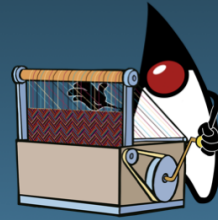


# Project Loom

## Fibers and Continuations



Project Loom is intended to explore, incubate and deliver Java VM features and APIs built on top of them for the purpose of supporting easy-to-use, high-throughput lightweight concurrency and new programming models on the Java platform. This is accomplished by the addition of the following constructs:

- Virtual threads
- Delimited continuations
- Tail-call elimination

This [OpenJDK](#) project is sponsored by the [HotSpot Group](#).

### Source Code

<https://github.com/openjdk/loom>

### Early Access Binaries

<http://jdk.java.net/loom/>

### Resources

[State of Loom](#)

[On the Performance of User-Mode Threads and Coroutines](#)

More on [inside.java](#)

### Talks

Joker 2020 - [Video](#)

AccentoDev 2020 - [Video](#)

Devvix BE 2019 - [Video](#)

JVMLS 2019 - [Video](#)

Curry On 2019 - [Video](#)

QCon London 2019 - [Video and Slides](#)

FOSDEM 2019 - [Video](#)

Devvix BE 2018 - [Video](#) | [Slides](#)

JVMLS 2018 – [Video](#) | [Slides](#)

JFokus 2018 – [Video](#)

### Meetings

October 2018 - [Slides](#)

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## Project

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### Note

Loom is under active development, which means that information and advice given here might change in the future.

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## Supported Platforms

Mac and Linux on x86-64

## Download and Build from Source

```
$ git clone https://github.com/openjdk/loom
$ cd loom
$ git checkout fibers
$ sh configure
$ make images
```

## How to Contribute

The most valuable way to contribute at this time is to try out the current prototype and provide feedback and bug reports to the loom-dev mailing list. In particular, we welcome feedback that includes a brief write-up of experiences adapting existing libraries and frameworks to work with Fibers.

If you have a login on the JDK Bug System then you can also submit bugs directly. We plan to use an Affects Version/s value of "repo-loom" to track bugs.

## How to run the JDK tests

1. Download [jtreg](#) (the JDK test harness) and place its `bin` subdirectory on your path.
2. Create a debug JDK configuration (inside the top directory of the Loom repo) and build it. This step requires having `jtreg` on your path, or running the tests would fail:

```
$ sh configure --with-jtreg --with-debug-level=fastdebug
$ make images
```

3. Run the tests. The following example assumes a Mac build (replace `macosx` with `linux` for a Linux build), and the `java/lang/Continuation/Basic.java` test, which contains some basic `Continuation` tests. The `java/lang/Continuation` directory contains `Continuation` test, while the `java/lang/Continuation` directory contains fiber tests. Supplying just the directory name runs all tests in the directory.

```
$ make run-test TEST=open/test/jdk/java/lang/Continuation/Basic.java CONF=macosx-x86_64-server-fastdebug
```

## Missing Features

- Yielding while a native VM frame is on the stack in the case of a privileged action, reflective invocation and `MethodHandle` invocation.
- Cloning continuations
- Serialization of fiber/continuation

## Continuations

### Design

The primitive continuation construct is that of a `scoped` (AKA multiple-named-prompt), stackful, one-shot (non-reentrant) delimited continuation. The continuation can be cloned, and thus used to implement reentrant delimited continuations. The construct is exposed via the `java.lang.Continuation` class. Continuations are intended as a low-level API, that application authors are not intended to use directly. They will use higher-level constructs built on top of continuations, such as fibers or generators.

A continuation object is constructed by passing two arguments to the constructor: a `Runnable` target that serves as the body of the continuation, and a `java.lang.ContinuationScope`. The scope is the delimited continuation's prompt, that allows continuations to be nested. One could think of such "scoped continuations" as nested `try/catch` blocks, where the scope is the type of the exception thrown, which determines the handler called.

