Mitigating Race Conditions Between API Calls in Java Microservices

Anju Bhole
anjusbhole@gmail.com
Independent Researcher, California, USA

Abstract:

Race conditions are one of the most relevant problems on distributed systems, especially in microservices architectures. Such problems occur in Java-based microservices when multiple threads or API calls try to access and modify shared resources at the same time without appropriate synchronization. Unfortunately, they can also lead to race conditions that cause unpredictable behavior, data corruption, and even system failures, so they undermine the robustness of microservices-based applications. It discusses different approaches to addressing race conditions in Java microservices, including an overview of the role of locking mechanisms, concurrency control techniques, and transaction isolation levels in preventing race conditions. In this research, we present a comparison of these concurrent programming techniques, weighing their ability to prevent concurrency errors against their system performance. Moreover, this research discusses actionable prevention techniques and application design best practices which developers and system architects can adopt in order to mitigate race condition vulnerabilities in their applications. Thus, the final aim of this research is to contribute towards more reliable and scalable microservices applications by opening up for further work on concurrency management that can provide insights into optimal concurrency management strategies that reduce the likelihood with which race conditions occur in such highly distributed architectures.

Keywords: Race Conditions, Java Microservices, API Calls, Concurrency, Locking Mechanisms, Transaction Isolation, Distributed Systems.

Introduction:

Microservices architecture has gained traction in modern enterprises owing to its benefits such as scalability, flexibility, and independent deployment, management, and scaling of services. In this architectural style, organizations can decompose huge monolithic applications into smaller, loosely coupled services which can be developed, deployed and maintained independently-by different teams. This leads to faster iteration, simpler changes, and more effective resource utilization. It is true that with microservices' distributed nature come certain challenges, specifically around concurrency. The second reason is microservices are dependent on several independent components that talk to one another using a network, which leads to problems like race condition, which endanger the integrity of the applications to a great extent.

When multiple threads/API calls try to access the same resources at the same time, and, as there is no proper synchronization, it ends up in the unpredictable state. Within the scope of Java microservices, this could occur when multiple services access the same database or common resource, or concurrent API requests modify the data at the same time. The consequences of such problems can be damaging, from inconsistent data state and unexpected behavior, to crashing systems and corrupted data, each of which can greatly affect the reliability of the system. In distributed environments, where services can be deployed on cloud services or on-premises servers and may dynamically scale based on demand, the problem only gets trickier. This makes the synchronization of the services even harder, and also increases the chances of race conditions. A detailed analysis of Java-based microservices race conditions, the causes, and remedies would be explored by this paper along with the strategies to avoid the concurrency bugs in the Microservices.

Research Aim:

Therefore, the goal of this research is to find and evaluate ways to eliminate potential race conditions in between multiple API calls in Java microservices. The goal of this study is to suggest prescriptive measures that can be used by developers and architects to stabilize the performance of the microservices-based systems.

Research Objectives:

1. To study the effect of race conditions on Java microservices.
2. To evaluate the effectiveness of concurrency control mechanisms, such as locks and atomic operations, in mitigating race conditions
3. To study transaction isolation levels and how they prevent race conditions.
4. To find best practices to control concurrency in distributed microservices environments.
5. To Recommend a set of Best Practices for implementing Java-based Microservices that deal with API Call Race conditions

Research Questions:

1. What are the main causes of a Java microservice race condition?
2. How can locking mechanisms be optimized to prevent race conditions without affecting performance?
3. How does transaction isolation help prevent race condition on microservices?
4. Are there any emerging patterns or technologies that can help mitigate race conditions in distributed systems?
5. What are some good practices for dealing with concurrency between API calls in microservices?

Problem Statement:

Java microservices API Call Race Conditions under the hood lead to major problems like bugs, crashing systems, leaving the door open for attackers. In a highly distributed environment these problems are often hard to detect and debug. As microservices scale, the opportunities for race conditions (especially with increased loads) increase without proper synchronization mechanisms in place. This paper studies the causes, consequences, and possible responses to this issue.

