

CS1632: Nondeterminism and QA

Wonsun Ahn

Learning Goals

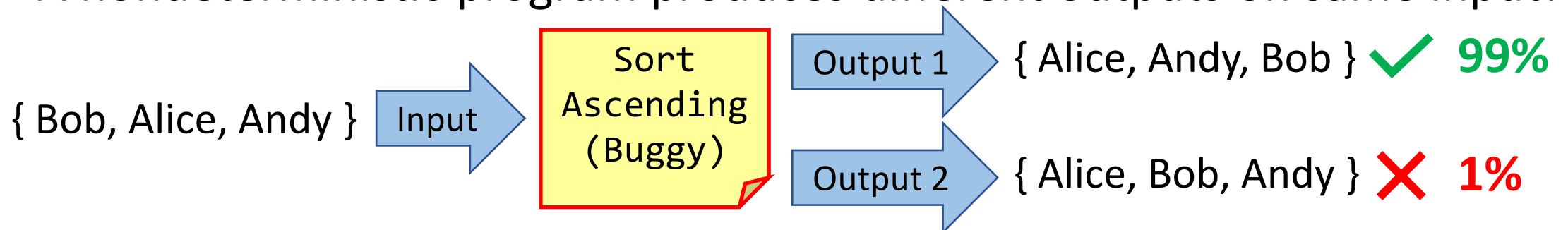
- Learn what **nondeterminism** is and why it is an issue with SW testing
- Learn **4 sources** of nondeterminism
- Learn **3 tools** that combat nondeterminism
- To understand this fully, it helps to know:
 - C programming
 - Concept of program stack and heap
 - Concept of threads and parallel execution
 - If you don't, I will go slowly on some concepts so don't worry

What is Nondeterminism?

- When the output of a program is not determined by its input
- A deterministic program produces the same output on the same input:

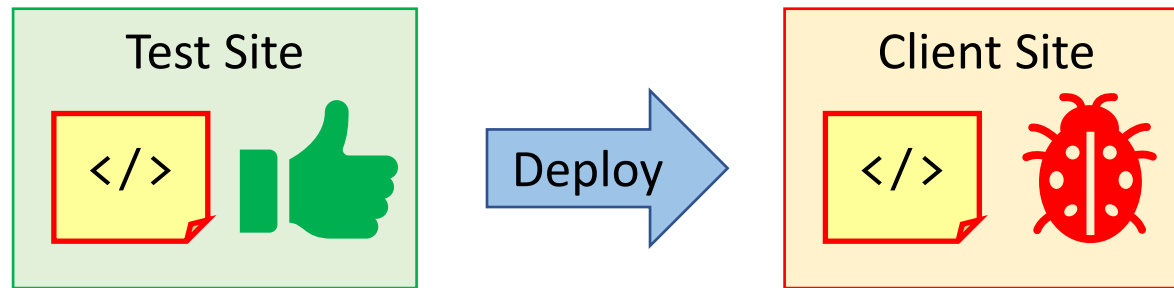


- A nondeterministic program produces different outputs on same input!



Nondeterminism Makes Testing Hard

- Surprise defects
 - Defect not revealed during testing suddenly pops up during usage



- Unreproducible defects
 - Defect revealed during testing doesn't show up when trying to debug it

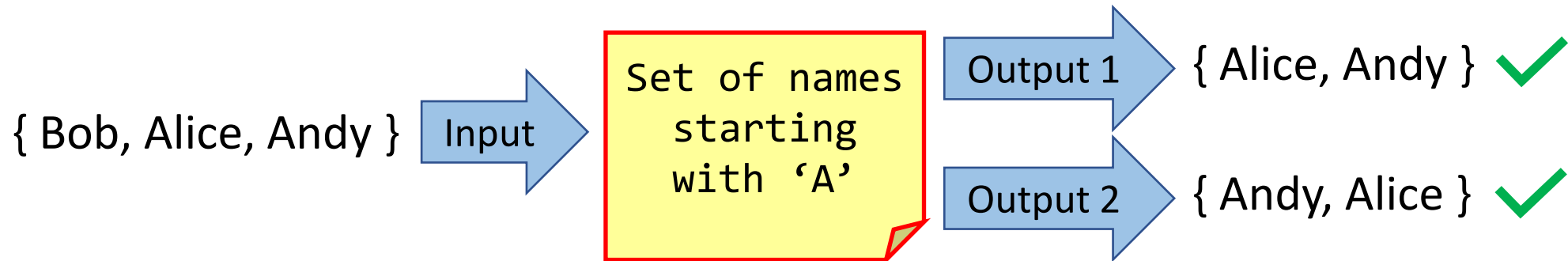


So What To Do?

- Depends on what kind of nondeterminism it is.
1. Nondeterminism by mistake
 - Coder never intended nondeterminism; nondeterminism itself is the defect
→ Stamp out the nondeterminism!
 2. Nondeterminism by design
 - Coder intended the nondeterminism
→ Must somehow deal with the nondeterminism.

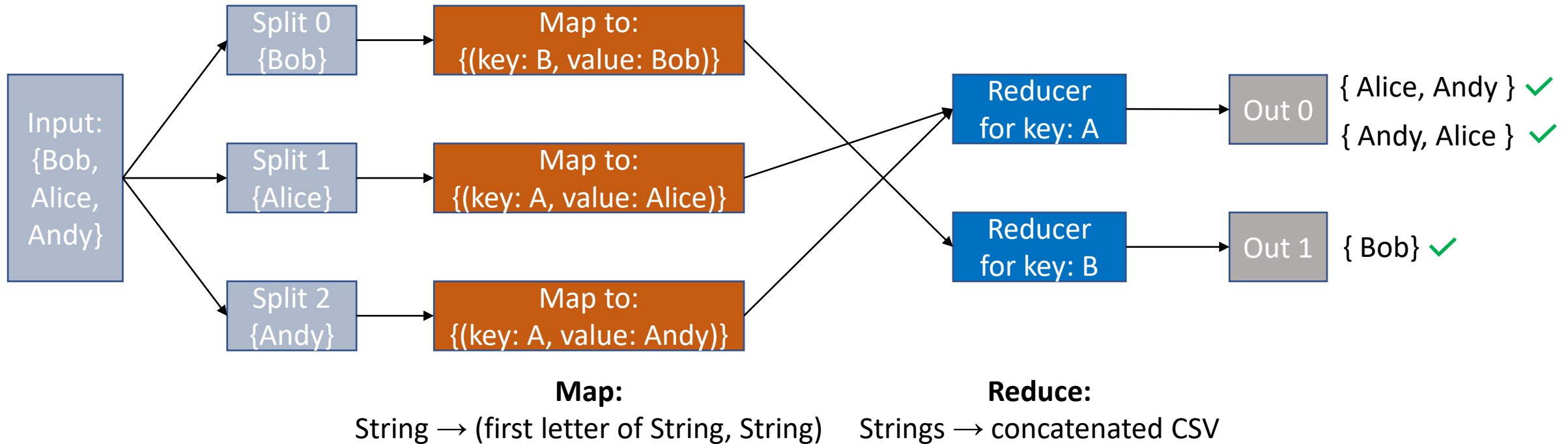
Why Nondeterminism by Design?

- Consider the following nondeterministic program:



- Both outputs are correct since there is no ordering constraint in a set
- Less constraints usually means the program can run faster!
 - A straightforward loop checking each name is deterministic but slow
 - But what if we used parallel MapReduce to speed up the program?

MapReduce Implementation of Filter Names



- Reducer concatenates in the order of arrival → nondeterministic output!
- All non-commutative reducers like concatenation have this property
- For determinism, must constrain order of mapping → slows down program!

Nondeterminism is Inherent in Parallelism

- “Nondeterminism in MapReduce considered harmful? An empirical study on non-commutative aggregators in MapReduce programs.”
 - Xiao, Tian et al., International Conference on Software Engineering, 2014.
 - <https://www.microsoft.com/en-us/research/wp-content/uploads/2016/02/icsecomp14seip-seipid15-p.pdf>
- Most other parallel frameworks suffer from nondeterminism as well
 - Including POSIX Threads, Java Threads, OpenMP, MPI, CUDA, TensorFlow
 - To allow flexibility in execution order for maximal performance

Why Nondeterminism by Design?

1. To make programs go faster through parallel execution
 - Sometimes all outputs are equally correct → nondeterminism is not a problem
 - Sometimes, for optimization problems, some outputs are “better” than others
 - Still, nondeterministic output is okay as long as it is better than deterministic output (given the same amount of time to run; i.e. nondeterministic approaches optimum faster)
 - True for NP-hard problems (e.g. integer linear programming, constraint solving, ...)
2. To intentionally introduce randomness (random number generation)
 - Video games – to introduce random events into the game
 - Cryptography – to make cryptographic keys unpredictable

Outline

- **Nondeterminism by mistake**
 - Memory errors (examples / solutions)
 - Data race errors (examples / solutions)
- **Nondeterminism by design**
 - Thread interleaving (examples / solutions)
 - Random number generation (examples / solutions)
- Summary

Nondeterminism by Mistake

It's a Mistake – Stamp out from your Code!

- Due to erroneous code
 - Memory errors
 - Datarace errors
- Runtime behavior of program is undefined or barely defined
 - Called errors because they are illegal in language specification
- Undefined behavior can hardly be intentional by design
 - These behaviors need to be banished!

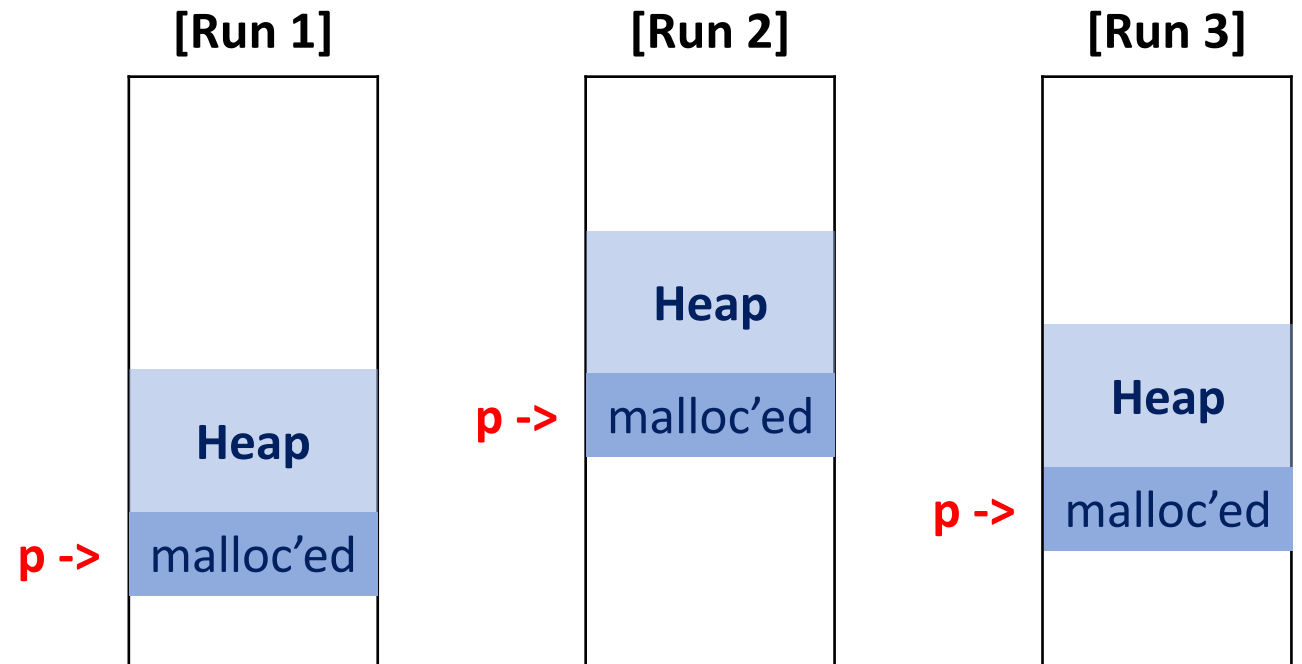
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It's Very Easy to Make a Random C Program

```
int main() {  
    char *p = malloc(8);  
    printf("p = %p\n", p);  
    free(p);  
    return 0;  
}
```

```
bash-4.2$ ./heap  
p = 0x10b2010  
bash-4.2$ ./heap  
p = 0x257e010  
bash-4.2$ ./heap  
p = 0x13a7010
```

