Reactor 3 Reference Guide

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Chapter 1. About the Documentation

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This section provides a brief overview of Reactor reference documentation. You do not need to read this guide in a linear fashion. Each piece stands on its own, though they often refer to other pieces.

Latest Version & Copyright Notice

The Reactor reference guide is available as HTML documents. The latest copy is available at projectreactor.io/docs/core/release/reference/index.html

Copies of this document may be made for your own use and for distribution to others, provided that you do not charge any fee for such copies and further provided that each copy contains this Copyright Notice, whether distributed in print or electronically.

Contributing to the Documentation

The reference guide is written in Asciidoc using Antora, and you can find its sources at github.com/reactor/reactor-core/tree/main/docs/.

If you have an improvement or a suggestion, we will be happy to get a pull request from you!

We recommend that you check out a local copy of the repository so that you can generate the documentation by running the `asciidoctor` gradle task and checking the rendering. Some of the sections rely on included files, so GitHub rendering is not always complete.

To facilitate documentation edits, you can edit the current page from the `Edit this Page` link located in the upper right corner sidebar. The link opens an edit `UI` directly on `GitHub` for the main source file for the current page. These links are only present in the `HTML5` version of this reference guide. They look like the following link: Edit this Page to make changes to About the Documentation page.

Getting Help

You can reach out for help in several ways with Reactor:

- Get in touch with the community on Gitter.
- Ask a question on stackoverflow.com at `project-reactor`.
- Report bugs in Github issues. We closely monitor the following repositories: reactor-core (which covers the essential features) and reactor-addons (which covers reactor-test and adapters issues).

All of Reactor is open source, including this documentation. If you find problems with the docs or if you want to improve them, please get involved.

Where to Go from Here

- Head to Getting Started if you feel like jumping straight into the code.
- If you are new to reactive programming, though, you should probably start with the Introduction to Reactive Programming.
- If you are familiar with Reactor concepts and are just looking for the right tool for the job but cannot think of a relevant operator, try the Which operator do I need? Appendix.
- In order to dig deeper into the core features of Reactor, head to Reactor Core Features to learn:
  - More about Reactor's reactive types in the `Flux`, an Asynchronous Sequence of 0-N Items and `Mono`, an Asynchronous 0-1 Result sections.
  - How to switch threading contexts using a scheduler.
  - How to handle errors in the Handling Errors section.
- Unit testing? Yes it is possible with the `reactor-test` project! See Testing.
- Programmatically creating a sequence offers a more advanced way of creating reactive sources.
- Other advanced topics are covered in Advanced Features and Concepts.

Chapter 2. Getting Started

This section contains information that should help you get going with Reactor. It includes the following sections:

- Introducing Reactor
- Prerequisites
- Understanding the BOM and versioning scheme
- Getting Reactor

Introducing Reactor

Reactor is a fully non-blocking reactive programming foundation for the JVM, with efficient demand management (in the form of managing "backpressure"). It integrates directly with the Java 8 functional APIs, notably `CompletableFuture`, `Stream`, and `Duration`. It offers composable asynchronous sequence APIs — `Flux` (for [N] elements) and `Mono` (for [0|1] elements) — and extensively implements the Reactive Streams specification.

Reactor also supports non-blocking inter-process communication with the `reactor-netty` project. Suited for Microservices Architecture, Reactor Netty offers backpressure-ready network engines for HTTP (including Websockets), TCP, and UDP. Reactive encoding and decoding are fully supported.

Prerequisites

Reactor Core runs on `Java 8` and above.

It has a transitive dependency on `org.reactivestreams:reactive-streams:1.0.3`.

Android Support

- Reactor 3 does not officially support or target Android (consider using RxJava 2 if such support is a strong requirement).
- However, it should work fine with Android SDK 26 (Android O) and above.
- It will likely work fine with Android SDK 21 (Android 5.0) and above when desugaring is enabled. See developer.android.com/studio/write/java8-support#library-desugaring
- We are open to evaluating changes that benefit Android support in a best-effort fashion. However, we cannot make guarantees. Each decision must be made on a case-by-case basis.

Understanding the BOM and versioning scheme

Reactor 3 uses a BOM (Bill of Materials) model (since `reactor-core 3.0.4`, with the `Aluminium` release train). This curated list groups artifacts that are meant to work well together, providing the relevant versions despite potentially divergent versioning schemes in these artifacts.

Note the versioning scheme has changed between 3.3.x and 3.4.x (Dysprosium and Europium).

Artifacts follow a versioning scheme of `MAJOR.MINOR.PATCH-QUALIFIER` while the BOM is versioned using a CalVer inspired scheme of `YYYY.MINOR.PATCH-QUALIFIER`, where:

- `MAJOR` is the current generation of Reactor, where each new generation can bring fundamental changes to the structure of the project (which might imply a more significant migration effort)
- `YYYY` is the year of the first GA release in a given release cycle (like 3.4.0 for 3.4.x)
- `.MINOR` is a 0-based number incrementing with each new release cycle
  - in the case of projects, it generally reflects wider changes and can indicate a moderate migration effort
  - in the case of the BOM it allows discerning between release cycles in case two get first released the same year
- `.PATCH` is a 0-based number incrementing with each service release
- `-QUALIFIER` is a textual qualifier, which is omitted in the case of GA releases (see below)

The first release cycle to follow that convention is thus `2020.0.x`, codename `Europium`. The scheme uses the following qualifiers (note the use of dash separator), in order:

- `-M1`..`-M9`: milestones (we don't expect more than 9 per service release)
- `-RC1`..`-RC9`: release candidates (we don't expect more than 9 per service release)
- `-SNAPSHOT`: snapshots
- *no qualifier* for GA releases

snapshots appear higher in the order above because, conceptually, they're always "the freshest pre-release" of any given PATCH. Even though the first deployed artifact of a PATCH cycle will always be a -SNAPSHOT, a similarly named but more up-to-date snapshot would also get released after eg. a milestone or between release candidates.

Each release cycle is also given a codename, in continuity with the previous codename-based scheme, which can be used to reference it more informally (like in discussions, blog posts, etc…). The codenames represent what would traditionally be the MAJOR.MINOR number. They (mostly) come from the Periodic Table of Elements, in increasing alphabetical order.

Up until Dysprosium, the BOM was versioned using a release train scheme with a codename followed by a qualifier, and the qualifiers were slightly different. For example: Aluminium-RELEASE (first GA release, would now be something like YYYY.0.0), Bismuth-M1, Californium-SR1 (service release would now be something like YYYY.0.1), Dysprosium-RC1, Dysprosium-BUILD-SNAPSHOT (after each patch, we'd go back to the same snapshot version. would now be something like YYYY.0.X-SNAPSHOT so we get 1 snapshot per PATCH)

Getting Reactor

As mentioned earlier, the easiest way to use Reactor in your core is to use the BOM and add the relevant dependencies to your project. Note that, when you add such a dependency, you must omit the version so that the version gets picked up from the BOM.

However, if you want to force the use of a specific artifact's version, you can specify it when adding your dependency, as you usually would. You can also forgo the BOM entirely and specify dependencies by their artifact versions.

As of this version (reactor-core 3.8.7), the latest stable BOM in the associated release train line is `2025.0.7`, which is what is used in snippets below. There might be newer versions since then (including snapshots, milestones and new release train lines), see projectreactor.io/docs for the latest artifacts and BOMs.

Maven Installation

Maven natively supports the BOM concept. First, you need to import the BOM by adding the following snippet to your `pom.xml`:

```
<dependencyManagement> ①
    <dependencies>
        <dependency>
            <groupId>io.projectreactor</groupId>
            <artifactId>reactor-bom</artifactId>
            <version>2025.0.7</version>
            <type>pom</type>
            <scope>import</scope>
        </dependency>
    </dependencies>
</dependencyManagement>
```

① Notice the `dependencyManagement` tag. This is in addition to the regular `dependencies` section.

If the top section (`dependencyManagement`) already exists in your pom, add only the contents.

Next, add your dependencies to the relevant reactor projects, as usual, except without a `<version>`, as follows:

```
<dependencies>
    <dependency>
        <groupId>io.projectreactor</groupId>
        <artifactId>reactor-core</artifactId> ①
②
    </dependency>
    <dependency>
        <groupId>io.projectreactor</groupId>
        <artifactId>reactor-test</artifactId> ③
```

```
        <scope>test</scope>
    </dependency>
</dependencies>
```

① Dependency on the core library.

② No version tag here.

③ `reactor-test` provides facilities to unit test reactive streams.

Gradle Installation

Prior to version 5.0, Gradle has no core support for Maven BOMs, but you can use Spring's gradle-dependency-management plugin.

First, apply the plugin from the Gradle Plugin Portal, as follows:

```
plugins {
    id "io.spring.dependency-management" version "1.0.7.RELEASE" ①
}
```

① as of this writing, 1.0.7.RELEASE is the latest version of the plugin. Check for updates.

Then use it to import the BOM, as follows:

```
dependencyManagement {
     imports {
          mavenBom "io.projectreactor:reactor-bom:2025.0.7"
     }
}
```

Finally add a dependency to your project, without a version number, as follows:

```
dependencies {
     implementation 'io.projectreactor:reactor-core' ①
}
```

① There is no third `:` separated section for the version. It is taken from the BOM.

Since Gradle 5.0, you can use the native Gradle support for BOMs:

```
dependencies {
     implementation platform('io.projectreactor:reactor-bom:2025.0.7')
     implementation 'io.projectreactor:reactor-core' ①
}
```

① There is no third `:` separated section for the version. It is taken from the BOM.

Milestones and Snapshots

Milestones and release candidates are distributed through `Maven Central`.

Milestone and release candidate releases are for testing purposes and are not intended for production use.

Snapshots are distributed through the `Spring Snapshots` repository rather than `Maven Central`. To add it to your build configuration file, use the following snippet: (for both Maven and Gradle):

-SNAPSHOTs in Maven

```
<repositories>
    <repository>
        <id>spring-snapshots</id>
        <name>Spring Snapshot Repository</name>
        <url>https://repo.spring.io/snapshot</url>
    </repository>
</repositories>
```

-SNAPSHOTs in Gradle

```
repositories {
  maven { url 'https://repo.spring.io/snapshot' }
  mavenCentral()
}
```

Support and policies

The entries below are mirroring github.com/reactor/.github/blob/main/SUPPORT.adoc

Do you have a question?

Search Stack Overflow first; discuss if necessary

If you're unsure why something isn't working or wondering if there is a better way of doing it please check on **Stack Overflow** first and if necessary start a discussion. Use relevant tags among the ones we monitor for that purpose:

- `reactor-netty` for specific reactor-netty questions
- `project-reactor` for generic reactor questions

If you prefer real-time discussion, we also have a few **Gitter channels**:

- `reactor` is the historic most active one, where most of the community can help
- `reactor-core` is intended for more advanced pinpointed discussions around the inner workings of the library

- `reactor-netty` is intended for netty-specific questions

Refer to each project's README for potential other sources of information.

We generally discourage opening GitHub issues for questions, in favor of the two channels above.

Our policy on deprecations

When dealing with deprecations, given a version `A.B.C`, we'll ensure that:

- deprecations introduced in version `A.B.0` will be removed **no sooner than** version `A.B+1.0`
- deprecations introduced in version `A.B.1+` will be removed **no sooner than** version `A.B+2.0`
- we'll strive to mention the following in the deprecation javadoc:
  - target minimum version for removal
  - pointers to replacements for the deprecated method
  - version in which method was deprecated

This policy is officially in effect as of January 2021, for all modules in `2020.0` BOMs and newer release trains, as well as `Dysprosium` releases after `Dysprosium-SR15`.

Deprecation removal targets are not a hard commitment, and the deprecated methods **could live on further than these minimum target GA versions** (ie. only the most problematic deprecated methods will be removed aggressively).

That said, deprecated code that has outlived its minimum removal target version may be removed in any subsequent release (including patch releases, aka service releases) without further notice. So users should still strive to update their code as early as possible.

Support Timeline

For a summary of support dates for each individual project and BOM support, please refer to the Reactor Support page.

Chapter 3. Introduction to Reactive Programming

Reactor is an implementation of the Reactive Programming paradigm, which can be summed up as follows:

> Reactive programming is an asynchronous programming paradigm concerned with data streams and the propagation of change. This means that it becomes possible to express static (e.g. arrays) or dynamic (e.g. event emitters) data streams with ease via the employed programming language(s).
>
> — https://en.wikipedia.org/wiki/Reactive_programming

As a first step in the direction of reactive programming, Microsoft created the Reactive Extensions (Rx) library in the .NET ecosystem. Then RxJava implemented reactive programming on the JVM. As time went on, a standardization for Java emerged through the Reactive Streams effort, a specification that defines a set of interfaces and interaction rules for reactive libraries on the JVM. Its interfaces have been integrated into Java 9 under the `Flow` class.

