OpenJDK

Java ORACLE

Why User-Mode Threads Are Often the Right Answer

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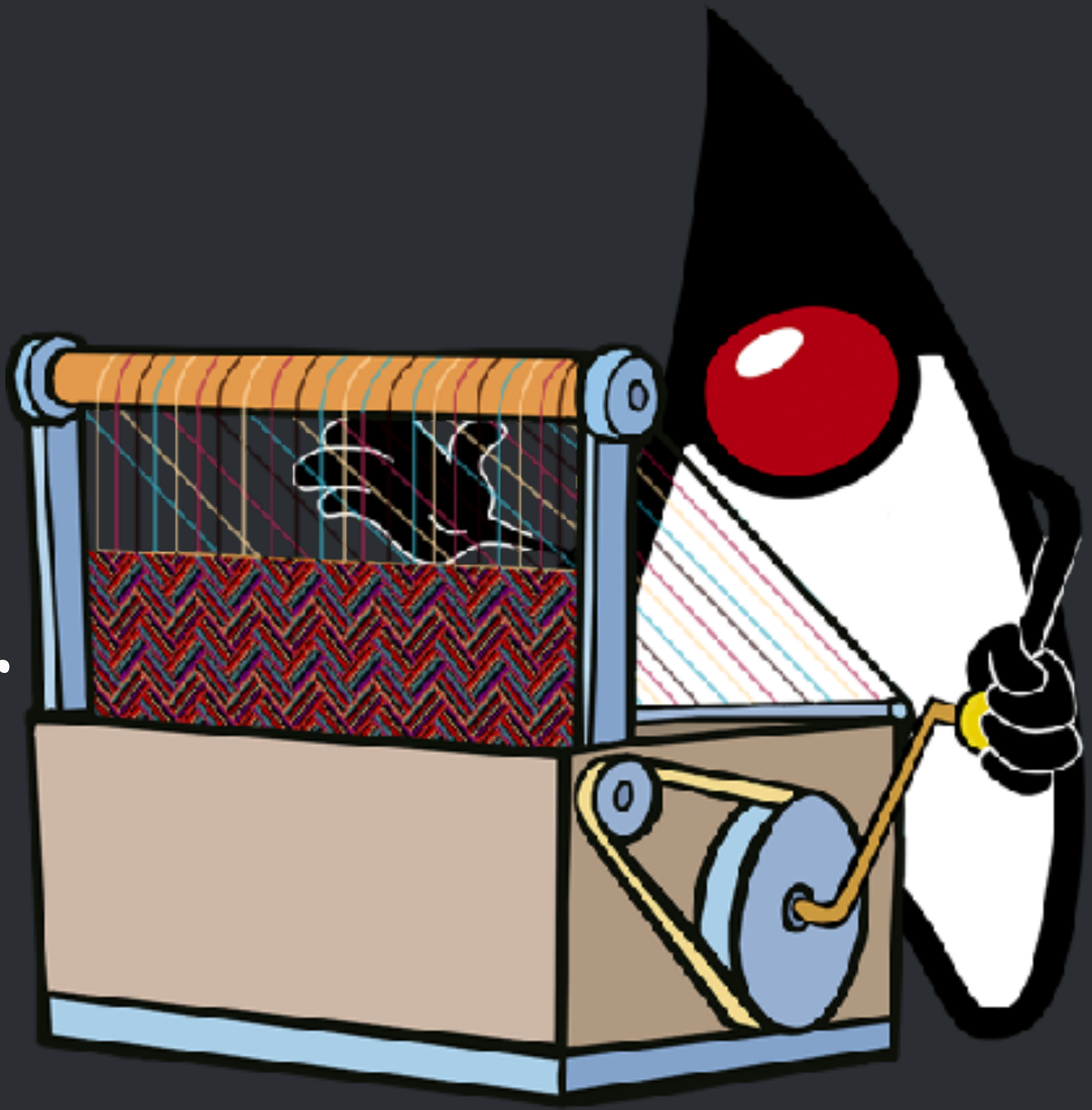
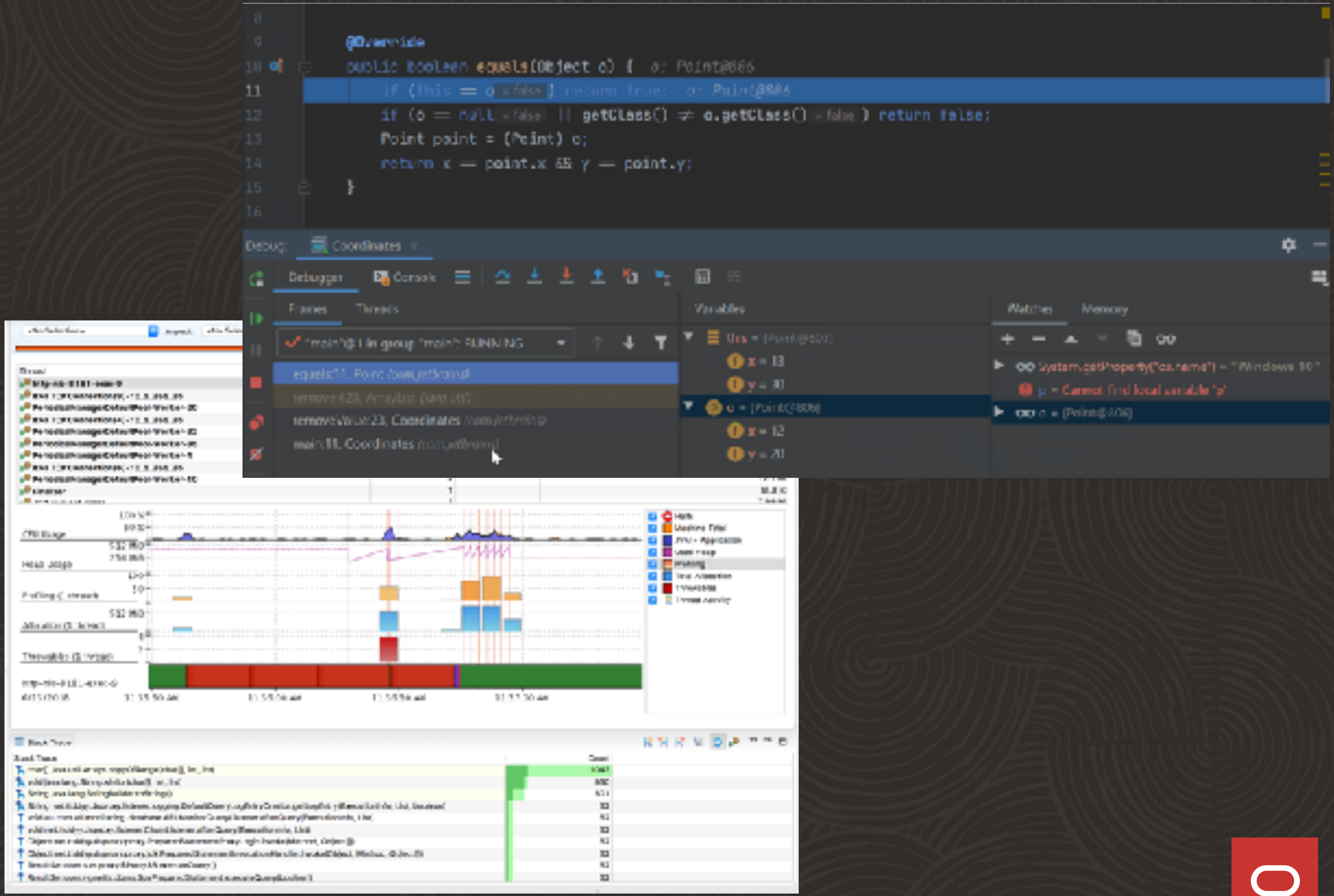
Java Platform Group

