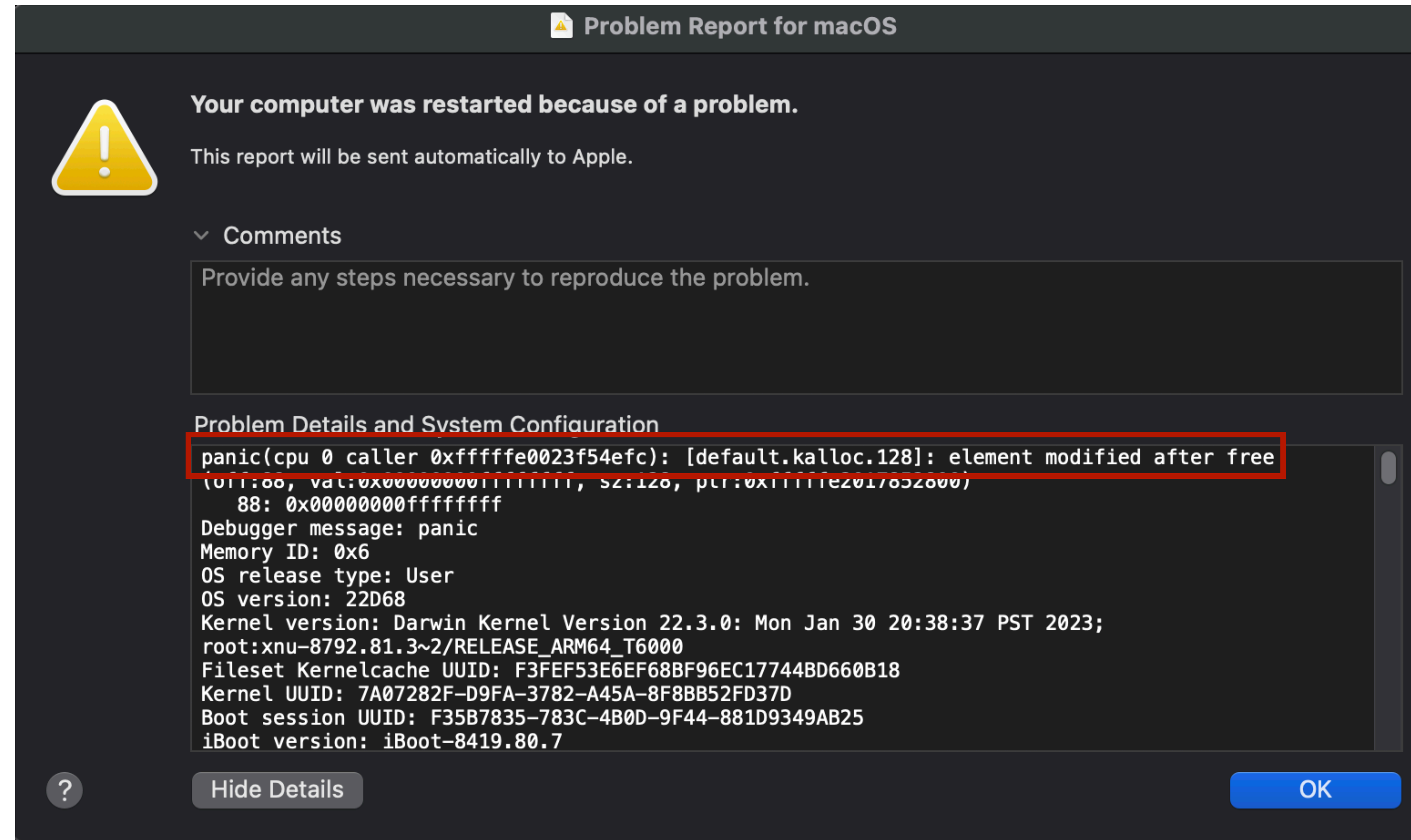


My laptop crashed because of a use-after-free bug!

# What can attackers do with memory errors?

**besides stealing money from an ATM**

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## EternalBlue and WannaCry (2017)

- **EternalBlue:** vulnerability found and kept secret by the NSA until it was leaked in April 2017
- **WannaCry** was a May 2017 ransomware attack using EternalBlue
  - Shut down critical health services and infrastructure
  - Economic damages on the order of $1 billion
- How? **Integer overflow** while determining much memory to allocate, leading to a **buffer overflow**

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- How? **Missing bounds check,** leading to a **buffer over-read**

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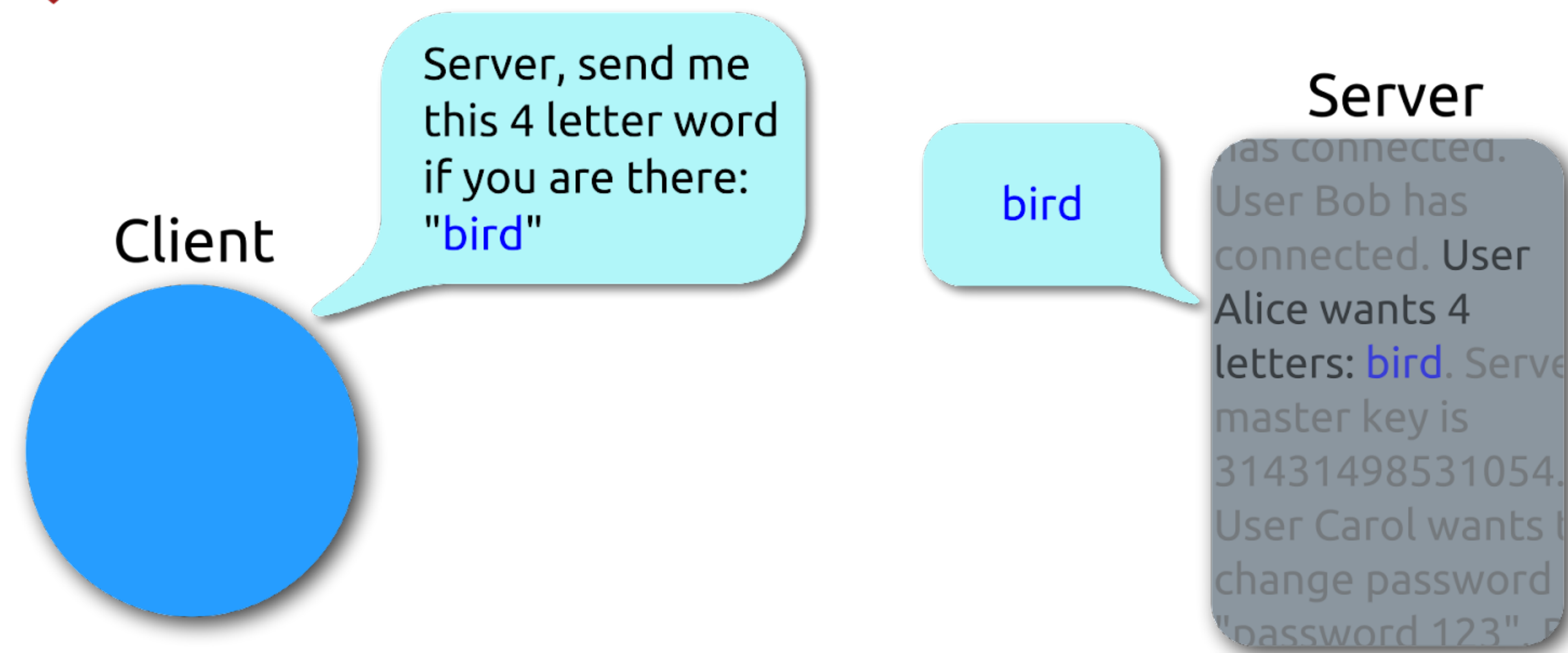
## Heartbleed (2014)

**Heartbeat – Normal usage**



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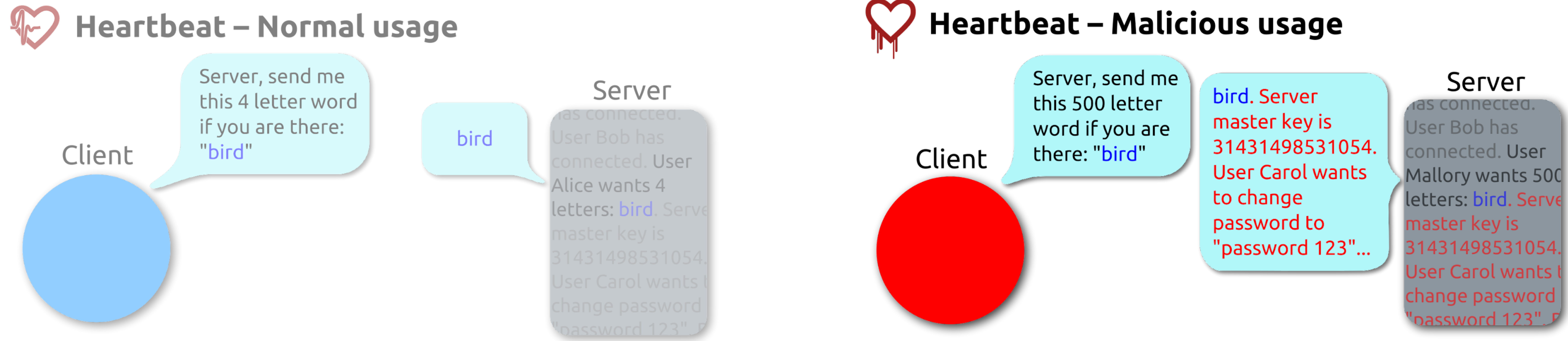

# What can attackers do with memory errors?

## Heartbleed (2014)

Forbes

ENERGY

What Heartbleed Means for Critical Infrastructure

CNET Your guide to a better future

News > Privacy

'Heartbleed' bug undoes Web encryption, reveals Yahoo passwords

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After 'Catastrophic' Security Bug, the Internet Needs a Password Reset

Security experts are calling Heartbleed, a bug in the internet's infrastructure, the worse thing they've seen in years. The bug is such problem, it may require what amounts to a massive password reset for the internet at large.

# Memory safety is difficult!

# Buggy Vector in C

## Struct Definition

```c
// Vec is short for "vector", a common term for a resizable array.
// For simplicity, our vector type can only hold ints.
typedef struct {
    int *data;     // Pointer to our array on the heap
    int length;    // How many elements are in our array
    int capacity; // How many elements our array can hold
} Vec;
```

# Buggy Vector in C

## What's wrong here?

```c
Vec *vec_create() {
    Vec vec;
    vec.data = malloc(sizeof(int));
    vec.length = 0;
    vec.capacity = 1;

    return &vec;
}
```

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**Our Vec is stack-allocated!**

We return a pointer, but that pointer will be invalid because the stack-allocated Vec will be destroyed when the function returns.

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```
Vec *vec_create() {
    Vec *vec = malloc(sizeof(Vec));
    vec->data = malloc(sizeof(int));
    vec->length = 0;
    vec->capacity = 1;

    return vec;
}
```

# Buggy Vector in C

## What's wrong here?