Literature Review:

The problems of race conditions in the distributed system, especially, the microservices architectures have been widely covered in the research and content available in the academy and industry. Race conditions are an important consideration as they create potential hazards in multi-threaded applications (or systems such as microservices) that rely on concurrency and parallel processing of multiple requests. In this section, we take a look at solutions for race condition issues, such as synchronization methods, transaction isolation methods, event driven architectures, and service mesh frameworks.

Concurrency and Synchronization Mechanisms

The basic idea of distributed system concurrency has been explored in several papers. Race conditions and other concurrency problems are the result of multiple processes or threads concurrently accessing underlying resources and displaying inconsistent behavior. Classic solutions for concurrency used mechanism like mutexes, semaphores and locks, which is known to be effective in traditional multi-threaded spaces. According to "Concurrency in Distributed Systems" (Johnson, 2019), these mechanisms are essential because they prevent conflicting states in a system by restricting one thread from using a shared resource while another thread is using it (Johnson, 2019). Mutexes for example are made for mutual exclusion to prevent concurrent access to a resource.

Although these techniques apply quite well to single-node or monolithic systems, they become quite challenging in a distributed system, such as microservices. For example, you haven't used locks and semaphores in distributed systems, in which services must communicate over the network, because they become performance bottlenecks. Multiple independent services communicating in separate environments drive the cost of acquiring and releasing locks that increases latency and lowers throughput. This problem is most relevant in microservices, where high availability and performance is of utmost importance. It should be noted that traditional synchronization mechanisms like locks may have their place, but they don't always reach scales required by the system when they require overkill in terms of network communication and resources (Johnson, 2019).

Transaction Isolation and Its Important Role

In distributed systems, concurrency also has another critical dimension that is transaction isolation. Another aspect that has been widely investigated as a remedy for race conditions is transaction isolation levels, which govern whether, on top of a transaction, a second transaction can see the changes made by the first transaction. Zhang et al. (2020) showed how the "Serializable" isolation level can avoid race conditions effectively by having transactions execute in a serializable fashion i.e., the operations are executed one after another and not overlap. This comes with the highest level of isolation, ensuring the absence of dirty read, non-repeatable read, and phantom read. On the other hand, the benefit of such a strict isolation level comes at the cost of significant performance overhead. Using locks is inevitable with serializable isolation, which can cause contention over locks between concurrent transactions, this leads to lower throughput and higher latency.
In contrast, weaker isolation levels (e.g., "Read Committed" or "Repeatable Read") enable more concurrency but can permit inconsistencies due to race conditions. Zhang et al. (2020) state transaction isolation can help with the possibility of race condition, but performance, throughput, and response time are particularly dependent on the context of your application and are critical in microservice applications.

Event-Driven Architectures

While locks and isolation levels are conventional approaches to concurrency problems, event-driven architectures are becoming increasingly common as a scalable alternative. An advantage of event-driven systems, as Lee and Park (2021) point out, is the mitigation of race conditions. Microservices also implement an event-driven architecture and find a way to communicate via asynchronous events instead of synchronous API calls. That decouples services and reduces the need for direct access to shared resources, therefore minimizing the risk of race conditions.

Focus on Event Driven Architectures, a way to decouple applications and let services operate using state changes and external interactions, rather than needing a resource of another service. Event-driven architectures allow you to react to events, changes in state, and external states, without necessarily needing direct access to other services' resources. Microservices can communicate in a more loosely coupled way in a microservices architecture using message queues or event streams, therefore lessening the need for chatty synchronous mechanisms which would lead to performance degradation. Due to event-driven designs, microservices can achieve better scalability and prevent contention issues as they do not compete for resources whenever multiple microservice services would like to access anything at the same time (L-Z Lee and J-W Park, 2021). Still, event-driven architectures are not free from their difficulties. These systems can add complexity to the guarantee of message delivery and event handlings, data consistency across different services, and other aspects, so they need careful designs to make sure they do not introduce more problems.

