OS05: Mutual Exclusion [*]

Based on Chapter 4 of [Hai19]

Jens Lechtenbörger

Computer Structures and Operating Systems 2021

1 Introduction

1.1 OS Plan

- OS Overview (Wk 23)
- OS Introduction (Wk 23)
- Interrupts and I/O (Wk 24)
- Threads (Wk 24)
- Thread Scheduling (Wk 25)
- Mutual Exclusion (MX) (Wk 25)
- MX in Java (Wk 26)
- MX Challenges (Wk 26)
- Virtual Memory I (Wk 27)
- Virtual Memory II (Wk 27)
- Processes (Wk 28)
- Security (Wk 28)

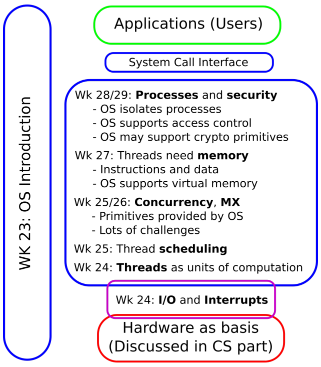
WK 23: OS Introduction
Applications (Users)
System Call Interface
Wk 28/29: Processes and security
- OS isolates processes
- OS supports access control
- OS may support crypto primitives
Wk 27: Threads need memory
- Instructions and data
- OS supports virtual memory
Wk 25/26: Concurrency, MX
- Primitives provided by OS
- Lots of challenges
Wk 25: Thread scheduling
Wk 24: Threads as units of computation
Wk 24: I/O and Interrupts
Hardware as basis
(Discussed in CS part)

Figure 1: OS course plan, summer 2021

1.2 Today's Core Questions

- What can go wrong with concurrent computations?
  - What is a race condition?
- How to avoid subtle programming bugs related to timing issues?
  - What mechanisms does the OS provide to help?

[*] This PDF document is an inferior version of an OER HTML page; free/libre Org mode source repository.

1.3 Learning Objectives

- Recognize and explain race conditions
  - (Playing Deadlock Empire helps)
- Explain notions of critical section and mutual exclusion
- Use mutexes and semaphores (and monitors after upcoming lectures) to enforce mutual exclusion

1.4 Retrieval Practice

1.4.1 Informatik 1

You have seen this advice before. It is repeated here for emphasis:

- What are **interfaces** and **classes** in Java, what is this?
- If you are not certain, consult a textbook; these self-check questions and preceding tutorials may help:
  - `https://docs.oracle.com/javase/tutorial/java/concepts/QandE/questions.html`
  - `https://docs.oracle.com/javase/tutorial/java/IandI/QandE/interfaces-questions.html`

1.4.2 Recall: Datenmanagement

- Give examples for **dirty read** and **lost update** anomalies.
- What is a database **transaction**?
- What does each of the four **ACID guarantees** mean?
- Explain **serializability** as notion of consistency.

The above is covered in this introduction to transaction processing.

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2 Race Conditions

2.1 Central Challenge: Races

Figure 2: “Ferrari Kiss” by Antoine Valentini under CC BY-SA 2.0; from flickr

2.2 Races (1/2)

- **Race (condition)**: a technical term
  - Multiple **activities** access **shared resources**
    - At least one writes, in parallel or concurrently
  - Overall outcome depends on **subtle timing** differences
    - “Nondeterminism” (recall Dijkstra on interrupts)
    - Missing synchronization
    - **Bug**!
- Previous picture
  - **Cars** are activities
  - **Street segments** represent shared resources
  - Timing determines whether a **crash** occurs or not
  - Crash = misjudgment = missing synchronization

2.3 Races (2/2)

- DBMS
  - **SQL commands** are activities
  - **Database objects** are shared resources
  - **Update anomalies** indicate missing synchronization

        - Serializability requires synchronization and avoids anomalies
            - E.g., ACID transactions via locking

- OS
    - **Threads** are activities
    - **Variables, memory, files** are shared resources
    - Missing synchronization is a **bug**, leading to anomalies just as in database systems