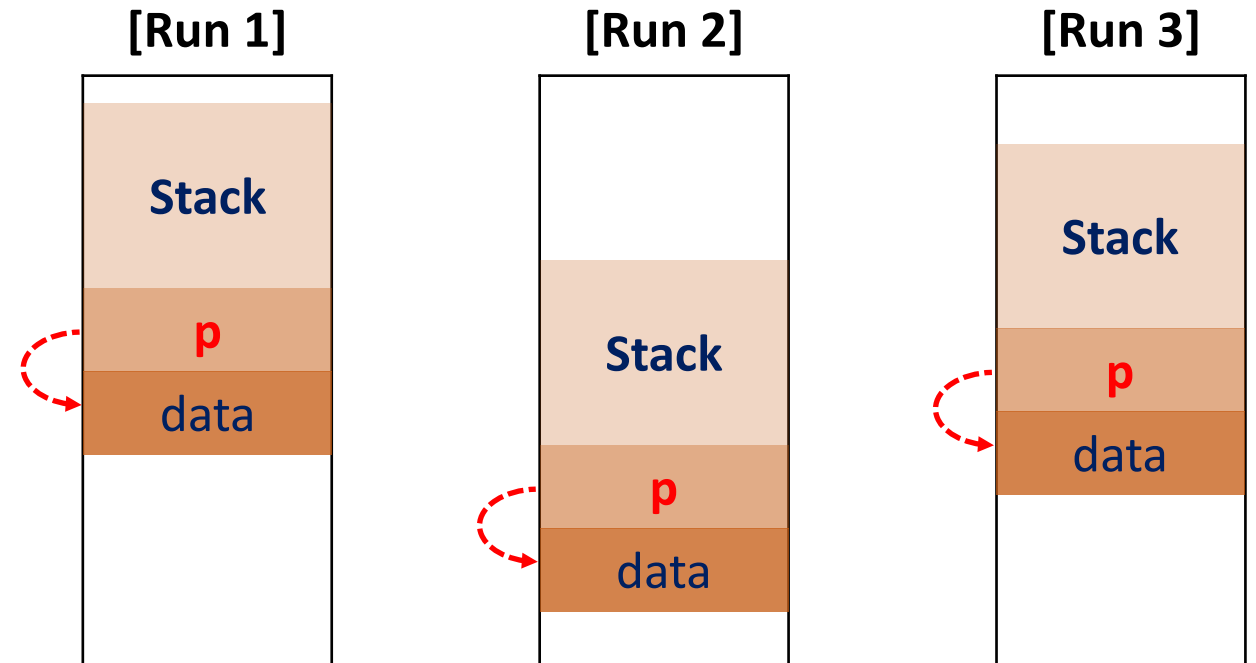


- Why is malloc returning a random address?
- Address Space Layout Randomization (ASLR)
- To prevent hackers from guessing memory layout

Stack Addresses are Random Too

```
int main() {  
    char *p;  
    char data[8];  
    p = data;  
    printf("p = %p\n", p);  
    return 0;  
}
```

```
bash-4.2$ ./stack  
p = 0x7ffff5443188  
bash-4.2$ ./stack  
p = 0x7ffedfb740f8  
bash-4.2$ ./stack  
p = 0x7fffc21002f8
```



- `p` is now pointing to a stack location
- Why is `data[8]` at a random address?
- ASLR is also applied to the stack

Does it Matter?

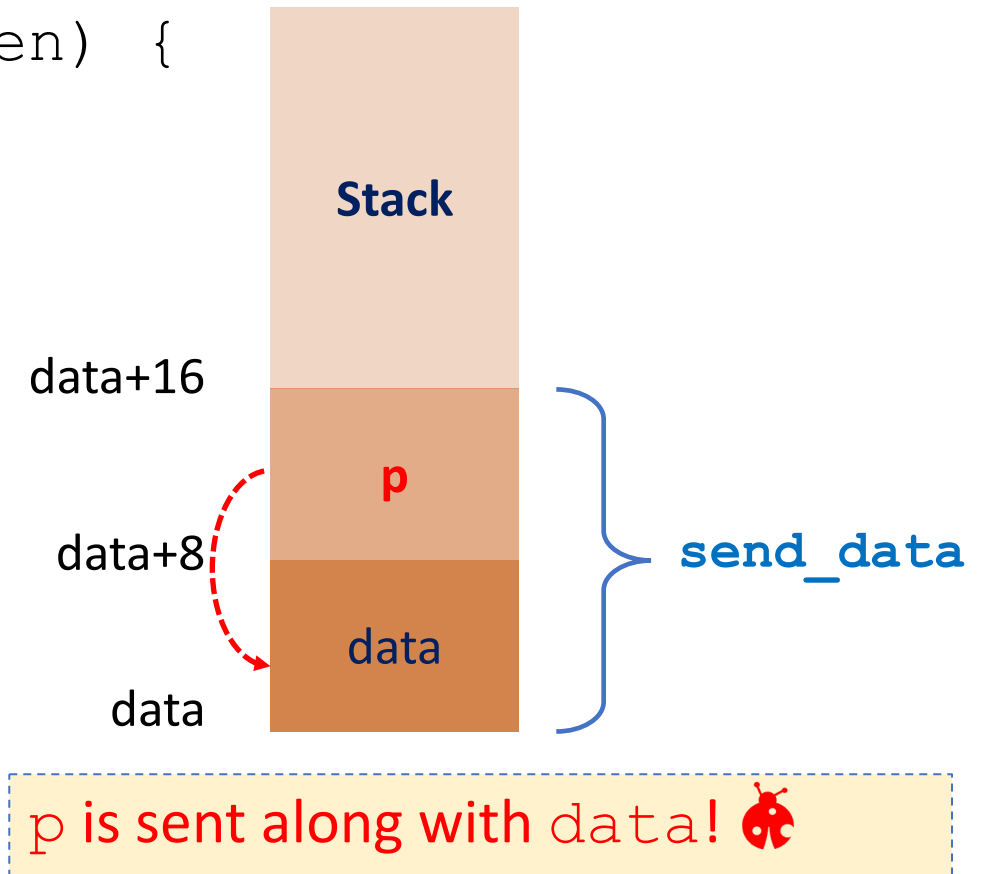
- Aren't these contrived examples?
- Pointer addresses are almost never part of program output anyway
 - Unless you are printing them out for debugging or diagnostic purposes
 - Most of the times you output the data stored inside those locations (e.g. You output the data inside a data structure node not the node address)
- But addresses can leak out to program output *by mistake*
- Specifically when you have *memory errors*

Memory Errors

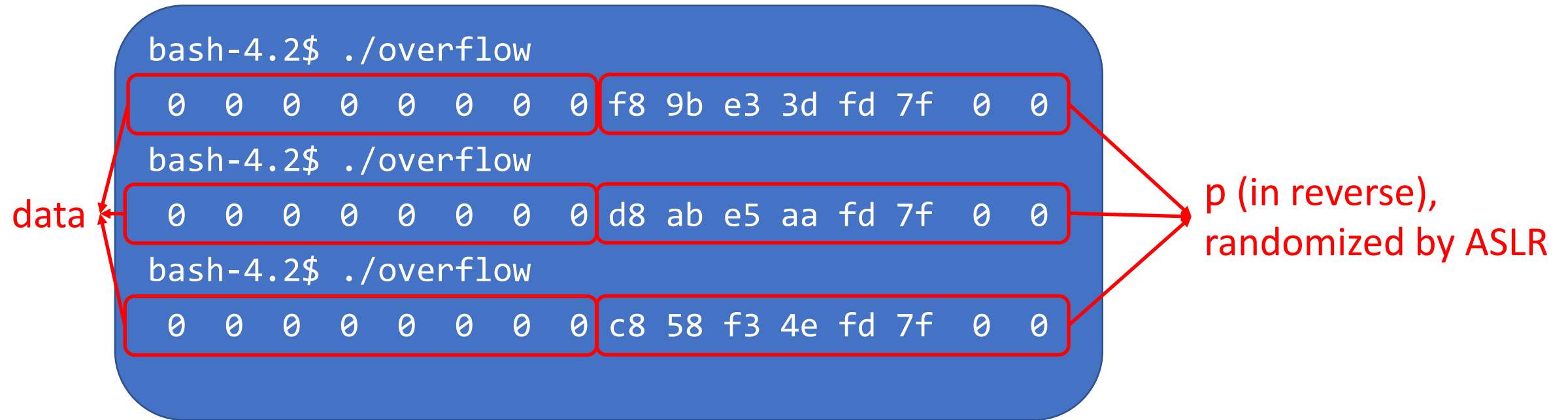
- Errors that access an illegal memory location are the culprits
 - Buffer overflow: access beyond the bounds of an array
 - Dangling pointer: access to already freed memory pointed to by pointer
- If illegal location contains an address, it can leak out to the output!
- Only happens in languages like C/C++ with direct access to memory
 - Does not happen in memory-managed languages like Java or Python
 - C/C++ is used to write most system code so still a big problem

Buffer Overflow Example

```
void send_data(char *data, int len) {  
    for (int i=0; i < len; i++)  
        printf("%2hhx ", data[i]);  
    printf("\n");  
}  
  
int main() {  
    char *p;  
    char data[8] = {0};  
    p = data;  
    send_data(data, 16);  
    return 0;  
}
```



Buffer Overflow Output



- Randomized addresses can leak out to output due to a memory error!

You could Turn Off ASLR ...

```
bash-4.2$ setarch `uname -m` -R /bin/bash
```

Turns off ASLR

```
bash-4.2$ ./overflow
```

```
0 0 0 0 0 0 0 0 38 dd ff ff ff 7f 0 0
```

```
bash-4.2$ ./overflow
```

```
0 0 0 0 0 0 0 0 38 dd ff ff ff 7f 0 0
```

```
bash-4.2$ ./overflow
```

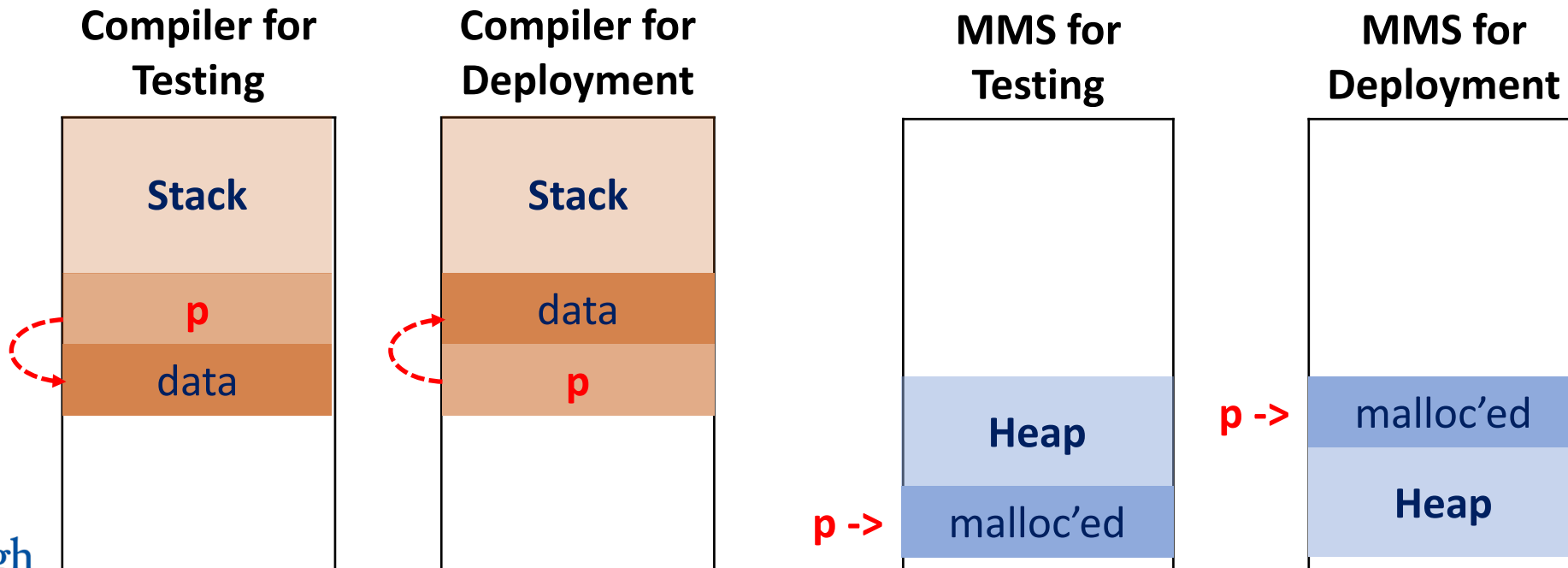
```
0 0 0 0 0 0 0 0 38 dd ff ff ff 7f 0 0
```

Now p is deterministic

- Can help in reproducing bugs in a debug setting
- But clients will still want ASLR on for security → surprise defects can still happen

You could Turn Off ASLR ...