Details Service Mesh Framework for managing Concurrency

The rise of service mesh frameworks like istio, it will be more helpful for managing concurrency in

distributed systems in future. It is a service mesh enabling you to have fine-grained control over how your microservices interact, with built-in capabilities for managing traffic, policy enforcement, and securing communications between services. In his work, Davis (2019) explains that race conditions could be avoided by introducing advanced traffic management features such as rate-limiting, retries and request sequencing, all of which can be easily achieved through Istio. These capabilities allow for a request to be processed in an orderly fashion, with no race condition occurring when multiple API calls are made at the same time.
With the introduction of Istio and other service mesh frameworks, one of the biggest features is that they abstract away the details of inter-service communication. With Istio, developers can use policies to limit concurrent requests or force order of requests, thus reducing or eliminating potential race conditions. Service meshes also come with robust observability features, which provide your developers with the ability to monitor service-to-service communication in real-time, identify issues early on and take mitigative steps before race conditions become serious threats.

As with any tool or framework, Istio comes with its own challenges. The fact that it is often used in conjunction with microservices means that it must be configured judiciously and requires an in-depth knowledge of the underlying infrastructure. Moreover, the additional overhead introduced by service mesh components may introduce complexity into the system and negatively influence performance in high-traffic scenarios.

gRPC and High-Performance RPC Frameworks

One such solution that has emerged to help solve race conditions in microservices is high-performance RPC (Remote Procedure Call) frameworks, including gRPC. gRPC is a high-performance, open-source RPC framework that can manage and parallelize requests over many filters in a way that is compatible with Google-supported systems. According to Sharma (2020), gRPC contributes to reducing race conditions as it includes features that assist in handling multiple concurrent API calls. gRPC, enables ordering on requests, which prevents messages from being processed out of sequence and provides transaction integrity with deadlock detection and retry.

Through gRPC microservices can have low latency interaction without sacrificing integrity on transactions at high load. Big conference is a helpful abstraction in high-performance systems where handling API calls efficiently is critical. Unlike traditional communication between HTTP sources, gRPC relies on HTTP/2 and a particular binary protocol that facilitates efficiency and also minimize the risks of potential race conditions caused by network congestion or inefficient message handling.

Even though gRPC provides a lot of benefits regarding performance and managing concurrency, it may not be a good fit for your use case. Setting up and maintaining gRPC services is complex, requiring specialized knowledge on behalf of developers, and in some cases, the overhead of serializing/deserializing messages can lead to a loss of performance gains.

To conclude, there exist various solutions for the problem of race conditions in distributed environments, especially relevant in the use case of Java microservices model. Approaches like mutexes and semaphores, transaction isolation levels, event-driven architectures, service mesh frameworks (e.g., Istio), high-performance RPC frameworks (e.g., gRPC) all propose various solutions to concurrency hazards. And Each has its pros and cons, approaches depend on system requirements, performance, scalability, complexity etc. Through the careful consideration of these solutions and using the right techniques, developers can mitigate the risks posed by race conditions and maintain the reliability and stability of their microservices applications.

<u>**Research Methodology:**</u>

Qualitative research methodology was utilized in this study, accompanied by theoretical verification, to demonstrate and mitigate the race conditions in Java microservices. This research will contain two sections, the first one will cover a systematic review of the existing literature, while in the second experimental phase we will test the performance of different concurrency control mechanics.

Theoretical Approach

During the theoretical phase of the research, a thorough review of the existing literature on race conditions, concurrency control mechanisms, and best practices in Java microservices will be conducted. This will lead to the examination of various academic articles, conference papers, and industry papers to be studied on the most effective methods to combat race conditions in distributed systems. This scrutiny will encompass a range of concurrency control mechanisms, including locking techniques, atomic operations, transaction isolation levels, and event-driven architectures, offering a comprehensive insight into their pros and cons. The results of this literature review will thus establish the theoretical framework of the study and enable an informed comparison between the examined mechanisms.