2.4 JiTT Tasks

2.4.1 JiTT Assignment: The Deadlock Empire, Part 1

- Play "Tutorial 1," "Tutorial 2," and the three games for "Unsynchronized Code" at `https://deadlockempire.github.io/`
    - The games make use of C#
        - (Which you do not need to know; the games include lots of explanations, also mouse-over helps)
- General idea
    - The game is about **mutual exclusion** and **critical sections**, to be discussed next
        - At any point in time just **one** thread is allowed to execute under mutual exclusion inside a critical section
        - If you manage to lead two threads into a critical section simultaneously (or, in some levels, to execute `Assert(false)`), you demonstrate a race condition
    - You **win** a game if you demonstrate a race condition
- Really, start playing **now**! (Nothing to submit here)

2.4.2 Transfer of Deadlock Empire

Consider the following piece of Java code (from Sec. 4.2 of [Hai19]) to sell tickets as long as seats are available. (That code is embedded in this sample program, which you can execute to see races yourself.)

```
if (seatsRemaining > 0) {
   dispenseTicket();
   seatsRemaining = seatsRemaining - 1;
} else displaySorrySoldOut();
```

Inspired by the Deadlock Empire, find and explain a race condition involving the counter `seatsRemaining`, which leads to single tickets being sold several times (to be revisited in exercises).

2.5 Non-Atomic Executions

- Races generally result from non-atomic executions
  - Even "single" instructions such as `i += 1` are **not atomic**
    - Execution via **sequences of machine instructions**
      - Load variable's value from RAM
      - Perform add in ALU
      - Write result to RAM
  - A context switch may happen after any of these machine instructions, i.e., "in the middle" of a high-level instruction
    - Intermediate results accessible elsewhere
      - **No isolation** in the sense of ACID transactions: races, dirty reads, lost updates
    - Demo: Play a game as instructed previously

This slide highlights that even simple statements of high-level programming languages are not executed atomically, which may be the source of race conditions.

Note that the word "atomic" is used in its literal sense here. So, an execution is **not** atomic if is really consists of multiple steps.

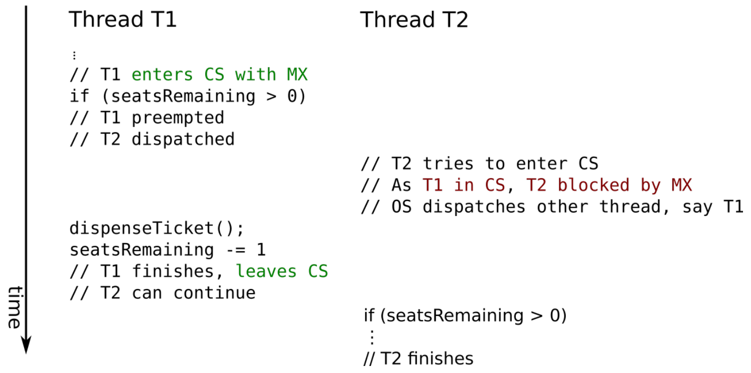
Be careful not to confuse this with the notion of atomicity of ACID transactions. In the ACID context, atomicity means that transactions appear to be either executed entirely or not at all; whether they consist of multiple steps or not is not an issue.

3 Critical Sections and Mutual Exclusion

3.1 Goal and Solutions (1/3)

- Goal
  - Concurrent executions that access **shared resources** should be **isolated** from one another
    - Cf. **I** in ACID transactions
- Conceptual solution
  - Declare **critical sections** (CSs)
    - CS = Block of code with potential for race conditions on shared resources
      - Cf. transaction as sequence of operations on shared data
  - Enforce **mutual exclusion** (MX) on CSs
    - At most one thread inside CS at any point in time
      - This avoids race conditions
      - Cf. serializability for transactions

3.2 MX with CSs: Ticket example



```
Thread T1                       Thread T2
⋮
// T1 enters CS with MX
if (seatsRemaining > 0)
// T1 preempted
// T2 dispatched
                                // T2 tries to enter CS
                                // As T1 in CS, T2 blocked by MX
                                // OS dispatches other thread, say T1
dispenseTicket();
seatsRemaining -= 1
// T1 finishes, leaves CS
// T2 can continue
                                if (seatsRemaining > 0)
                                ⋮
                                // T2 finishes
```

Figure 3: "Interleaved execution of threads with MX for code from Sec. 4.2 of book by Max Hailperin, CC BY-SA 3.0." by Jens Lechtenbörger under CC BY-SA 4.0; from GitLab

1. The animation on this slide illustrates the effect of mutual exclusion on interleaved executions to avoid races based on a previously shown code fragment to sell tickets for seats. If you did not think about the JiTT assignment for that code fragment yet, please do so now and come back afterwards. Actually, this animation may also help you solving the JiTT assignment.