- Even if client does not use ASLR, things can still go wrong
 - If binary deployed to client uses different *compiler* than test version
(Or same compiler but different compile options)
 - If client uses a different runtime *memory management system* (MMS)
(Or same MMS but MMS is nondeterministic on parallel mallocs)



What to do? Stamp Out the Error!

- Let's use Google Address Sanitizer for this purpose

```
bash-4.2$ clang overflow.c -fsanitize=address -g -o overflow
```

```
bash-4.2$ ./overflow
```

```
==357==ERROR: AddressSanitizer: stack-buffer-overflow on ...
```

```
READ of size 1 at 0x7fffffffddc88 thread T0
```

```
#0 0x4f858c in send_data overflow.c:7:22
```

```
#1 0x4f86f1 in main overflow.c:17:3
```

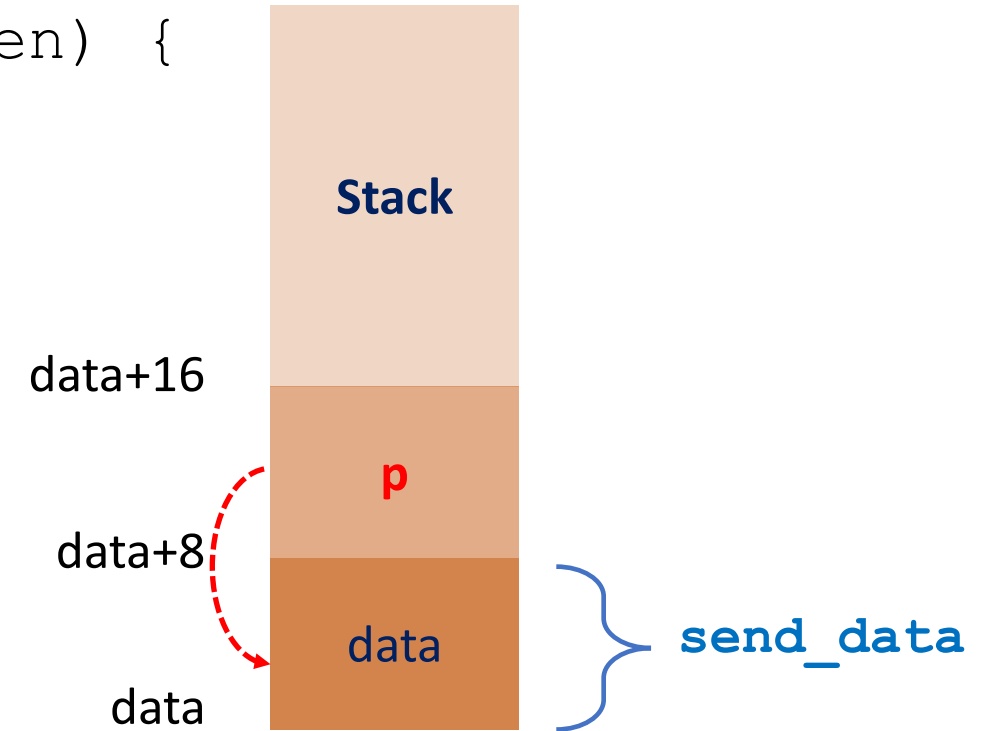
```
...
```

Tells compiler to
sanitize addresses

Where in code
buffer overflow
happened

Buffer Overflow Fixed

```
void send_data(char *data, int len) {  
    for (int i=0; i < len; i++)  
        printf("%2hhx ", data[i]);  
    printf("\n");  
}  
  
int main() {  
    char *p;  
    char data[8] = {0};  
    p = data;  
    printf("p = %p\n", p);  
    send_data(data, 8);  
    return 0;  
}
```



Now only data is sent! 📺

Google Address Sanitizer (ASAN)

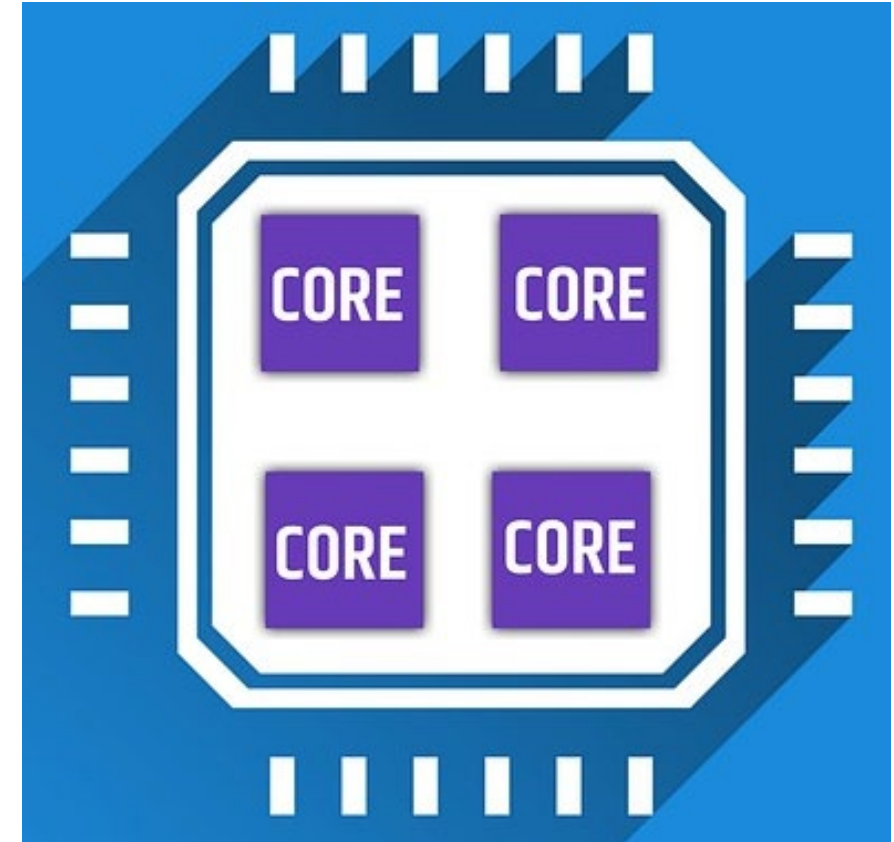
- Part of Google sanitizer suite
 - Address Sanitizer (ASAN)
 - Thread Sanitizer (TSAN)
 - Memory Sanitizer (MSAN)
 - And more.
- Works through *instrumentation*
 - Inserting extra instructions into program for the purpose of monitoring
 - Instrumentation code reports back issues during/after execution of code
- Compilers where available (with the `-fsanitize=address` switch)
 - LLVM (clang) starting with version 3.1
 - GCC starting with version 4.8

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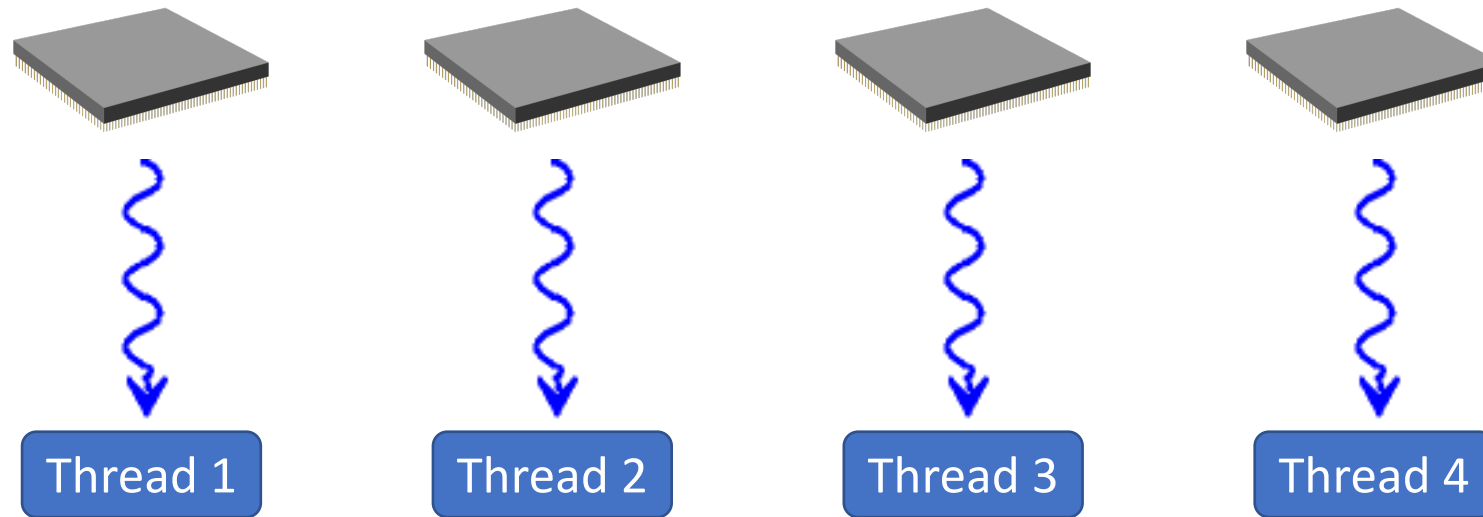
First, an Intro to Parallel Programming

- Your laptop or cellphone has multiple CPUs
(Seen on the right: quad-core with 4 CPUs)
- A program runs on just 1 CPU by default
(Using just 25% of the computing power!)
- A parallel program can use all 4 CPUs
(Utilizing your computer 100%)



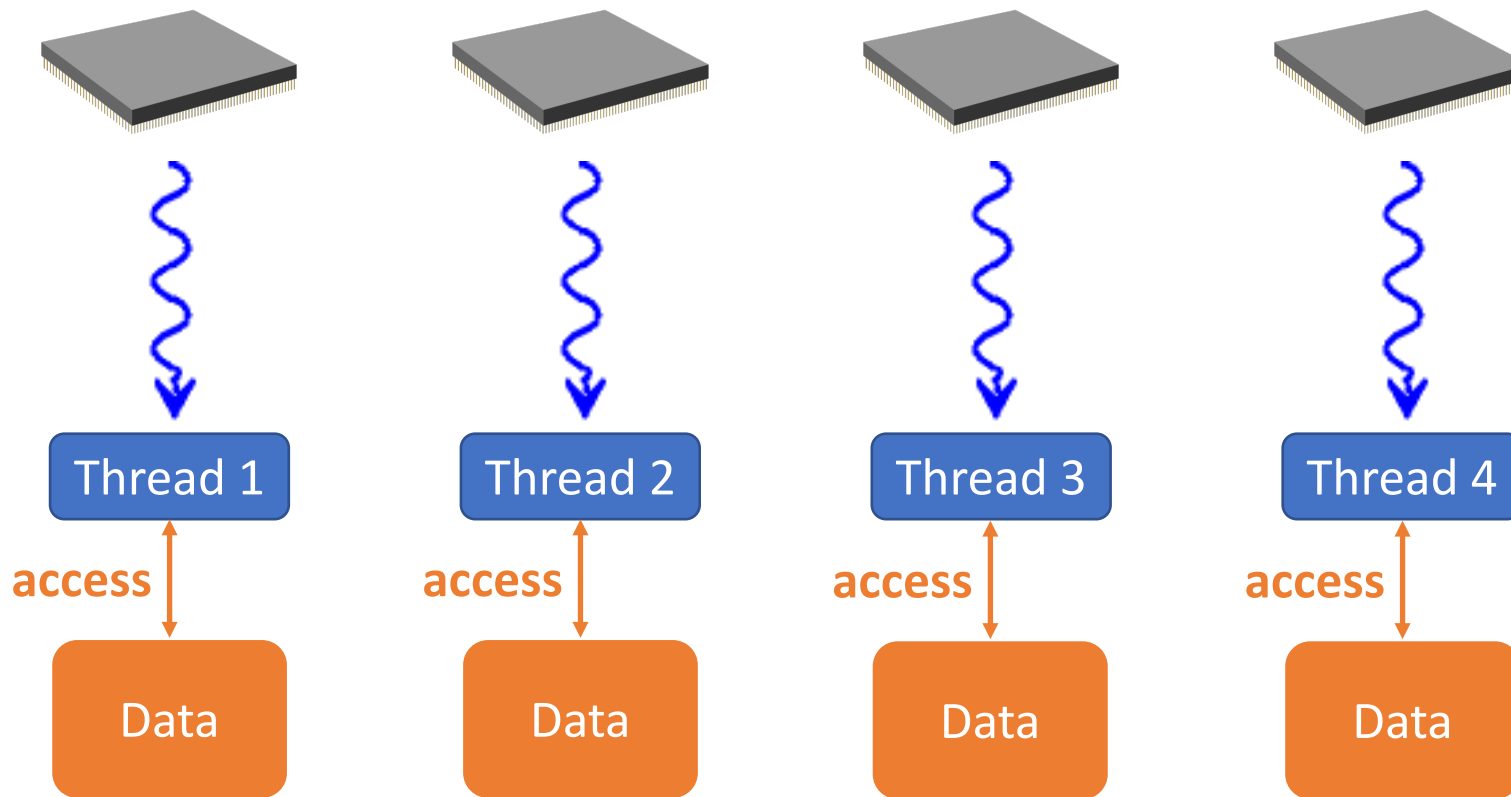
A Parallel Program Runs 1 Thread per CPU