The reactive programming paradigm is often presented in object-oriented languages as an extension of the Observer design pattern. You can also compare the main reactive streams pattern with the familiar Iterator design pattern, as there is a duality to the `Iterable`-`Iterator` pair in all of these libraries. One major difference is that, while an Iterator is pull-based, reactive streams are push-based.

Using an iterator is an imperative programming pattern, even though the method of accessing values is solely the responsibility of the `Iterable`. Indeed, it is up to the developer to choose when to access the `next()` item in the sequence. In reactive streams, the equivalent of the above pair is `Publisher-Subscriber`. But it is the `Publisher` that notifies the Subscriber of newly available values *as they come*, and this push aspect is the key to being reactive. Also, operations applied to pushed values are expressed declaratively rather than imperatively: The programmer expresses the logic of the computation rather than describing its exact control flow.

In addition to pushing values, the error-handling and completion aspects are also covered in a well defined manner. A `Publisher` can push new values to its `Subscriber` (by calling `onNext`) but can also signal an error (by calling `onError`) or completion (by calling `onComplete`). Both errors and completion terminate the sequence. This can be summed up as follows:

```
onNext x 0..N [onError | onComplete]
```

This approach is very flexible. The pattern supports use cases where there is no value, one value, or n values (including an infinite sequence of values, such as the continuing ticks of a clock).

But why do we need such an asynchronous reactive library in the first place?

Blocking Can Be Wasteful

Modern applications can reach huge numbers of concurrent users, and, even though the capabilities of modern hardware have continued to improve, performance of modern software is still a key concern.

There are, broadly, two ways one can improve a program's performance:

- **parallelize** to use more threads and more hardware resources.
- **seek more efficiency** in how current resources are used.

Usually, Java developers write programs by using blocking code. This practice is fine until there is a performance bottleneck. Then it is time to introduce additional threads, running similar blocking code. But this scaling in resource utilization can quickly introduce contention and concurrency problems.

Worse still, blocking wastes resources. If you look closely, as soon as a program involves some latency (notably I/O, such as a database request or a network call), resources are wasted because threads (possibly many threads) now sit idle, waiting for data.

So the parallelization approach is not a silver bullet. It is necessary to access the full power of the hardware, but it is also complex to reason about and susceptible to resource wasting.

Asynchronicity to the Rescue?

The second approach mentioned earlier, seeking more efficiency, can be a solution to the resource wasting problem. By writing asynchronous, non-blocking code, you let the execution switch to another active task that uses the same underlying resources and later comes back to the current process when the asynchronous processing has finished.

But how can you produce asynchronous code on the JVM? Java offers two models of asynchronous programming:

- **Callbacks**: Asynchronous methods do not have a return value but take an extra `callback` parameter (a lambda or anonymous class) that gets called when the result is available. A well known example is Swing's `EventListener` hierarchy.
- **Futures**: Asynchronous methods *immediately* return a `Future<T>`. The asynchronous process computes a `T` value, but the `Future` object wraps access to it. The value is not immediately available, and the object can be polled until the value is available. For instance, an `ExecutorService` running `Callable<T>` tasks use `Future` objects.

Are these techniques good enough? Not for every use case, and both approaches have limitations.

Callbacks are hard to compose together, quickly leading to code that is difficult to read and maintain (known as "Callback Hell").

Consider an example: showing the top five favorites from a user on the UI or suggestions if she does not have a favorite. This goes through three services (one gives favorite IDs, the second fetches favorite details, and the third offers suggestions with details), as follows:

Example of Callback Hell

```
userService.getFavorites(userId, new Callback<List<String>>() { ①
  public void onSuccess(List<String> list) { ②
    if (list.isEmpty()) { ③
      suggestionService.getSuggestions(new Callback<List<Favorite>>() {
        public void onSuccess(List<Favorite> list) { ④
          UiUtils.submitOnUiThread(() -> { ⑤
            list.stream()
                .limit(5)
                .forEach(uiList::show); ⑥
            });
        }

        public void onError(Throwable error) { ⑦
          UiUtils.errorPopup(error);
        }
      });
    } else {
      list.stream() ⑧
          .limit(5)
          .forEach(favId -> favoriteService.getDetails(favId, ⑨
            new Callback<Favorite>() {
              public void onSuccess(Favorite details) {
                UiUtils.submitOnUiThread(() -> uiList.show(details));
              }

              public void onError(Throwable error) {
                UiUtils.errorPopup(error);
              }
            }
          ));
    }
  }

  public void onError(Throwable error) {
    UiUtils.errorPopup(error);
  }
});
```

① We have callback-based services: a `Callback` interface with a method invoked when the asynchronous process was successful and one invoked when an error occurs.

② The first service invokes its callback with the list of favorite IDs.

③ If the list is empty, we must go to the `suggestionService`.

④ The `suggestionService` gives a `List<Favorite>` to a second callback.

⑤ Since we deal with a UI, we need to ensure our consuming code runs in the UI thread.

⑥ We use a Java 8 `Stream` to limit the number of suggestions processed to five, and we show them in a graphical list in the UI.

⑦ At each level, we deal with errors the same way: We show them in a popup.

⑧ Back to the favorite ID level. If the service returned a full list, we need to go to the `favoriteService` to get detailed `Favorite` objects. Since we want only five, we first stream the list of IDs to limit it to five.

⑨ Once again, a callback. This time we get a fully-fledged `Favorite` object that we push to the UI inside the UI thread.

That is a lot of code, and it is a bit hard to follow and has repetitive parts. Consider its equivalent in Reactor:

Example of Reactor code equivalent to callback code

```
userService.getFavorites(userId) ①
           .flatMap(favoriteService::getDetails) ②
           .switchIfEmpty(suggestionService.getSuggestions()) ③
           .take(5) ④
           .publishOn(UiUtils.uiThreadScheduler()) ⑤
           .subscribe(uiList::show, UiUtils::errorPopup); ⑥
```

① We start with a flow of favorite IDs.

② We *asynchronously transform* these into detailed `Favorite` objects (`flatMap`). We now have a flow of `Favorite`.

③ If the flow of `Favorite` is empty, we switch to a fallback through the `suggestionService`.

④ We are only interested in, at most, five elements from the resulting flow.

⑤ At the end, we want to process each piece of data in the UI thread.

⑥ We trigger the flow by describing what to do with the final form of the data (show it in a UI list) and what to do in case of an error (show a popup).

What if you want to ensure the favorite IDs are retrieved in less than 800ms or, if it takes longer, get them from a cache? In the callback-based code, that is a complicated task. In Reactor it becomes as easy as adding a `timeout` operator in the chain, as follows:

Example of Reactor code with timeout and fallback

```
userService.getFavorites(userId)
           .timeout(Duration.ofMillis(800)) ①
           .onErrorResume(cacheService.cachedFavoritesFor(userId)) ②
           .flatMap(favoriteService::getDetails) ③
           .switchIfEmpty(suggestionService.getSuggestions())
           .take(5)
           .publishOn(UiUtils.uiThreadScheduler())
           .subscribe(uiList::show, UiUtils::errorPopup);
```

① If the part above emits nothing for more than 800ms, propagate an error.

② In case of an error, fall back to the `cacheService`.

③ The rest of the chain is similar to the previous example.

`Future` objects are a bit better than callbacks, but they still do not do well at composition, despite the improvements brought in Java 8 by `CompletableFuture`. Orchestrating multiple `Future` objects together is doable but not easy. Also, `Future` has other problems:

- It is easy to end up with another blocking situation with `Future` objects by calling the `get()` method.
- They do not support lazy computation.
- They lack support for multiple values and advanced error handling.

Consider another example: We get a list of IDs from which we want to fetch a name and a statistic and combine these pair-wise, all of it asynchronously. The following example does so with a list of type `CompletableFuture`:

Example of `CompletableFuture` combination

```
CompletableFuture<List<String>> ids = ifhIds(); ①

CompletableFuture<List<String>> result = ids.thenComposeAsync(l -> { ②
    Stream<CompletableFuture<String>> zip =
            l.stream().map(i -> { ③
                CompletableFuture<String> nameTask = ifhName(i); ④
                CompletableFuture<Integer> statTask = ifhStat(i); ⑤

                return nameTask.thenCombineAsync(statTask, (name, stat) -> "Name " +
name + " has stats " + stat); ⑥
            });
    List<CompletableFuture<String>> combinationList = zip.collect(Collectors.
toList()); ⑦
    CompletableFuture<String>[] combinationArray = combinationList.toArray(new
CompletableFuture[combinationList.size()]);

    CompletableFuture<Void> allDone = CompletableFuture.allOf(combinationArray); ⑧
    return allDone.thenApply(v -> combinationList.stream()
            .map(CompletableFuture::join) ⑨
            .collect(Collectors.toList()));
});

List<String> results = result.join(); ⑩
assertThat(results).contains(
        "Name NameJoe has stats 103",
        "Name NameBart has stats 104",
        "Name NameHenry has stats 105",
        "Name NameNicole has stats 106",
        "Name NameABSLAJNFOAJNFOANFANSF has stats 121");
```

① We start off with a future that gives us a list of `id` values to process.

② We want to start some deeper asynchronous processing once we get the list.

③ For each element in the list:

④ Asynchronously get the associated name.

⑤ Asynchronously get the associated statistic.

⑥ Combine both results.

⑦ We now have a list of futures that represent all the combination tasks. To execute these tasks, we need to convert the list to an array.

⑧ Pass the array to `CompletableFuture.allOf`, which outputs a `Future` that completes when all tasks have completed.

⑨ The tricky bit is that `allOf` returns `CompletableFuture<Void>`, so we reiterate over the list of futures, collecting their results by using `join()` (which, here, does not block, since `allOf` ensures the futures are all done).

⑩ Once the whole asynchronous pipeline has been triggered, we wait for it to be processed and return the list of results that we can assert.

Since Reactor has more combination operators out of the box, this process can be simplified, as follows:

Example of Reactor code equivalent to future code

```
Flux<String> ids = ifhrIds(); ①

Flux<String> combinations =
        ids.flatMap(id -> { ②
            Mono<String> nameTask = ifhrName(id); ③
            Mono<Integer> statTask = ifhrStat(id); ④

            return nameTask.zipWith(statTask, ⑤
                    (name, stat) -> "Name " + name + " has stats " + stat);
        });

Mono<List<String>> result = combinations.collectList(); ⑥

List<String> results = result.block(); ⑦
assertThat(results).containsExactly( ⑧
        "Name NameJoe has stats 103",
        "Name NameBart has stats 104",
        "Name NameHenry has stats 105",
        "Name NameNicole has stats 106",
        "Name NameABSLAJNFOAJNFOANFANSF has stats 121"
);
```

① This time, we start from an asynchronously provided sequence of `ids` (a `Flux<String>`).

② For each element in the sequence, we asynchronously process it (inside the function that is the body `flatMap` call) twice.

③ Get the associated name.

④ Get the associated statistic.

⑤ Asynchronously combine the two values.

⑥ Aggregate the values into a `List` as they become available.

⑦ In production, we would continue working with the `Flux` asynchronously by further combining it or subscribing to it. Most probably, we would return the `result Mono`. Since we are in a test, we instead block, waiting for the processing to finish, and then directly return the aggregated list of values.

⑧ Assert the result.

The perils of using callbacks and `Future` objects are similar and are what reactive programming addresses with the `Publisher-Subscriber` pair.

From Imperative to Reactive Programming

Reactive libraries, such as Reactor, aim to address these drawbacks of "classic" asynchronous approaches on the JVM while also focusing on a few additional aspects:

- **Composability** and **readability**
- Data as a **flow** manipulated with a rich vocabulary of **operators**
- Nothing happens until you **subscribe**
- **Backpressure** or *the ability for the consumer to signal the producer that the rate of emission is too high*
- **High level** but **high value** abstraction that is *concurrency-agnostic*

Composability and Readability

By "composability", we mean the ability to orchestrate multiple asynchronous tasks, in which we use results from previous tasks to feed input to subsequent ones. Alternatively, we can run several tasks in a fork-join style. In addition, we can reuse asynchronous tasks as discrete components in a higher-level system.