```
void vec_push(Vec *vec, int n) {
    // Double the capacity of our vector if it is full
    if (vec->length == vec->capacity) {
        vec->data = realloc(vec->data, vec->capacity * 2);
        assert(vec->data != NULL);

        vec->capacity *= 2;
    }

    // Append the element to the end of our vector
    vec->data[vec->length] = n;
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**Not realloc'ing with the correct size!**

realloc requires the number of bytes, not elements

Multiply by sizeof(int)

# Buggy Vector in C

## What's wrong here?

```
void main() {
    Vec *vec = vec_create();
    vec_push(vec, 107);
    int *n = &vec->data[0];

    vec_push(vec, 111);
    printf("%d\n", *n);

    free(vec);
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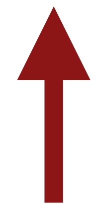

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**2. Is it safe to dereference the n pointer here?**

**No!** vec_push() will resize the data array by calling realloc(). This can **invalidate** the pointer to old memory!

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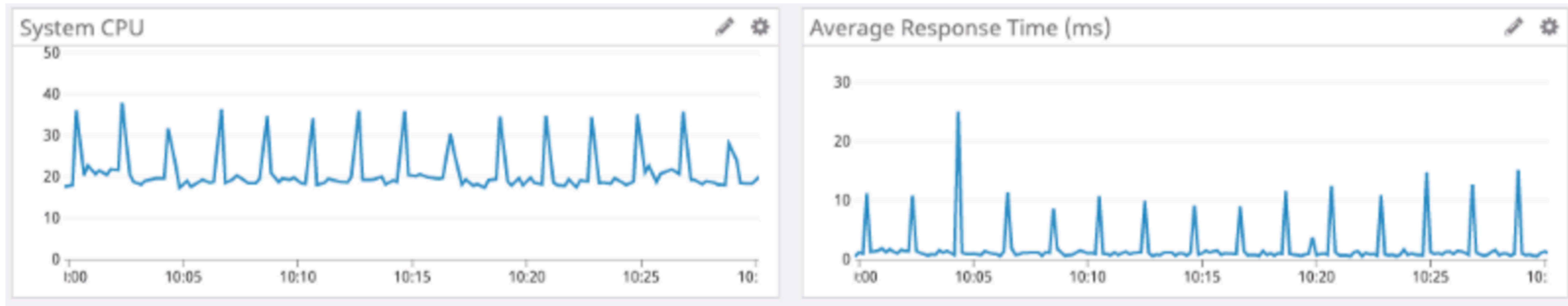
  - Sometimes at the cost of performance…

# Memory safe languages

## Cost of runtime safety

This graph shows a couple performance metrics for one of Discord's core services to keep track of what messages a user has read (lower is better)

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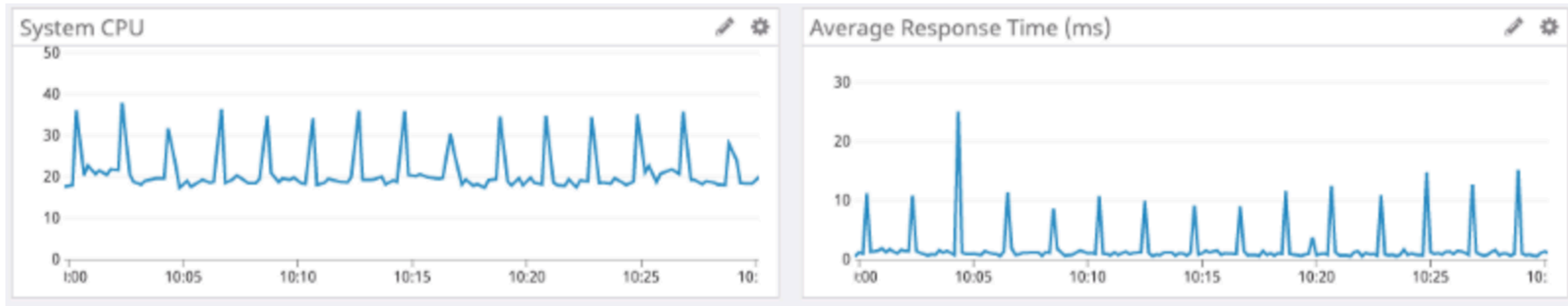


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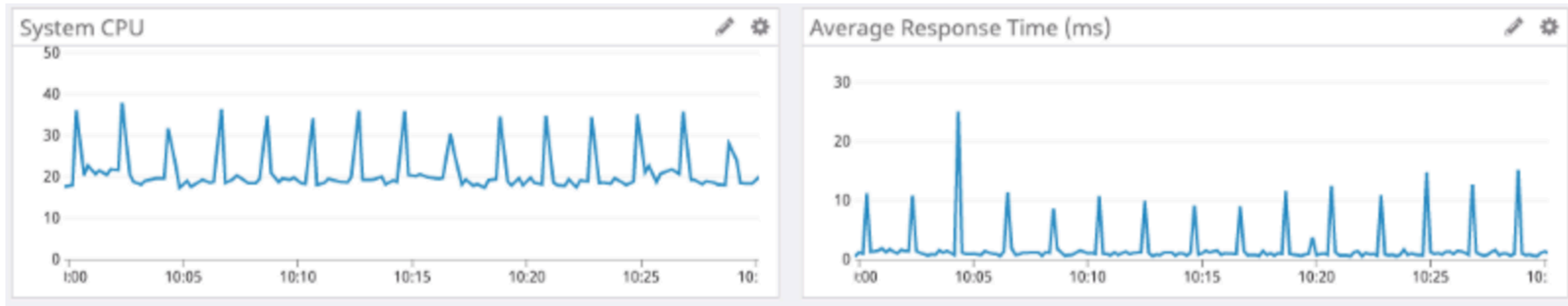


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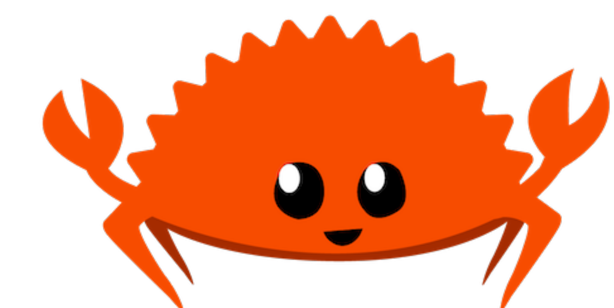

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- Each value in memory has a variable called its *owner*
- A value can only have one owner at a time
- When the owner goes out of scope, the value is “dropped” (deallocated)

# Rust Ownership Model

```
{
    let s1: String = String::from("Hello");
    println!("{}", s1);
}
```

**Output:**

```
Hello
```

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**Stack** **Heap**

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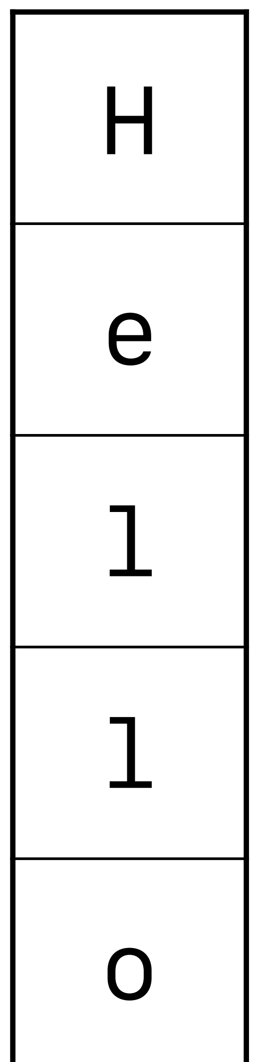


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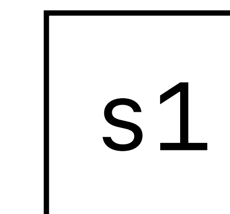


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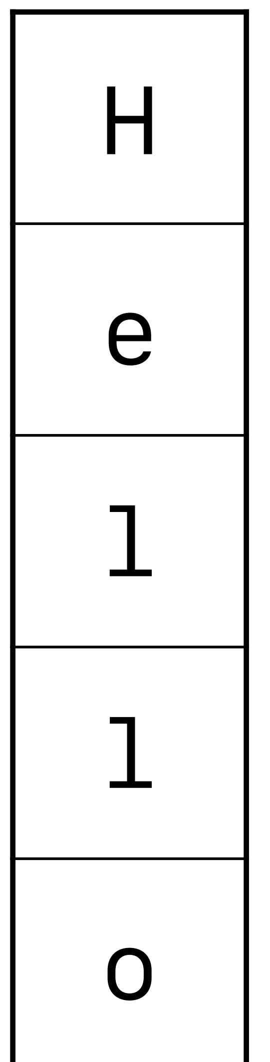


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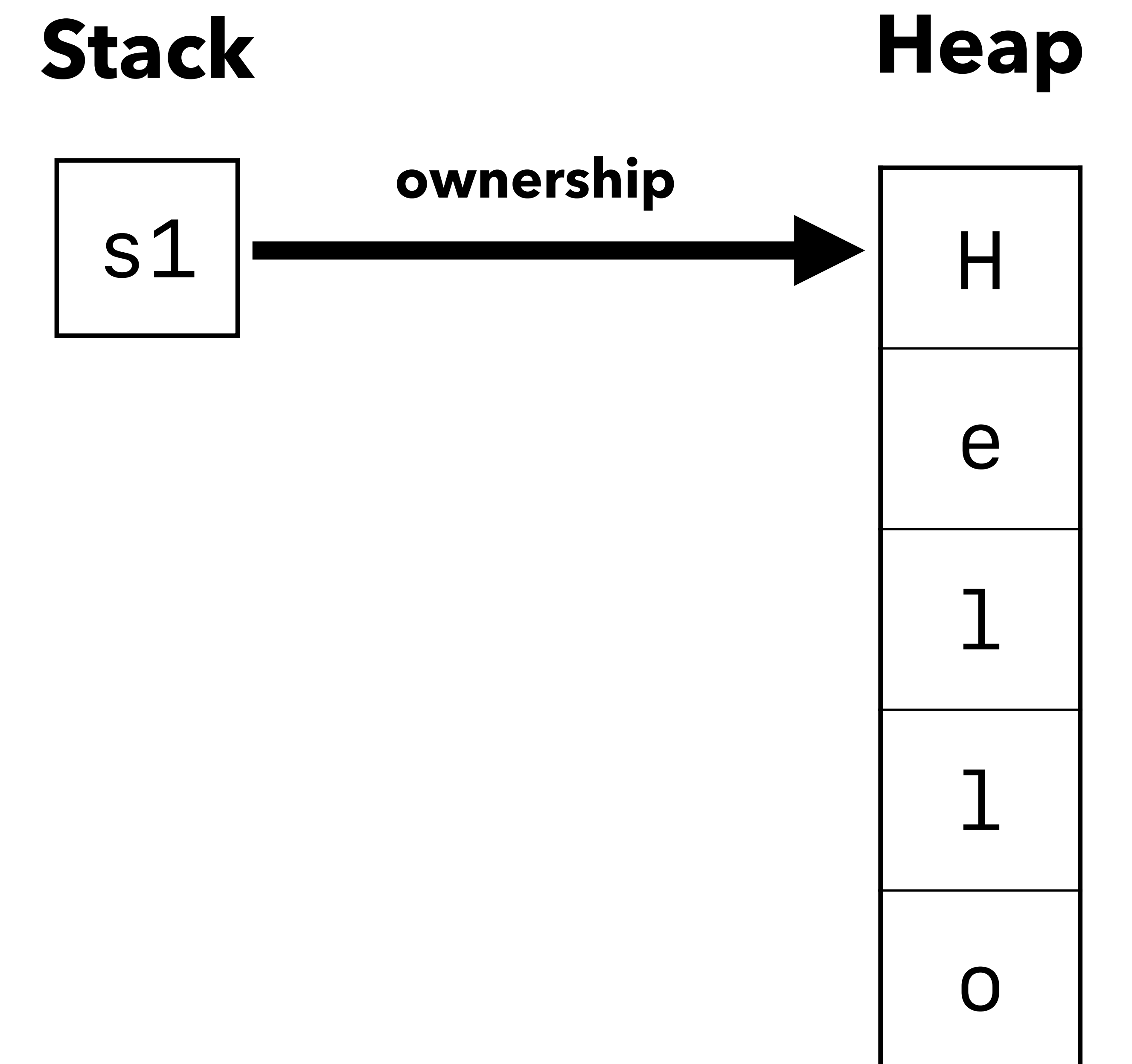


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# Rust Ownership Model