- Thread: a unit of code that runs on 1 CPU



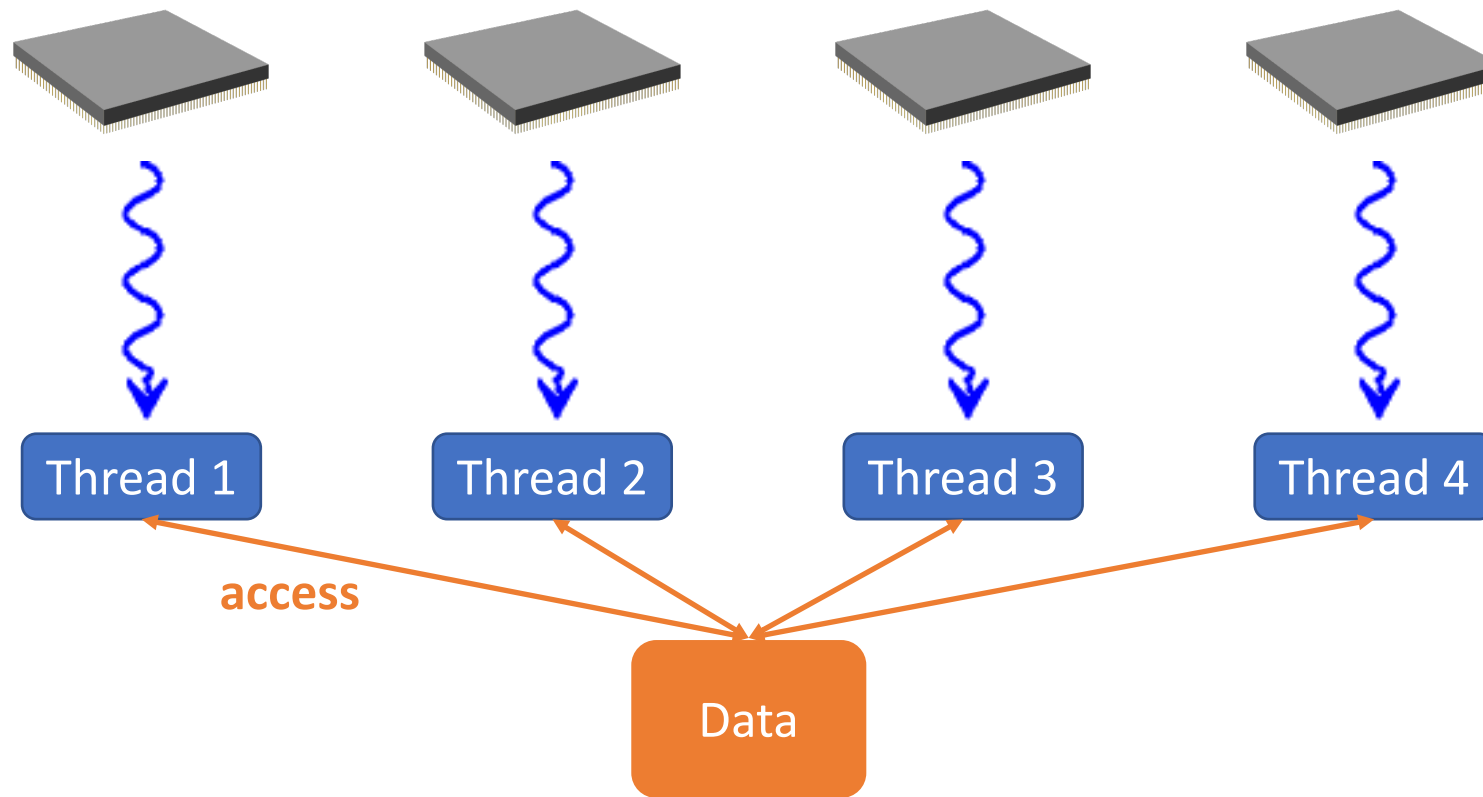
Mostly, a Thread Works on its Own Data

- Thread: a unit of code that runs on 1 CPU



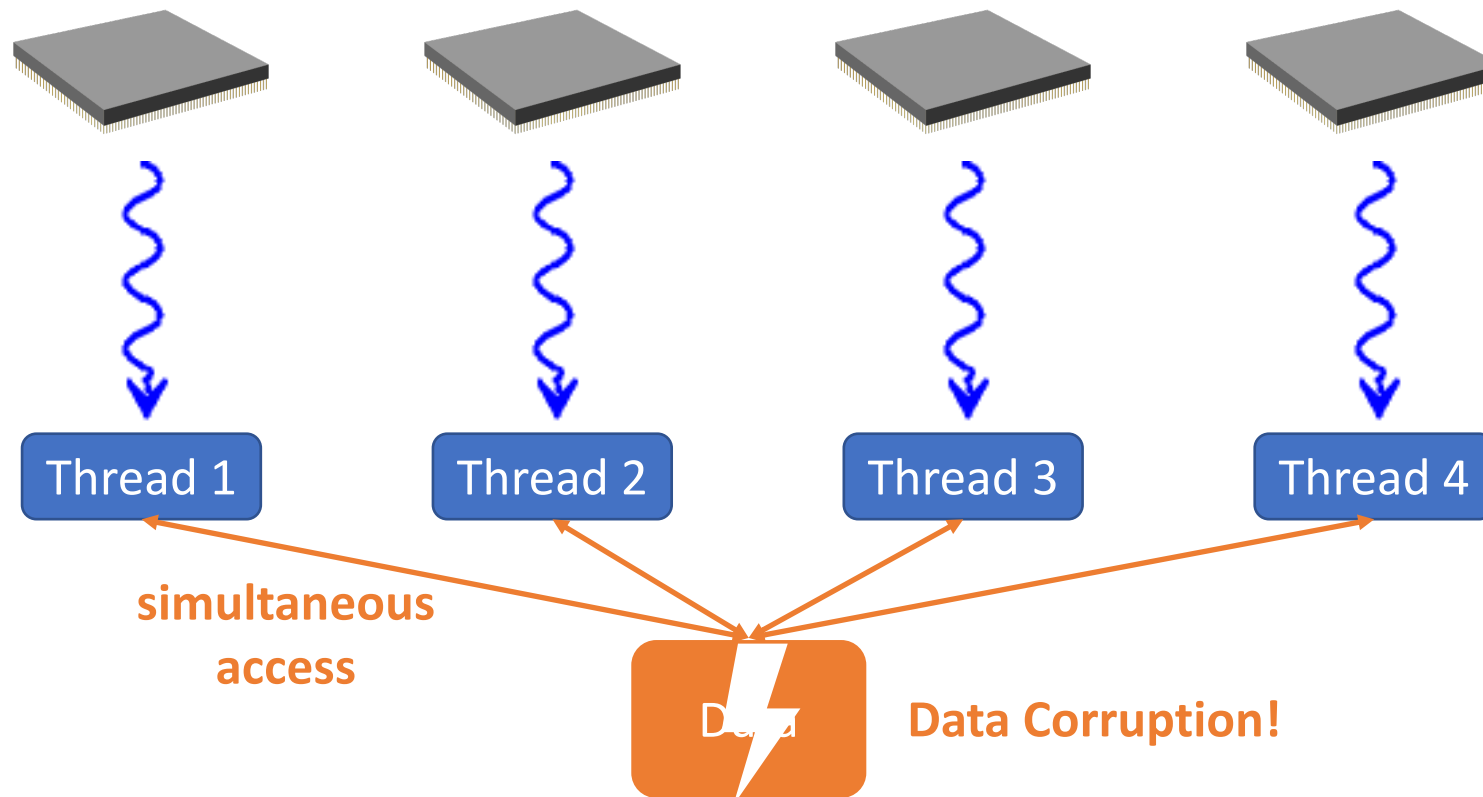
Sometimes, Threads Work on Shared Data

- Thread: a unit of code that runs on 1 CPU



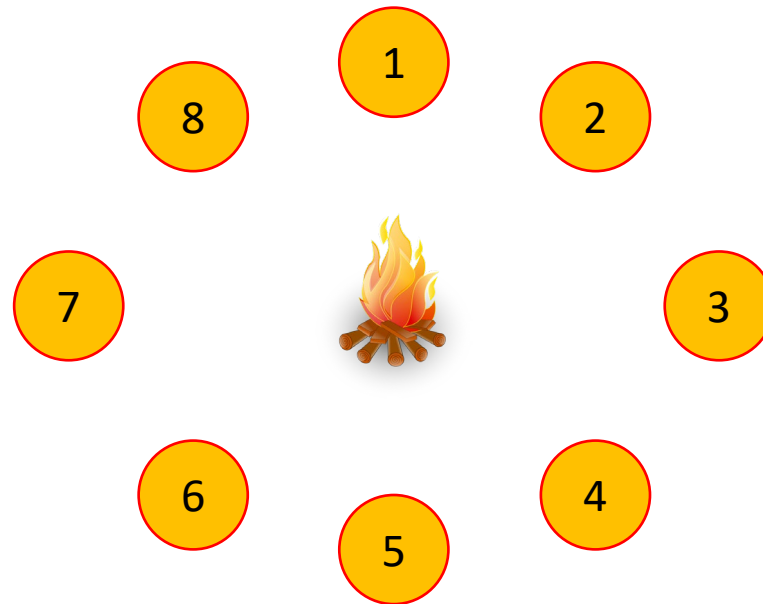
If not Careful, Data can be Corrupted!

- If threads don't take turns, and access data simultaneously



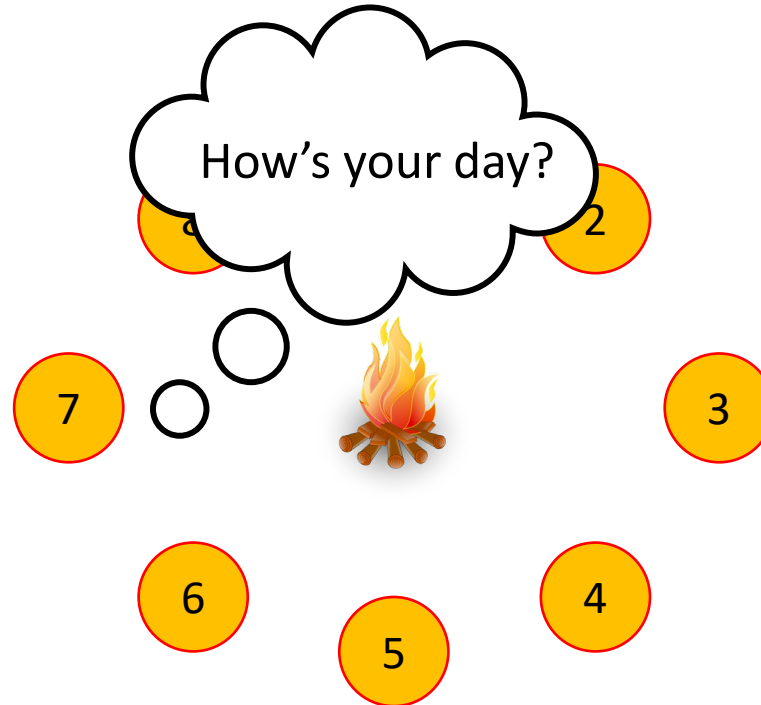
Why Data Corruption on Simultaneous Access?