The ability to orchestrate tasks is tightly coupled to the readability and maintainability of code. As the layers of asynchronous processes increase in both number and complexity, being able to compose and read code becomes increasingly difficult. As we saw, the callback model is simple, but one of its main drawbacks is that, for complex processes, you need to have a callback executed from a callback, itself nested inside another callback, and so on. That mess is known as "Callback Hell". As you can guess (or know from experience), such code is pretty hard to go back to and reason about.

Reactor offers rich composition options, wherein code mirrors the organization of the abstract process, and everything is generally kept at the same level (nesting is minimized).

The Assembly Line Analogy

You can think of data processed by a reactive application as moving through an assembly line. Reactor is both the conveyor belt and the workstations. The raw material pours from a source (the original `Publisher`) and ends up as a finished product ready to be pushed to the consumer (or

`Subscriber`).

The raw material can go through various transformations and other intermediary steps or be part of a larger assembly line that aggregates intermediate pieces together. If there is a glitch or clogging at one point (perhaps boxing the products takes a disproportionately long time), the afflicted workstation can signal upstream to limit the flow of raw material.

Operators

In Reactor, operators are the workstations in our assembly analogy. Each operator adds behavior to a `Publisher` and wraps the previous step's `Publisher` into a new instance. The whole chain is thus linked, such that data originates from the first `Publisher` and moves down the chain, transformed by each link. Eventually, a `Subscriber` finishes the process. Remember that nothing happens until a `Subscriber` subscribes to a `Publisher`, as we will see shortly.

Understanding that operators create new instances can help you avoid a common mistake that would lead you to believe that an operator you used in your chain is not being applied. See this item in the FAQ.

While the Reactive Streams specification does not specify operators at all, one of the best added values of reactive libraries, such as Reactor, is the rich vocabulary of operators that they provide. These cover a lot of ground, from simple transformation and filtering to complex orchestration and error handling.

Nothing Happens Until You `subscribe()`

In Reactor, when you write a `Publisher` chain, data does not start pumping into it by default. Instead, you create an abstract description of your asynchronous process (which can help with reusability and composition).

By the act of **subscribing**, you tie the `Publisher` to a `Subscriber`, which triggers the flow of data in the whole chain. This is achieved internally by a single `request` signal from the `Subscriber` that is propagated upstream, all the way back to the source `Publisher`.

Backpressure

Propagating signals upstream is also used to implement **backpressure**, which we described in the assembly line analogy as a feedback signal sent up the line when a workstation processes more slowly than an upstream workstation.

The real mechanism defined by the Reactive Streams specification is pretty close to the analogy: A subscriber can work in *unbounded* mode and let the source push all the data at its fastest achievable rate or it can use the `request` mechanism to signal the source that it is ready to process at most `n` elements.

Intermediate operators can also change the request in-transit. Imagine a `buffer` operator that groups elements in batches of ten. If the subscriber requests one buffer, it is acceptable for the source to produce ten elements. Some operators also implement **prefetching** strategies, which avoid `request(1)` round-trips and is beneficial if producing the elements before they are requested

is not too costly.

This transforms the push model into a **push-pull hybrid**, where the downstream can pull n elements from upstream if they are readily available. But if the elements are not ready, they get pushed by the upstream whenever they are produced.

Hot vs Cold

The Rx family of reactive libraries distinguishes two broad categories of reactive sequences: **hot** and **cold**. This distinction mainly has to do with how the reactive stream reacts to subscribers:

- A **Cold** sequence starts anew for each `Subscriber`, including at the source of data. For example, if the source wraps an HTTP call, a new HTTP request is made for each subscription.
- A **Hot** sequence does not start from scratch for each `Subscriber`. Rather, late subscribers receive signals emitted *after* they subscribed. Note, however, that some hot reactive streams can cache or replay the history of emissions totally or partially. From a general perspective, a hot sequence can even emit when no subscriber is listening (an exception to the "nothing happens before you subscribe" rule).

For more information on hot vs cold in the context of Reactor, see this reactor-specific section.

Chapter 4. Reactor Core Features

The Reactor project main artifact is `reactor-core`, a reactive library that focuses on the Reactive Streams specification and targets Java 8.

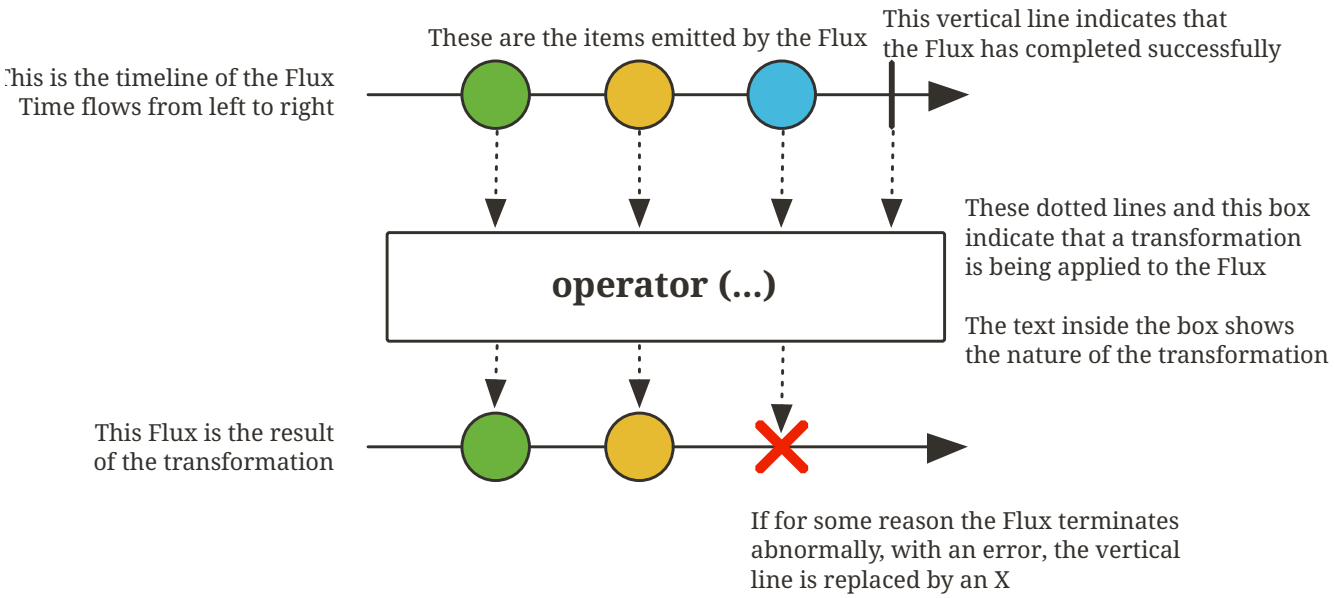
Reactor introduces composable reactive types that implement `Publisher` but also provide a rich vocabulary of operators: `Flux` and `Mono`. A `Flux` object represents a reactive sequence of 0..N items, while a `Mono` object represents a single-value-or-empty (0..1) result.

This distinction carries a bit of semantic information into the type, indicating the rough cardinality of the asynchronous processing. For instance, an HTTP request produces only one response, so there is not much sense in doing a `count` operation. Expressing the result of such an HTTP call as a `Mono<HttpResponse>` thus makes more sense than expressing it as a `Flux<HttpResponse>`, as it offers only operators that are relevant to a context of zero items or one item.

Operators that change the maximum cardinality of the processing also switch to the relevant type. For instance, the `count` operator exists in `Flux`, but it returns a `Mono<Long>`.

4.1. Flux, an Asynchronous Sequence of 0-N Items

The following image shows how a `Flux` transforms items:

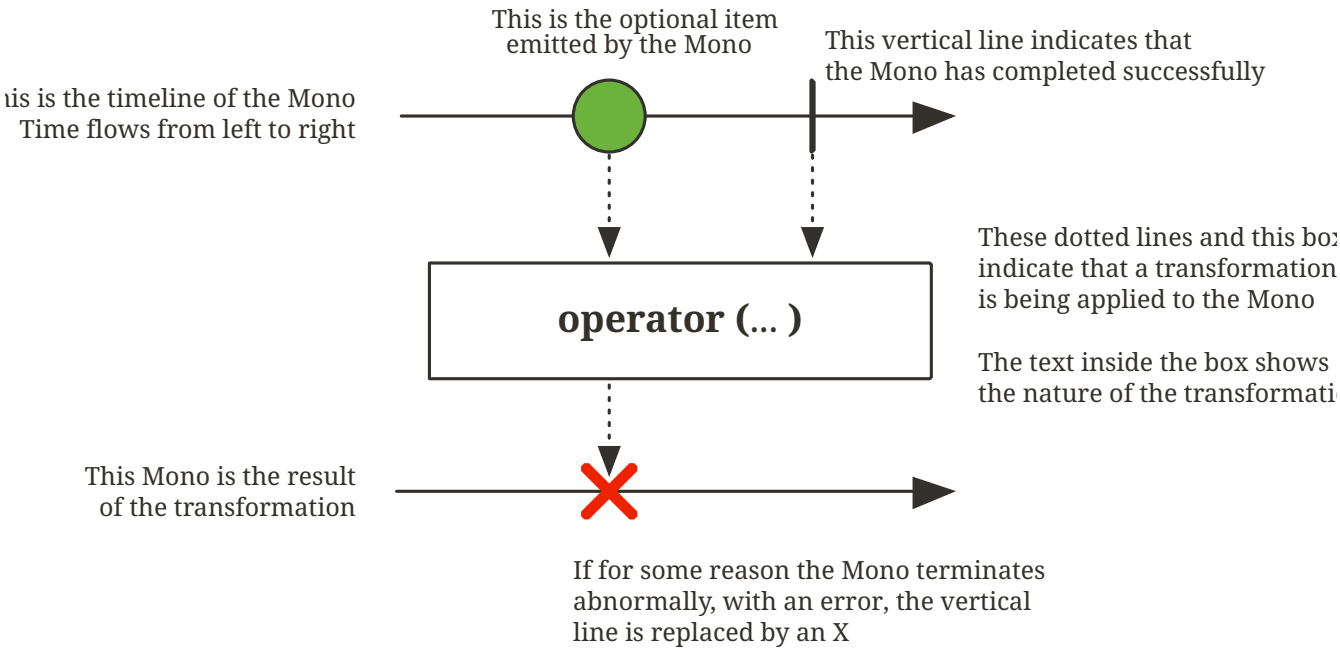


A `Flux<T>` is a standard `Publisher<T>` that represents an asynchronous sequence of 0 to N emitted items, optionally terminated by either a completion signal or an error. As in the Reactive Streams spec, these three types of signal translate to calls to a downstream Subscriber's `onNext`, `onComplete`, and `onError` methods.

With this large scope of possible signals, `Flux` is the general-purpose reactive type. Note that all events, even terminating ones, are optional: no `onNext` event but an `onComplete` event represents an *empty* finite sequence, but remove the `onComplete` and you have an *infinite* empty sequence (not particularly useful, except for tests around cancellation). Similarly, infinite sequences are not necessarily empty. For example, `Flux.interval(Duration)` produces a `Flux<Long>` that is infinite and emits regular ticks from a clock.

4.2. Mono, an Asynchronous 0-1 Result

The following image shows how a `Mono` transforms an item:



A `Mono<T>` is a specialized `Publisher<T>` that emits at most one item *via* the `onNext` signal then terminates with an `onComplete` signal (successful `Mono`, with or without value), or only emits a single `onError` signal (failed `Mono`).

Most `Mono` implementations are expected to immediately call `onComplete` on their `Subscriber` after having called `onNext`. `Mono.never()` is an outlier: it doesn't emit any signal, which is not technically forbidden although not terribly useful outside of tests. On the other hand, a combination of `onNext` and `onError` is explicitly forbidden.

`Mono` offers only a subset of the operators that are available for a `Flux`, and some operators (notably those that combine the `Mono` with another `Publisher`) switch to a `Flux`. For example, `Mono#concatWith(Publisher)` returns a `Flux` while `Mono#then(Mono)` returns another `Mono`.

Note that you can use a `Mono` to represent no-value asynchronous processes that only have the concept of completion (similar to a `Runnable`). To create one, you can use an empty `Mono<Void>`.

4.3. Simple Ways to Create a Flux or Mono and Subscribe to It

The easiest way to get started with `Flux` and `Mono` is to use one of the numerous factory methods found in their respective classes.

For instance, to create a sequence of `String`, you can either enumerate them or put them in a collection and create the Flux from it, as follows:

```
Flux<String> seq1 = Flux.just("foo", "bar", "foobar");

List<String> iterable = Arrays.asList("foo", "bar", "foobar");
Flux<String> seq2 = Flux.fromIterable(iterable);
```

Other examples of factory methods include the following:

```
Mono<String> noData = Mono.empty(); ①

Mono<String> data = Mono.just("foo");

Flux<Integer> numbersFromFiveToSeven = Flux.range(5, 3); ②
```

① Notice the factory method honors the generic type even though it has no value.