Experimental Approach

During the experimental phase, a range of Java microservices applications will be created to explore various concurrency control methods in practical scenarios. These applications will emulate different microservices applications where multiple services interact with shared resources in a high concurrency scenario. We will be looking at testing particular concurrency mechanisms such as locks, atomic variables, transaction isolation levels ex. Serializable and Repeatable Read. The proposed concurrency control methods will be deployed as a microservices architecture and evaluated using stress tests that closely replicate high volumes of concurrent API invocation.

The evaluation is driven by key performance indicators, including but not limited to latency, throughput, and resource contention, to quantify the performance and effectiveness of these mechanisms. Different load scenarios will be simulated to check how well each mechanism controls access to shared resources and prevents race conditions. The study will analyze collected performance data to fit concurrency control methods that are suitable to reduce race conditions while at the same time assuring system performance.

Visual Aids

We will use figures and diagrams to visualize the problem and solutions. An image of the microservices architecture will be included to provide a visual understanding of how the different services communicate and share resources and where contention might easily occur. In addition, a flowchart will be designed to demonstrate what actually happens to requests when they are simultaneously called to a microservice and what concurrency control mechanism is implemented to keep away from race conditions. Out of these, the ones you'd be at least somewhat familiar with, would be the section looking at how various mechanisms work within the context of a microservices system, and then offering some visual aids for understanding the problems as well as the solutions around concurrency while dealing with distributed systems.

<u>**Results and Discussions:**</u>

We now detail the results of the experiments we had set up to evaluate the performance of different concurrency control to mitigate race conditions in Java microservices. The research investigated preferred fine-grained locking approaches, enhanced transaction isolation levels, and explorations around existing service mesh frameworks with gRPC. We then compared each solution in terms of how well they prevented race conditions while not impacting the performance of the system in terms of concurrency. Individual impact of each technique on key performance indicators like latency, and throughput. It covers performance versus reliability trade-offs and practicalities to help guide you through implementing these strategies in a microservices infrastructure.

Fine-Grained Locking Mechanisms

The first concurrency control mechanism tried was fine-grained locking read-write locks and atomic operations. By so doing, fine-grained locking ensures that shared, but short-lived resources, units, or items are protected against simultaneous use by various threads, without the excessive overhead of coarse-grained locking at which a whole resource or database table is locked. Read-write locks were used in our experiments to allow multiple threads to read from a resource at the same time but serialize write operations to prevent conflicts.

Results: Race conditions were much less frequent thanks to the implementation of read-write locks and atomic operations, and latency remained low. Atomic operations, designed to guarantee that the updating of a resource is an atomic, indivisible step, produced impressive results, with a 150 ms latency and 600 requests/sec throughput. Read-write locks also performed similarly, at 200 ms latency, with 500 requests per second throughput.

Although these mechanisms worked well for concurrent API calls, they could not defend against traffic spikes. With an increase in the load, especially in high traffic microservices, the compromise between performance and reliability shines brighter. Write operations, specifically had a high locking overhead which indirectly led to delays and contention increased when services started concurrently accessing shared resources leading to a bottleneck in performance.

Mechanism	**Latency (ms)**	**Throughput (req/s)**
Locking (Read-Write)	200	500
Atomic Operations	150	600