- Imagine a group of village elders having a discussion around a campfire



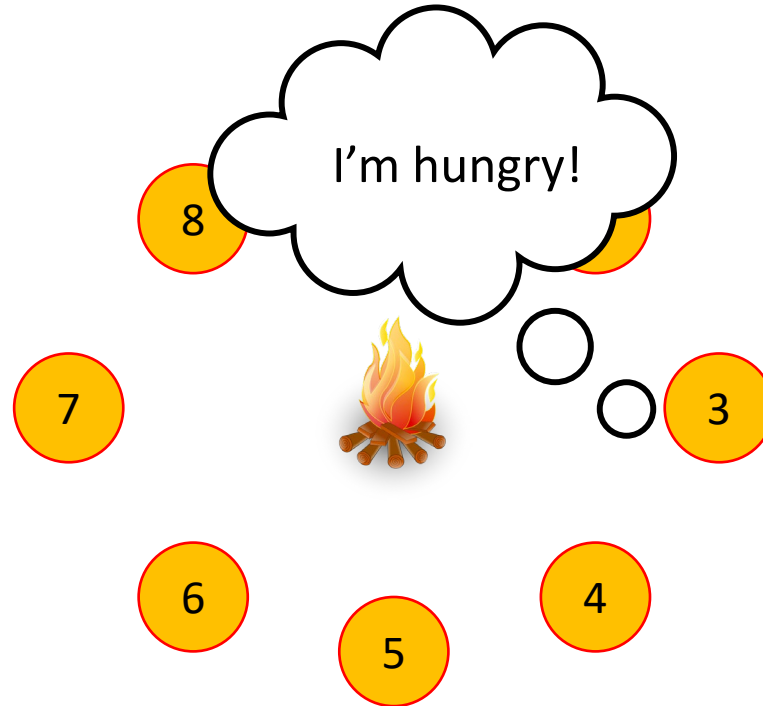
Why Data Corruption on Simultaneous Access?

- If the elders speak one at a time, they will understand each other



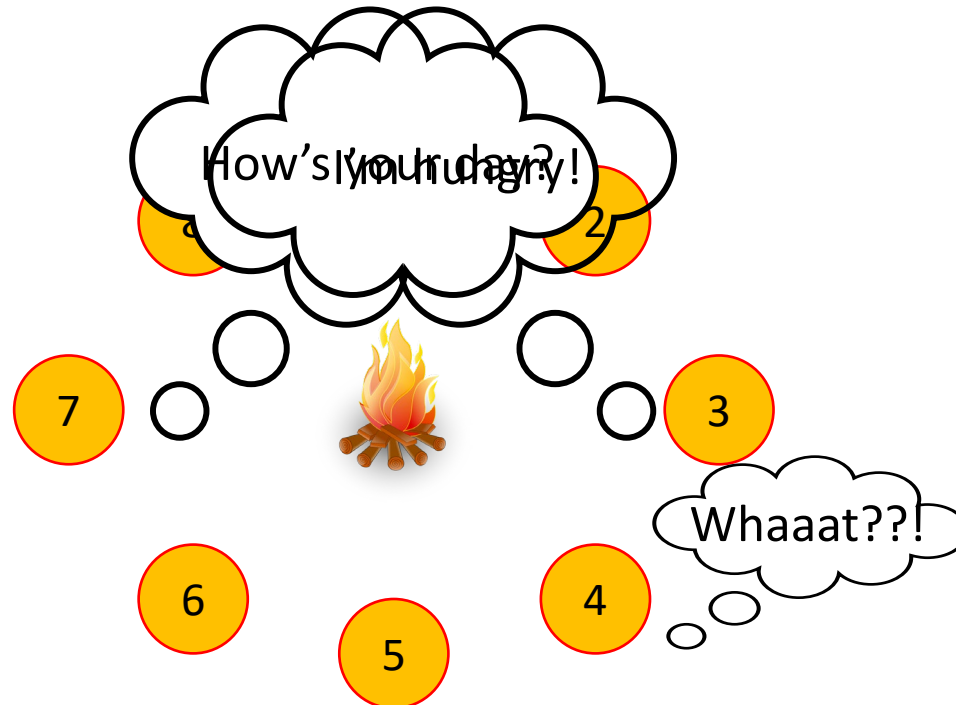
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Why Data Corruption on Simultaneous Access?

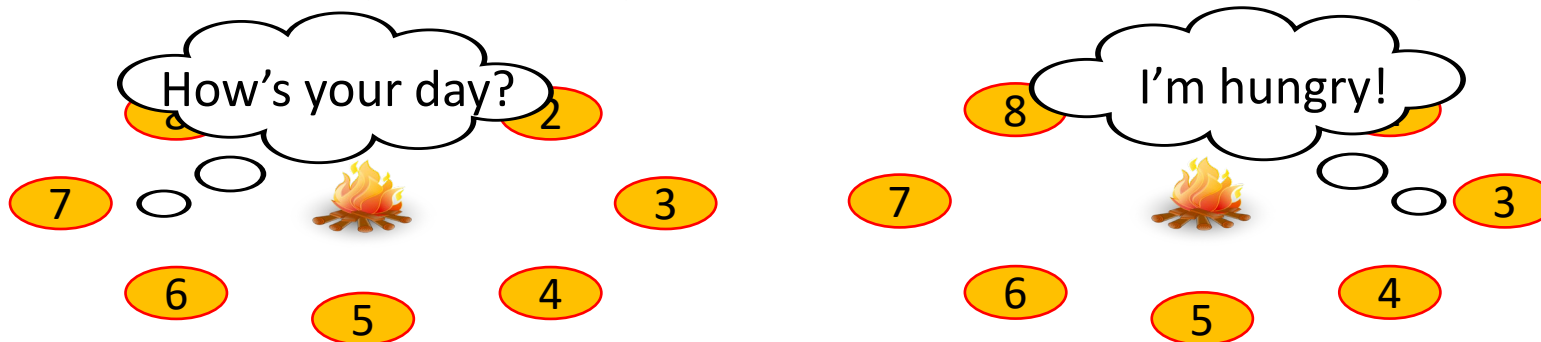
- But if they talk at the same time, the speech becomes garbled



- Same thing happens with data. This is called a *data race*.

Worst Part: Data Races are Nondeterministic

- If lucky, meeting may adjourn with everyone taking turns speaking



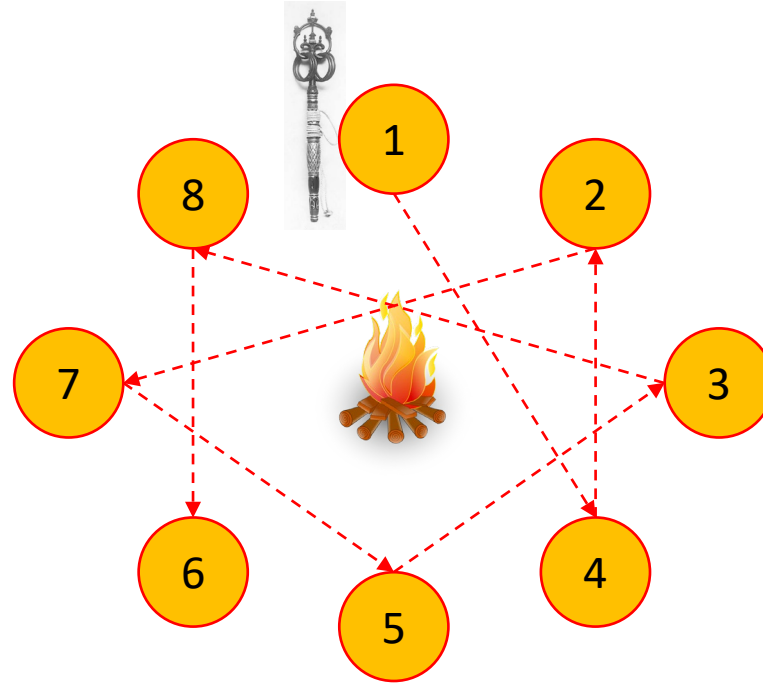
- If unlucky, two elders may speak at the same time causing the problem



- It all depends on timing ...

Solution: Speaking Staff

- Rule: only the elder with the speaking staff shall speak
- Forces elders to take turns speaking by passing around the staff



Speaking Staff in Software is the *Lock*

- *Lock*: a software object that only one thread can hold at a time
- Threads take turn accessing shared data by passing around a lock
- Data races can be removed with proper use of locks

Datarace Example

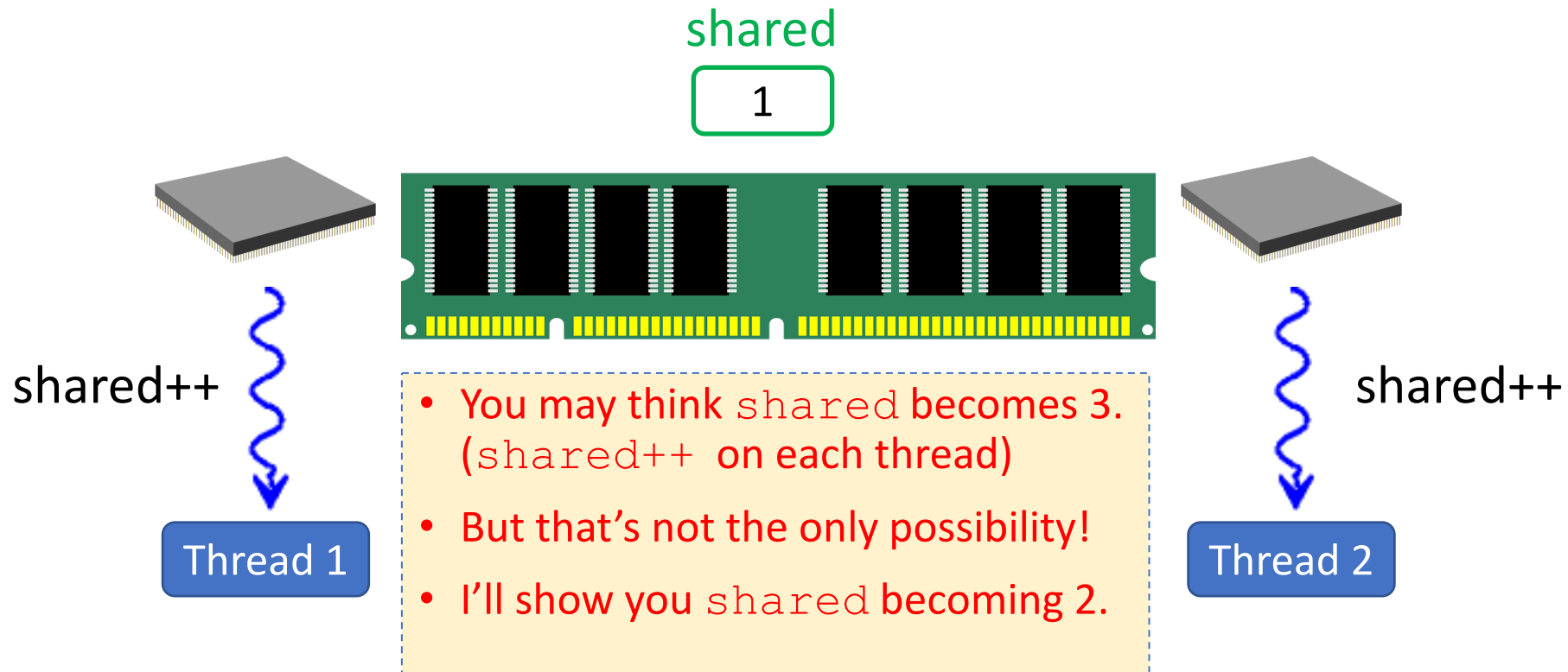
```
int shared = 0;
void *add(void *unused) {
    for(int i=0; i < 1000000; i++) { shared++; }
    return NULL;
}
int main() {
    pthread_t t;
    // Child thread starts running add
    pthread_create(&t, NULL, add, NULL);
    // Main thread starts running add
    add(NULL);
    pthread_join(t, NULL);
    printf("shared=%d\n", shared);
    return 0;
}
```

```
bash-4.2$ ./datarace
shared=1085894
bash-4.2$ ./datarace
shared=1101173
bash-4.2$ ./datarace
shared=1065494
```

- What do you expect from running this?
- Maybe shared=2000000 ?
- Due to datarace on shared.