② The first parameter is the start of the range, while the second parameter is the number of items to produce.

When it comes to subscribing, `Flux` and `Mono` make use of Java 8 lambdas. You have a wide choice of `.subscribe()` variants that take lambdas for different combinations of callbacks, as shown in the following method signatures:

Lambda-based subscribe variants for `Flux`

```
subscribe(); ①

subscribe(Consumer<? super T> consumer); ②

subscribe(Consumer<? super T> consumer,
          Consumer<? super Throwable> errorConsumer); ③

subscribe(Consumer<? super T> consumer,
          Consumer<? super Throwable> errorConsumer,
          Runnable completeConsumer); ④

subscribe(Consumer<? super T> consumer,
          Consumer<? super Throwable> errorConsumer,
          Runnable completeConsumer,
          Consumer<? super Subscription> subscriptionConsumer); ⑤
```

① Subscribe and trigger the sequence.

② Do something with each produced value.

③ Deal with values but also react to an error.

④ Deal with values and errors but also run some code when the sequence successfully completes.

⑤ Deal with values and errors and successful completion but also do something with the `Subscription` produced by this `subscribe` call.

These variants return a reference to the subscription that you can use to cancel the subscription when no more data is needed. Upon cancellation, the source should stop producing values and clean up any resources it created. This cancel-and-clean-up behavior is represented in Reactor by the general-purpose `Disposable` interface.

`subscribe` Method Examples

This section contains minimal examples of each of the five signatures for the `subscribe` method. The following code shows an example of the basic method with no arguments:

```
Flux<Integer> ints = Flux.range(1, 3); ①
ints.subscribe(); ②
```

① Set up a `Flux` that produces three values when a subscriber attaches.

② Subscribe in the simplest way.

The preceding code produces no visible output, but it does work. The `Flux` produces three values. If we provide a lambda, we can make the values visible. The next example for the `subscribe` method shows one way to make the values appear:

```
Flux<Integer> ints = Flux.range(1, 3); ①
ints.subscribe(i -> System.out.println(i)); ②
```

① Set up a `Flux` that produces three values when a subscriber attaches.

② Subscribe with a subscriber that will print the values.

The preceding code produces the following output:

```
1
2
3
```

To demonstrate the next signature, we intentionally introduce an error, as shown in the following example:

```
Flux<Integer> ints = Flux.range(1, 4) ①
      .map(i -> { ②
        if (i <= 3) return i; ③
        throw new RuntimeException("Got to 4"); ④
      });
ints.subscribe(i -> System.out.println(i), ⑤
      error -> System.err.println("Error: " + error));
```

① Set up a Flux that produces four values when a subscriber attaches.

② We need a map so that we can handle some values differently.

③ For most values, return the value.

④ For one value, force an error.

⑤ Subscribe with a subscriber that includes an error handler.

We now have two lambda expressions: one for the content we expect and one for errors. The preceding code produces the following output:

```
1
2
3
Error: java.lang.RuntimeException: Got to 4
```

The next signature of the `subscribe` method includes both an error handler and a handler for completion events, as shown in the following example:

```
Flux<Integer> ints = Flux.range(1, 4); ①
ints.subscribe(i -> System.out.println(i),
    error -> System.err.println("Error " + error),
    () -> System.out.println("Done")); ②
```

① Set up a Flux that produces four values when a subscriber attaches.

② Subscribe with a Subscriber that includes a handler for completion events.

Error signals and completion signals are both terminal events and are exclusive of one another (you never get both). To make the completion consumer work, we must take care not to trigger an error.

The completion callback has no input, as represented by an empty pair of parentheses: It matches the `run` method in the `Runnable` interface. The preceding code produces the following output:

```
1
2
3
4
Done
```

Cancelling a `subscribe()` with Its `Disposable`

All these lambda-based variants of `subscribe()` have a `Disposable` return type. In this case, the `Disposable` interface represents the fact that the subscription can be *cancelled*, by calling its `dispose()` method.

For a `Flux` or `Mono`, cancellation is a signal that the source should stop producing elements. However, it is NOT guaranteed to be immediate: Some sources might produce elements so fast that they could

complete even before receiving the cancel instruction.

Some utilities around `Disposable` are available in the `Disposables` class. Among these, `Disposables.swap()` creates a `Disposable` wrapper that lets you atomically cancel and replace a concrete `Disposable`. This can be useful, for instance, in a UI scenario where you want to cancel a request and replace it with a new one whenever the user clicks on a button. Disposing the wrapper itself closes it. Doing so disposes the current concrete value and all future attempted replacements.

Another interesting utility is `Disposables.composite(…)`. This composite lets you collect several `Disposable` — for instance, multiple in-flight requests associated with a service call — and dispose all of them at once later on. Once the composite's `dispose()` method has been called, any attempt to add another `Disposable` immediately disposes it.

An Alternative to Lambdas: `BaseSubscriber`

There is an additional `subscribe` method that is more generic and takes a full-blown `Subscriber` rather than composing one out of lambdas. In order to help with writing such a `Subscriber`, we provide an extendable class called `BaseSubscriber`.

Instances of `BaseSubscriber` (or subclasses of it) are **single-use**, meaning that a `BaseSubscriber` cancels its subscription to the first `Publisher` if it is subscribed to a second `Publisher`. That is because using an instance twice would violate the Reactive Streams rule that the `onNext` method of a `Subscriber` must not be called in parallel. As a result, anonymous implementations are fine only if they are declared directly within the call to `Publisher#subscribe(Subscriber)`.

Now we can implement one of these. We call it a `SampleSubscriber`. The following example shows how it would be attached to a `Flux`:

```
SampleSubscriber<Integer> ss = new SampleSubscriber<Integer>();
Flux<Integer> ints = Flux.range(1, 4);
ints.subscribe(ss);
```

The following example shows what `SampleSubscriber` could look like, as a minimalistic implementation of a `BaseSubscriber`:

```
package io.projectreactor.samples;

import org.reactivestreams.Subscription;

import reactor.core.publisher.BaseSubscriber;

public class SampleSubscriber<T> extends BaseSubscriber<T> {

    @Override
    public void hookOnSubscribe(Subscription subscription) {
        System.out.println("Subscribed");
        request(1);
    }

    @Override
    public void hookOnNext(T value) {
        System.out.println(value);
        request(1);
    }
}
```

The `SampleSubscriber` class extends `BaseSubscriber`, which is the recommended abstract class for user-defined `Subscribers` in Reactor. The class offers hooks that can be overridden to tune the subscriber's behavior. By default, it triggers an unbounded request and behaves exactly as `subscribe()`. However, extending `BaseSubscriber` is much more useful when you want a custom request amount.

For a custom request amount, the bare minimum is to implement `hookOnSubscribe(Subscription subscription)` and `hookOnNext(T value)`, as we did. In our case, the `hookOnSubscribe` method prints a statement to standard out and makes the first request. Then the `hookOnNext` method prints a statement and performs additional requests, one request at a time.

The `SampleSubscriber` class produces the following output:

```
Subscribed
1
2
3
4
```

`BaseSubscriber` also offers a `requestUnbounded()` method to switch to unbounded mode (equivalent to `request(Long.MAX_VALUE)`), as well as a `cancel()` method.

It also has additional hooks: `hookOnComplete`, `hookOnError`, `hookOnCancel`, and `hookFinally` (which is always called when the sequence terminates, with the type of termination passed in as a `SignalType` parameter)

You almost certainly want to implement the `hookOnError`, `hookOnCancel`, and

> `hookOnComplete` methods. You may also want to implement the `hookFinally` method. `SampleSubscriber` is the absolute minimum implementation of a `Subscriber` *that performs bounded requests*.

Subscription Patterns

In a typical reactive application, users rarely explicitly call `subscribe()` themselves. Instead, they declaratively define the processing pipeline as a `Flux` or `Mono` and hand it to their library (like `reactor-netty`) or framework (like `Spring WebFlux`) of choice to hook into a non-blocking execution engine (typically an event loop). The user logic is composed of chaining the reactive operators.

There are times when you explicitly want to start the subscription and this section aims to list the typical patterns.

Fire-and-forget

When you ignore the `Disposable` returned by `subscribe()`, you lose the ability to cancel the execution. In most cases this is an anti-pattern, but there are legitimate imperative boundaries (e.g. event listeners) where it is unavoidable — in those cases, handle errors explicitly.

Fire-and-forget

```
Mono<Void> handle(T arg) {
  sideEffectService.doSomething(arg).subscribe(); ①
  return Mono.empty();
}
```

① Downstream can no longer coordinate cancellation or error handling for this inner subscription.

Preferred: compose and return

```
Mono<Void> handle(T arg) {
  return sideEffectService.doSomething(arg).then();
}
```

Error handling at an imperative boundary: overload with error consumer

```
public void onEvent(T arg) {
  sideEffectService.doSomething(arg)
      .subscribe(ignored -> { }, e -> logger.warn("Operation failed", e));
}
```

Dispatch and reference

For a more robust alternative, store the reference to the `Disposable` and perform cleanup (`dispose()`) at a later stage.

```
AtomicReference<Disposable> disposableRef = new AtomicReference<>();
```

```
Disposable disposable = sideEffectService.doSomething(arg)
    .subscribe(
        result -> { /* handle next */ },
        e -> logger.warn("Operation failed", e)
    );

disposableRef.set(disposable);

// during cleanup
disposableRef.get().dispose();
```

Use `BaseSubscriber`

The third option — providing the most control — is to extend `BaseSubscriber`. This is appropriate when you need fine-grained backpressure control, custom cancellation logic, or want to handle all lifecycle signals (`onSubscribe`, `onNext`, `onError`, `onComplete`, `onCancel`) in a single coherent class.

See An Alternative to Lambdas: `BaseSubscriber` for a full example.

On Backpressure and Ways to Reshape Requests

When implementing backpressure in Reactor, the way consumer pressure is propagated back to the source is by sending a `request` to the upstream operator. The sum of current requests is sometimes referenced to as the current "demand", or "pending request". Demand is capped at `Long.MAX_VALUE`, representing an unbounded request (meaning "produce as fast as you can" — basically disabling backpressure).

The first request comes from the final subscriber at subscription time, yet the most direct ways of subscribing all immediately trigger an unbounded request of `Long.MAX_VALUE`:

- `subscribe()` and most of its lambda-based variants (to the exception of the one that has a `Consumer<Subscription>`)
- `block()`, `blockFirst()` and `blockLast()`
- iterating over a `toIterable()` or `toStream()`

The simplest way of customizing the original request is to `subscribe` with a `BaseSubscriber` with the `hookOnSubscribe` method overridden, as the following example shows:

```
Flux.range(1, 10)
    .doOnRequest(r -> System.out.println("request of " + r))
    .subscribe(new BaseSubscriber<Integer>() {

      @Override
      public void hookOnSubscribe(Subscription subscription) {
        request(1);
      }

      @Override
      public void hookOnNext(Integer integer) {
        System.out.println("Cancelling after having received " + integer);
        cancel();
      }
    });
```

The preceding snippet prints out the following:

```
request of 1
Cancelling after having received 1
```

When manipulating a request, you must be careful to produce enough demand for the sequence to advance, or your Flux can get "stuck". That is why `BaseSubscriber` defaults to an unbounded request in `hookOnSubscribe`. When overriding this hook, you should usually call `request` at least once.

Operators that Change the Demand from Downstream

One thing to keep in mind is that demand expressed at the subscribe level **can** be reshaped by each operator in the upstream chain. A textbook case is the `buffer(N)` operator: If it receives a `request(2)`, it is interpreted as a demand for **two full buffers**. As a consequence, since buffers need `N` elements to be considered full, the `buffer` operator reshapes the request to `2 x N`.

You might also have noticed that some operators have variants that take an `int` input parameter called `prefetch`. This is another category of operators that modify the downstream request. These are usually operators that deal with inner sequences, deriving a `Publisher` from each incoming element (like `flatMap`).

Prefetch is a way to tune the initial request made on these inner sequences. If unspecified, most of these operators start with a demand of `32`.

These operators usually also implement a **replenishing optimization**: Once the operator has seen 75% of the prefetch request fulfilled, it re-requests 75% from upstream. This is a heuristic optimization made so that these operators proactively anticipate the upcoming requests.

Finally, a couple of operators let you directly tune the request: `limitRate` and `limitRequest`.