14 April 2021



Java Is Made of Threads

- Exceptions
- Thread Locals
- Debugger
- Profiler (JFR)



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Threads in Java

- `java.lang.Thread`
- One implementation: OS threads
- OS threads support all languages.
- RAM-heavy — megabyte-scale; page granularity; can’t uncommit.
- Task-switching requires switch to kernel.
- Scheduling is a compromise for all usages. Bad cache locality.

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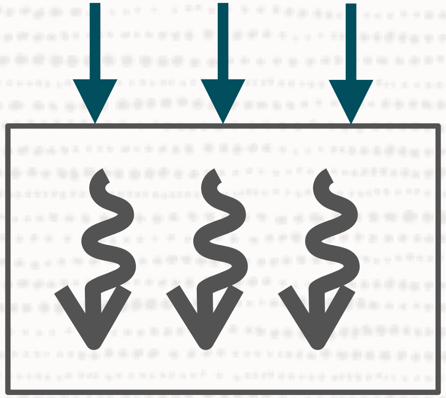
Synchronous

- Easy to read
- Fits well with language (control flow, exceptions)
- Fits well with tooling (debuggers, profilers)



Programmer 😀

OS / Hardware ☹️

But

- A costly resource

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Concurrency

$$L = \lambda W$$

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Reuse with Thread Pools

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Reuse with Thread Pools

- Return at end
  - Leaking ThreadLocals
  - Complex cancellation (interruption)

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Reuse with Thread Pools

- Return at end
  - Leaking ThreadLocals
  - Complex cancellation (interruption)
- Return at wait
  - Incompatible APIs
  - Lost context

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Asynchronous

- Scalable

But

- Hard to read
- Lost context: Very hard to debug and profile
- Intrusive; nearly impossible to migrate

Programmer ☹️

OS / Hardware 😀

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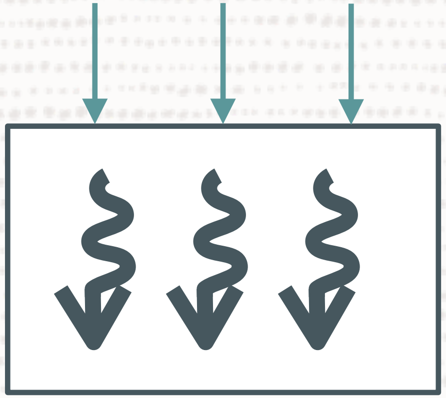
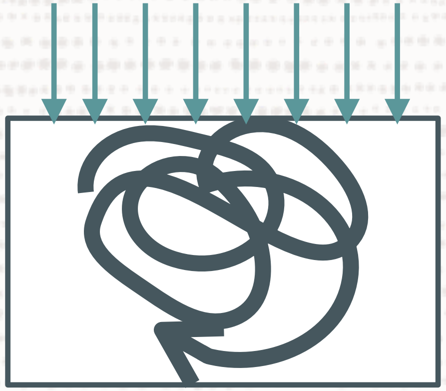


simple
less scalable

SYNC

Programmer 😀
OS / Hardware ☹️

OR



scalable,
complex,
non-interoperable,
hard to debug/profile

ASYNC

Programmer ☹️
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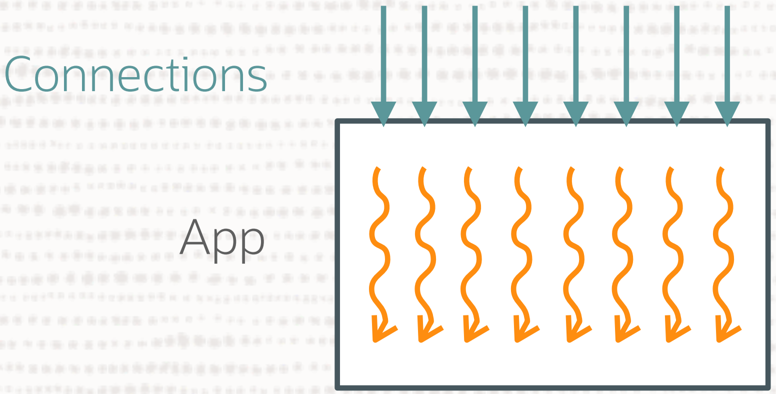
Codes Like Sync, Scales Like Async