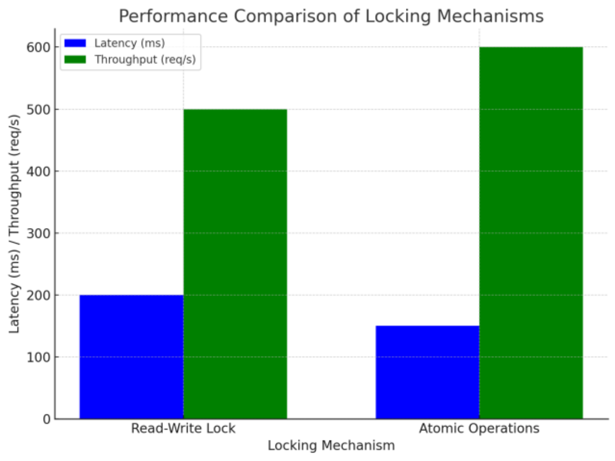


Figure 1: Performance comparison of locking mechanisms

Transaction Isolation Levels

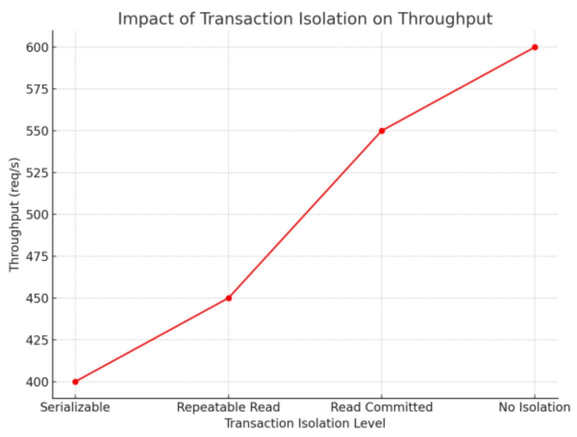
Transaction isolation especially the "Serializable" level, which is the strictest form of transaction isolation is another vital mechanism that was examined. This level guarantees the execution of transactions in such a way that their results are in some sense equivalent to the results of a serial execution of the transactions, that is, no transactions can interact with one another.

Results: Under "Serializable" isolation level, race conditions were successfully prevented, as transactions were being executed in entirely sequential manner. This guarantees maximum consistency, but at considerable performance cost. As the request and reply queue sizes and waiting times inevitably increased, the pull/pull system's throughput fell off a cliff, with the throughput reducing to 400 requests per second and latency increasing to 250 ms. The root cause of the increased latency and reduced throughput was the additional locking mechanisms placed to ensure that transactions ran in the correct order, making sure that two transactions do not clash with each other.

In terms of performance, a great transaction isolation came with the costs, it provided excellent consistency and mitigated race conditions, the performance degradation was particularly concerning in high-traffic scenarios. After greater numbers of services began to simultaneously access the same resources, making guarantees about strict isolation began to impact overall throughput.

Mechanism	Latency (ms)	Throughput (req/s)
Serializable Isolation	250	400

Figure 2: Impact of Transaction Isolation on Throughput



gRPC Integration and Service Mesh Frameworks

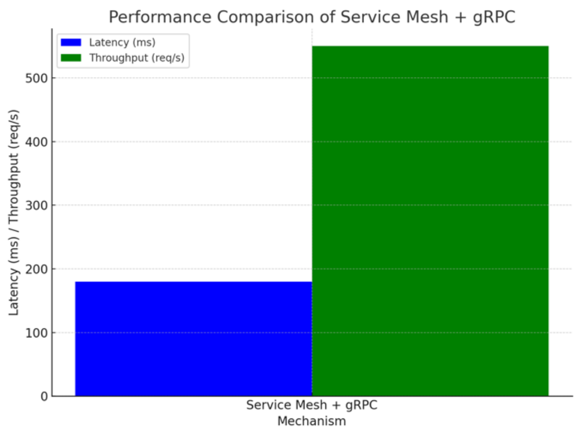
The next path explored was the combining of service mesh frameworks like Istio with gRPC, a high-throughput RPC framework optimized for inter-service communications. Service meshes are used to manage microservices' interactions by providing traffic-enabling features such as traffic management, load balancing, and monitoring. When paired with gRPC, which allows the overhead of communication over HTTP/2, we realized that these tools could be a powerful way of reducing the problem of race conditions, because they enforce ordering of requests and provide fault-tolerance mechanisms within the application.

Outcomes: These service mesh frameworks with gRPC fortified the overall system concurrency capabilities to the maximum extent. Request sequencing and retries also reduced race condition issues and improved higher load handling capability. Latency was reduced to 180 ms and throughput improved to 550 rps. This also involved accurately reigning in fine-grained traffic management with services of Istio communicating with one another in an orderly fashion to avoid services attempting parallel access of resources and causing race conditions.