`limitRate(N)` splits the downstream requests so that they are propagated upstream in smaller

batches. For instance, a request of `100` made to `limitRate(10)` would result in, at most, `10` requests of `10` being propagated to the upstream. Note that, in this form, `limitRate` actually implements the replenishing optimization discussed earlier.

The operator has a variant that also lets you tune the replenishing amount (referred to as the `lowTide` in the variant): `limitRate(highTide, lowTide)`. Choosing a `lowTide` of `0` results in **strict** batches of `highTide` requests, instead of batches further reworked by the replenishing strategy.

`limitRequest(N)`, on the other hand, **caps** the downstream request to a maximum total demand. It adds up requests up to `N`. If a single `request` does not make the total demand overflow over `N`, that particular request is wholly propagated upstream. After that amount has been emitted by the source, `limitRequest` considers the sequence complete, sends an `onComplete` signal downstream, and cancels the source.

4.4. Programmatically creating a sequence

In this section, we introduce the creation of a `Flux` or a `Mono` by programmatically defining its associated events (`onNext`, `onError`, and `onComplete`). All these methods share the fact that they expose an API to trigger the events that we call a **sink**. There are actually a few sink variants, which we'll get to shortly.

Synchronous `generate`

The simplest form of programmatic creation of a `Flux` is through the `generate` method, which takes a generator function.

This is for **synchronous** and **one-by-one** emissions, meaning that the sink is a `SynchronousSink` and that its `next()` method can only be called at most once per callback invocation. You can then additionally call `error(Throwable)` or `complete()`, but this is optional.

The most useful variant is probably the one that also lets you keep a state that you can refer to in your sink usage to decide what to emit next. The generator function then becomes a `BiFunction<S, SynchronousSink<T>, S>`, with `<S>` the type of the state object. You have to provide a `Supplier<S>` for the initial state, and your generator function now returns a new state on each round.

For instance, you could use an `int` as the state:

Example of state-based `generate`

```
Flux<String> flux = Flux.generate(
    () -> 0, ①
    (state, sink) -> {
      sink.next("3 x " + state + " = " + 3*state); ②
      if (state == 10) sink.complete(); ③
      return state + 1; ④
    });
```

① We supply the initial state value of 0.

② We use the state to choose what to emit (a row in the multiplication table of 3).

③ We also use it to choose when to stop.

④ We return a new state that we use in the next invocation (unless the sequence terminated in this one).

The preceding code generates the table of 3, as the following sequence:

```
3 x 0 = 0
3 x 1 = 3
3 x 2 = 6
3 x 3 = 9
3 x 4 = 12
3 x 5 = 15
3 x 6 = 18
3 x 7 = 21
3 x 8 = 24
3 x 9 = 27
3 x 10 = 30
```

You can also use a mutable `<S>`. The example above could for instance be rewritten using a single `AtomicLong` as the state, mutating it on each round:

Mutable state variant

```
Flux<String> flux = Flux.generate(
    AtomicLong::new, ①
    (state, sink) -> {
      long i = state.getAndIncrement(); ②
      sink.next("3 x " + i + " = " + 3*i);
      if (i == 10) sink.complete();
      return state; ③
    });
```

① This time, we generate a mutable object as the state.

② We mutate the state here.

③ We return the **same** instance as the new state.

If your state object needs to clean up some resources, use the `generate(Supplier<S>, BiFunction, Consumer<S>)` variant to clean up the last state instance.

The following example uses the `generate` method that includes a `Consumer`:

```
Flux<String> flux = Flux.generate(
    AtomicLong::new,
      (state, sink) -> { ①
      long i = state.getAndIncrement(); ②
      sink.next("3 x " + i + " = " + 3*i);
```

```
      if (i == 10) sink.complete();
      return state; ③
    }, (state) -> System.out.println("state: " + state)); ④
```

① Again, we generate a mutable object as the state.

② We mutate the state here.

③ We return the **same** instance as the new state.

④ We see the last state value (11) as the output of this `Consumer` lambda.

In the case of the state containing a database connection or other resource that needs to be handled at the end of the process, the `Consumer` lambda could close the connection or otherwise handle any tasks that should be done at the end of the process.

Asynchronous and Multi-threaded: `create`

`create` is a more advanced form of programmatic creation of a `Flux` which is suitable for multiple emissions per round, even from multiple threads.

It exposes a `FluxSink`, with its `next`, `error`, and `complete` methods. Contrary to `generate`, it doesn't have a state-based variant. On the other hand, it can trigger multi-threaded events in the callback.

`create` can be very useful to bridge an existing API with the reactive world - such as an asynchronous API based on listeners.

`create` **doesn't parallelize your code nor does it make it asynchronous**, even though it *can* be used with asynchronous APIs. If you block within the `create` lambda, you expose yourself to deadlocks and similar side effects. Even with the use of `subscribeOn`, there's the caveat that a long-blocking `create` lambda (such as an infinite loop calling `sink.next(t)`) can lock the pipeline: the requests would never be performed due to the loop starving the same thread they are supposed to run from. Use the `subscribeOn(Scheduler, false)` variant: `requestOnSeparateThread = false` will use the `Scheduler` thread for the `create` and still let data flow by performing `request` in the original thread.

Imagine that you use a listener-based API. It processes data by chunks and has two events: (1) a chunk of data is ready and (2) the processing is complete (terminal event), as represented in the `MyEventListener` interface:

```
interface MyEventListener<T> {
    void onDataChunk(List<T> chunk);
    void processComplete();
}
```

You can use `create` to bridge this into a `Flux<T>`:

```
Flux<String> bridge = Flux.create(sink -> {
    myEventProcessor.register( ④
      new MyEventListener<String>() { ①

        public void onDataChunk(List<String> chunk) {
          for(String s : chunk) {
            sink.next(s); ②
          }
        }

        public void processComplete() {
            sink.complete(); ③
        }
    });
});
```

① Bridge to the `MyEventListener` API

② Each element in a chunk becomes an element in the `Flux`.

③ The `processComplete` event is translated to `onComplete`.

④ All of this is done asynchronously whenever the `myEventProcessor` executes.

Additionally, since `create` can bridge asynchronous APIs and manages backpressure, you can refine how to behave backpressure-wise, by indicating an `OverflowStrategy`:

- `IGNORE` to Completely ignore downstream backpressure requests. This may yield `IllegalStateException` when queues get full downstream.
- `ERROR` to signal an `IllegalStateException` when the downstream can't keep up.
- `DROP` to drop the incoming signal if the downstream is not ready to receive it.
- `LATEST` to let downstream only get the latest signals from upstream.
- `BUFFER` (the default) to buffer all signals if the downstream can't keep up. (this does unbounded buffering and may lead to `OutOfMemoryError`).

`Mono` also has a `create` generator. The `MonoSink` of Mono's create doesn't allow several emissions. It will drop all signals after the first one.

Asynchronous but single-threaded: `push`

`push` is a middle ground between `generate` and `create` which is suitable for processing events from a single producer. It is similar to `create` in the sense that it can also be asynchronous and can manage backpressure using any of the overflow strategies supported by `create`. However, **only one producing thread** may invoke `next`, `complete` or `error` at a time.

```
Flux<String> bridge = Flux.push(sink -> {
    myEventProcessor.register(
      new SingleThreadEventListener<String>() { ①

        public void onDataChunk(List<String> chunk) {
          for(String s : chunk) {
            sink.next(s); ②
          }
        }

        public void processComplete() {
            sink.complete(); ③
        }

        public void processError(Throwable e) {
            sink.error(e); ④
        }
    });
});
```

① Bridge to the `SingleThreadEventListener` API.

② Events are pushed to the sink using `next` from a single listener thread.

③ `complete` event generated from the same listener thread.

④ `error` event also generated from the same listener thread.

A hybrid push/pull model

Most Reactor operators, like `create`, follow a hybrid **push/pull** model. What we mean by that is that despite most of the processing being asynchronous (suggesting a *push* approach), there is a small *pull* component to it: the request.

The consumer *pulls* data from the source in the sense that it won't emit anything until first requested. The source *pushes* data to the consumer whenever it becomes available, but within the bounds of its requested amount.

Note that `push()` and `create()` both allow to set up an `onRequest` consumer in order to manage the request amount and to ensure that data is pushed through the sink only when there is pending request.

```
Flux<String> bridge = Flux.create(sink -> {
    myMessageProcessor.register(
      new MyMessageListener<String>() {

        public void onMessage(List<String> messages) {
          for(String s : messages) {
            sink.next(s); ③
          }
        }
    });
    sink.onRequest(n -> {
        List<String> messages = myMessageProcessor.getHistory(n); ①
        for(String s : messages) {
           sink.next(s); ②
        }
    });
});
```

① Poll for messages when requests are made.

② If messages are available immediately, push them to the sink.

③ The remaining messages that arrive asynchronously later are also delivered.

Cleaning up after `push()` or `create()`

Two callbacks, `onDispose` and `onCancel`, perform any cleanup on cancellation or termination. `onDispose` can be used to perform cleanup when the `Flux` completes, errors out, or is cancelled. `onCancel` can be used to perform any action specific to cancellation prior to cleanup with `onDispose`.

```
Flux<String> bridge = Flux.create(sink -> {
    sink.onRequest(n -> channel.poll(n))
        .onCancel(() -> channel.cancel()) ①
        .onDispose(() -> channel.close())  ②
    });
```

① `onCancel` is invoked first, for cancel signal only.

② `onDispose` is invoked for complete, error, or cancel signals.

Handle

The `handle` method is a bit different: it is an instance method, meaning that it is chained on an existing source (as are the common operators). It is present in both `Mono` and `Flux`.

It is close to `generate`, in the sense that it uses a `SynchronousSink` and only allows one-by-one emissions. However, `handle` can be used to generate an arbitrary value out of each source element, possibly skipping some elements. In this way, it can serve as a combination of `map` and `filter`. The signature of handle is as follows:

```
Flux<R> handle(BiConsumer<T, SynchronousSink<R>>);
```

Let's consider an example. The reactive streams specification disallows `null` values in a sequence. What if you want to perform a `map` but you want to use a preexisting method as the map function, and that method sometimes returns null?

For instance, the following method can be applied safely to a source of integers:

```
public String alphabet(int letterNumber) {
    if (letterNumber < 1 || letterNumber > 26) {
        return null;
    }
    int letterIndexAscii = 'A' + letterNumber - 1;
    return "" + (char) letterIndexAscii;
}
```

We can then use `handle` to remove any nulls:

Using `handle` for a "map and eliminate nulls" scenario

```
Flux<String> alphabet = Flux.just(-1, 30, 13, 9, 20)
    .handle((i, sink) -> {
        String letter = alphabet(i); ①
        if (letter != null) ②
            sink.next(letter); ③
    });

alphabet.subscribe(System.out::println);
```

① Map to letters.

② If the "map function" returns null....

③ Filter it out by not calling `sink.next`.

Which will print out:

```
M
I
T
```

4.5. Threading and Schedulers

Reactor, like RxJava, can be considered to be **concurrency-agnostic**. That is, it does not enforce a concurrency model. Rather, it leaves you, the developer, in command. However, that does not prevent the library from helping you with concurrency.

Obtaining a `Flux` or a `Mono` does not necessarily mean that it runs in a dedicated `Thread`. Instead,

most operators continue working in the `Thread` on which the previous operator executed. Unless specified, the topmost operator (the source) itself runs on the `Thread` in which the `subscribe()` call was made. The following example runs a `Mono` in a new thread:

```
public static void main(String[] args) throws InterruptedException {
  final Mono<String> mono = Mono.just("hello "); ①

  Thread t = new Thread(() -> mono
      .map(msg -> msg + "thread ")
      .subscribe(v -> ②
          System.out.println(v + Thread.currentThread().getName()) ③
      )
  );
  t.start();
  t.join();

}
```

① The `Mono<String>` is assembled in thread `main`.

② However, it is subscribed to in thread `Thread-0`.

③ As a consequence, both the `map` and the `onNext` callback actually run in `Thread-0`

The preceding code produces the following output:

```
hello thread Thread-0
```

In Reactor, the execution model and where the execution happens is determined by the `Scheduler` that is used. A `Scheduler` has scheduling responsibilities similar to an `ExecutorService`, but having a dedicated abstraction lets it do more, notably acting as a clock and enabling a wider range of implementations (virtual time for tests, trampolining or immediate scheduling, and so on).