Programmer 😀

OS / Hardware 😀

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“We must carefully balance **conservation** and **innovation**”

— Mark Reinhold

- **Forward Compatibility**: we want existing code to enjoy new functionality
- We want to **correct past mistakes** and **start afresh**

“The solutions of **yesterday** are the problems of **today**”

— Brian Goetz

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Threads *in Java*

- The use of `Thread.currentThread()` and `ThreadLocal` is pervasive. Without support, or with changed behaviour, little existing code would run.
- Other parts are superseded by new APIs since Java 5 so their datedness/clunkiness is mostly hidden/ignored.

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Threads *in Java*

- `java.lang.Thread`
- The Java runtime is well positioned to implement threads.
- Resizable stacks (possible b/c we only need to support Java).
- Context-switching in user-mode.
- Pluggable schedulers, default optimised for transaction processing.

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Threads *in Java*

When code in a virtual thread calls an I/O method in the JDK,
suspend the virtual thread,
start a non-blocking I/O operation in the OS,
the scheduler schedules another virtual thread,
when I/O completes re-submit waiting thread to scheduler.

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Module java.base
Package java.util.concurrent

Class ConcurrentHashMap<K,V>

java.lang.Object
    java.util.AbstractMap<K,V>
        java.util.concurrent.ConcurrentHashMap<K,V>

Type Parameters:

K - the type of keys maintained by this map

V - the type of mapped values

All Implemented Interfaces:

Serializable, ConcurrentMap<K,V>, Map<K,V>

```
public class ConcurrentHashMap<K,V>
extends AbstractMap<K,V>
implements ConcurrentMap<K,V>, Serializable
```

A hash table supporting full concurrency of retrievals and high expected concurrency for updates. This class obeys the same functional specification as `Hashtable`, and includes versions of methods corresponding to each method of `Hashtable`. However, even though all operations are thread-safe, retrieval operations do *not* entail locking, and there is *not* any support for locking the entire table in a way that prevents all access. This class is fully interoperable with `Hashtable` in programs that rely on its thread safety but not on its synchronization

Module java.base
Package java.util.concurrent.locks

Class ReentrantLock

java.lang.Object
    java.util.concurrent.locks.ReentrantLock

All Implemented Interfaces:

Serializable, Lock

```
public class ReentrantLock
extends Object
implements Lock, Serializable
```

A reentrant mutual exclusion `Lock` with the same basic behavior and semantics as the implicit monitor lock accessed using `synchronized` methods and statements, but with extended capabilities.

A `ReentrantLock` is *owned* by the thread last successfully locking, but not yet unlocking it. A thread invoking `lock` will return, successfully acquiring the lock, when the lock is not owned by another thread. The method will return immediately if the current thread already owns the lock. This can be checked using methods `isHeldByCurrentThread()`, and `getHoldCount()`.

The constructor for this class accepts an optional *fairness* parameter. When set `true`, under contention, locks favor granting access to the longest-waiting thread. Otherwise this lock does not guarantee any particular access order. Programs using fair locks accessed by many threads may display lower overall throughput (i.e., are slower;

Module java.base
Package java.nio.channels

Class SocketChannel

java.lang.Object
    java.nio.channels.spi.AbstractInterruptibleChannel
        java.nio.channels.SelectableChannel
            java.nio.channels.spi.AbstractSelectableChannel
                java.nio.channels.SocketChannel

All Implemented Interfaces:

Closeable, AutoCloseable, ByteChannel, Channel, GatheringByteChannel, InterruptibleChannel, NetworkChannel, ReadableByteChannel, ScatteringByteChannel, WritableByteChannel

```
public abstract class SocketChannel
extends AbstractSelectableChannel
implements ByteChannel, ScatteringByteChannel, GatheringByteChannel, NetworkChannel
```

A selectable channel for stream-oriented connecting sockets.

A socket channel is created by invoking one of the `open` methods of this class. It is not possible to create a channel for an arbitrary, pre-existing socket. A newly-created socket channel is open but not yet connected. An attempt to invoke an I/O operation upon an unconnected channel will cause a `NotYetConnectedException` to be thrown. A socket channel can be connected by invoking its `connect` method; once connected, a socket channel remains connected until it is closed. Whether or not a socket channel is connected may be determined by invoking its

Module java.base
Package java.io

Class InputStream

java.lang.Object
    java.io.InputStream

All Implemented Interfaces:

Closeable, AutoCloseable

Direct Known Subclasses:

AudioInputStream, ByteArrayInputStream, FileInputStream, FilterInputStream, ObjectInputStream, PipedInputStream, SequenceInputStream, StringBufferInputStream

```
public abstract class InputStream
extends Object
implements Closeable
```

This abstract class is the superclass of all classes representing an input stream of bytes.

Applications that need to define a subclass of `InputStream` must always provide a method that returns the next byte of input.