   Consider two threads that simultaneously try to obtain seats, and suppose that the code fragment is executed as critical section under mutual exclusion. How MX can actually be enforced via locking, semaphores, or monitors is the topic of later slides.

2. T1 enters the CS first. Suppose its time slice runs out after the check that seats are still remaining. Now the OS dispatches T2, which wants to execute the same CS. However, as T1 is currently executing inside that CS and as MX is enforced for that CS, T2 is blocked by the OS. Thus, the OS schedules another thread for execution, say T1.

3. Consequently, T1 can finish the CS without intermediate modifications by any other thread.

4. Afterwards, T2 can enter the CS, check whether seats are still available etc. In essence, MX enforces the serial execution of CSs. On the one hand, serial executions are good as they avoids races; on the other, they inhibit parallelism, which is generally bad for performance.

3.3 Goal and Solutions (2/3)

- New goal
  - Implementations/mechanisms for MX on CS
- Solutions, to be discussed in detail
  - **Locks**, also called **mutexes**
    - Cf. 2PL for database transactions
    - Acquire lock/mutex at start of CS, release it at end
      - Choices: Busy waiting (spinning) or blocking when lock/mutex not free?
  - **Semaphores**

        - ∗ Abstract datatype, generalization of locks, blocking, signaling
    - **Monitors**
        - ∗ Abstract datatype, think of Java class, methods as CS with MX
        - ∗ Keyword `synchronized` turns Java method into CS with MX!

3.4 Challenges

- Above solutions restrict entry to CS
    - Thus, they restrict access to the resource CPU
- Major synchronization challenges arise
    - **Starvation** (related to (un-) fairness)
        - Thread never enters CS
            - (More generally: never receives some resource, e.g., CPU under scheduling)
    - **Deadlock** (discussed in later presentation)
        - Set of threads is stuck
        - Circular wait for additional locks/semaphores/resources/messages
    - In addition, programming errors, e.g., races involving `seatsRemaining`
        - Difficult to locate, time-dependent
        - Difficult to reproduce, “non-determinism”

3.5 Goal and Solutions (3/3)

- Recall above loose definition
    - MX = At most one thread inside CS at any point in time
        - This avoids race conditions
- Stricter definitions also address deadlocks, starvation, failures
    - Our **definition**: Solution **ensures MX** if
        - At most one thread inside CS at any point in time
        - Deadlocks are ruled out
    - (Not our focus: Starvation does not occur)
        - (E.g., requests granted under fairness guarantees such as first-come first-serve or with “luck” based on randomness)
    - ([Lam86] provides detailed discussion, also addressing failures)

4 Locking

4.1 Mutexes

Warning! External figure **not** included: “Mutexes” © 2016 Julia Evans, all rights reserved from julia’s drawings. Displayed here with personal permission. (See HTML presentation instead.)

4.2 Locks and Mutexes

- Lock = mutex = object with methods
  - `lock()` or `acquire()`: Lock/acquire/take the object
    - A lock can only be `lock()`'ed by one thread at a time
    - Further threads trying to `lock()` need to wait for `unlock()`
  - `unlock()` or `release()`: Unlock/release the object
    - Can be `lock()`'ed again afterwards
  - E.g., interface java.util.concurrent.locks.Lock in Java.

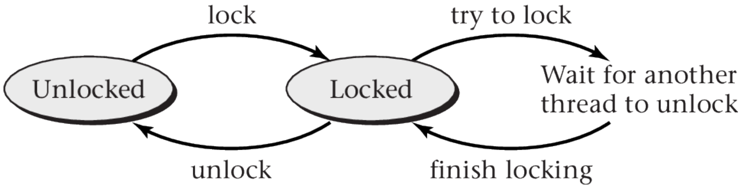


Figure 4: "Figure 4.4 of [Hai17]" by Max Hailperin under CC BY-SA 3.0; converted from GitHub

First of all, note that the terms "lock" and "mutex" are synonyms.

Locks (and mutexes) are special-purpose objects, which essentially have two states, namely Unlocked and Locked, which you can see in the figure here, along with possible state transitions when the lock's methods lock() and unlock() are invoked. These methods are explained in the bullet points.