The `Schedulers` class has static methods that give access to the following execution contexts:

- No execution context (`Schedulers.immediate()`): at processing time, the submitted `Runnable` will be directly executed, effectively running them on the current `Thread` (can be seen as a "null object" or no-op `Scheduler`).
- A single, reusable thread (`Schedulers.single()`). Note that this method reuses the same thread for all callers, until the Scheduler is disposed. If you want a per-call dedicated thread, use `Schedulers.newSingle()` for each call.
- An unbounded elastic thread pool (`Schedulers.elastic()`). This one is no longer preferred with the introduction of `Schedulers.boundedElastic()`, as it has a tendency to hide backpressure problems and lead to too many threads (see below).
- A bounded elastic thread pool (`Schedulers.boundedElastic()`). This is a handy way to give a blocking process its own thread so that it does not tie up other resources. This is a better choice for I/O blocking work. See How Do I Wrap a Synchronous, Blocking Call?, but doesn't pressure the system too much with new threads. Starting from 3.6.0 this can offer two different

implementations depending on the setup:

  - `ExecutorService`-based, which reuses platform threads between tasks. This implementation, like its predecessor `elastic()`, creates new worker pools as needed and reuses idle ones. Worker pools that stay idle for too long (the default is 60s) are also disposed. Unlike its `elastic()` predecessor, it has a cap on the number of backing threads it can create (default is number of CPU cores x 10). Up to 100 000 tasks submitted after the cap has been reached are enqueued and will be re-scheduled when a thread becomes available (when scheduling with a delay, the delay starts when the thread becomes available).
  - Thread-per-task-based, designed to run on `VirtualThread` instances. To embrace that functionality, the application should run in Java 21+ environment and set the `reactor.schedulers.defaultBoundedElasticOnVirtualThreads` system property to `true`. Once the above is set, the shared `Schedulers.boundedElastic()` return a specific implementation of `BoundedElasticScheduler` tailored to run every task on a new instance of the `VirtualThread` class. This implementation is similar in terms of the behavior to the `ExecutorService`-based one but does not have idle pool and creates a new `VirtualThread` for each task.

- A fixed pool of workers that is tuned for parallel work (`Schedulers.parallel()`). It creates as many workers as you have CPU cores.

Additionally, you can create a `Scheduler` out of any pre-existing `ExecutorService` by using `Schedulers.fromExecutorService(ExecutorService)`. (You can also create one from an `Executor`, although doing so is discouraged.)

You can also create new instances of the various scheduler types by using the `newXXX` methods. For example, `Schedulers.newParallel(yourScheduleName)` creates a new parallel scheduler named `yourScheduleName`.

While `boundedElastic` is made to help with legacy blocking code if it cannot be avoided, `single` and `parallel` are not. As a consequence, the use of Reactor blocking APIs (`block()`, `blockFirst()`, `blockLast()` (as well as iterating over `toIterable()` or `toStream()`) inside the default single and parallel schedulers) results in an `IllegalStateException` being thrown.

Custom `Schedulers` can also be marked as "non blocking only" by creating instances of `Thread` that implement the `NonBlocking` marker interface.

Some operators use a specific scheduler from `Schedulers` by default (and usually give you the option of providing a different one). For instance, calling the `Flux.interval(Duration.ofMillis(300))` factory method produces a `Flux<Long>` that ticks every 300ms. By default, this is enabled by `Schedulers.parallel()`. The following line changes the Scheduler to a new instance similar to `Schedulers.single()`:

```
Flux.interval(Duration.ofMillis(300), Schedulers.newSingle("test"))
```

Reactor offers two means of switching the execution context (or `Scheduler`) in a reactive chain: `publishOn` and `subscribeOn`. Both take a `Scheduler` and let you switch the execution context to that scheduler. But the placement of `publishOn` in the chain matters, while the placement of `subscribeOn`

does not. To understand that difference, you first have to remember that nothing happens until you subscribe .

In Reactor, when you chain operators, you can wrap as many `Flux` and `Mono` implementations inside one another as you need. Once you subscribe, a chain of `Subscriber` objects is created, backward (up the chain) to the first publisher. This is effectively hidden from you. All you can see is the outer layer of `Flux` (or `Mono`) and `Subscription`, but these intermediate operator-specific subscribers are where the real work happens.

With that knowledge, we can have a closer look at the `publishOn` and `subscribeOn` operators:

The `publishOn` Method

`publishOn` applies in the same way as any other operator, in the middle of the subscriber chain. It takes signals from upstream and replays them downstream while executing the callback on a worker from the associated `Scheduler`. Consequently, it **affects where the subsequent operators execute** (until another `publishOn` is chained in), as follows:

- Changes the execution context to one `Thread` picked by the `Scheduler`
- as per the specification, `onNext` calls happen in sequence, so this uses up a single thread
- unless they work on a specific `Scheduler`, operators after `publishOn` continue execution on that same thread

The following example uses the `publishOn` method:

```
Scheduler s = Schedulers.newParallel("parallel-scheduler", 4); ①

final Flux<String> flux = Flux
    .range(1, 2)
    .map(i -> 10 + i)  ②
    .publishOn(s)  ③
    .map(i -> "value " + i);  ④

new Thread(() -> flux.subscribe(System.out::println));  ⑤
```

① Creates a new `Scheduler` backed by four `Thread` instances.

② The first `map` runs on the anonymous thread in <5>.

③ The `publishOn` switches the whole sequence on a `Thread` picked from <1>.

④ The second `map` runs on the `Thread` from <1>.

⑤ This anonymous `Thread` is the one where the *subscription* happens. The print happens on the latest execution context, which is the one from `publishOn`.

The `subscribeOn` Method

`subscribeOn` applies to the subscription process, when the backward chain is being constructed. It is usually recommended to place it immediately after the source of data, as intermediate operators can affect the context of the execution.

However, this does not affect the behavior of subsequent calls to `publishOn` — they still switch the execution context for the part of the chain after them.

- Changes the `Thread` from which the **whole chain** of operators subscribes
- Picks one thread from the `Scheduler`

Only the closest `subscribeOn` call in the downstream chain effectively schedules subscription and request signals to the source or operators that can intercept them (`doFirst`, `doOnRequest`). Using multiple `subscribeOn` calls will introduce unnecessary Thread switches that have no value.

The following example uses the `subscribeOn` method:

```
Scheduler s = Schedulers.newParallel("parallel-scheduler", 4); ①

final Flux<String> flux = Flux
    .range(1, 2)
    .map(i -> 10 + i)  ②
    .subscribeOn(s)  ③
    .map(i -> "value " + i);  ④

new Thread(() -> flux.subscribe(System.out::println));  ⑤
```

① Creates a new `Scheduler` backed by four `Thread`.

② The first `map` runs on one of these four threads…

③ …because `subscribeOn` switches the whole sequence right from subscription time (<5>).

④ The second `map` also runs on same thread.

⑤ This anonymous `Thread` is the one where the *subscription* initially happens, but `subscribeOn` immediately shifts it to one of the four scheduler threads.

4.6. Handling Errors

For a quick look at the available operators for error handling, see the relevant operator decision tree.

In Reactive Streams, errors are terminal events. As soon as an error occurs, it stops the sequence and gets propagated down the chain of operators to the last step, the `Subscriber` you defined and its `onError` method.

Such errors should still be dealt with at the application level. For instance, you might display an error notification in a UI or send a meaningful error payload in a REST endpoint. For this reason, the subscriber's `onError` method should always be defined.

If not defined, `onError` throws an `UnsupportedOperationException`. You can further detect and triage it with the `Exceptions.isErrorCallbackNotImplemented` method.

Reactor also offers alternative means of dealing with errors in the middle of the chain, as error-handling operators. The following example shows how to do so:

```
Flux.just(1, 2, 0)
    .map(i -> "100 / " + i + " = " + (100 / i)) //this triggers an error with 0
    .onErrorReturn("Divided by zero :("); // error handling example
```

Before you learn about error-handling operators, you must keep in mind that *any error in a reactive sequence is a terminal event*. Even if an error-handling operator is used, it does not let the original sequence continue. Rather, it converts the `onError` signal into the start of a new sequence (the fallback one). In other words, it replaces the terminated sequence *upstream* of it.

Now we can consider each means of error handling one-by-one. When relevant, we make a parallel with imperative programming's `try` patterns.

Error Handling Operators

You may be familiar with several ways of dealing with exceptions in a try-catch block. Most notably, these include the following:

- Catch and return a static default value.
- Catch and execute an alternative path with a fallback method.
- Catch and dynamically compute a fallback value.
- Catch, wrap to a `BusinessException`, and re-throw.
- Catch, log an error-specific message, and re-throw.
- Use the `finally` block to clean up resources or a Java 7 "try-with-resource" construct.

All of these have equivalents in Reactor, in the form of error-handling operators. Before looking into these operators, we first want to establish a parallel between a reactive chain and a try-catch block.

When subscribing, the `onError` callback at the end of the chain is akin to a `catch` block. There, execution skips to the catch in case an `Exception` is thrown, as the following example shows:

```
Flux<String> s = Flux.range(1, 10)
    .map(v -> doSomethingDangerous(v)) ①
    .map(v -> doSecondTransform(v)); ②
s.subscribe(value -> System.out.println("RECEIVED " + value), ③
            error -> System.err.println("CAUGHT " + error) ④
);
```

① A transformation that can throw an exception is performed.

② If everything went well, a second transformation is performed.

③ Each successfully transformed value is printed out.

④ In case of an error, the sequence terminates and an error message is displayed.

The preceding example is conceptually similar to the following try-catch block:

```
try {
    for (int i = 1; i < 11; i++) {
        String v1 = doSomethingDangerous(i); ①
        String v2 = doSecondTransform(v1); ②
        System.out.println("RECEIVED " + v2);
    }
} catch (Throwable t) {
    System.err.println("CAUGHT " + t); ③
}
```

① If an exception is thrown here…

② …the rest of the loop is skipped…

③ … and the execution goes straight to here.

Now that we have established a parallel, we can look at the different error handling cases and their equivalent operators.

Static Fallback Value

The equivalent of “Catch and return a static default value” is `onErrorReturn`. The following example shows how to use it:

```
try {
  return doSomethingDangerous(10);
}
catch (Throwable error) {
  return "RECOVERED";
}
```

The following example shows the Reactor equivalent:

```
Flux.just(10)
    .map(this::doSomethingDangerous)
    .onErrorReturn("RECOVERED");
```

You also have the option of applying a `Predicate` on the exception to decide whether or not to recover, as the following example shows:

```
Flux.just(10)
    .map(this::doSomethingDangerous)
    .onErrorReturn(e -> e.getMessage().equals("boom10"), "recovered10"); ①
```

① Recover only if the message of the exception is `"boom10"`

Catch and swallow the error

If you don't even want to replace the exception with a fallback value, but instead to ignore it and only propagate elements that have been produced so far, what you want is essentially replacing the `onError` signal with an `onComplete` signal. This can be done by the `onErrorComplete` operator:

```
Flux.just(10,20,30)
    .map(this::doSomethingDangerousOn30)
    .onErrorComplete(); ①
```

① Recover by turning the `onError` into an `onComplete`

Like `onErrorReturn`, `onErrorComplete` has variants that let you filter which exceptions to fall back on, based either on the exception's class or on a `Predicate`.

Fallback Method

If you want more than a single default value and you have an alternative (safer) way of processing your data, you can use `onErrorResume`. This would be the equivalent of "Catch and execute an alternative path with a fallback method".

For example, if your nominal process is fetching data from an external and unreliable service but you also keep a local cache of the same data that *can* be a bit more out of date but is more reliable, you could do the following:

```
String v1;
try {
  v1 = callExternalService("key1");
}
catch (Throwable error) {
  v1 = getFromCache("key1");
}

String v2;
try {
  v2 = callExternalService("key2");
}
catch (Throwable error) {
  v2 = getFromCache("key2");
}
```

The following example shows the Reactor equivalent:

```
Flux.just("key1", "key2")
    .flatMap(k -> callExternalService(k) ①
        .onErrorResume(e -> getFromCache(k)) ②
    );
```

① For each key, asynchronously call the external service.

② If the external service call fails, fall back to the cache for that key. Note that we always apply the same fallback, whatever the source error, `e`, is.

Like `onErrorReturn`, `onErrorResume` has variants that let you filter which exceptions to fall back on, based either on the exception's class or on a `Predicate`. The fact that it takes a `Function` also lets you choose a different fallback sequence to switch to, depending on the error encountered. The following example shows how to do so:

```
Flux.just("timeout1", "unknown", "key2")
    .flatMap(k -> callExternalService(k)
        .onErrorResume(error -> { ①
            if (error instanceof TimeoutException) ②
                return getFromCache(k);
            else if (error instanceof UnknownKeyException)  ③
                return registerNewEntry(k, "DEFAULT");
            else
                return Flux.error(error); ④
        })
    );
```

① The function allows dynamically choosing how to continue.