```
{
    let s1: String = String::from("Hello");
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}
```
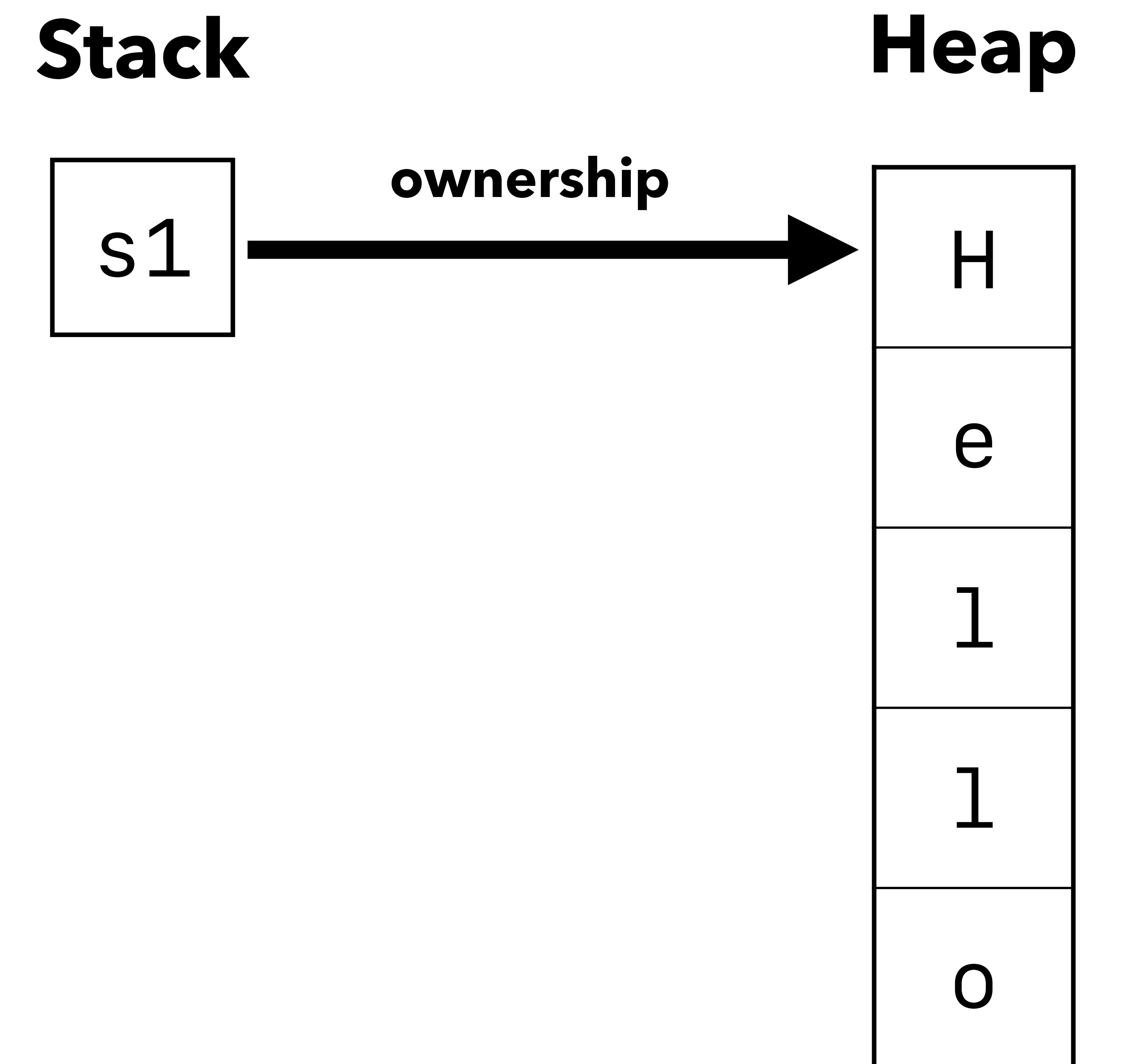

Compiler sees end of scope and drops s1 to deallocate the string. Hooray for no memory leaks!

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## Preventing use-after-free

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```
error[E0382]: borrow of moved value: `s1`
 --> src/main.rs:5:24
  |
3 |         let s1: String = String::from("Hello");
  |             -- move occurs because `s1` has type `String`, which does not implement the `Copy` trait
4 |         drop(s1);
  |              -- value moved here
5 |         println!("{}", s1);
  |                        ^^ value borrowed here after move
  |
```

# Rust Ownership Model

## This code won’t compile!

```
{
    let s1: String = String::from(“Hello");
    let s2: String = s1;
    println!("{}", s1);
    println!("{}", s2);
}
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**Values are “moved” by default: ownership is transferred to s2**

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  |                          -- value moved here
5 |         println!("{}", s1);
  |                        ^^ value borrowed here after move
  |
```

# Rust Ownership Model

## This code won't compile!

```
{
    let s1: String = String::from("Hello");
    let s2: String = s1;
    println!("{}", s1);
    println!("{}", s2);
}
```

Values are "moved" by default: ownership is transferred to s2

**Stack** **Heap**

```
error[E0382]: borrow of moved value: `s1`
 --> src/main.rs:5:24
  |
3 |         let s1: String = String::from("Hello");
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# Rust Ownership Model

## This code won't compile!

```
{
    let s1: String = String::from("Hello");
    let s2: String = s1;
    println!("{}", s1);
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}
```

Values are "moved" by default: ownership is transferred to s2

Stack

Heap

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```
error[E0382]: borrow of moved value: `s1`
 --> src/main.rs:5:24
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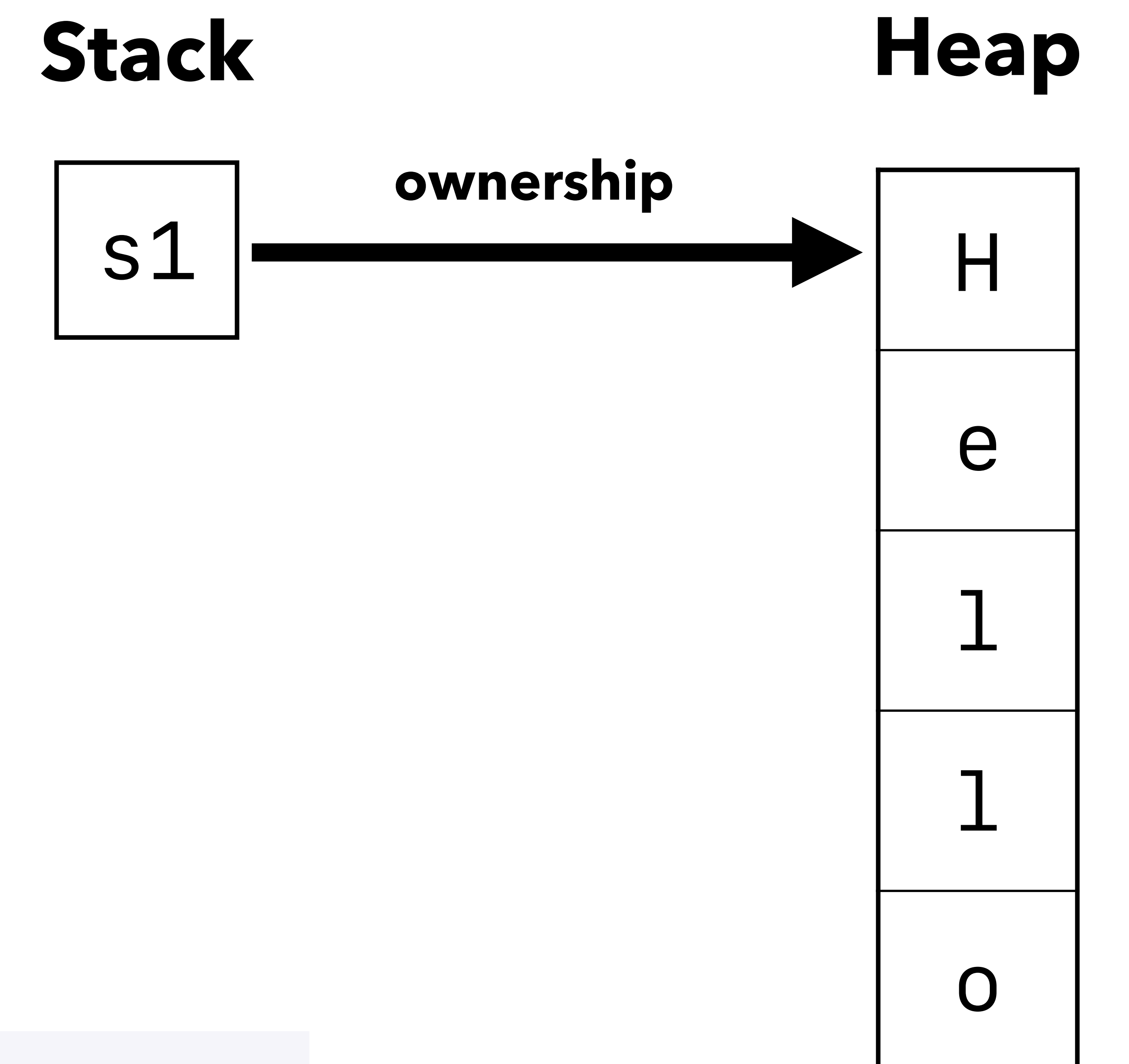
5 |         println!("{}", s1);
  |                        ^^ value borrowed here after move
  |
```

# Rust Ownership Model

## This code won’t compile!

```
{
    let s1: String = String::from(“Hello");
    let s2: String = s1;
    println!("{}", s1);
    println!("{}", s2);
}
```

Values are “moved” by default: ownership is transferred to s2

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error[E0382]: borrow of moved value: `s1`
 --> src/main.rs:5:24
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# Rust Ownership Model