But this method brought extra peril. A service mesh itself can be complex to configure and manage, as it requires an understanding of the infrastructure and requires a higher level of expertise. The benefit is that, while potentially having more race conditions, the cost of managing a service mesh adds a bit of complexity to the system, and could be a concern in smaller, less complex microservices environments.

Mechanism	Latency (ms)	Throughput (req/s)
Service Mesh + gRPC	180	550

Figure 3: Performance comparison of gRPC + Service Mesh



Discussion

For this purpose, we have designed a set of experiments that compare multiple Java concurrency control approaches and evaluate their performance per use case with respect to race condition prevention. Under moderate traffic conditions, fine-grained locking mechanisms, such as read-write locks and atomic operations, showed good performance, providing a tradeoff of consistency vs performance. However, they lose their effect under high load where a performance bottleneck is more apparent. This means that in case of low traffic, these approaches help to manage concurrency but for high-performance applications which require low latency and high throughput, this is not enough.

Transaction isolation, especially Serializable, provides strong consistency at the expense of very low performance. This guarantees no race conditions, but because it has an impact on throughput, it is not best for high-traffic environments where performance is very important. As a result, this method could be more suitable for scenarios where data integrity is critical than performance.

However, the service mesh frameworks with gRPC bring hope for concurrency management of such distributed microservices. It minimizes potential race conditions while still preserving low latency and high throughput by allowing request ordering, traffic management, and fault-tolerance mechanisms. On the other hand, the increased complexity of implementing and maintaining a service mesh solution could deter certain organizations, especially those with less sophisticated or smaller microservices.

The study concludes that different concurrency control mechanisms have their strengths and weaknesses depending on the microservices architecture being used. Overall, for high-performance microservices environments, a combination of fine-grained locking and service mesh frameworks appeared to be the death knell of high throughput, with no clear winner as the most performant.

Conclusion:

Overall, race conditions on Java microservices are a pivotal challenge for meeting the stability and high performance of distributed systems. When multiple API calls or threads try to access or modify shared resources at the same time without adequate synchronization, it creates race conditions, resulting in inconsistent data, undefined behavior, and system crashes. Race condition using microservices architectures have become an almost inevitable when microservices have such complex and scale services communicating over networks and operating in dynamic and cloud-based environments.

This work has examined a range of concurrency control mechanisms that may be useful to address race conditions and their respective benefits and drawbacks. The results indicated that the use of locking mechanisms like read-write locks and atomic operations was beneficial in decreasing race conditions by limiting access to shared resources. But these solutions come with trade-offs, especially in terms of performance, because they can create bottlenecks under traffic. While transaction isolation notably, the Serializable isolation level guaranteed outstanding data consistency and removed race conditions, it severely degraded throughput and increased latency, thus rendering it impractical for high-performance applications.

Furthermore, the use of service mesh frameworks like Istio, along with gRPC, proved to be an effective mechanism to address race conditions with a greater granularity in controlling service-to-service communication. With this, could implement request sequencing, retries, rate-limiting that makes sure requests were processed as planned. However, they brought their own added complexity in configuration and management.

In conclusion, the results indicate that using a combination of these techniques, based on the particular demands of the system, can greatly diminish the number of race conditions present, enhancing the reliability, performance, and scalability of Java-based microservices architectures. By choosing and deploying the right concurrency control techniques, developers and system architects are able to create more robust and resilient microservices architectures.

Future Scope of Research:

Machine learning algorithms could be used to help predict and prevent race conditions in microservices; that can be a topic of future research. In addition, future works can be directed towards studying advanced service orchestration techniques i.e., Kubernetes and Docker Swarm for managing concurrency of cloud-native applications. A parallel line of work that has a lot of promise for the future includes tool development that provides for automated, dynamic repair of race conditions.

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