② If the source times out, hit the local cache.

③ If the source says the key is unknown, create a new entry.

④ In all other cases, "re-throw".

Dynamic Fallback Value

Even if you do not have an alternative (safer) way of processing your data, you might want to compute a fallback value out of the exception you received. This would be the equivalent of "Catch and dynamically compute a fallback value".

For instance, if your return type (`MyWrapper`) has a variant dedicated to holding an exception (think `Future.complete(T success)` versus `Future.completeExceptionally(Throwable error)`), you could instantiate the error-holding variant and pass the exception.

An imperative example would look like the following:

```
try {
  Value v = erroringMethod();
  return MyWrapper.fromValue(v);
}
catch (Throwable error) {
  return MyWrapper.fromError(error);
}
```

You can do this reactively in the same way as the fallback method solution, by using `onErrorResume`, with a tiny bit of boilerplate, as follows:

```
erroringFlux.onErrorResume(error -> Mono.just( ①
        MyWrapper.fromError(error) ②
));
```

① Since you expect a `MyWrapper` representation of the error, you need to get a `Mono<MyWrapper>` for `onErrorResume`. We use `Mono.just()` for that.

② We need to compute the value out of the exception. Here, we achieved that by wrapping the exception with a relevant `MyWrapper` factory method.

Catch and Rethrow

"Catch, wrap to a `BusinessException`, and re-throw" looks like the following in the imperative world:

```
try {
  return callExternalService(k);
}
catch (Throwable error) {
  throw new BusinessException("oops, SLA exceeded", error);
}
```

In the “fallback method” example, the last line inside the `flatMap` gives us a hint at achieving the same reactively, as follows:

```
Flux.just("timeout1")
    .flatMap(k -> callExternalService(k))
    .onErrorResume(original -> Flux.error(
            new BusinessException("oops, SLA exceeded", original))
    );
```

However, there is a more straightforward way of achieving the same effect with `onErrorMap`:

```
Flux.just("timeout1")
    .flatMap(k -> callExternalService(k))
    .onErrorMap(original -> new BusinessException("oops, SLA exceeded", original));
```

Log or React on the Side

For cases where you want the error to continue propagating but still want to react to it without modifying the sequence (logging it, for instance), you can use the `doOnError` operator. This is the equivalent of "Catch, log an error-specific message, and re-throw" pattern, as the following example shows:

```
try {
  return callExternalService(k);
}
catch (RuntimeException error) {
  //make a record of the error
  log("uh oh, falling back, service failed for key " + k);
  throw error;
}
```

The `doOnError` operator, as well as all operators prefixed with `doOn` , are sometimes referred to as having a "side-effect". They let you peek inside the sequence's events without modifying them.

Like the imperative example shown earlier, the following example still propagates the error yet ensures that we at least log that the external service had a failure:

```
LongAdder failureStat = new LongAdder();
Flux<String> flux =
Flux.just("unknown")
    .flatMap(k -> callExternalService(k) ①
        .doOnError(e -> {
            failureStat.increment();
            log("uh oh, falling back, service failed for key " + k); ②
        })
③
    );
```

① The external service call that can fail…

② …is decorated with a logging and stats side-effect…

③ …after which, it still terminates with an error, unless we use an error-recovery operator here.

We can also imagine we have statistic counters to increment as a second error side-effect.

Using Resources and the Finally Block

The last parallel to draw with imperative programming is the cleaning up that can be done either by using a "Use of the `finally` block to clean up resources" or by using a "Java 7 try-with-resource

construct", both shown below:

Imperative use of finally

```
Stats stats = new Stats();
stats.startTimer();
try {
  doSomethingDangerous();
}
finally {
  stats.stopTimerAndRecordTiming();
}
```

Imperative use of try-with-resource

```
try (SomeAutoCloseable disposableInstance = new SomeAutoCloseable()) {
  return disposableInstance.toString();
}
```

Both have their Reactor equivalents: `doFinally` and `using`.

`doFinally` is about side-effects that you want to be executed whenever the sequence terminates (with `onComplete` or `onError`) or is cancelled. It gives you a hint as to what kind of termination triggered the side-effect. The following example shows how to use `doFinally`:

Reactive finally: `doFinally()`

```
Stats stats = new Stats();
LongAdder statsCancel = new LongAdder();

Flux<String> flux =
Flux.just("foo", "bar")
    .doOnSubscribe(s -> stats.startTimer())
    .doFinally(type -> { ①
        stats.stopTimerAndRecordTiming();②
        if (type == SignalType.CANCEL) ③
          statsCancel.increment();
    })
    .take(1); ④
```

① `doFinally` consumes a `SignalType` for the type of termination.

② Similarly to `finally` blocks, we always record the timing.

③ Here we also increment statistics in case of cancellation only.

④ `take(1)` requests exactly 1 from upstream, and cancels after one item is emitted.

On the other hand, `using` handles the case where a `Flux` is derived from a resource and that resource must be acted upon whenever processing is done. In the following example, we replace the `AutoCloseable` interface of "try-with-resource" with a `Disposable`:

The Disposable resource

```
AtomicBoolean isDisposed = new AtomicBoolean();
Disposable disposableInstance = new Disposable() {
    @Override
    public void dispose() {
        isDisposed.set(true); ④
    }

    @Override
    public String toString() {
        return "DISPOSABLE";
    }
};
```

Now we can do the reactive equivalent of "try-with-resource" on it, which looks like the following:

Reactive try-with-resource: `using()`

```
Flux<String> flux =
Flux.using(
        () -> disposableInstance, ①
        disposable -> Flux.just(disposable.toString()), ②
        Disposable::dispose ③
);
```

① The first lambda generates the resource. Here, we return our mock `Disposable`.

② The second lambda processes the resource, returning a `Flux<T>`.

③ The third lambda is called when the `Flux` from <2> terminates or is cancelled, to clean up resources.

④ After subscription and execution of the sequence, the `isDisposed` atomic boolean becomes `true`.

Demonstrating the Terminal Aspect of `onError`

In order to demonstrate that all these operators cause the upstream original sequence to terminate when an error happens, we can use a more visual example with a `Flux.interval`. The `interval` operator ticks every x units of time with an increasing `Long` value. The following example uses an `interval` operator:

```
Flux<String> flux =
Flux.interval(Duration.ofMillis(250))
    .map(input -> {
        if (input < 3) return "tick " + input;
        throw new RuntimeException("boom");
    })
    .onErrorReturn("Uh oh");

flux.subscribe(System.out::println);
Thread.sleep(2100); ①
```

① Note that `interval` executes on a **timer** `Scheduler` by default. If we want to run that example in a main class, we would need to add a `sleep` call here so that the application does not exit immediately without any value being produced.

The preceding example prints out one line every 250ms, as follows:

```
tick 0
tick 1
tick 2
Uh oh
```

Even with one extra second of runtime, no more tick comes in from the `interval`. The sequence was indeed terminated by the error.

Retrying

There is another operator of interest with regards to error handling, and you might be tempted to use it in the case described in the previous section. `retry`, as its name indicates, lets you retry an error-producing sequence.

The thing to keep in mind is that it works by **re-subscribing** to the upstream `Flux`. This is really a different sequence, and the original one is still terminated. To verify that, we can re-use the previous example and append a `retry(1)` to retry once instead of using `onErrorReturn`. The following example shows how to do so:

```
Flux.interval(Duration.ofMillis(250))
    .map(input -> {
        if (input < 3) return "tick " + input;
        throw new RuntimeException("boom");
    })
    .retry(1)
    .elapsed() ①
    .subscribe(System.out::println, System.err::println); ②

Thread.sleep(2100); ③
```

① `elapsed` associates each value with the duration since previous value was emitted.

② We also want to see when there is an `onError`.

③ Ensure we have enough time for our 4x2 ticks.

The preceding example produces the following output:

```
259,tick 0
249,tick 1
251,tick 2
506,tick 0 ①
248,tick 1
253,tick 2
java.lang.RuntimeException: boom
```

① A new `interval` started, from tick 0. The additional 250ms duration is coming from the 4th tick, the one that causes the exception and subsequent retry.

As you can see from the preceding example, `retry(1)` merely re-subscribed to the original `interval` once, restarting the tick from 0. The second time around, since the exception still occurs, it gives up and propagates the error downstream.

There is a more advanced version of `retry` (called `retryWhen`) that uses a "companion" `Flux` to tell whether or not a particular failure should retry. This companion `Flux` is created by the operator but decorated by the user, in order to customize the retry condition.

The companion `Flux` is a `Flux<RetrySignal>` that gets passed to a `Retry` strategy/function, supplied as the sole parameter of `retryWhen`. As the user, you define that function and make it return a new `Publisher<?>`. The `Retry` class is an abstract class, but it offers a factory method if you want to transform the companion with a simple lambda (`Retry.from(Function)`).

Retry cycles go as follows:

1. Each time an error happens (giving potential for a retry), a `RetrySignal` is emitted into the companion `Flux`, which has been decorated by your function. Having a `Flux` here gives a bird eye's view of all the attempts so far. The `RetrySignal` gives access to the error as well as metadata around it.
2. If the companion `Flux` emits a value, a retry happens.
3. If the companion `Flux` completes, the error is swallowed, the retry cycle stops, and the resulting sequence completes, too.
4. If the companion `Flux` produces an error (`e`), the retry cycle stops and the resulting sequence errors with `e`.

The distinction between the previous two cases is important. Simply completing the companion would effectively swallow an error. Consider the following way of emulating `retry(3)` by using `retryWhen`:

```
Flux<String> flux = Flux
    .<String>error(new IllegalArgumentException()) ①
    .doOnError(System.out::println) ②
    .retryWhen(Retry.from(companion -> ③
        companion.take(3))); ④
```

① This continuously produces errors, calling for retry attempts.

② `doOnError` before the retry lets us log and see all failures.

③ The `Retry` is adapted from a very simple `Function` lambda

④ Here, we consider the first three errors as retry-able (`take(3)`) and then give up.

In effect, the preceding example results in an empty `Flux`, but it completes successfully. Since `retry(3)` on the same `Flux` would have terminated with the latest error, this `retryWhen` example is not exactly the same as a `retry(3)`.

Getting to the same behavior involves a few additional tricks:

```
AtomicInteger errorCount = new AtomicInteger();
Flux<String> flux =
        Flux.<String>error(new IllegalArgumentException())
                .doOnError(e -> errorCount.incrementAndGet())
                .retryWhen(Retry.from(companion -> ①
                        companion.map(rs -> { ②
                            if (rs.totalRetries() < 3) return rs.totalRetries(); ③
                            else throw Exceptions.propagate(rs.failure()); ④
                        })
                ));
```

① We customize `Retry` by adapting from a `Function` lambda rather than providing a concrete class

② The companion emits `RetrySignal` objects, which bear number of retries so far and last failure

③ To allow for three retries, we consider indexes < 3 and return a value to emit (here we simply return the index).

④ In order to terminate the sequence in error, we throw the original exception after these three retries.

One can use the builders exposed in `Retry` to achieve the same in a more fluent manner, as well as more finely tuned retry strategies. For example: `errorFlux.retryWhen(Retry.max(3));`.

You can use similar code to implement an “exponential backoff and retry” pattern, as shown in the FAQ.

The core-provided `Retry` helpers, `RetrySpec` and `RetryBackoffSpec`, both allow advanced customizations like:

- setting the `filter(Predicate)` for the exceptions that can trigger a retry
- modifying such a previously set filter through `modifyErrorFilter(Function)`
- triggering a side effect like logging around the retry trigger (ie for backoff before and after the delay), provided the retry is validated (`doBeforeRetry()` and `doAfterRetry()` are additive)
- triggering an asynchronous `Mono<Void>` around the retry trigger, which allows to add asynchronous behavior on top of the base delay but thus further delay the trigger (`doBeforeRetryAsync` and `doAfterRetryAsync` are additive)
- customizing the exception in case the maximum number of attempts has been reached, through `onRetryExhaustedThrow(BiFunction)`. By default, `Exceptions.retryExhausted(…)` is used, which can be distinguished with `Exceptions.isRetryExhausted(Throwable)`
- activating the handling of *transient errors* (see below)

Retrying with transient errors

Some long-lived sources may see sporadic bursts of errors followed by longer periods of time during which all is running smoothly. This documentation refers to this pattern of errors as *transient errors*.