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```
{
    let s1: String = String::from("Hello");
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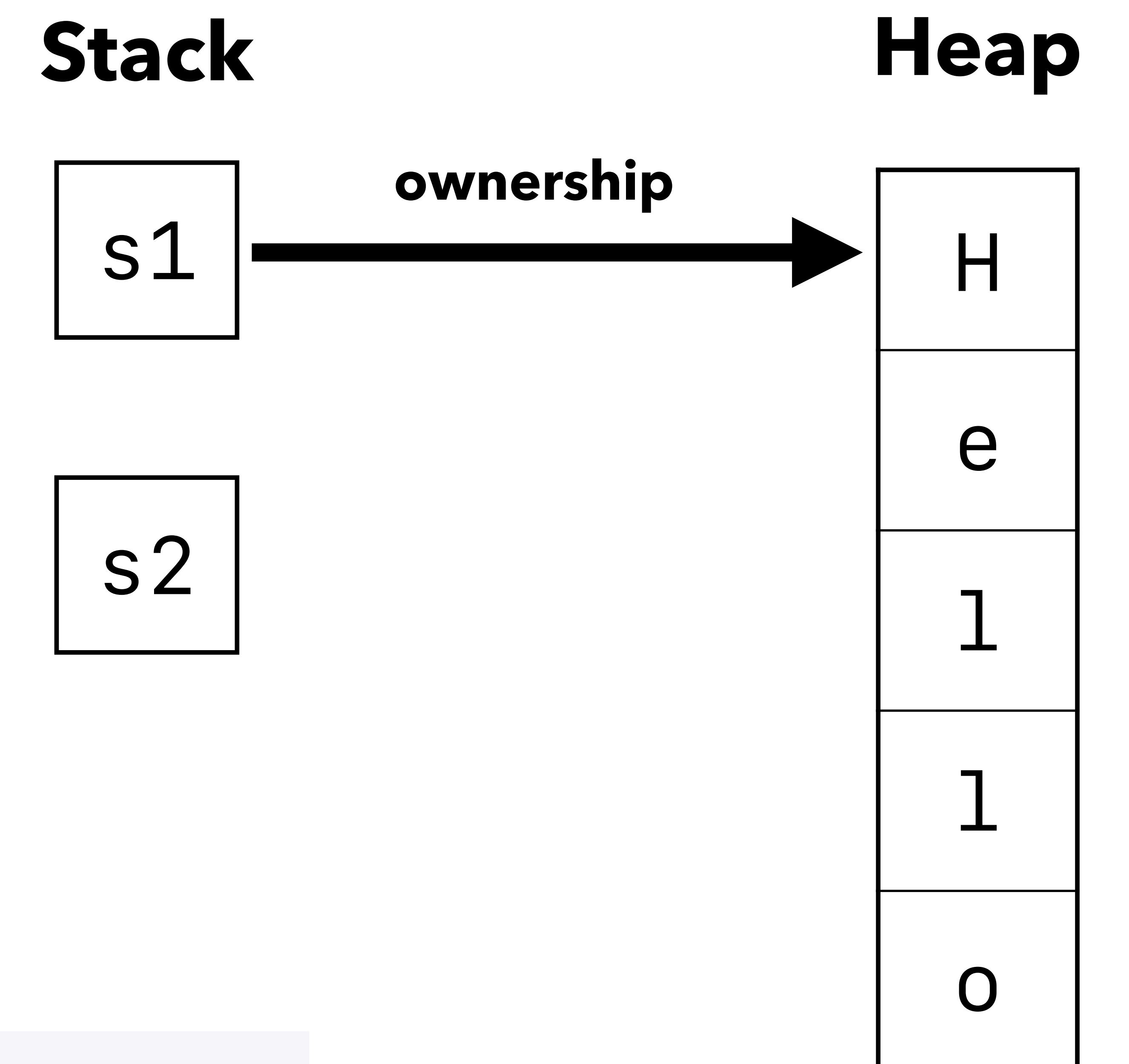
    println!("{}", s1);
    println!("{}", s2);
}
```

Values are "moved" by default: ownership is transferred to s2




```
error[E0382]: borrow of moved value: `s1`
 --> src/main.rs:5:24
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3 |         let s1: String = String::from("Hello");
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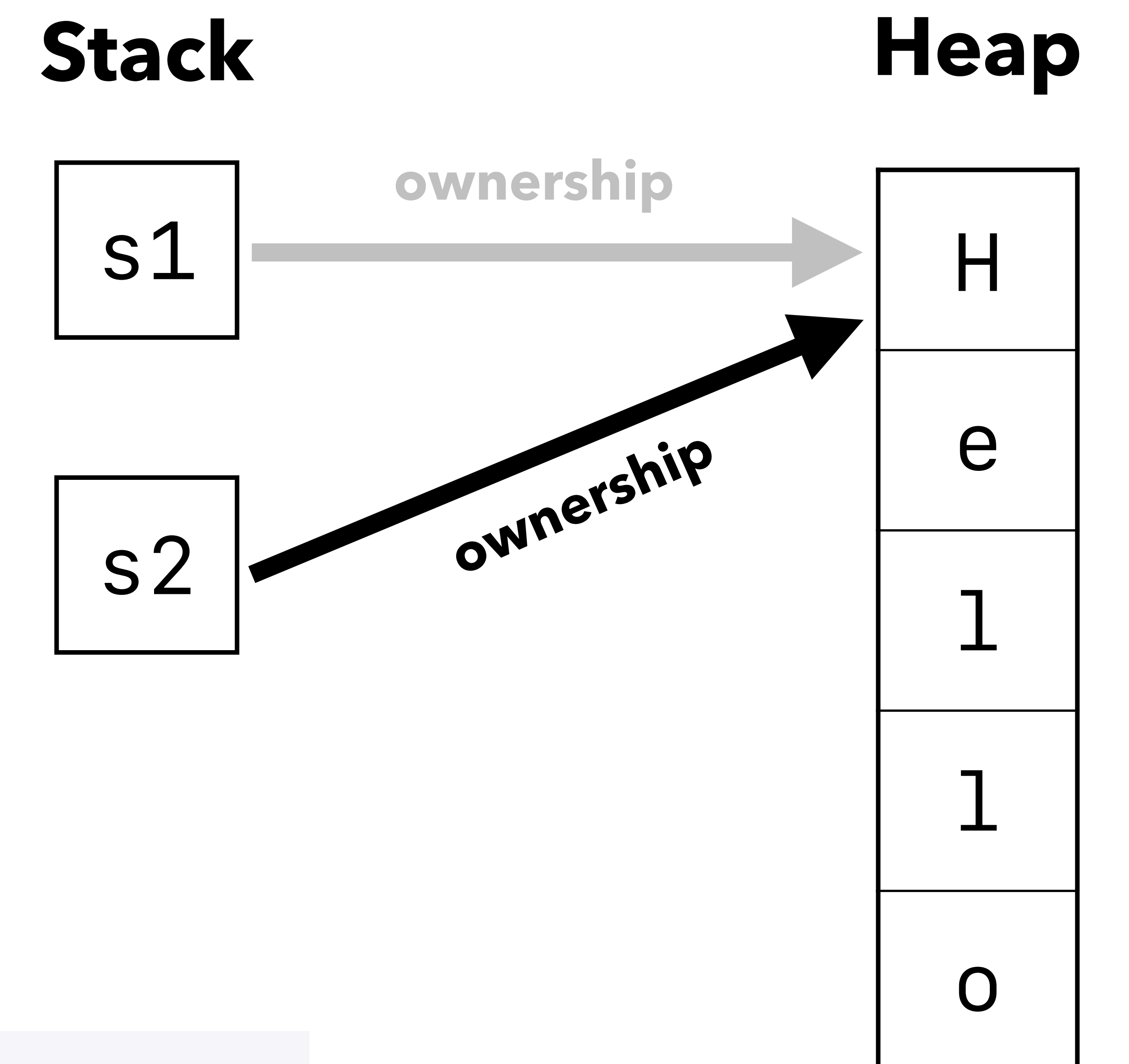
```

# Rust Ownership Model

## This code won’t compile!

```
{
    let s1: String = String::from(“Hello");
    let s2: String = s1;
    println!("{}", s1);
    println!("{}", s2);
}
```

Values are “moved” by default: ownership is transferred to s2




```
error[E0382]: borrow of moved value: `s1`
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```

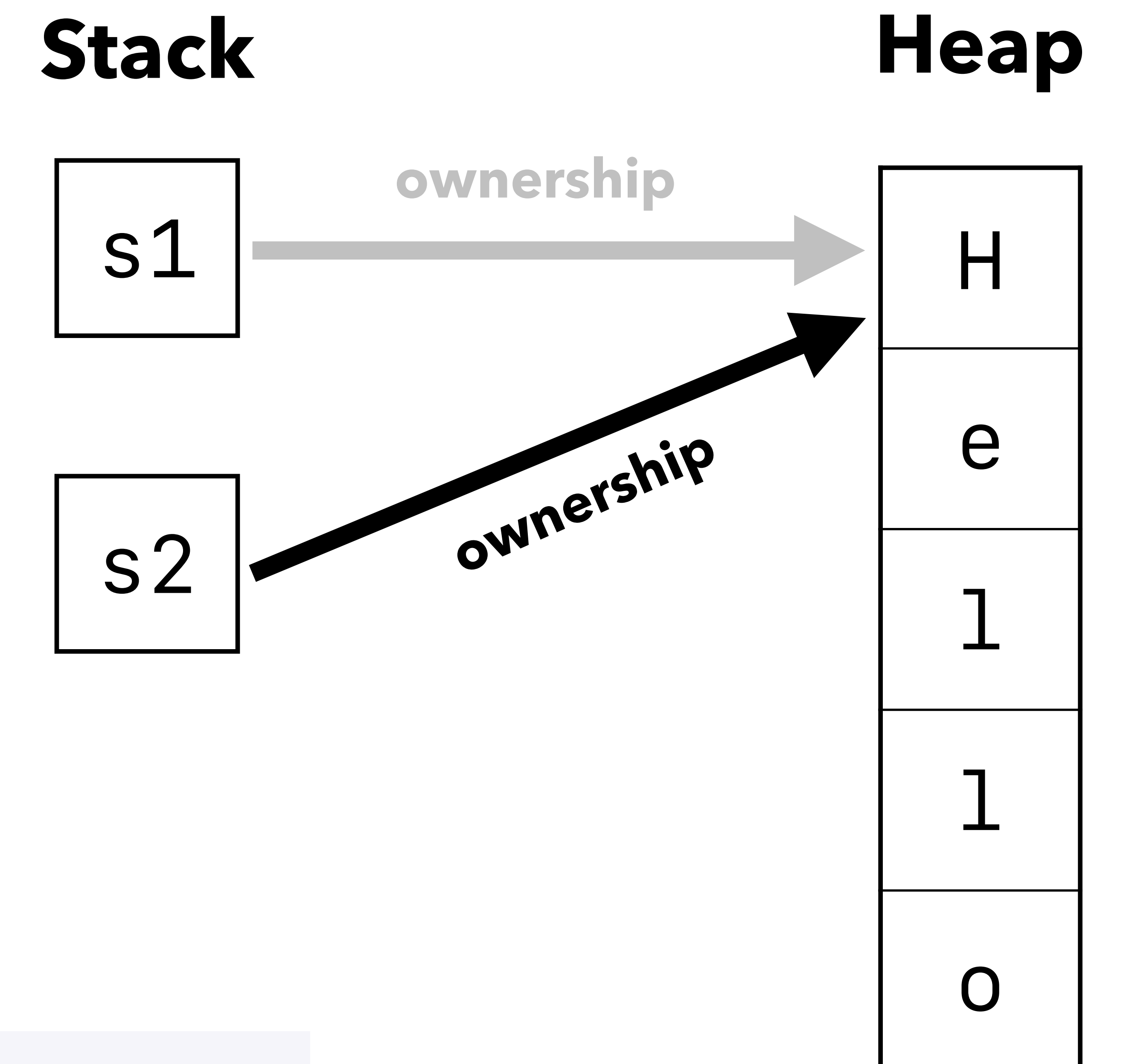
# Rust Ownership Model

## This code won't compile!

```
{
    let s1: String = String::from(“Hello");
    let s2: String = s1;
    println!("{}", s1);
    println!("{}", s2);
}
```