A continuation is started by calling `Continuation.run`, which would start executing the body in the continuation's target, and returns either when the continuation terminates (the body runs to completion, and terminates either normally or abnormally), or when it yields on the continuation's scope. To query the reason for `run` returning, use `Continuation.isDone`, which returns `true` if the body has terminated, or `false` if it has yielded.

A call to the static `Continuation.yield` suspends the current continuation and all enclosing continuations up until the innermost one with the scope passed to `yield`, causing the `run` method of that continuation to return.

The scoping mechanism means that not only are Loom's continuations composable, but they are also well encapsulated. By keeping the scope object hidden (say, in a private static field), a construct using implementations can prevent its continuations from being yielded directly and circumventing the construct's API (e.g. it is impossible to directly yield a fiber's continuation because the scope of those continuations is private to the fiber implementation).

The `Continuation` class does not provide a mechanism of communication between `run` and `yield` (i.e., neither takes or returns a value that is passed to/received from the other), unlike most implementations of delimited continuations. However, implementing a class that does allow this kind of communication on top of the `Continuation` class is straightforward, and will likely be included in the JDK.

### Implementation

The current prototype limits the situation in which a continuation can be yielded: a continuation cannot yield while a native method is on its stack (i.e. on the stack used by the continuation body when it attempts to yield) – this can happen when a VM or a JNI method is called from the continuation body and then calls back into Java code that attempts to yield – or while the body of the continuation holds a native monitor (i.e. a yield is called – directly or indirectly – from inside a synchronized method or a synchronized block). In these situations, the continuation is said to be *pinned* (to the mounted thread). Attempting to yield while pinned results in a call to the protected method `Continuation.onPinned`, which by default throws an exception (fibers override this behavior; see below).

It is likely that we will never support yielding with a JNI method on the stack, but we will support most common cases of VM methods – privileged actions (this may be resolved by implementing that security feature in Java), reflective invocation (this may also be a non-issue, as reflection does support a pure Java path by generating bytecode), and `MethodHandle` invocation. It is not yet decided whether or not we will choose to support yielding while holding native monitors.

The `Continuation` class is implemented natively in Hotspot (except for scoping; that is implemented in Java). Every continuation has its own stack. From the perspective of the implementation, starting or continuing a continuation *mounts* it and its stack on the current thread – conceptually concatenating the continuation's stack to the thread's – while yielding a continuation *unmounts* or *dismounts* it.

The current prototype implements the mount/dismount operations by copying stack frames from the continuation stack – stored on the Java heap as two Java arrays, an `Object` array for the references on the stack and a primitive array for primitive values and metadata. Copying a frame from the thread stack (which we also call the *vertical* stack, or the *v-stack*) to the continuation stack (also, the *horizontal* stack, or the *h-stack*) is called *freezing* it, while copying a frame from the h-stack to the v-stack is called *thawing*. The prototype also optionally thaws just a small portion of the h-stack when mounting using an approach called *lazy copy*; see the JVMLS 2018 talk as well as the section on performance for more detail.

Hypothetically, the most efficient implementation of the mounting operations involves merely linking the current thread stack to the continuation's (with dismounting translating to unlinking). When a continuation is mounted, its body executes "in" (i.e. using) the continuation's stack. The current prototype, however, employs copying due to technical constraints which make implementing the linking approach costly. Some of Hotspot's GCs cannot easily support heap objects that can store references in memory offsets that change throughout the lifetime of the heap object; changing that assumption would require deep changes to some of Hotspot's GCs. Storing h-stacks in some special off-heap memory area would not help because this means that the GCs would need to scan them (like they scan thread stacks) – which is potentially a slow operation, especially given the need to support a very large number of continuations – sometimes even during stop-the-world (STW) phases, like young-gen collection. Ordinarily, heap objects do not need to be scanned because writing to them updates efficient GC data-structures, but those updates (called write barriers) are not executed for stack writes in the execution "engines" (the interpreter and compilers); inserting those barriers when running a continuation body would require changing all four OpenJDK execution engines: the interpreter, C1, C2 and Graal. This, too, is costly.