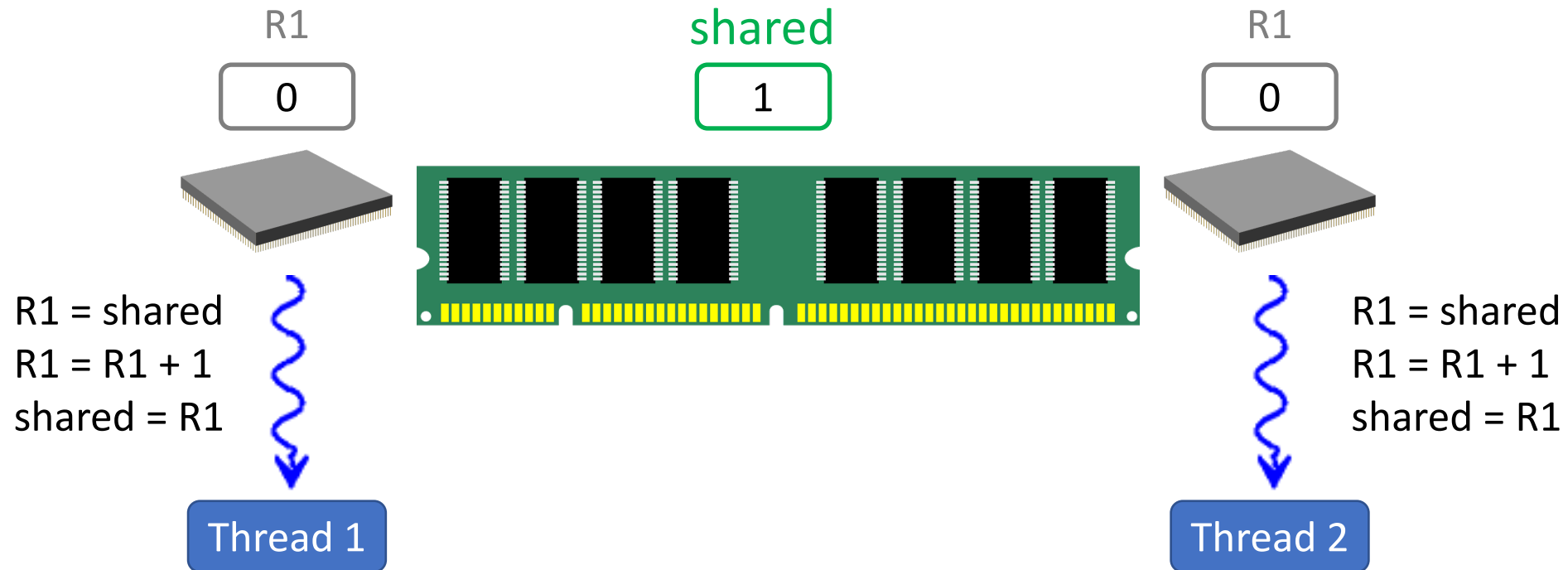
Datarace: Sequence of Events

- When two threads do `shared++`; initially `shared = 1`



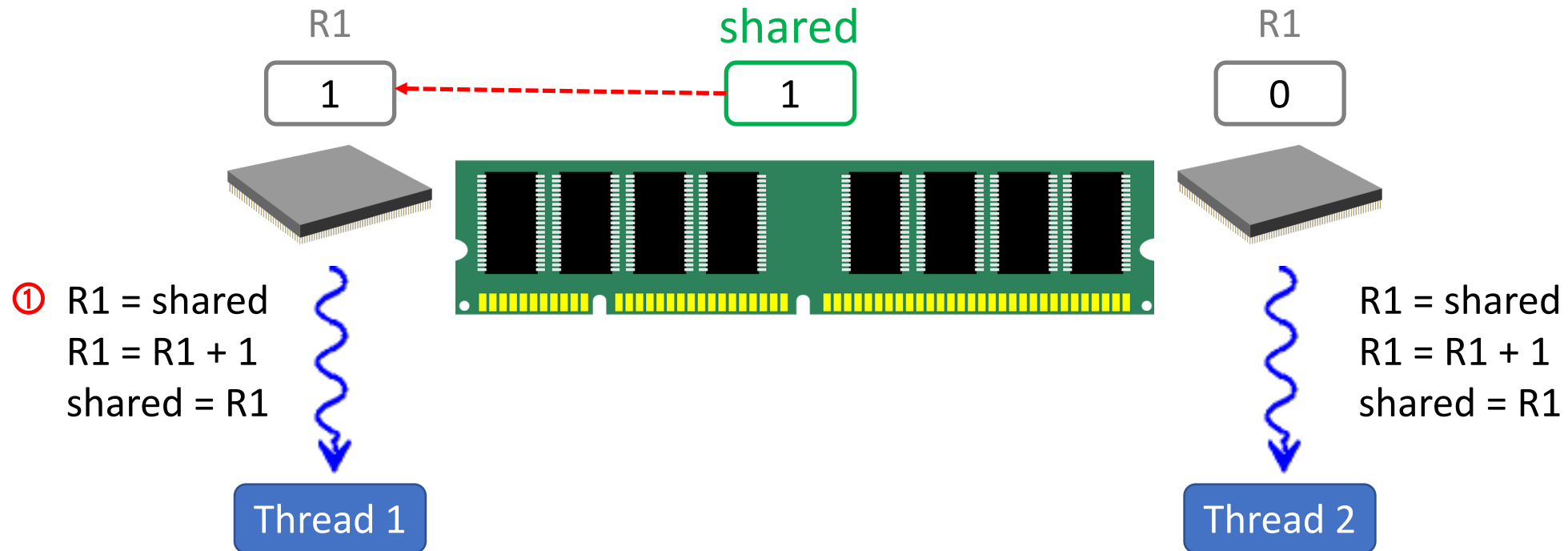
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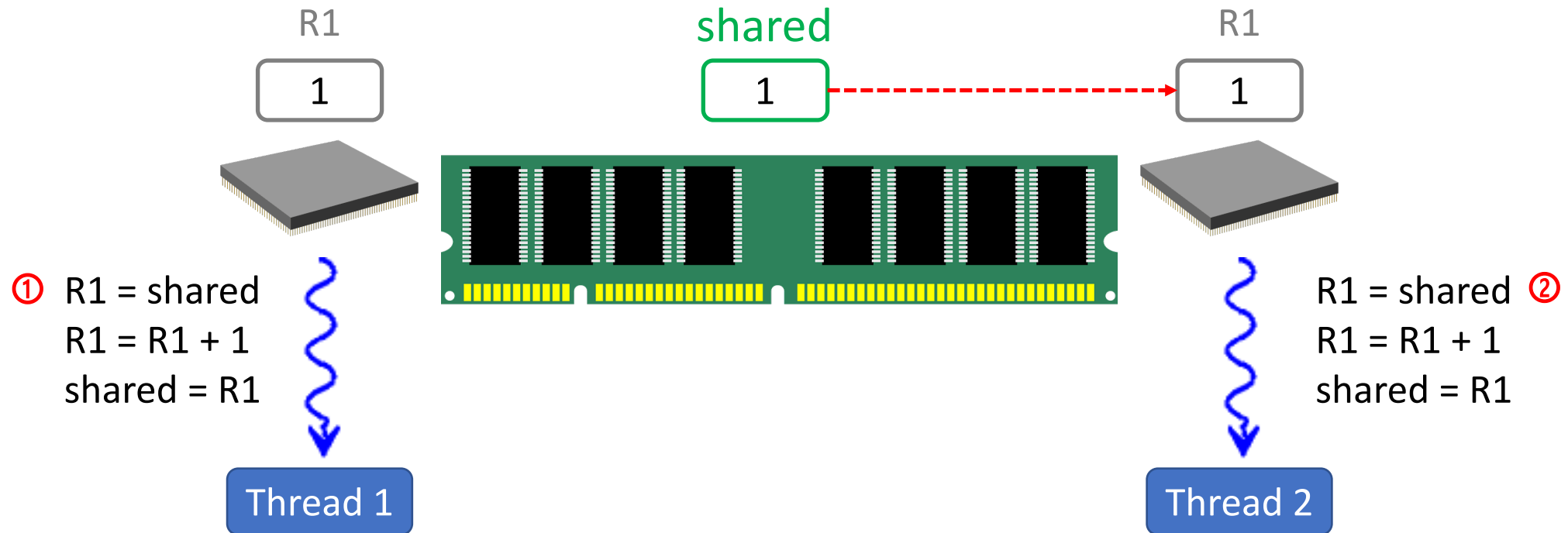
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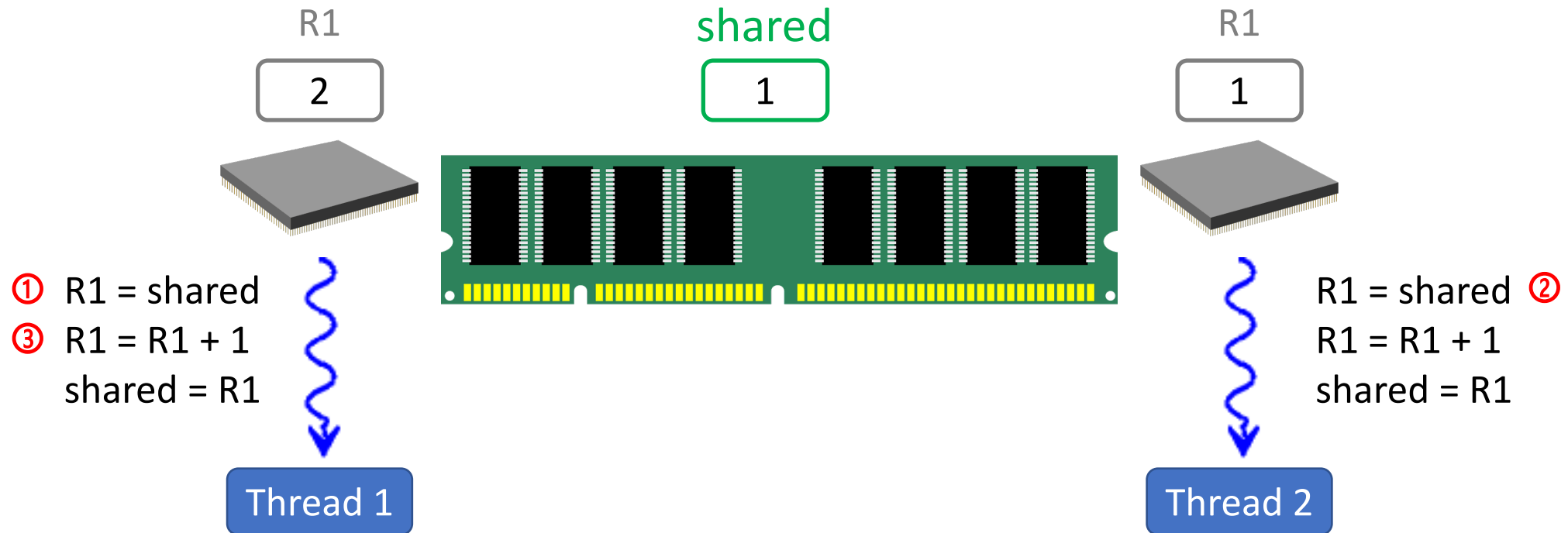
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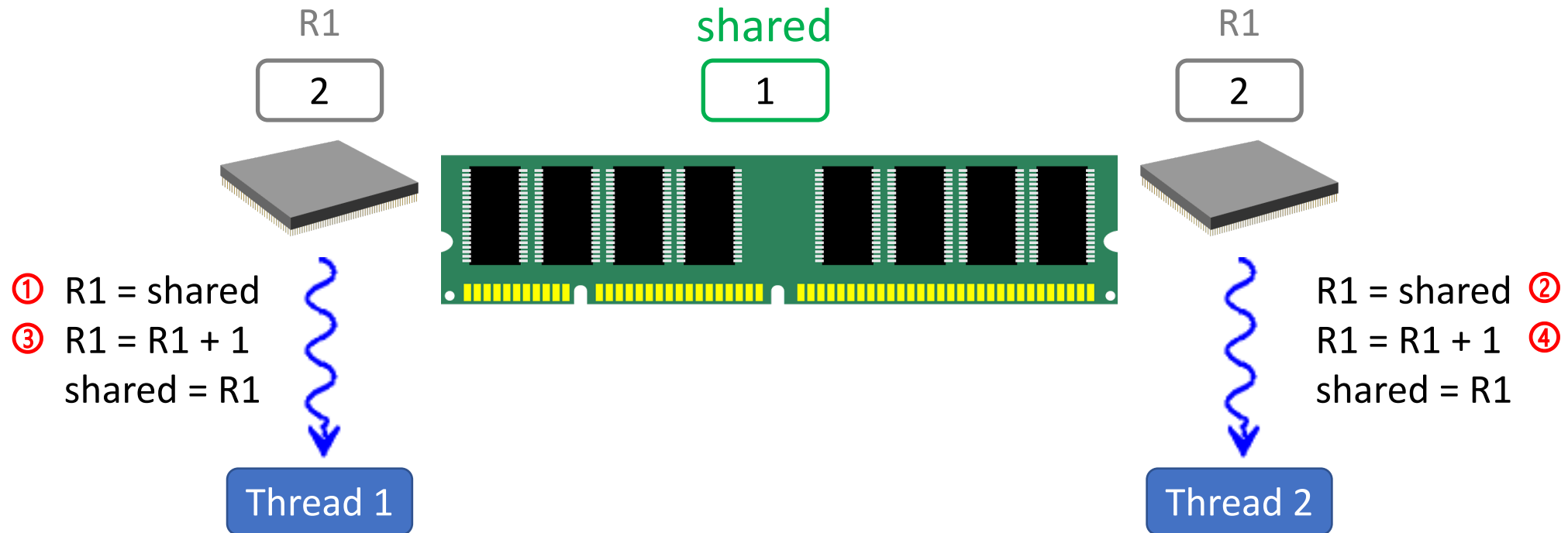
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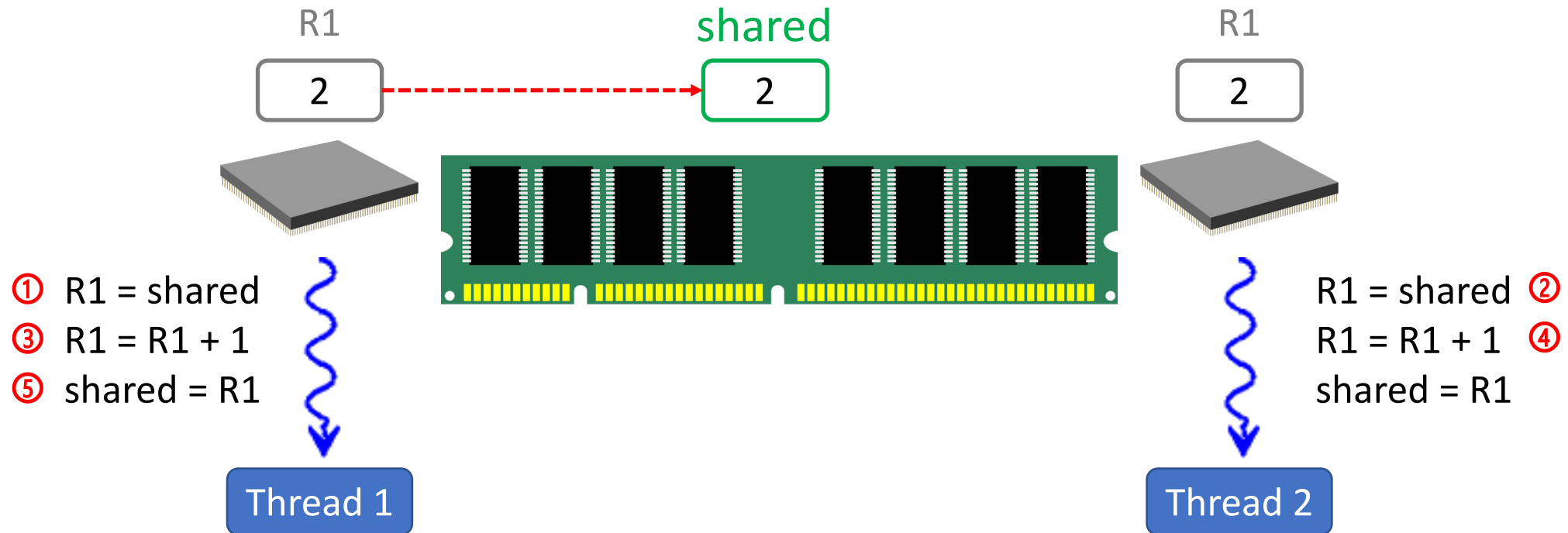
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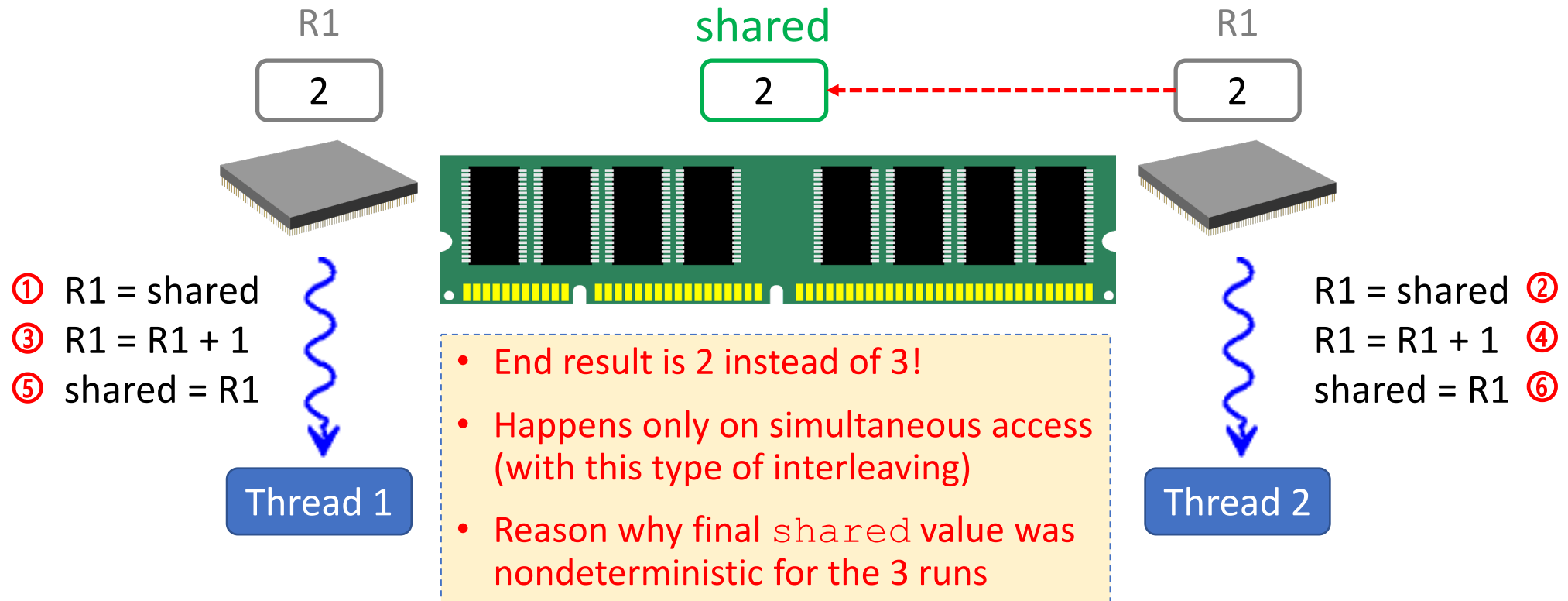
Datarace: Sequence of Events