Since:

1.0

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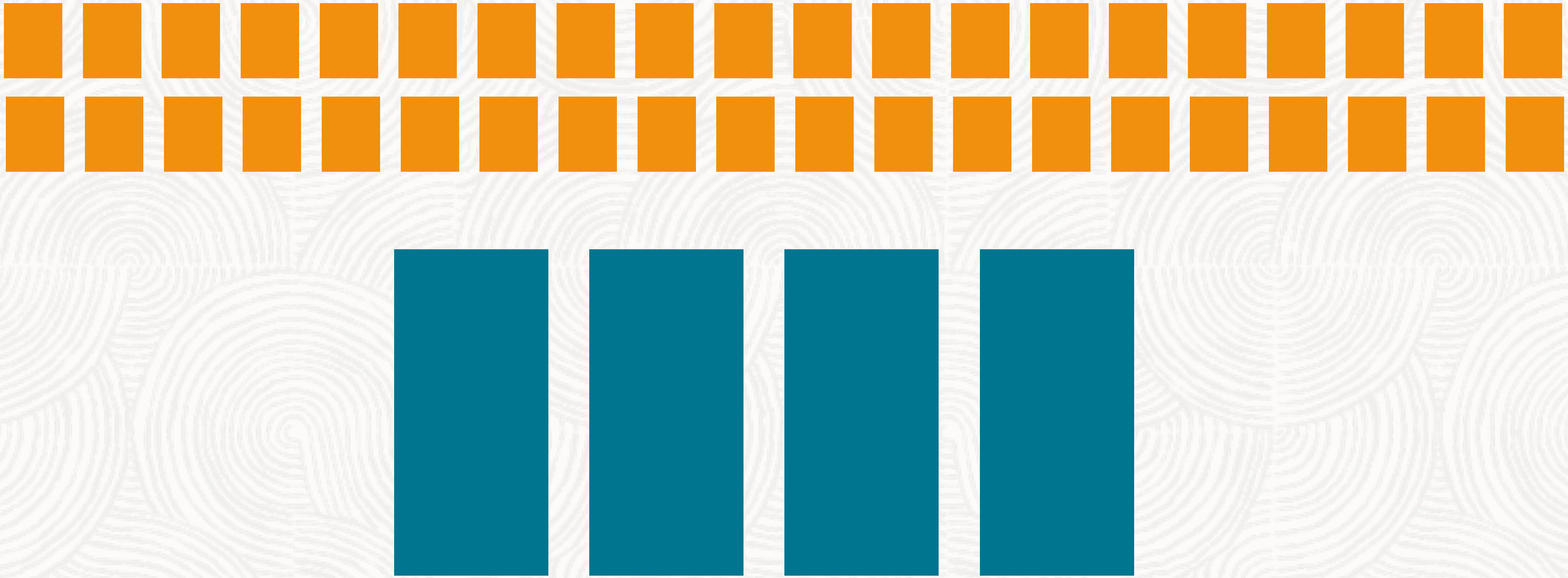
virtual threads



“carrier” platform threads managed by a scheduler

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async/await

C#
JavaScript
Kotlin
C++/Rust

User-Mode Threads

Erlang
Go
Java

Zig

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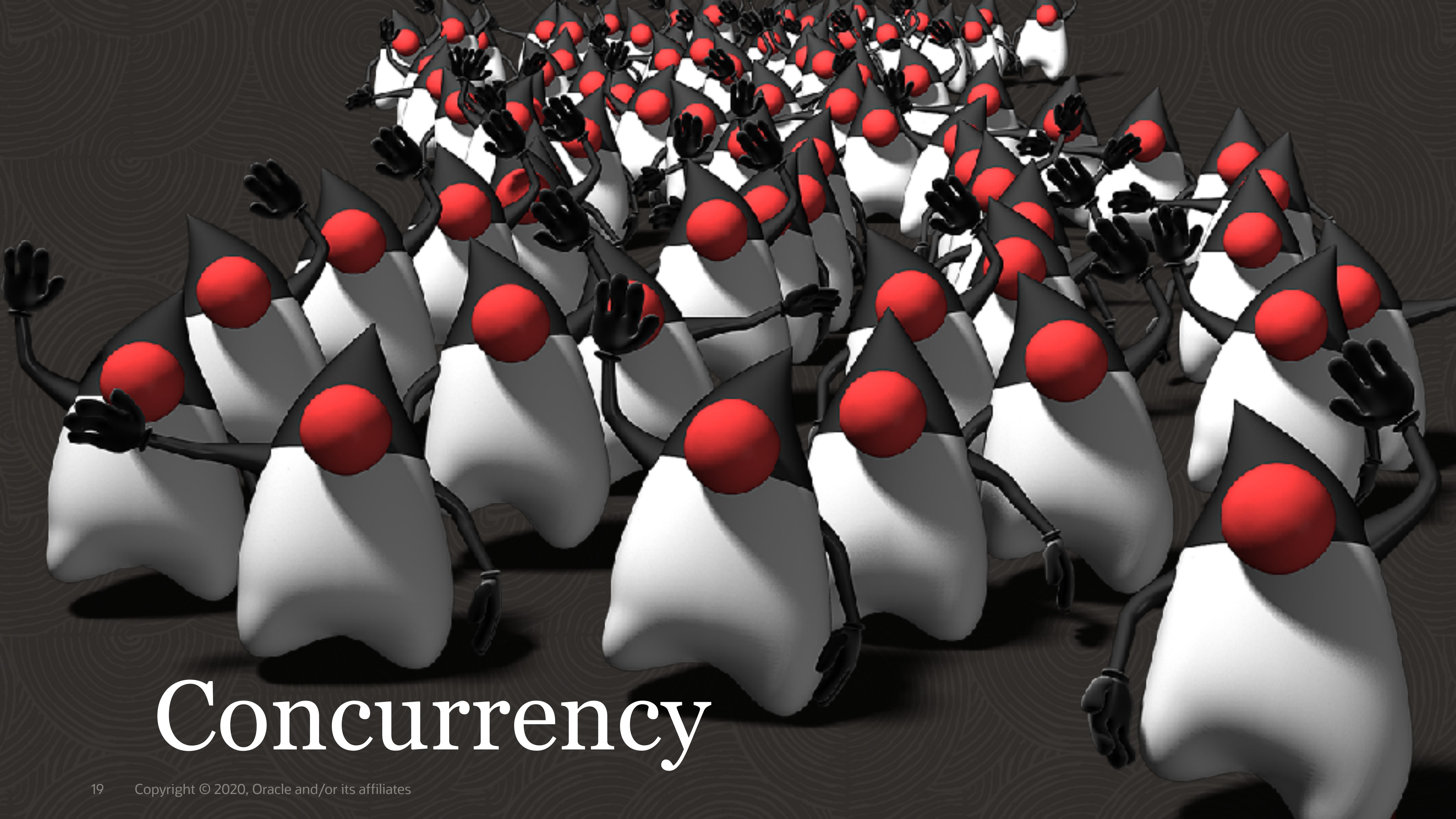