Values are "moved" by default: ownership is transferred to s2

The compiler drops both s1 and s2. Without the ownership restriction, that would be a double free!




```
error[E0382]: borrow of moved value: `s1`
 --> src/main.rs:5:24
  |
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4 |         let s2: String = s1;
  |                          -- value moved here
5 |         println!("{}", s1);
  |                        ^^ value borrowed here after move
  |
```

# Rust Ownership Model

## Borrowing

```
{
    let s1: String = String::from("Hello");
    let s2: &String = &s1;
    println!("{}", s1);
    println!("{}", s2);
}
```

**Output:**

```
Hello
Hello
```

# Rust Ownership Model

## Borrowing

```
{
    let s1: String = String::from("Hello");
    let s2: &String = &s1;
    println!("{}", s1);
    println!("{}", s2);
}
```

s2 “borrows” a reference to s1

**Output:**

```
Hello
Hello
```

# Rust Ownership Model

## Borrowing

```
{
    let s1: String = String::from("Hello");
    let s2: &String = &s1;
    println!("{}", s1);
    println!("{}", s2);
}
```

s2 “borrows” a reference to s1

**Stack**

**Heap**

**Output:**

```
Hello
Hello
```

# Rust Ownership Model

## Borrowing

```
{
    let s1: String = String::from("Hello");
    let s2: &String = &s1;
    println!("{}", s1);
    println!("{}", s2);
}
```

s2 “borrows” a reference to s1

**Stack**

**Heap**

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**Output:**

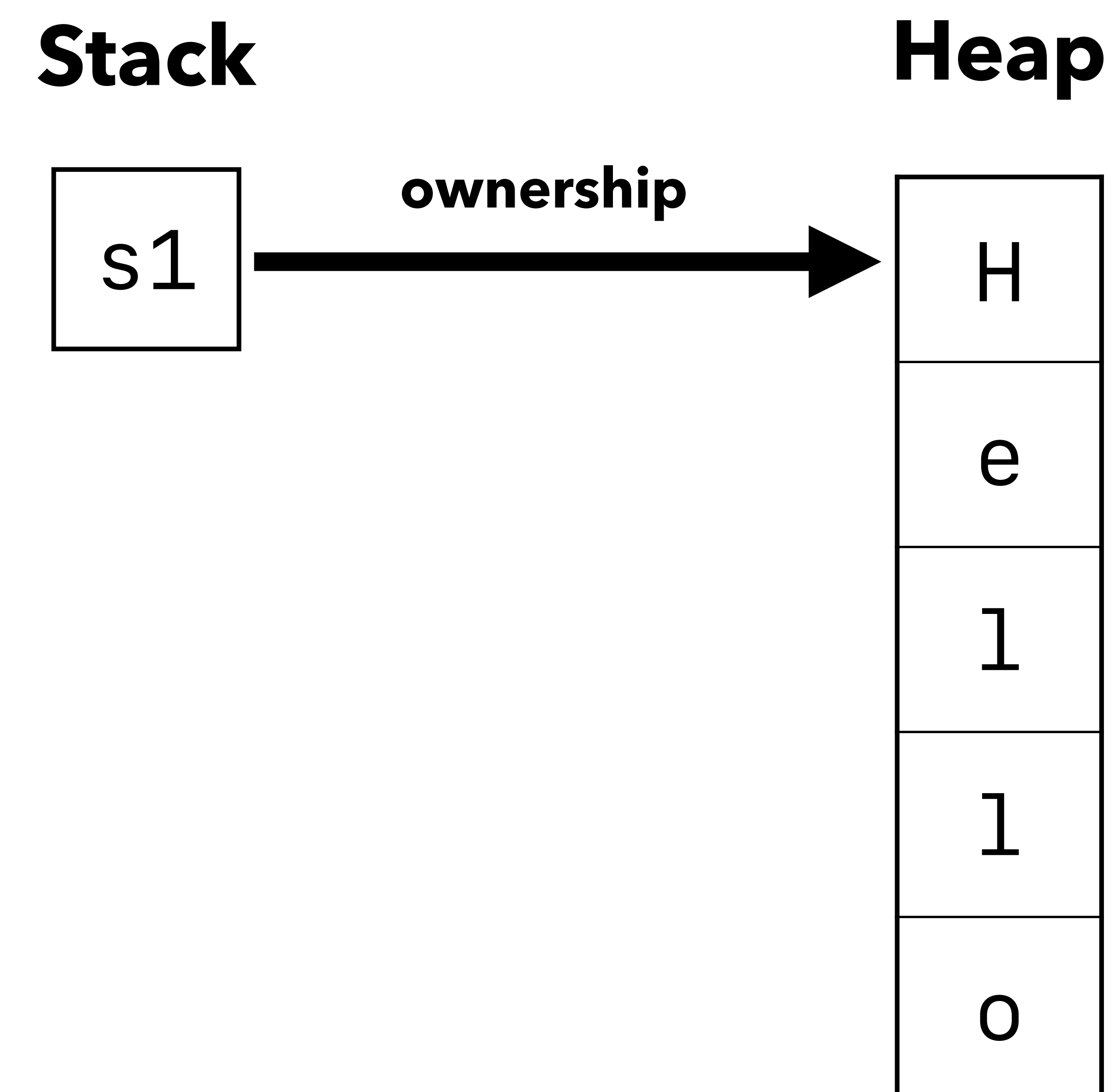
```
Hello
Hello
```

# Rust Ownership Model

## Borrowing

```
{
    let s1: String = String::from("Hello");
    let s2: &String = &s1;
    println!("{}", s1);
    println!("{}", s2);
}
```

s2 "borrows" a reference to s1




**Output:**

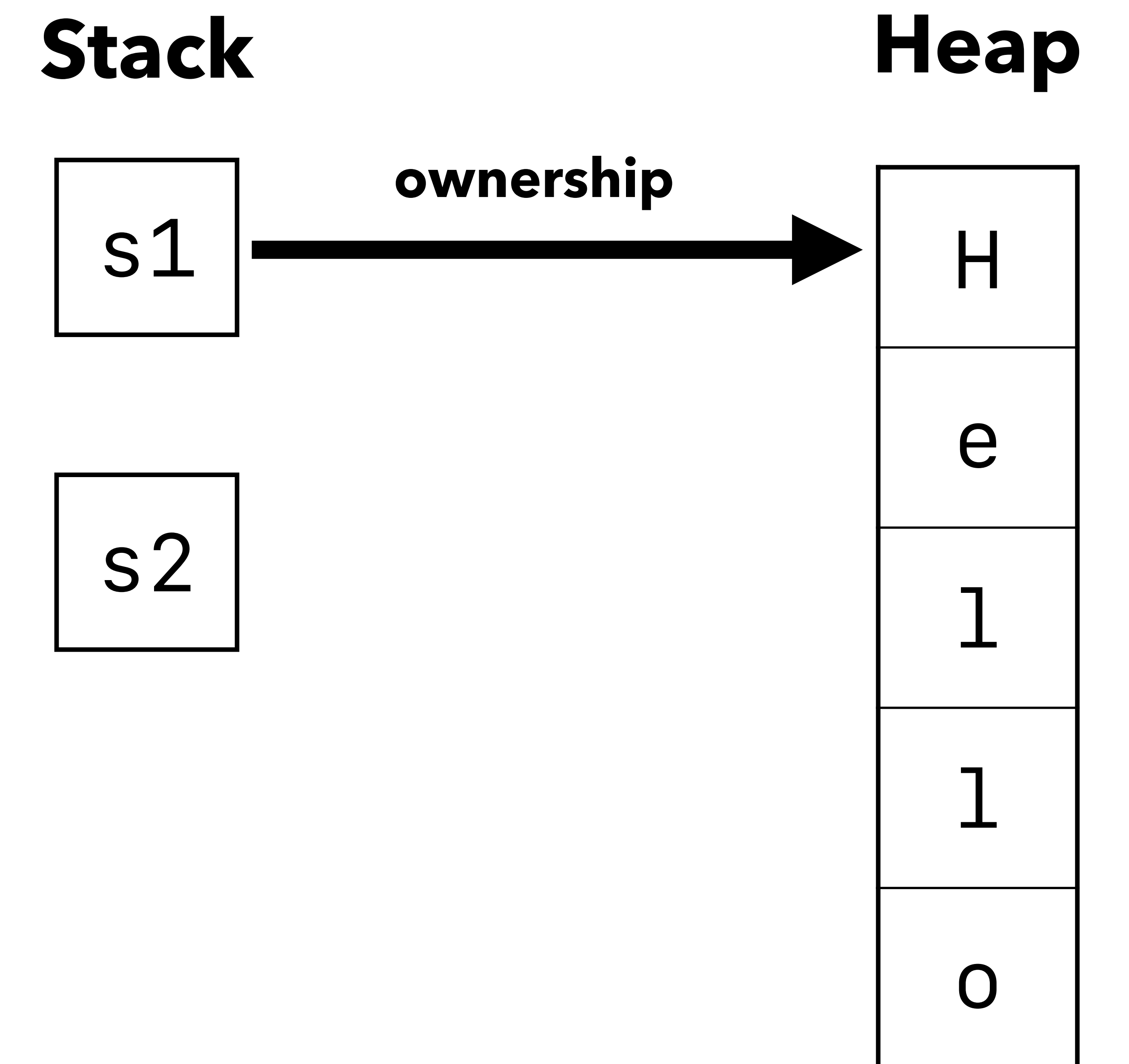
```
Hello
Hello
```

# Rust Ownership Model

## Borrowing

```
{
    let s1: String = String::from("Hello");
    let s2: &String = &s1;
    println!("{}", s1);
    println!("{}", s2);
}
```