When mutual exclusion (MX) is necessary to prevent races for a critical section (CS), a lock object shared by the racing threads can be used, for example seatlock on the next slide. To enforce MX, method lock() needs to be invoked on the lock object at the beginning of the CS, and unlock() at the end.

When the first thread executes lock(), the locks's state changes from Unlocked to Locked. If other threads try to execute lock() in state Locked, these threads get blocked until the first thread executes unlock(), which changes the lock's state to Unlocked and which allows the blocked threads to continue their locking attempts; of course, only one of them will be successful.

The question whether the lock really changes its state from Locked to Unlocked upon unlock() or whether it is immediately reassigned to one of the blocked threads (e.g., in FIFO order) is a design decision, which will be revisited later in the context of the so-called convoy problem.

4.3 Use of Locks/Mutexes

- Programming discipline **required** to prevent races
  - Create one (shared) lock for each shared data structure
  - Take lock before operating on shared data structure
  - Release lock afterwards
- ([Hai19] has sample code following POSIX standard)
- Ticket example modified (leading to MX behavior):

```
seatlock.lock();
if (seatsRemaining > 0) {
   dispenseTicket();
   seatsRemaining = seatsRemaining - 1;
} else displaySorrySoldOut();
seatlock.unlock();
```

4.4 Quiz on MX Vocabulary

5 Semaphores

5.1 Semaphore Origin

- Proposed by Dijkstra, 1965
  - Based on **waiting** (sleeping) for **signals** (wake-up calls)
    - Thread waiting for signal is **blocked**
- **Abstract data type**
  - Non-negative integer
    - Number of available resources; 1 for MX on CPU
  - Queue for blocked threads
  - **Atomic** operations
    - Initialize integer
    - `acquire` (wait, sleep, down, P [passeren, proberen]): entry into CS
      - Decrement integer by 1
      - As integer must be non-negative, **block** when 0
    - `release` (signal, wakeup, up, V [vrijgeven, verlaten]): exit from CS
      - Increment integer by 1 (value may grow without bound)
      - Potentially **unblock** blocked thread

5.2 Use of Semaphores for MX

- Programming discipline **required** similarly to locks
  - Create semaphore for shared data structure
  - `acquire()` before CS, `release()` after
- Ticket example modified with `seatSem` initialized to `1` (leading to MX behavior):
  - (The semaphore initialized to 1 behaves exactly like a lock here)

```
seatSem.acquire();
if (seatsRemaining > 0) {
   dispenseTicket();
   seatsRemaining = seatsRemaining - 1;
} else displaySorrySoldOut();
seatSem.release();
```

5.2.1 Semaphores for Capacity Control

- Semaphores initialized to other values than 1 are typically used to model capacities
- Example from stack overflow: bouncer in nightclub
  - Nightclub has limited capacity, i.e., number of people allowed in club at any moment: n
    - Bouncer (semaphore initialized to n) makes sure that no more than n people can be inside
    - If club is full, a queue collects waiting people
  - Guests (threads) call `acquire()` on bouncer/semaphore to enter
  - Guests (threads) call `release()` on bouncer/semaphore to leave
- Example later on: `SemaphoreBoundedBuffer`

5.3 JiTT Tasks

5.3.1 The Deadlock Empire – Remarks

- The games at `https://deadlockempire.github.io/` make use of C#
- What is called "monitor" in C# is **not** a Hoare style monitor to be discussed in the upcoming presentation
  - In C#, a "monitor" needs to be (un)locked explicitly
  - Whereas Hoare style monitors are locked implicitly and automatically
- Class context
  - Hoare style monitors in Java
  - Producer/consumer scenarios mentioned in games
    - Classical synchronization problems (this presentation)
    - Revisited as BoundedBuffer in Java

5.3.2 The Deadlock Empire, Part 2

Play the following games at `https://deadlockempire.github.io/`

- "Locks" and "Semaphores"
  - Incorrect use of both, sometimes leading to deadlocks. For locks, `Enter()` and `Exit()` represent `lock()` and `unlock()`
- "Condition Variables"
  - Here, `if (queue.Count == 0)` is meant to avoid removal attempts from empty queues. However, `PulseAll()` wakes up all waiting (blocked) threads (similarly to `notifyAll()` for Java later on)