Concurrency

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Algorithm (semantic)

(an abstract description of) *What* the computer does

Expression (syntactic)

How the algorithm is written (in a specific programming language/paradigm)

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Concurrency: The Algorithmic View

Schedule multiple largely independent tasks to a set of computational resources

Performance: throughput (tasks/time unit)

COMPETITION

Parallelism: The Algorithmic View

Speed up a task by splitting it to sub-tasks and exploiting multiple processing units

Performance: latency (time unit)

COOPERATION

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Concurrency: The Syntactic View

- `;` — Sequential composition

  E.g `X;Y`, `await X;Y`, `X.andThen(Y)`

- `|` — Parallel composition

  E.g. `Thread.start(X)`, `Promise.submit(X)`

- `(a|b);c` — join

  E.g. `Thread.join`, `Future.get`

- assignment/channels/locks/IO

```
a;((b;c)|(d|(e;f));g));h
```


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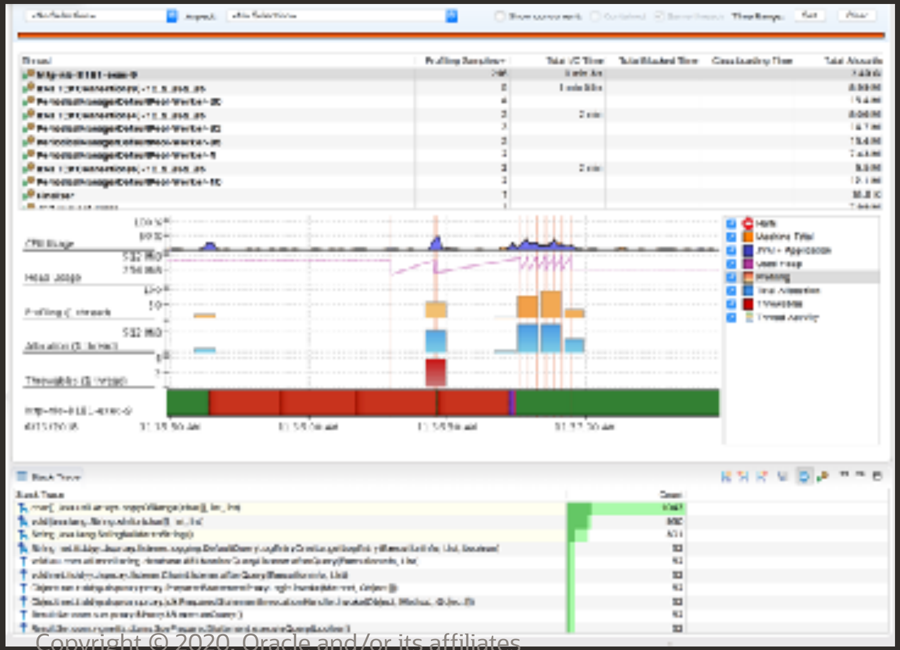
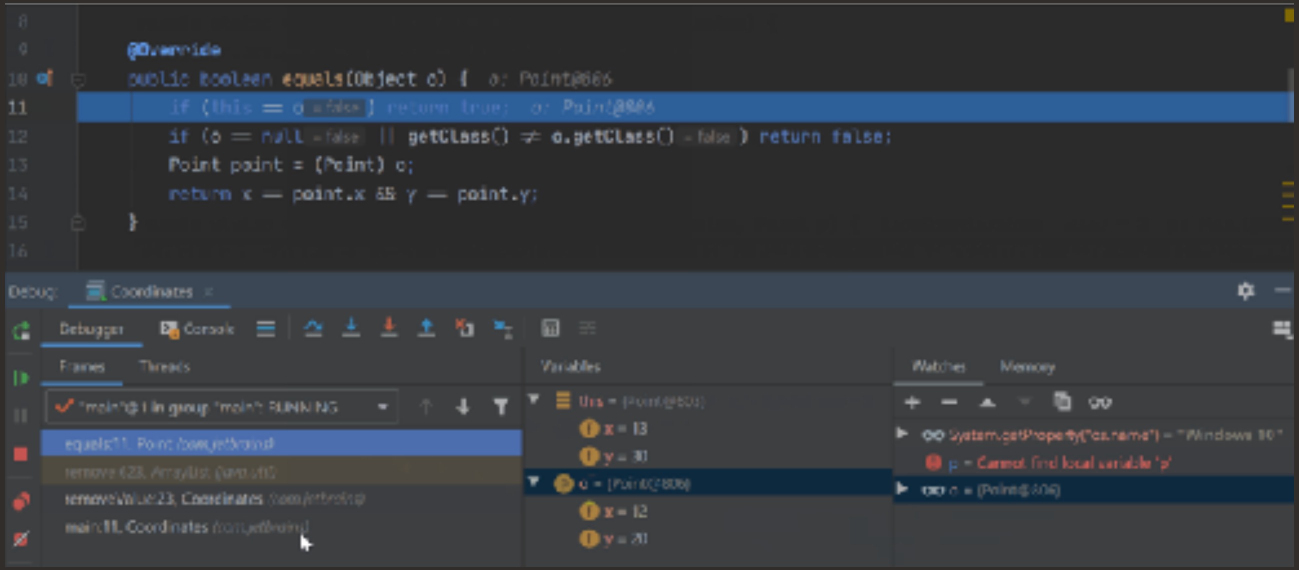
Process: Unit of Concurrency