s2 “borrows” a reference to s1




**Output:**

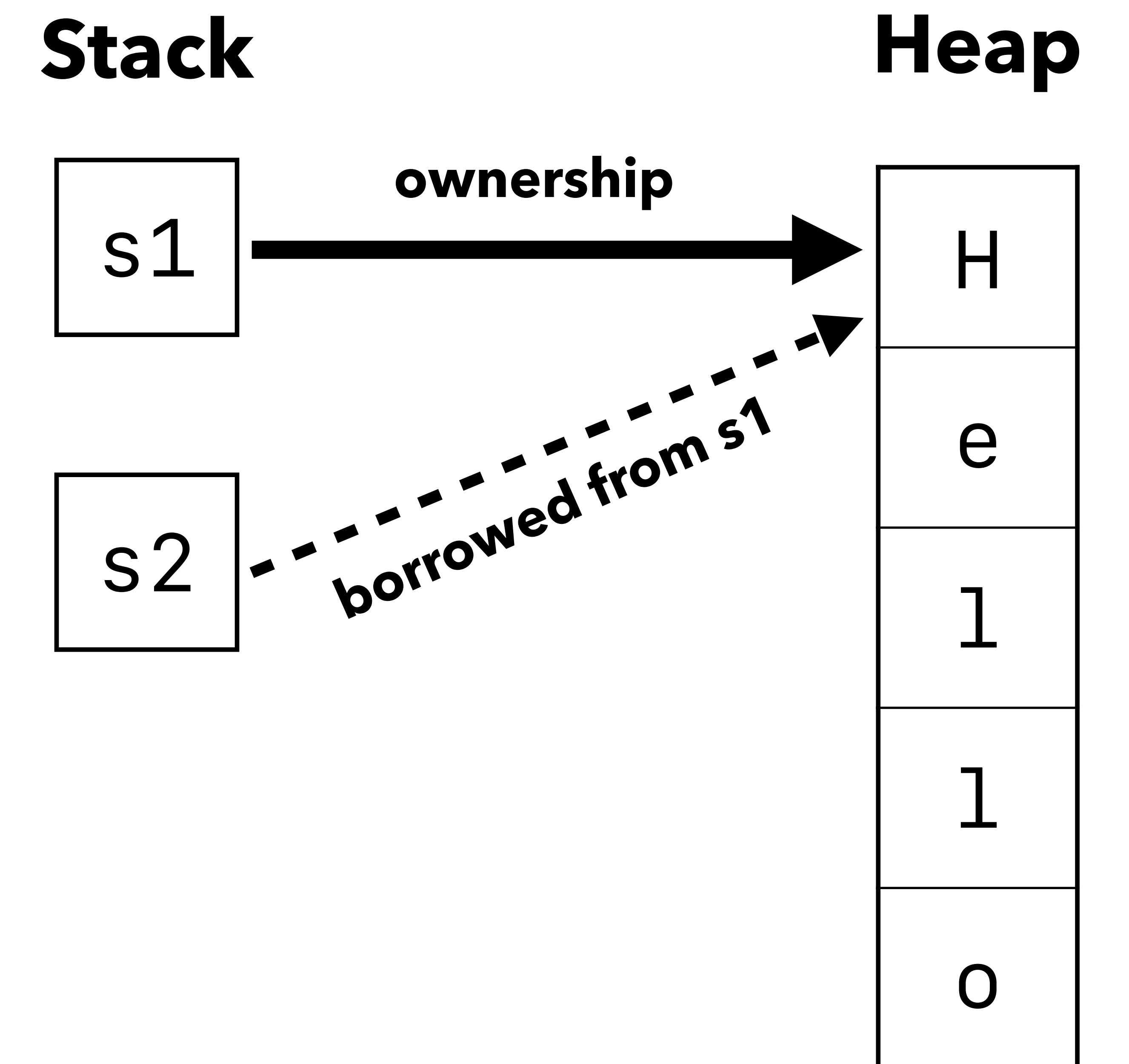
```
Hello
Hello
```

# Rust Ownership Model

## Borrowing

```
{
    let s1: String = String::from("Hello");
    let s2: &String = &s1;
    println!("{}", s1);
    println!("{}", s2);
}
```

s2 “borrows” a reference to s1




**Output:**

```
Hello
Hello
```

# Rust Ownership Model

## This code won't compile!

```
{
    let mut s1: String = String::from("Hello");
    let s2: &String = &s1;
    s1 = String::from(“World");
    println!("{}", s1);
    println!("{}", s2);
}
```

# Rust Ownership Model

## This code won’t compile!

```
{
    let mut s1: String = String::from("Hello");
    let s2: &String = &s1;
    s1 = String::from(“World");
    println!("{}", s1);
    println!("{}", s2);
}
```

```
error[E0506]: cannot assign to `s1` because it is borrowed
 --> src/main.rs:5:9
  |
4 |         let s2: &String = &s1;
  |                           --- borrow of `s1` occurs here
5 |         s1 = String::from("Hello");
  |         ^^ assignment to borrowed `s1` occurs here
6 |         println!("{}", s1);
7 |         println!("{}", s2);
  |                        -- borrow later used here
```

# Rust Ownership Model

## This code won't compile!

Stack

Heap

```
{
    let mut s1: String = String::from("Hello");
    let s2: &String = &s1;
    s1 = String::from("World");
    println!("{}", s1);
    println!("{}", s2);
}
```

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# Rust Ownership Model

## This code won't compile!

Stack

Heap

```
{
    let mut s1: String = String::from("Hello");
    let s2: &String = &s1;
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```

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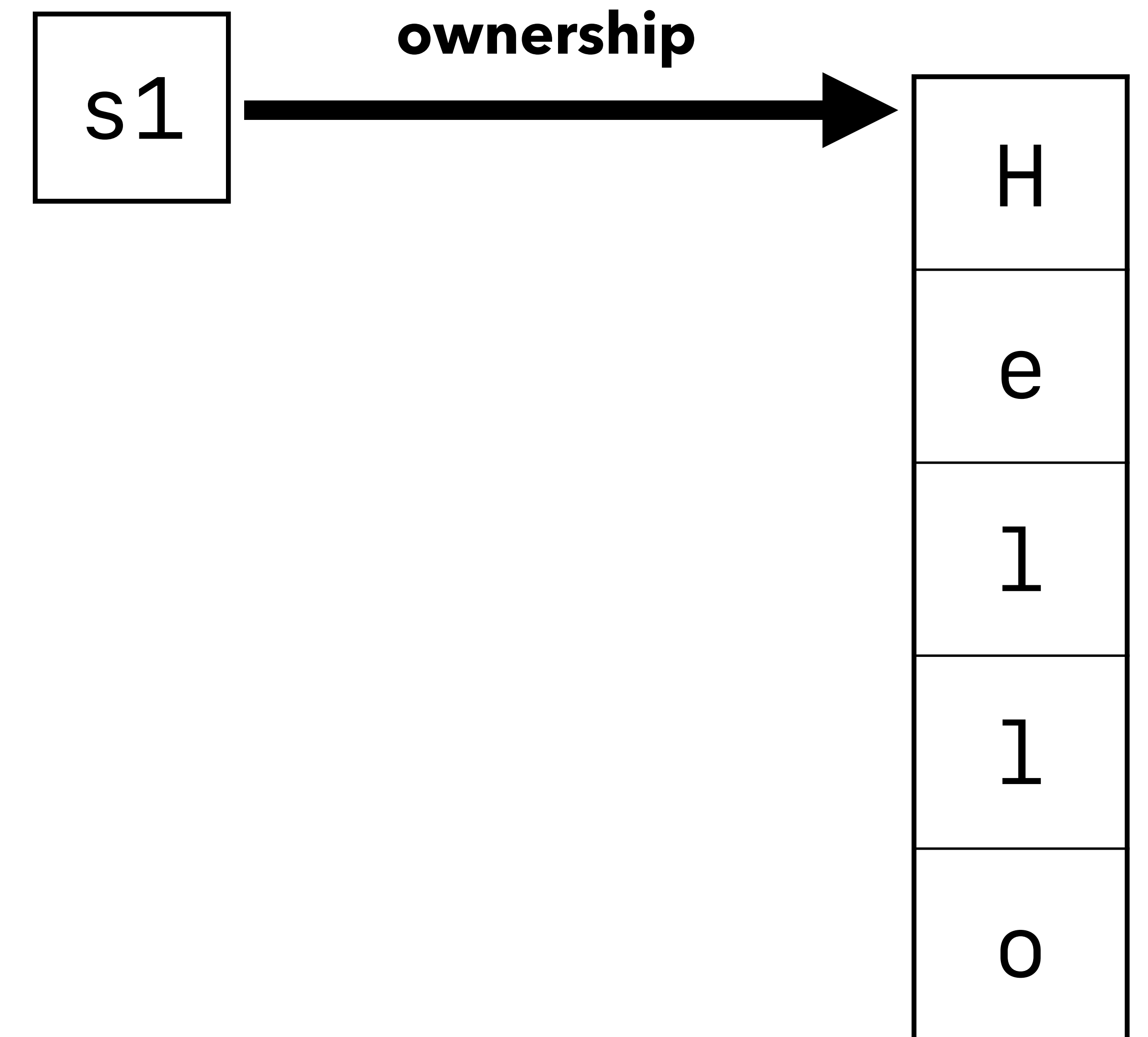
# Rust Ownership Model

## This code won’t compile!

Stack Heap

```
{
    let mut s1: String = String::from("Hello");
    let s2: &String = &s1;
    s1 = String::from(“World");
    println!("{}", s1);
    println!("{}", s2);
}
```

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# Rust Ownership Model

## This code won't compile!