However, we believe we can make the copying approach efficient enough, and that complex changes to the GC or the execution engines will prove unnecessary.

## Performance

Current yield/continue performance is far from stellar. The reason is that we focused on getting a working prototype using existing Hotspot mechanisms, some of which have not been designed to be used so frequently. We are now working on improving performance both by optimizing the actual freeze/thaw logic, as well as optimizing those existing VM mechanisms.

One mechanism that is particularly slow is the one used to detect whether a frame is holding a native monitor (synchronized block). Because this mechanism is so slow, the monitor detection can be turned off (which will break fiber code that runs through synchronized blocks) by adding `-XX:-DetectLocksInCompiledFrames` to the `java` command line.

An important performance feature is lazy-copying of frames. This feature is currently turned off by default. To turn lazy copying on, add `-XX:+UnlockDiagnosticVMOptions -XX:+UseNewCode` to the `java` command line.

## Virtual Threads

### Design

Virtual threads are threads that are scheduled by the Java virtual machine rather than the operating system. Virtual threads allow synchronous (blocking) code to be efficiently scheduled, so that it performs as well as asynchronous code, but is simpler to read and write, debug, monitor and profile. There is a tension in the design of virtual threads between attempting to run as much existing code as possible and our desire to take the opportunity to rethink how modern threads should work, with an eye to new software requirements, programming styles and new/changing hardware.

In the current prototype, virtual threads are implemented by the `java.lang.Thread` API. The Thread API has been updated to define static factory methods and a builder API to create and start virtual threads. With a few exceptions (like the deprecated `suspend` and `resume` methods), the Thread API works as before. All threads locals (`ThreadLocal`, `InheritedThreadLocal`, thread context class loader, ...) are virtual thread local. It is possible to use the new APIs to create virtual threads that do not support thread locals.

Project Loom is exploring some of the concepts of [Structured Concurrency](#) so that virtual threads are scheduled in a scope that can not be exited until all threads (or tasks) scheduled in the scope have terminated (or completed). There is also interoperability with code using the `java.util.concurrent` `ExecutorService` and `CompletableFuture` APIs.

To allow existing code to run in the context of a virtual thread, the current prototype emulates `Thread.currentThread()` so that the existing Thread APIs, `ThreadLocal`, `InheritedThreadLocal` etc. work as before. In essence, all locals are *fiber local*.

### Implementation

Virtual threads are implemented in the core libraries. A virtual thread is implemented as a continuation that is wrapped as a task and scheduled by a `java.util.concurrent.Executor`. Parking (blocking) a virtual thread results in yielding its continuation, and unparking it results in the continuation being resubmitted to the scheduler. The scheduler worker thread executing a virtual thread (while its continuation is mounted) is called a *carrier* thread.

The continuations used in the virtual thread implementation override `onPinned` so that if a virtual thread attempts to park while its continuation is pinned (see above), it will block the underlying carrier thread.

The implementation of the networking APIs in the `java.net` and `java.nio.channels` packages have as been updated so that virtual threads doing blocking I/O operations park, rather than block in a system call, when a socket is not ready for I/O. When a socket is not ready for I/O it is registered with a background multiplexer thread. The virtual thread is then unpacked when the socket is ready for I/O.

### Debugging

See the [Virtual Thread Debugging Support](#) page.

## Tail Calls

### Design

We envision tail-call elimination that pops one or perhaps even an arbitrary number of stack frames at explicitly marked call-sites. It is not the intention of this project to implement *automatic* tail-call optimization.

## **Implementation**

The implementation of this feature requires cross-cutting changes to the VM, VM specification (bytecode), and possibly the front-end Java compiler (javac). As a result, in order not to delay the completion of continuations and fibers, we will only begin specifying and implementing this feature only when the project is at a more advanced phase.