E.g. a transaction

- Code (writing/reading)
- Troubleshooting: stack traces, debugger single-stepping
- Profiling





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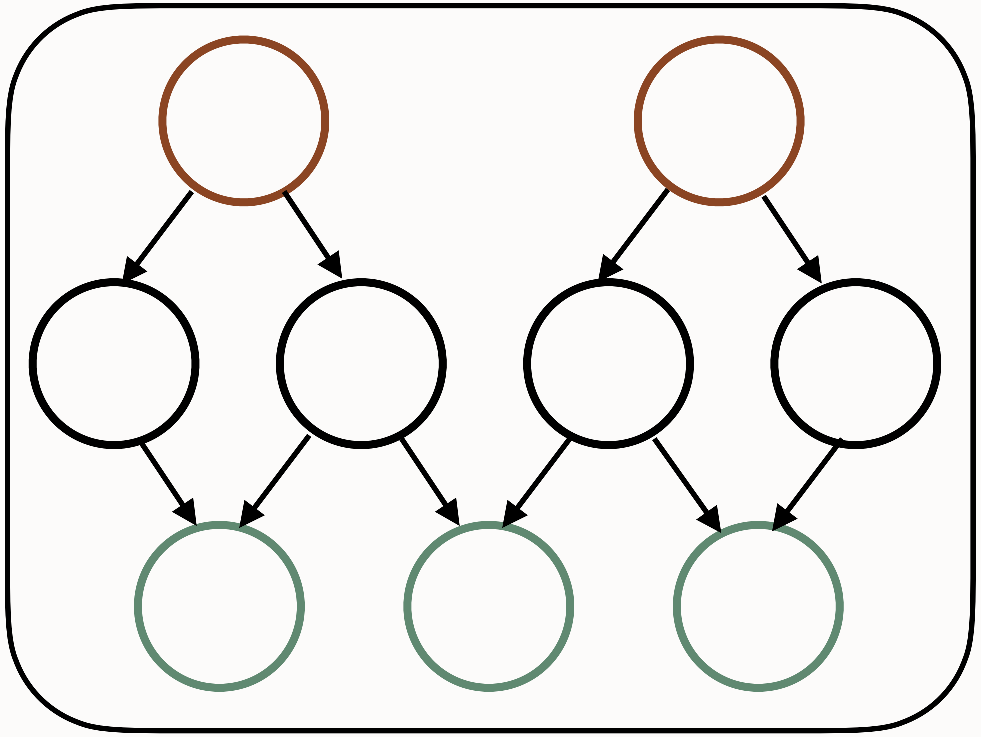
Process

```
a;b;c;d = (a;b);(c;d)
```



(Nondeterminism https://youtu.be/9vupFNsND6o)

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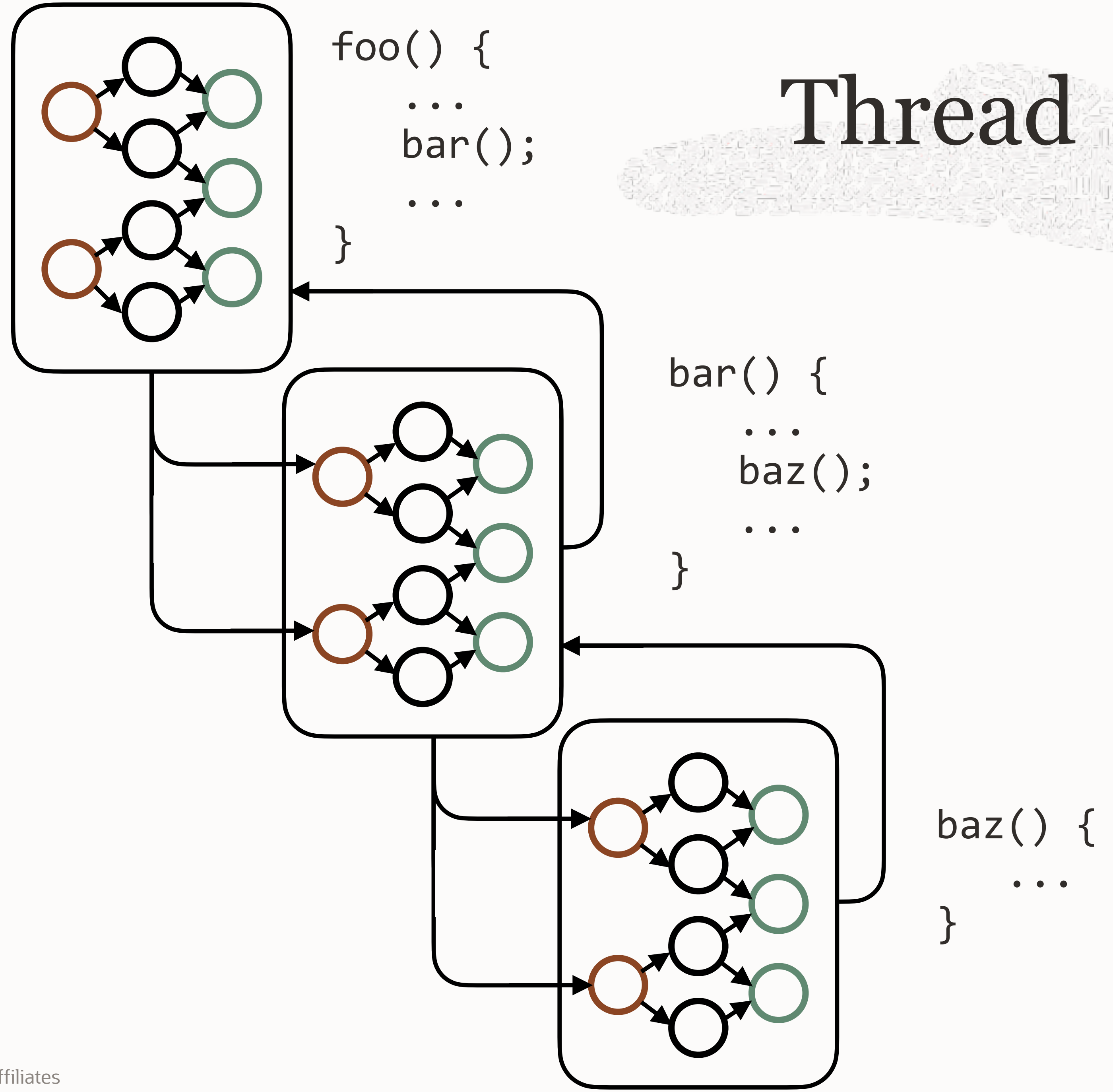
Thread