```
{
    let mut s1: String = String::from("Hello");
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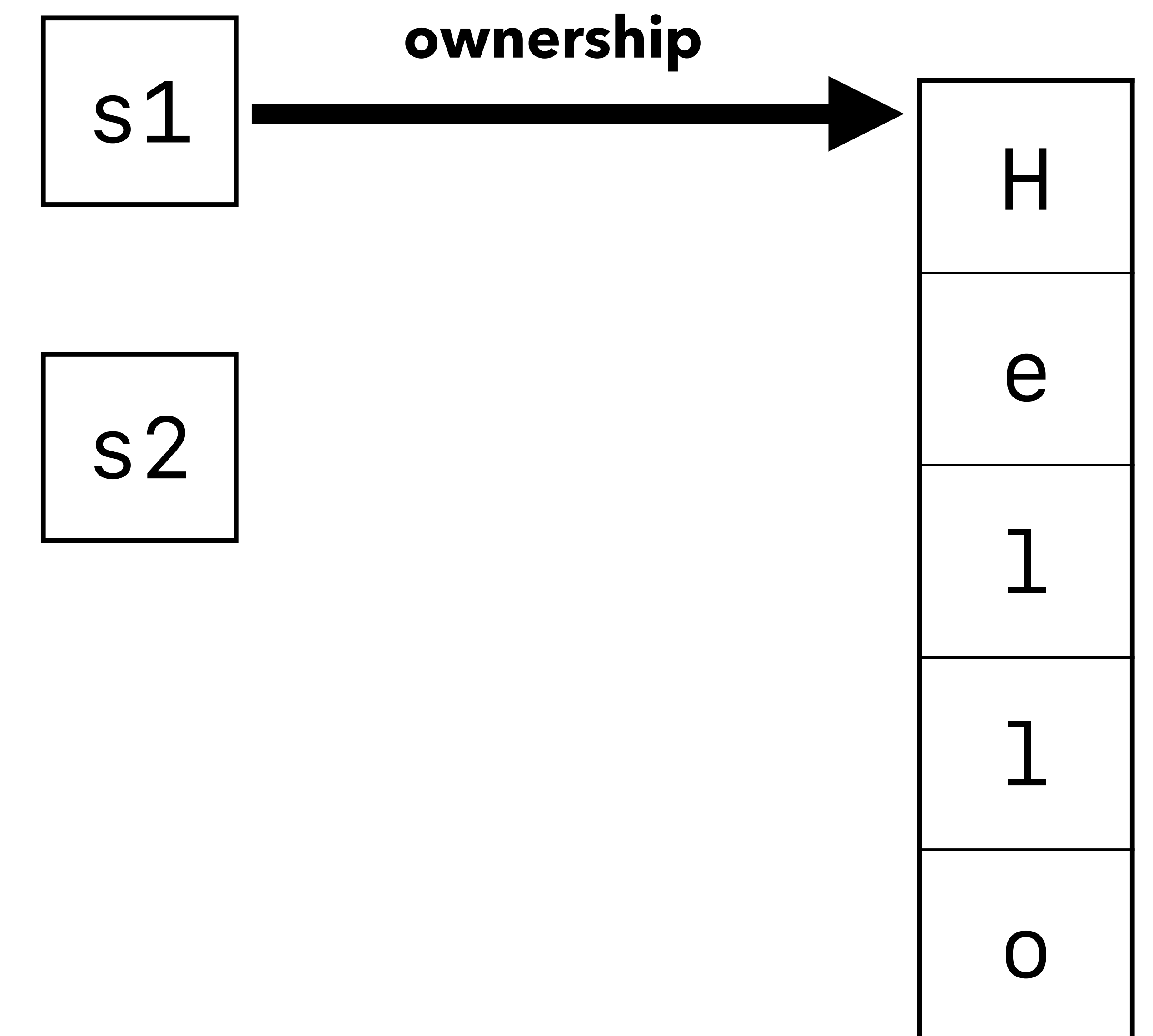
**Stack** **Heap**