6 Implementation Aspects

6.1 Atomic Instructions

- Typical building block for MX: Atomic machine instruction
  - Several memory accesses with guarantee of isolation/no interference
- E.g., `exchange`, which exchanges contents of register and memory location

6.2 Mutex with Simplistic Spinlock Implementation

- Single memory location called `mutex`
  - Value `1`: unlocked
  - Value `0`: locked
- Operations
  - `unlock()`: Store `1` into `mutex`
  - `lock()`: Atomically check for `1` and store `0` as follows ([Hai19]):

```
to lock mutex:
  let temp = 0
  repeat
    atomically exchange temp and mutex
  until temp = 1
```

Consider a simplistic mutex implementation, where the mutex itself is represented by a single memory location, called `mutex`, which can have the values 1 for unlocked and 0 for locked. The operation `lock()` uses an atomic machine instruction to exchange the contents of memory location `mutex` with another value (here `temp`, which could be a CPU register).

Please convince yourself that out of multiple threads invoking `lock()` concurrently on the unlocked mutex, only the first one will pass the `repeat` loop, while subsequent ones are stuck (or "spin") in that loop, until the first thread performs an unlock operation by writing 1 into memory location `mutex`.

This type of lock, where threads waiting for the release of a lock spin in a loop, is called **spinlock** (to be revisited shortly), and it differs from locks where waiting threads are blocked by the OS, which we assumed on earlier slides. Recall that actively waiting in a loop is also called **busy waiting** as we have seen in the context of I/O polling.

Spinlocks are mainly used for low-level programming where the duration of lock periods can be guaranteed to be short.

See [Hai19] for a cache-conscious spinlock variant (beyond scope of class).

6.3 On Spinlocks

- **Spinlock**: Thread spins **actively** in loop on CPU while waiting for lock to be released
  - **Busy waiting**
  - Avoids overhead of scheduling and context switch coming with blocking locks
- Note: Spinning thread keeps CPU core busy
  - No blocking by OS
  - **Waste** of CPU resources unless lock periods are short

6.4 Mutex with Queue

- Mutex as OS mechanism
  - When `lock()` fails on a locked mutex, OS **blocks** thread
  - Blocked threads are collected in queue
  - **No** busy waiting
    - Thus, CPU time not wasted for long waiting periods
    - However, scheduling with its own **overhead** required
      - Wasteful, if waiting periods are short
- Different variants of `unlock()`
  1. Unblock thread in FIFO order from queue (if one exists)
     - And reassign mutex to that thread
  2. Make all threads runnable without reassigning mutex
     - Upcoming presentation: convoy problem and its solution
- Pseudocode in [Hai19]

6.5 Quiz on Locking

6.6 JiTT: Questions and Feedback

- What did you find difficult or confusing about the **contents** of the presentation? Please be as specific as possible. For example, you could describe your current understanding (which might allow us to identify misunderstandings), ask questions that allow us to help you, or suggest improvements (maybe on GitLab). Please use the session's shared document or MoodleOverflow. Most questions turn out to be of general interest; please do not hesitate to ask and answer where others can benefit. If you created additional original content that might help others (e.g., a new exercise, an experiment, explanations concerning relationships with different courses, . . .), please share.

7 Outlook

7.1 Producer/Consumer problems

- Classical synchronization problems, revisited in next presentation
  - One or more **producers**
    - Generate data
      - Records, messages, tasks
    - Place data into **buffer** (shared resource)
      - Two buffer variants: unbounded or bounded
      - Producer **blocks**, if bounded buffer is full
  - One or more **consumers**

        - Consume data
            - Take data out of **buffer**
            - Consumer **blocks**, if buffer is empty