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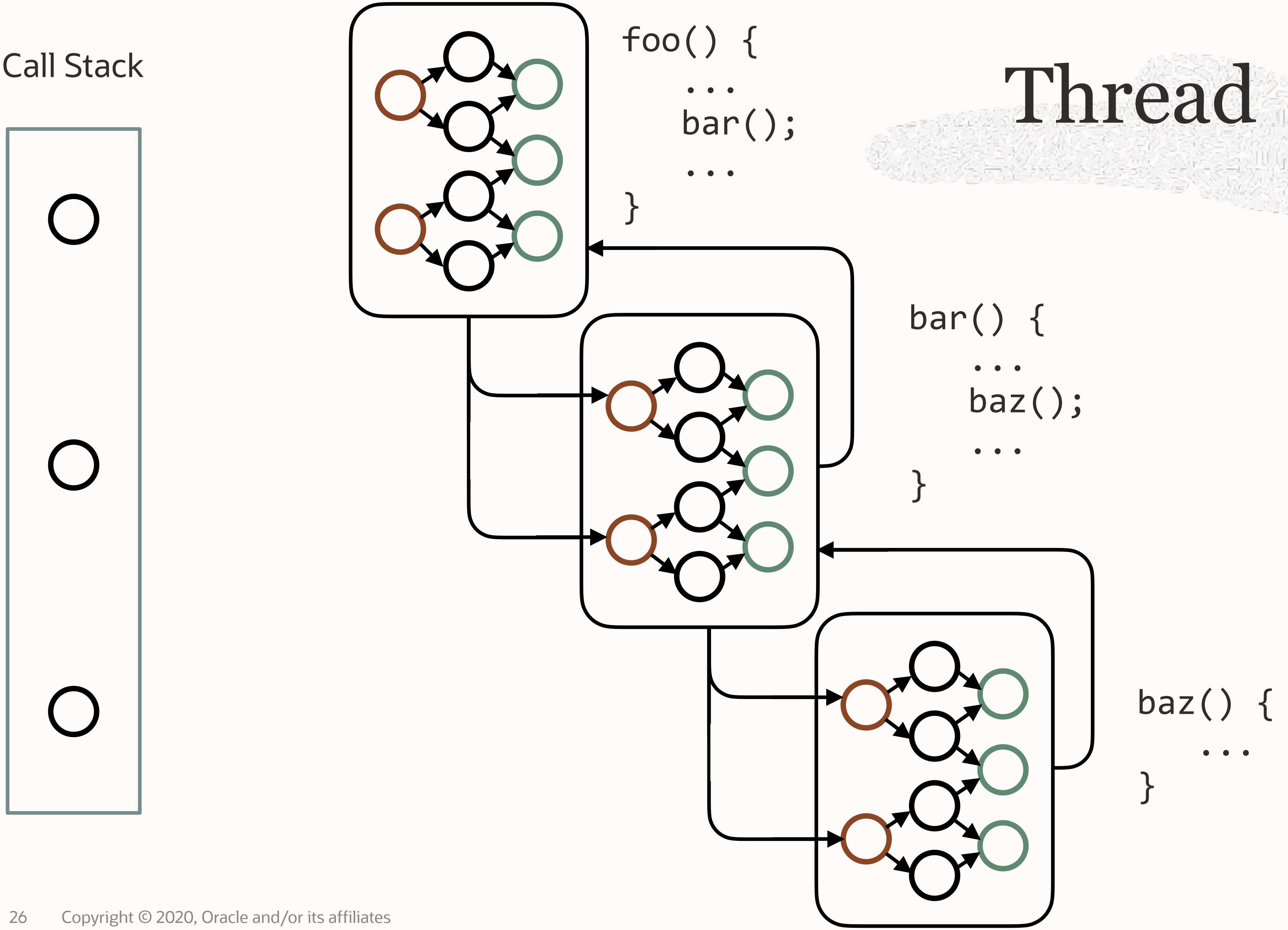
Thread