- When two threads do `shared++`; initially `shared = 1`



Datarace: Sequence of Events

- When two threads do `shared++`; initially `shared = 1`



What to do? Stamp Out the Error!

- Let's use Google Thread Sanitizer this time!

```
bash-4.2$ clang datarace.c -fsanitize=thread -g -o datarace
```

```
bash-4.2$ ./datarace
```

```
WARNING: ThreadSanitizer: data race (pid=14291)
```

```
Write of size 4 at 0x00000112d618 by main thread:
```

```
#0 add datarace.c:5:42 (datarace+0x4ca832)
```

```
#1 main datarace.c:11:3 (datarace+0x4ca89f)
```

```
Previous write of size 4 at 0x00000112d618 by thread T1:
```

```
#0 add datarace.c:5:42 (datarace+0x4ca832)
```

```
...
```

Tells compiler to
sanitize threads

Where in code
dataraces
happened

Datarace Fixed

```
pthread_mutex_t lock;  
int shared = 0;  
void *add(void *unused) {  
    for(int i=0; i < 1000000; i++) {  
        pthread_mutex_lock(&lock);  
        shared++;  
        pthread_mutex_unlock(&lock);  
    }  
    return NULL;  
}  
int main() {  
    ...  
}
```

```
bash-4.2$ ./datarace  
shared=2000000  
bash-4.2$ ./datarace  
shared=2000000  
bash-4.2$ ./datarace  
shared=2000000
```

- Now result is deterministic
- Threads take turns accessing shared

Nondeterminism by Design

It's by Design – Deal with it!

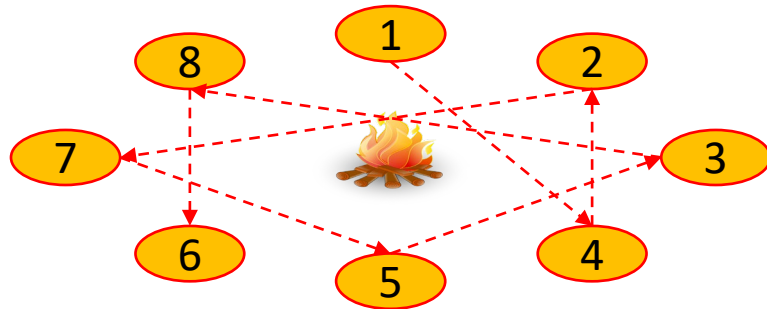
- Due to randomness by design
 - Random number generation
 - Thread interleaving
- You can't just stamp out the nondeterminism. It's by design.
- Somehow deal with the nondeterminism such that
 - You do not get any surprise defects at the client site
 - Defects are reproducible while debugging

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Speaking Staff doesn't Remove All Nondeterminism

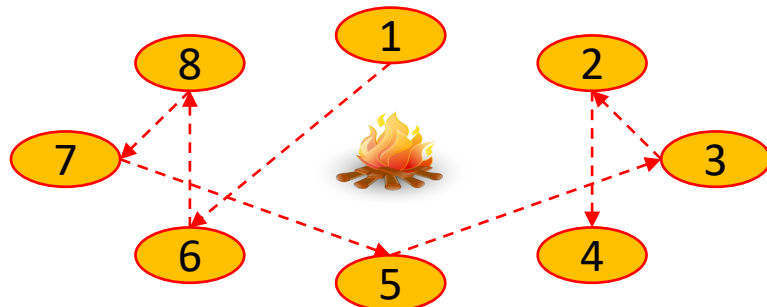
- Depending on the order the staff is passed, meeting script can change
- Order 1:



Meeting Script 1:



- Order 2:

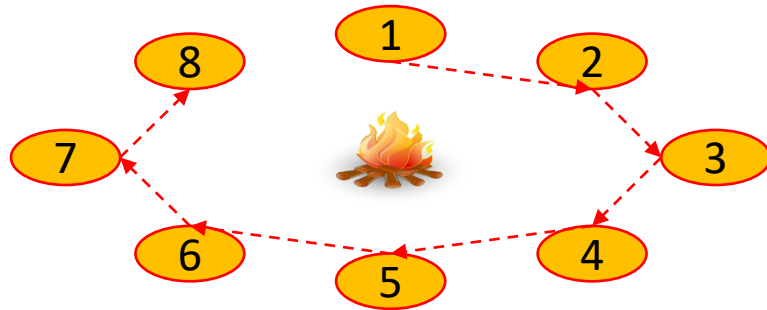


Meeting Script 2:



For Full Determinism, Must Fix Passing Order

- For example, fix staff passing order to clockwise direction
- Fixed clockwise order:



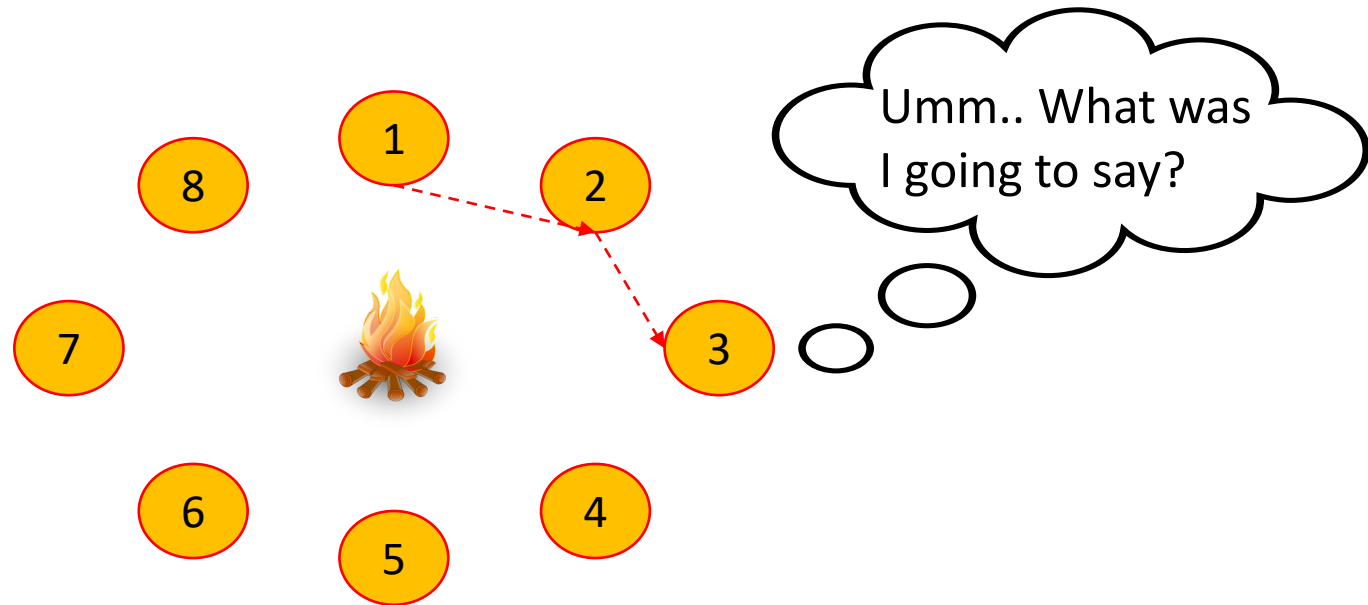
Fixed meeting script



- But programmers don't like doing this because it hurts performance

Performance Slow Down due to Fixed Order

- If an elder is not ready to speak, it can slow down the entire meeting



- Doesn't happen if staff is passed nondeterministically on demand
→ Many programs don't constrain thread interleaving for this reason

Nondeterministic Interleaving Example

```
class Interleaving implements Runnable {  
    public static String script = "";  
    public void run() {  
        synchronized(this) {  
            script += Thread.currentThread().getName() + " ";  
        }  
        synchronized(this) {  
            script += Thread.currentThread().getName() + " ";  
        }  
    }  
  
    public static void main(String[] args) throws InterruptedException {  
        Interleaving m = new Interleaving();  
        Thread t = new Thread(m);  
  
        t.start();    // Child thread does run()  
        m.run();      // Main thread does run()  
  
        t.join();  
        System.out.println(script);  
    }  
}
```

Java version of a lock, so no datarace.
But still nondeterministic due to interleaving.

- Main thread appends "main" twice
- Child thread appends "Thread-1" twice
- What are all the possible outputs?

Nondeterministic Interleaving Output

- 6 different possible outcomes!

```
bash-4.2$ java Interleaving  
main main Thread-1 Thread-1
```

```
bash-4.2$ java Interleaving  
main Thread-1 main Thread-1
```

```
bash-4.2$ java Interleaving  
main Thread-1 Thread-1 main
```

```
bash-4.2$ java Interleaving  
Thread-1 main main Thread-1
```

```
bash-4.2$ java Interleaving  
Thread-1 main Thread-1 main
```

```
bash-4.2$ java Interleaving  
Thread-1 Thread-1 main main
```

- All could be correct – if you don't care about the ordering. Or not.

Nondeterministic Interleaving is Problematic

- A defect may show up only on a particular interleaving
- No guarantee which interleaving will be chosen at runtime
- So testing becomes unreliable and unreproducible
- What to do? We'll get to it soon, but let's first talk about ...

Outline

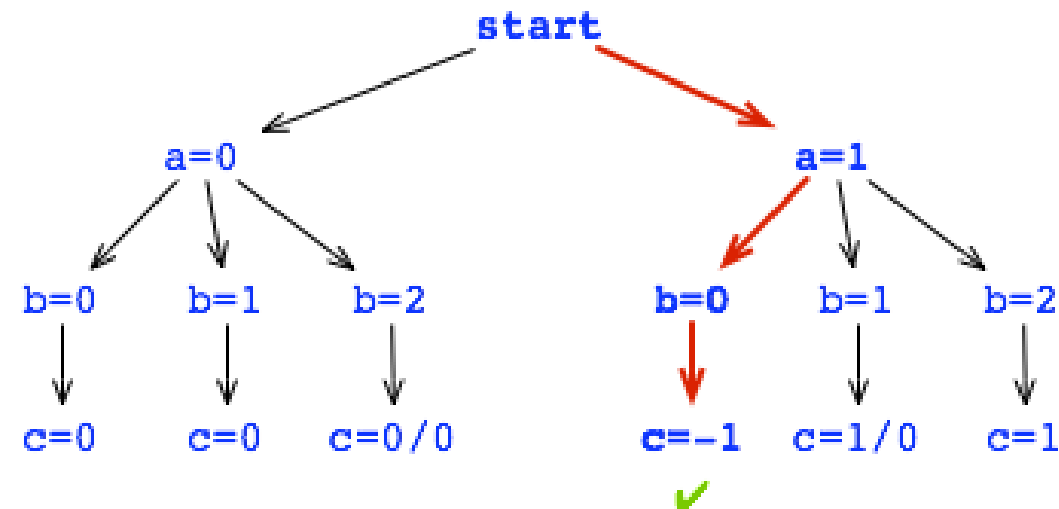
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Random Number Generation Example

Given this code:

```
int a = random.nextInt(2);  
int b = random.nextInt(3);  
int c = a / (b + a - 2);
```

If unlucky, paths with defects will not be covered during testing and bug may never be found!



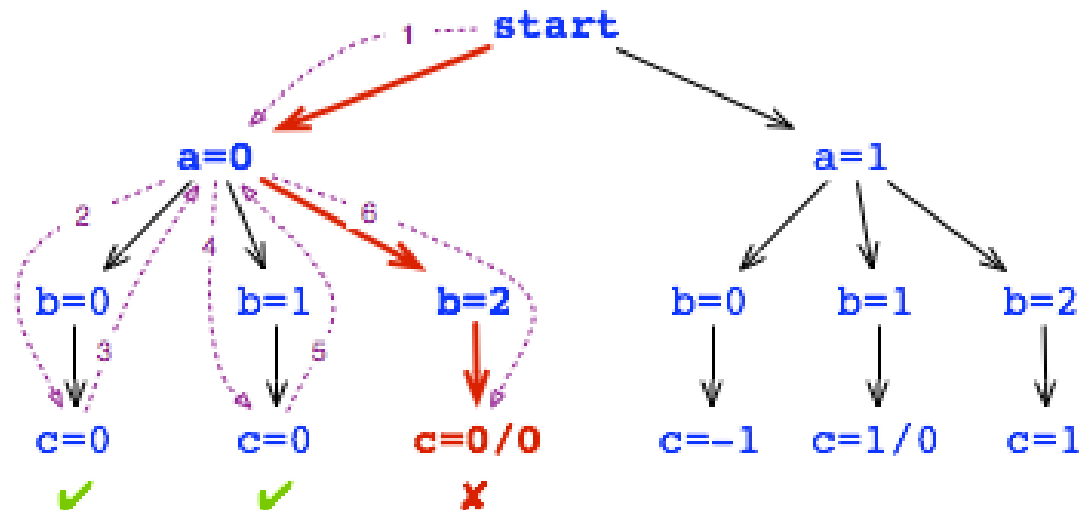
- ① `Random random = new Random();`
- ② `int a = random.nextInt(2);`
- ③ `int b = random.nextInt(3);`
- ④ `int c = a / (b + a - 2);`

What to do? Deal with it!

Given this code:

```
int a = random.nextInt(2);  
int b = random.nextInt(3);  
int c = a / (b + a - 2);
```

Exhaustively search through all possible paths to find the defect!



① `Random random = new Random();`

② `int a = random.nextInt(2);`

③ `int b = random.nextInt(3);`

④ `int c = a / (b + a - 2);`

Java Path Finder (JPF)

- Model checker developed by NASA to verify mission critical code
- Exhaustively searches through all possible states of a program
 - Enumerates all possible values from random number generators
 - Enumerates all possible interleavings between threads

JPF on Random Number Generation

```
int a = random.nextInt(2);  
int b = random.nextInt(3);  
int c = a / (b + a - 2);
```

Not shown, but also generates a
“trace” of random values chosen

```
-bash-4.2$ ./runJPF.sh Random.jpf  
JavaPathfinder core system v8.0 (C) 2005-2014 United States Government.  
...  
===== error 1  
gov.nasa.jpf.vm.NoUncaughtExceptionsProperty  
java.lang.ArithmeticException: division by zero  
    at Rand.main(Rand.java:34)  
...
```

Where in code
exception happened

JPF on Thread Interleaving

```
-bash-4.2$ ./runJPF.sh Interleaving.jpf
```

```
JavaPathfinder core system v8.0 (C) 2005-2014 United States  
Government.
```

```
...
```

```
===== search started
```

```
main main Thread-1 Thread-1  
main Thread-1 main Thread-1  
main Thread-1 Thread-1 main  
Thread-1 main main Thread-1  
Thread-1 main Thread-1 main  
Thread-1 Thread-1 main main
```

Able to explore all interleavings and
generate all possible outputs!

Summary

Summary

- We learned there are two types of nondeterminism
 - Nondeterminism by mistake – stamp it out!
 - Memory errors
 - Data race errors
 - Nondeterminism by design – deal with it!
 - Random number generation
 - Thread interleaving
- We also learned three tools that can help you
 - Google Address Sanitizer
 - Google Thread Sanitizer
 - NASA Java Path Finder

Open Source Resources

- Google Address Sanitizer:
<https://github.com/google/sanitizers/wiki/AddressSanitizer>
- Google Thread Sanitizer:
<https://github.com/google/sanitizers/wiki/ThreadSanitizerCppManual>
- NASA Java Path Finder:
<https://github.com/javapathfinder/jpf-core/wiki>
<https://github.com/javapathfinder/jpf-core/wiki/GSoC-2022-Project-Ideas>

References

- Konstantin Serebryany et al. “AddressSanitizer: A Fast Address Sanity Checker”. USENIX, 2012: <https://research.google/pubs/pub37752/>
- Konstantin Serebryany et al. “ThreadSanitizer – data race detection in practice”. Workshop on Binary Instrumentation and Applications (WBIA), 2009: <https://research.google/pubs/pub35604/>
- Ranjit Jhala and Rupak Majumdar. “Software model checking”. ACM Computing Surveys, 2009: <https://people.mpi-sws.org/~rupak/Papers/SoftwareModelChecking.pdf>
- 11th Competition on Software Verification (SV-COMP), 2022: <https://sv-comp.sosy-lab.org/2022/results/results-verified/>

Questions?