# Rust Ownership Model

## This code won't compile!

```
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    let mut s1: String = String::from("Hello");
    let s2: &String = &s1;
    s1 = String::from(“World");
    println!("{}", s1);
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error[E0506]: cannot assign to `s1` because it is borrowed
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```
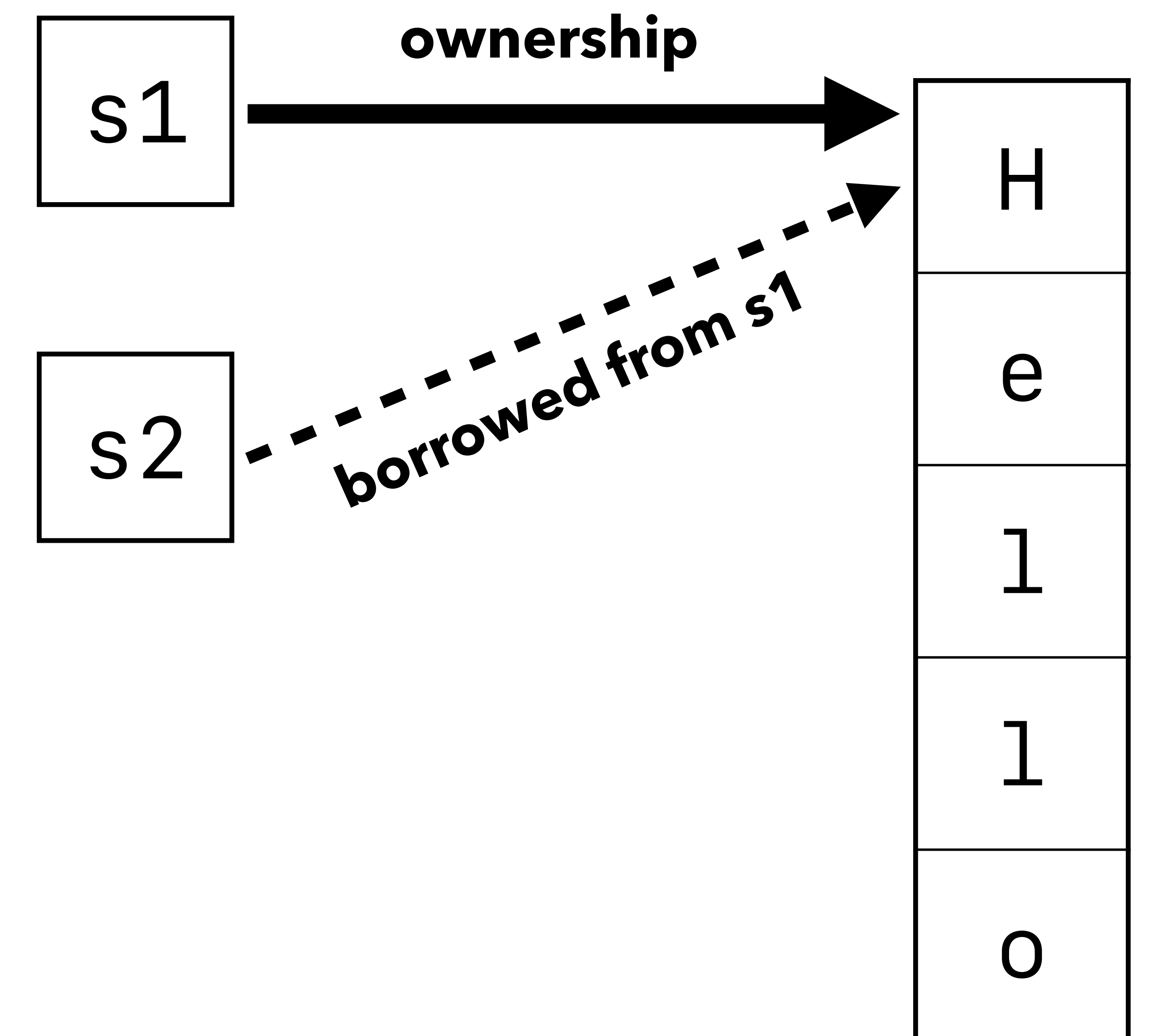

**Stack** **Heap**



# Rust Ownership Model

## This code won't compile!

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    let s2: &String = &s1;
    s1 = String::from(“World");
    println!("{}", s1);
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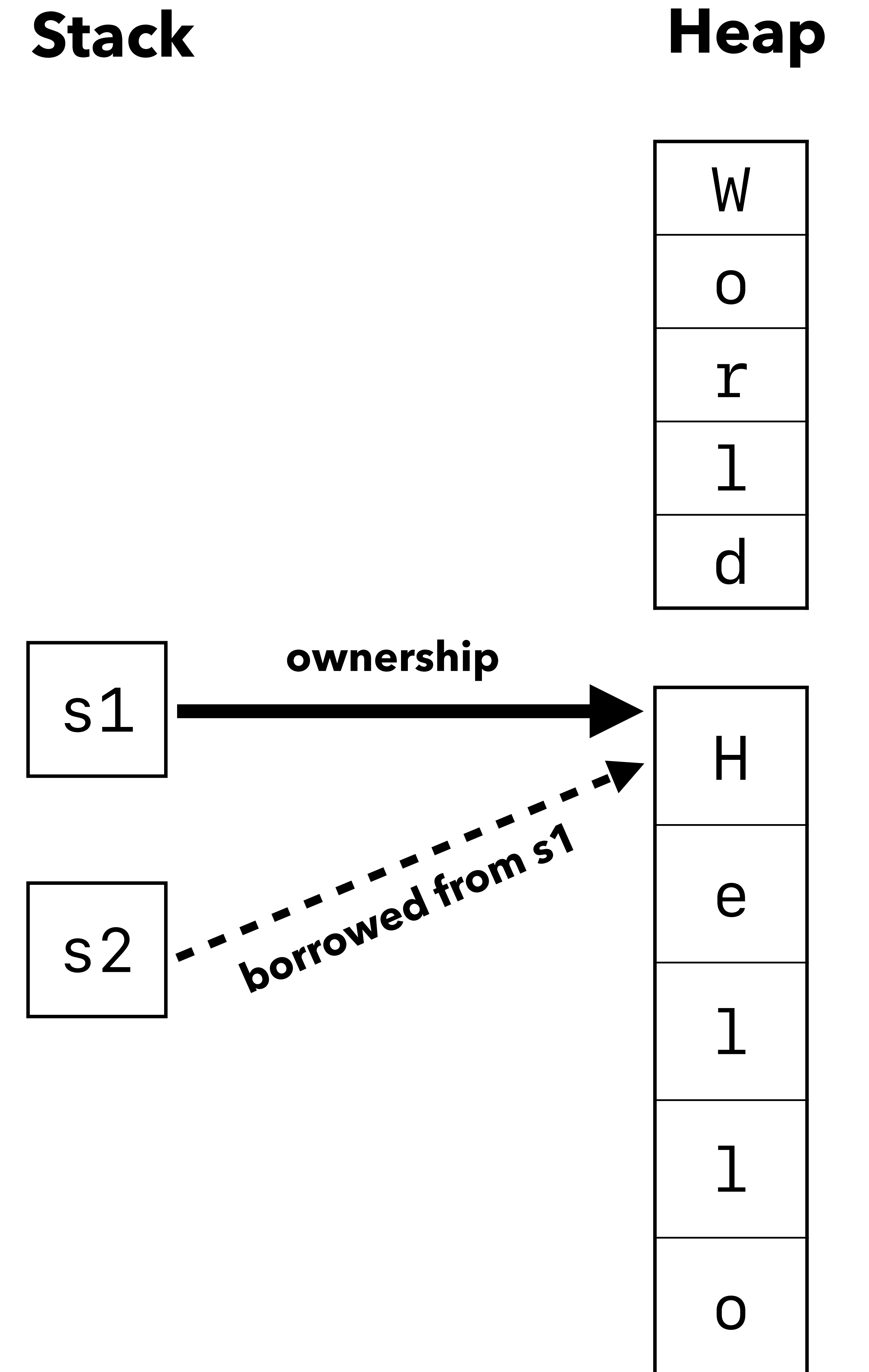

# Rust Ownership Model

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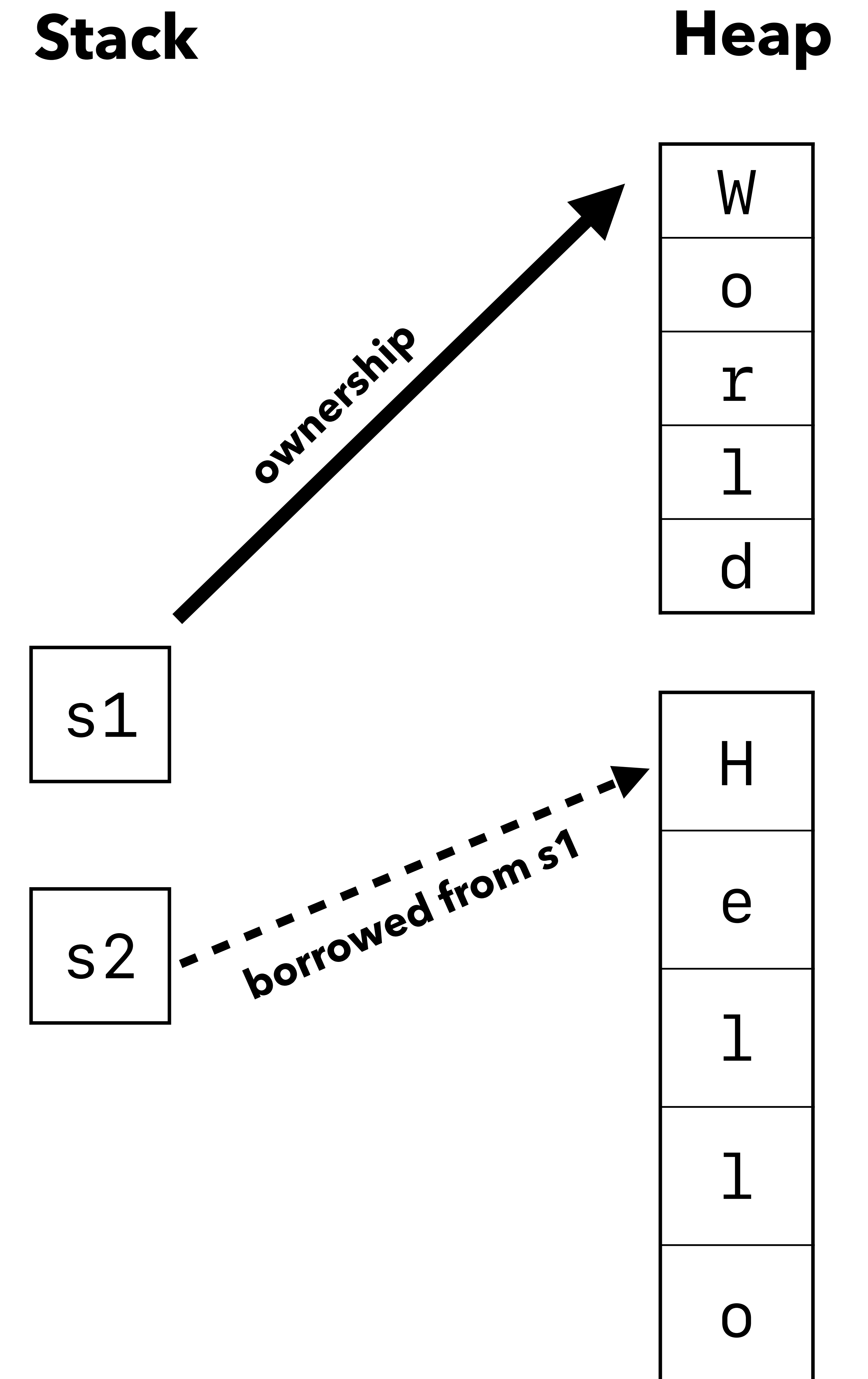

# Rust Ownership Model

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    let mut s1: String = String::from("Hello");
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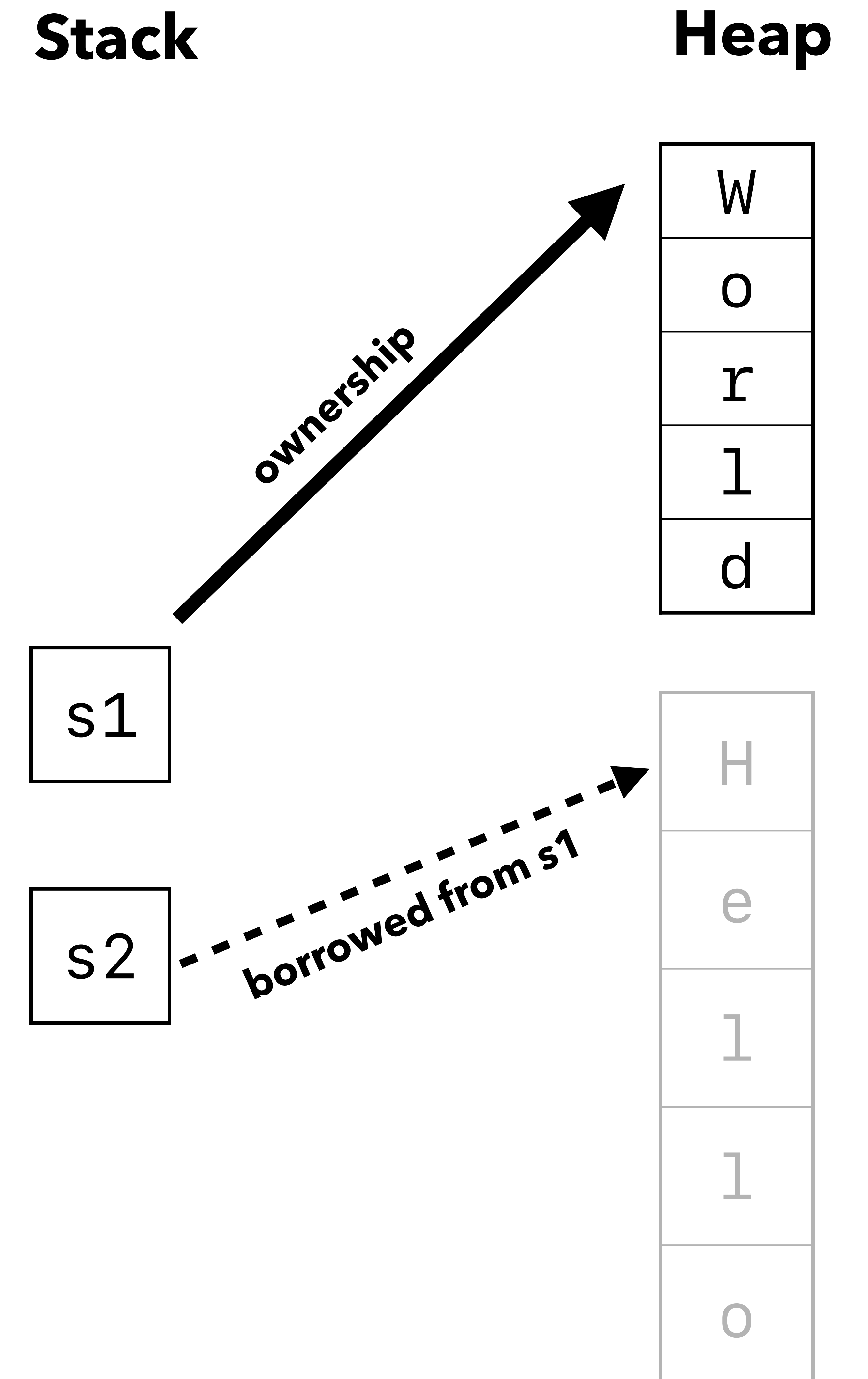

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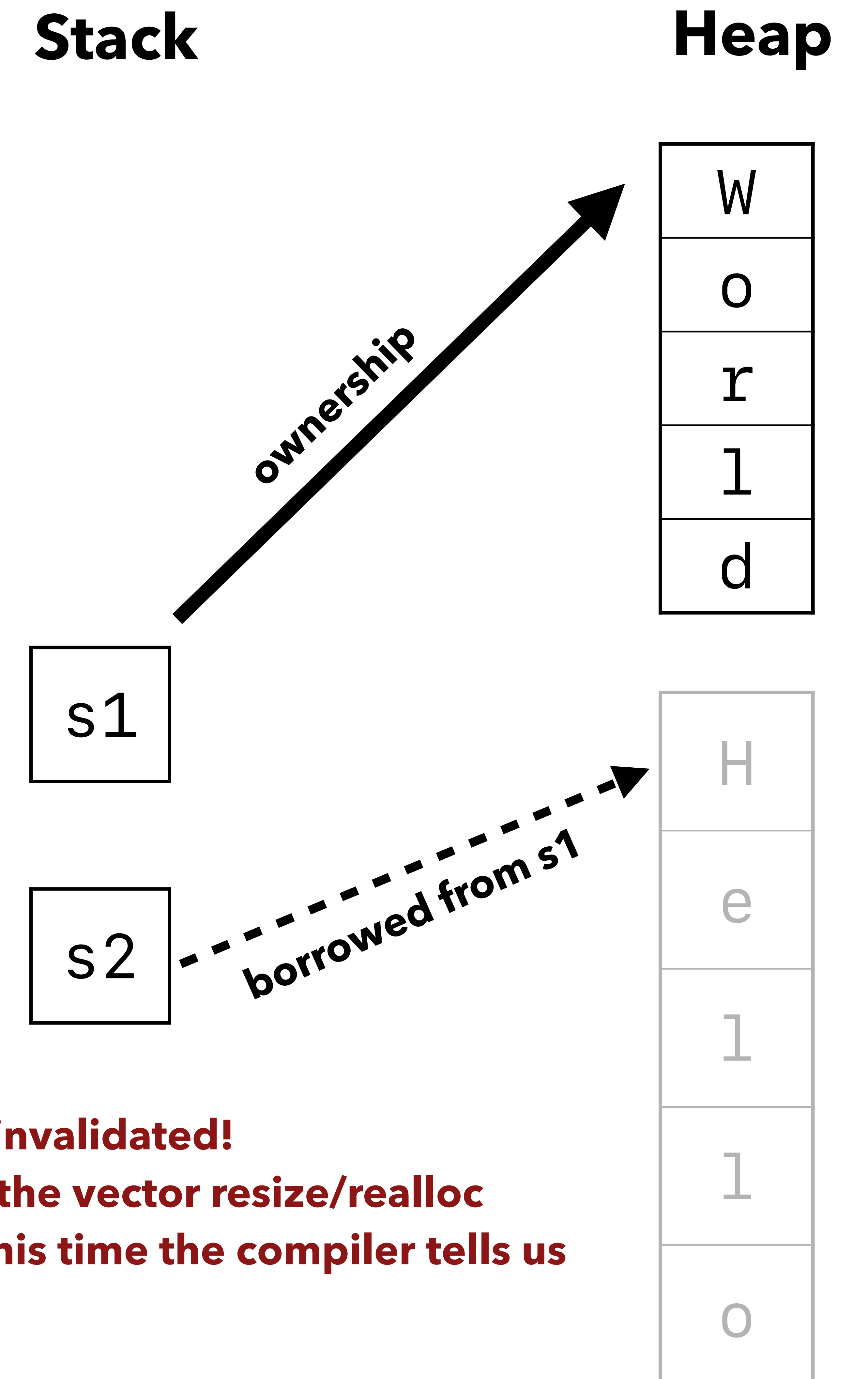


s2 is now invalidated!
Similar to the vector resize/realloc bug, but this time the compiler tells us

# Additional Resources

- Interested in security and/or how memory errors can actually be exploited? Take CS155!
- Want to learn more Rust?
  - The Rust book online
  - CS110L used to be offered, but the materials are still available at cs110L.stanford.edu
- Curious about programming languages? CS242 and CS343D