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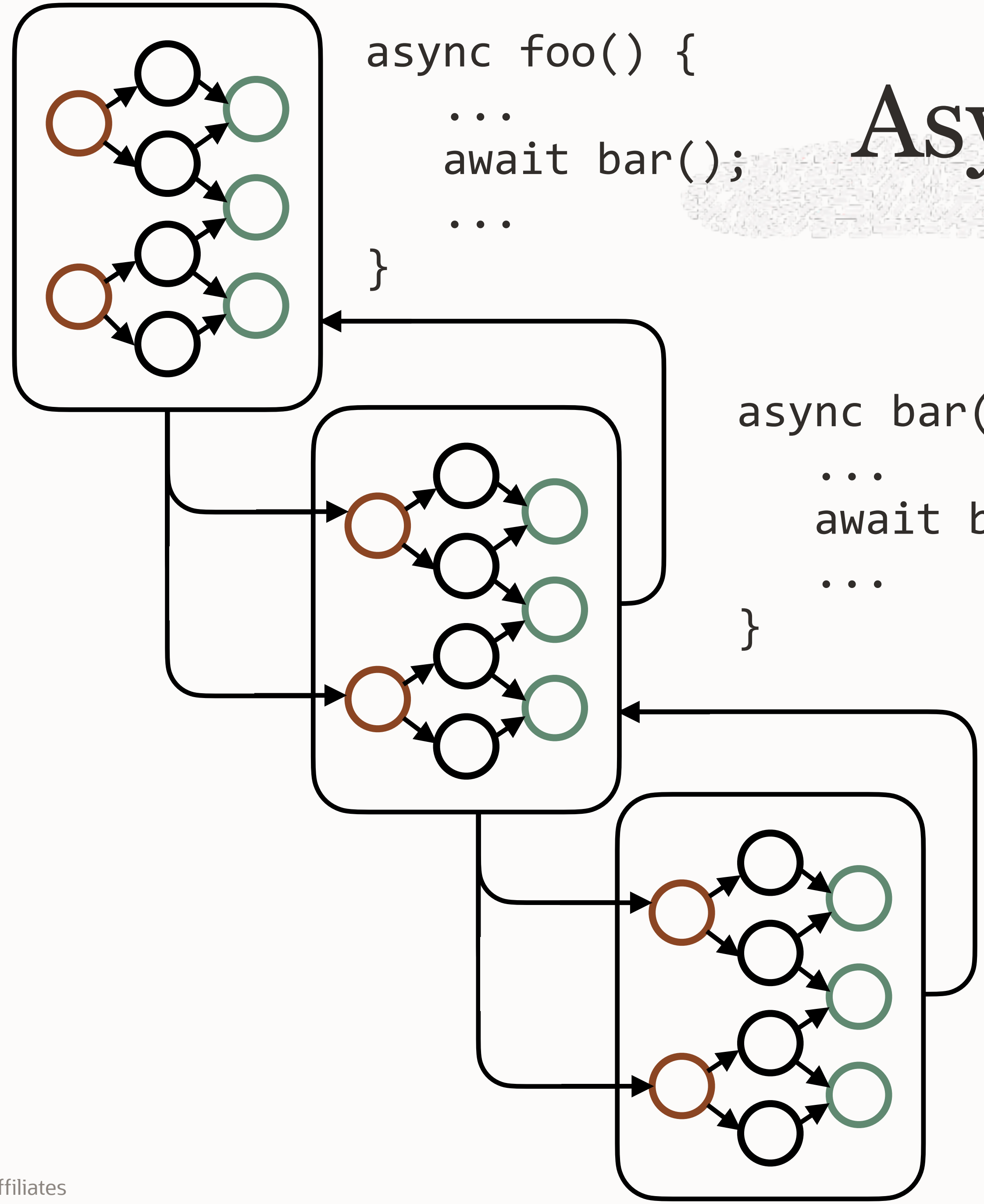
Async/Await



```
async foo() {
    ...
    await bar();
    ...
}
```

```
async bar() {
    ...
    await baz();
    ...
}
```

```
async baz() {
    ...
}
```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Thread vs. Async/Await

Scheduling/interleaving points

Thread: Everywhere *except* where explicitly forbidden (with a CS)

async/await: Nowhere *except* where explicitly allowed (with `await`)

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Thread vs. Async/Await

Scheduling/interleaving points

Thread: Everywhere *except* where explicitly forbidden (with a CS)

async/await: Nowhere *except* where explicitly allowed (with `await`)

JavaScript

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Thread vs. Async/Await

Implementation

Thread: Requires integrating with the implementation of subroutines (control over backend)

async/await: Can be implemented in the compiler frontend

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Thread vs. Async/Await

Implementation

Thread: Requires integrating with the implementation of subroutines (control over backend)

async/await: Can be implemented in the compiler frontend

Kotlin

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Thread vs. Async/Await

Recursion & virtual calls

Thread: Yes (requires ~~large~~/resizable stacks)

async/await: Can be excluded

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Thread vs. Async/Await

Recursion & virtual calls

Thread: Yes (requires ~~large~~/resizable stacks)

async/await: Can be excluded

C++/Rust

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Resizable Stack

- Transparent allocation
- Efficient allocation
- No internal pointers/tracked pointers (no FFI)

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Performance

Latency — How long an operation takes (*s*)

Throughput — How many operations complete per time unit (*ops/s*)

Impact — How much a metric would improve with full optimisation (%)

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Syntactic Concurrency: Generators et al.

- Updating simulation entities in a frame
- Generators (two processes with an unbuffered channel)

```
def rev_str(my_str):
    length = len(my_str)
    for i in range(length - 1, -1, -1):
        yield my_str[i]

for char in rev_str("hello"):
    print(char)
```


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Context-Switching Impact: Generators

- Impact: 100%
- Best case latency: ~0ns (monomorphic, fits in cache)

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Concurrency: Transactions

$$L = \lambda W$$

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https://inside.java/2020/08/07/loom-performance/

Throughput: $\lambda = L/W$

Context-switch impact on throughput: t/μ

t — Mean context-switch latency

μ — Mean wait (I/O) latency

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Context-Switching Impact: Transactions

- Impact: low if blocking for external events
- Best case latency: 60ns (polymorphic, doesn't fit in cache) (1.5% impact)
- Target latency for ≤5% impact: ≤200ns

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Conclusion

- Control over backend
- Rare I/O in FFI
- No internal pointers/pointers tracked
- Efficient and transparent stack resizing
- Threads already in the platform, libraries and tooling

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async/await

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User-Mode Threads

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Thank you

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