- Synchronization for **buffer manipulations** necessary

7.2 Use of Semaphores to Track Resources

```
import java.util.concurrent.Semaphore;
/*
  This code is based on Figure 4.18 of the following book:
  Max Hailperin, Operating Systems and Middleware - Supporting
  Controlled Interaction, revised edition 1.3, 2017.
  https://gustavus.edu/mcs/max/os-book/

  In Figure 4.18, synchronizedList() is used, whereas here a
  plain LinkedList is used, which is protected by the additional
  semaphore mutex.
  Also, the class here is renamed and implements a new interface.
*/
public class SemaphoreBoundedBuffer implements BoundedBuffer {
  private java.util.List<Object> buffer =
      new java.util.LinkedList<Object>();

  private static final int SIZE = 20; // arbitrary

  private Semaphore mutex = new Semaphore(1);
  private Semaphore occupiedSem = new Semaphore(0);
  private Semaphore freeSem = new Semaphore(SIZE);

  /* invariant: occupiedSem + freeSem = SIZE
     buffer.size() = occupiedSem
     buffer contains entries from oldest to youngest */

  public void insert(Object o) throws InterruptedException {
    // Called by producer thread
    freeSem.acquire();
    mutex.acquire();
    buffer.add(o);
    mutex.release();
    occupiedSem.release();
  }

  public Object retrieve() throws InterruptedException {
    // Called by consumer thread
    occupiedSem.acquire();
    mutex.acquire();
    Object retrieved = buffer.remove(0);
    mutex.release();
    freeSem.release();
    return retrieved;
  }

  public int size() {
    return buffer.size();
  }
}
```

8 Pointers beyond class topics

8.1 GNU/Linux: Futex

- Fast user space mutex
  - No system call for single user (fastpath)
  - System calls for blocking/waiting (slowpath)
- Meant as building block for libraries
- Like semaphore: Integer with `up()` and `down()`
  - Assembler code with atomic instructions for integer access
- Documentation
  - `man futex`
  - PI-futex.txt
    - (Topic for upcoming presentation: PI stands for priority inheritance, a counter-measure against priority inversion)

8.2 Lock-free Data Structures

- Core idea: Handle critical sections without locks
- Typically based on hardware support for atomicity guarantees
  - Atomic instructions as explained above
    - E.g., Bw-Tree, see [LLS13]
  - Transactional memory, see [LK08]
- See Section 4.9 of [Hai19]

8.3 “Safer” Programming Languages

- High-level programming languages may help with MX
- See [Jun+21] for introduction to Rust
  - Strong type system allows to detect common bugs at **compile** time
    - Thread safety (absence of race conditions) for shared data structures with compile-time checks
  - Ongoing research into safety proofs
- (Besides, the OS Redox is implemented in Rust)

8.4 Massively Parallel Programming

- For massively parallel (big data) processing in clusters or cloud environments, specialized frameworks exist
  - Breaking down “large” tasks with partitioning into smaller ones that are processed in parallel
    - Smaller tasks usually independent of each other (no race conditions)
    - (Built-in fault tolerance with replication)
  - E.g., Apache Hadoop (MapReduce), Apache Spark, Apache Flink

9 Conclusions

9.1 Summary

- Parallelism is a fact of life
  - Multi-core, multi-threaded programming
  - Race conditions arise
  - Synchronization is necessary
- Mutual exclusion for critical section
  - Locking
  - Monitors
  - Semaphores

Bibliography

[Hai17] Max Hailperin. *Operating Systems and Middleware – Supporting Controlled Interaction*. revised edition 1.3, 2017. URL: https://gustavus.edu/mcs/max/os-book/.

[Hai19] Max Hailperin. *Operating Systems and Middleware – Supporting Controlled Interaction*. revised edition 1.3.1, 2019. URL: https://gustavus.edu/mcs/max/os-book/.

[Jun+21] Ralf Jung et al. “Safe Systems Programming in Rust”. In: *Commun. ACM* 64.4 (2021), pp. 144–152. DOI: 10.1145/3418295. URL: https://doi.org/10.1145/3418295.

[Lam86] Leslie Lamport. “The Mutual Exclusion Problem: Part II—Statement and Solutions”. In: *J. ACM* 33.2 (1986), pp. 327–348. DOI: 10.1145/5383.5385. URL: https://doi.org/10.1145/5383.5385.

[LK08] James Larus and Christos Kozyrakis. “Transactional Memory”. In: *CACM* 51.7 (July 2008), pp. 80–88. ISSN: 0001-0782. DOI: 10.1145/1364782.1364800. URL: https://dl.acm.org/citation.cfm?doid=1364782.1364800.

[LLS13] Justin Levandoski, David Lomet, and Sudipta Sengupta. “The Bw-Tree: A B-tree for New Hardware Platforms”. In: *ICDE 2013*. IEEE, Apr. 2013. URL: https://www.microsoft.com/en-us/research/publication/the-bw-tree-a-b-tree-for-new-hardware/.

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