In such cases, it would be desirable to deal with each burst in isolation, so that the next burst doesn't inherit the retry state from the previous one. For instance, with an exponential backoff strategy each subsequent burst should delay retry attempts starting from the minimum backoff `Duration` instead of an ever-growing one.

The `RetrySignal` interface, which represents `retryWhen` state, has a `totalRetriesInARow()` value which can be used for this. Instead of the usual monotonically-increasing `totalRetries()` index, this secondary index is reset to 0 each time an error is recovered from by the retry (ie. when a retry attempt results in an incoming `onNext` instead of an `onError` again).

When setting the `transientErrors(boolean)` configuration parameter to `true` in the `RetrySpec` or `RetryBackoffSpec`, the resulting strategy makes use of that `totalRetriesInARow()` index, effectively dealing with *transient errors*. These specs compute the retry pattern from the index, so in effect all other configuration parameters of the spec apply to each burst of error independently.

```
AtomicInteger errorCount = new AtomicInteger(); ①
Flux<Integer> transientFlux = httpRequest.get() ②
        .doOnError(e -> errorCount.incrementAndGet());

transientFlux.retryWhen(Retry.max(2).transientErrors(true))  ③
             .blockLast();
assertThat(errorCount).hasValue(6); ④
```

① We will count the number of errors in the retried sequence for illustration.

② We assume a http request source, eg. a streaming endpoint that will sometimes fail two times in a row, then recover.

③ We use `retryWhen` on that source, configured for at most 2 retry attempts, but in `transientErrors` mode.

④ At the end, a valid response is achieved and the `transientFlux` successfully completes after `6` attempts have been registered in `errorCount`.

Without the `transientErrors(true)`, the configured maximum attempt of `2` would be exceeded by the second burst and the whole sequence would have ultimately failed.

If you want to locally try this without an actual http remote endpoint, you can implement a pseudo `httpRequest` method as a `Supplier`, as follows:

```
final AtomicInteger transientHelper = new AtomicInteger();
Supplier<Flux<Integer>> httpRequest = () ->
    Flux.generate(sink -> { ①
        int i = transientHelper.getAndIncrement();
        if (i == 10) { ②
            sink.next(i);
            sink.complete();
        }
        else if (i % 3 == 0) { ③
            sink.next(i);
        }
        else {
            sink.error(new IllegalStateException("Transient error
at " + i)); ④
        }
    });
```

① We `generate` a source that has bursts of errors.

② It will successfully complete when the counter reaches 10.

③ If the `transientHelper` atomic is at a multiple of `3`, we emit `onNext` and thus end the current burst.

④ In other cases we emit an `onError`. That's 2 out of 3 times, so bursts of 2 `onError` interrupted by 1 `onNext`.

Handling Exceptions in Operators or Functions

In general, all operators can themselves contain code that potentially trigger an exception or calls to a user-defined callback that can similarly fail, so they all contain some form of error handling.

As a rule of thumb, an unchecked exception is always propagated through `onError`. For instance, throwing a `RuntimeException` inside a `map` function translates to an `onError` event, as the following code shows:

```
Flux.just("foo")
    .map(s -> { throw new IllegalArgumentException(s); })
    .subscribe(v -> System.out.println("GOT VALUE"),
               e -> System.out.println("ERROR: " + e));
```

The preceding code prints out the following:

```
ERROR: java.lang.IllegalArgumentException: foo
```

You can tune the `Exception` before it is passed to `onError`, through the use of a hook.

Reactor, however, defines a set of exceptions (such as `OutOfMemoryError`) that are always deemed to be fatal. See the `Exceptions.throwIfFatal` method. These errors mean that Reactor cannot keep operating and are thrown rather than propagated.

Internally, there are also cases where an unchecked exception still cannot be propagated (most notably during the subscribe and request phases), due to concurrency races that could lead to double `onError` or `onComplete` conditions. When these races happen, the error that cannot be propagated is "dropped". These cases can still be managed to some extent by using customizable hooks. See Dropping Hooks.

You may ask: "What about checked exceptions?"

If, for example, you need to call some method that declares it `throws` exceptions, you still have to deal with those exceptions in a `try-catch` block. You have several options, though:

1. Catch the exception and recover from it. The sequence continues normally.
2. Catch the exception, wrap it into an *unchecked* exception, and then throw it (interrupting the sequence). The `Exceptions` utility class can help you with that (we get to that next).
3. If you need to return a `Flux` (for example, you are in a `flatMap`), wrap the exception in an error-producing `Flux`, as follows: `return Flux.error(checkedException)`. (The sequence also terminates.)

Reactor has an `Exceptions` utility class that you can use to ensure that exceptions are wrapped only if they are checked exceptions:

- Use the `Exceptions.propagate` method to wrap exceptions, if necessary. It also calls `throwIfFatal` first and does not wrap `RuntimeException`.
- Use the `Exceptions.unwrap` method to get the original unwrapped exception (going back to the root cause of a hierarchy of reactor-specific exceptions).

Consider the following example of a `map` that uses a conversion method that can throw an `IOException`:

```
public String convert(int i) throws IOException {
    if (i > 3) {
        throw new IOException("boom " + i);
    }
    return "OK " + i;
}
```

Now imagine that you want to use that method in a `map`. You must now explicitly catch the exception, and your map function cannot re-throw it. So you can propagate it to the map's `onError` method as a `RuntimeException`, as follows:

```
Flux<String> converted = Flux
    .range(1, 10)
    .map(i -> {
        try { return convert(i); }
        catch (IOException e) { throw Exceptions.propagate(e); }
    });
```

Later on, when subscribing to the preceding `Flux` and reacting to errors (such as in the UI), you could revert back to the original exception if you want to do something special for IOExceptions. The following example shows how to do so:

```
converted.subscribe(
    v -> System.out.println("RECEIVED: " + v),
    e -> {
        if (Exceptions.unwrap(e) instanceof IOException) {
            System.out.println("Something bad happened with I/O");
        } else {
            System.out.println("Something bad happened");
        }
    }
);
```

4.7. Sinks

In Reactor a sink is a class that allows safe manual triggering of signals in a standalone fashion, creating a `Publisher`-like structure capable of dealing with multiple `Subscriber` (with the exception of `unicast()` flavors).

Before `3.5.0`, there was also a set of `Processor` implementations which has been phased out.

Safely Produce from Multiple Threads by Using `Sinks.One` and `Sinks.Many`

Default flavors of `Sinks` exposed by reactor-core ensure that multi-threaded usage is detected and cannot lead to spec violations or undefined behavior from the perspective of downstream subscribers. When using the `tryEmit*` API, parallel calls fail fast. When using the `emit*` API, the

provided EmissionFailureHandler may allow to retry on contention (eg. busy looping), otherwise the sink will terminate with an error.

This is an improvement over Processor.onNext, which must be synchronized externally or lead to undefined behavior from the perspective of the downstream subscribers.

Processors are a special kind of Publisher that are also a Subscriber. They were originally intended as a possible representation of an intermediate step that could then be shared between Reactive Streams implementations. In Reactor however, such steps are rather represented by operators that are Publisher.

A common mistake when coming across a Processor for the first time is the temptation to directly call the exposed onNext, onComplete and onError methods from the Subscriber interface.

Such manual calls should be made with care, especially regarding external synchronization of calls with respect to the Reactive Streams specification. Processors are actually probably marginally useful, unless one comes across a Reactive Streams based API that requires a Subscriber to be passed, rather than exposing a Publisher.

Sinks are usually a better alternative.

The Sinks builder provide a guided API to the main supported producer types. You will recognize some of the behavior found in Flux such as onBackpressureBuffer.

```
Sinks.Many<Integer> replaySink = Sinks.many().replay().all();
```

Multiple producer threads may concurrently generate data on the sink by doing the following:

```
//thread1
replaySink.emitNext(1, EmitFailureHandler.FAIL_FAST);

//thread2, later
replaySink.emitNext(2, EmitFailureHandler.FAIL_FAST);

//thread3, concurrently with thread 2
//would retry emitting for 2 seconds and fail with EmissionException if unsuccessful
replaySink.emitNext(3, EmitFailureHandler.busyLooping(Duration.ofSeconds(2)));

//thread3, concurrently with thread 2
//would return FAIL_NON_SERIALIZED
EmitResult result = replaySink.tryEmitNext(4);
```

When using the busyLooping, be aware that returned instances of EmitFailureHandler can not be reused, e.g., it should be one call of busyLooping per emitNext. Also, it is recommended to use a timeout above 100ms since smaller

> values don't make practical sense.

The `Sinks.Many` can be presented to downstream consumers as a `Flux`, like in the below example:

```
Flux<Integer> fluxView = replaySink.asFlux();
fluxView
    .takeWhile(i -> i < 10)
    .log()
    .blockLast();
```

Similarly, the `Sinks.Empty` and `Sinks.One` flavors can be viewed as a `Mono` with the `asMono()` method.

The `Sinks` categories are:

1. `many().multicast()`: a sink that will transmit only newly pushed data to its subscribers, honoring their backpressure (newly pushed as in "after the subscriber's subscription").
2. `many().unicast()`: same as above, with the twist that data pushed before the first subscriber registers is buffered.
3. `many().replay()`: a sink that will replay a specified history size of pushed data to new subscribers then continue pushing new data live.
4. `one()`: a sink that will play a single element to its subscribers
5. `empty()`: a sink that will play a terminal signal only to its subscribers (error or complete), but can still be viewed as a `Mono<T>` (notice the generic type `<T>`).

Overview of Available Sinks

Sinks.many().unicast().onBackpressureBuffer(args?)

A unicast `Sinks.Many` can deal with backpressure by using an internal buffer. The trade-off is that it can have *at most one* `Subscriber`.

The basic unicast sink is created via `Sinks.many().unicast().onBackpressureBuffer()`. But there are a few additional `unicast` static factory methods in `Sinks.many().unicast()` allowing finer tuning.

For instance, by default, it is unbounded: if you push any amount of data through it while its `Subscriber` has not yet requested data, it buffers all of the data. You can change this by providing a custom `Queue` implementation for the internal buffering in the `Sinks.many().unicast().onBackpressureBuffer(Queue)` factory method. If that queue is bounded, the sink could reject the push of a value when the buffer is full and not enough requests from downstream have been received.

Sinks.many().multicast().onBackpressureBuffer(args?)

A multicast `Sinks.Many` can emit to several subscribers while honoring backpressure for each of its subscribers. Subscribers receive only the signals pushed through the sink after they have subscribed.

The basic multicast sink is created via `Sinks.many().multicast().onBackpressureBuffer()`.

By default, if all of its subscribers are cancelled (which basically means they have all un-subscribed), it clears its internal buffer and stops accepting new subscribers. You can tune this by using the `autoCancel` parameter in the `multicast` static factory methods under `Sinks.many().multicast()`.

Sinks.many().multicast().directAllOrNothing()

A multicast `Sinks.Many` with a simplistic handling of backpressure: if **any** of the subscribers is too slow (has zero demand), the `onNext` is dropped for **all** subscribers.

However, the slow subscribers are not terminated and once the slow subscribers have started requesting again, all will resume receiving elements pushed from there on.

Once the `Sinks.Many` has terminated (usually through its `emitError(Throwable)` or `emitComplete()` methods being called), it lets more subscribers subscribe but replays the termination signal to them immediately.

Sinks.many().multicast().directBestEffort()

A multicast `Sinks.Many` with a best effort handling of backpressure: if a subscriber is too slow (has zero demand), the `onNext` is dropped for **this slow subscriber only**.

However, the slow subscribers are not terminated and once they have started requesting again they will resume receiving newly pushed elements.

Once the `Sinks.Many` has terminated (usually through its `emitError(Throwable)` or `emitComplete()` methods being called), it lets more subscribers subscribe but replays the termination signal to them immediately.

Sinks.many().replay()

A replay `Sinks.Many` caches emitted elements and replays them to late subscribers.

It can be created in multiple configurations:

- Caching a limited history (`Sinks.many().replay().limit(int)`) or an unbounded history (`Sinks.many().replay().all()`).
- Caching a time-based replay window (`Sinks.many().replay().limit(Duration)`).
- Caching a combination of history size and time window (`Sinks.many().replay().limit(int, Duration)`).

Additional overloads for fine tuning of the above can also be found under `Sinks.many().replay()`, as well as a variant that allows caching of a single element (`latest()` and `latestOrDefault(T)`).

Sinks.unsafe().many()

Advanced users and operators builders might want to consider using `Sinks.unsafe().many()` which will provide the same `Sinks.Many` factories *without* the extra producer thread safety. As a result

there will be less overhead per sink, since thread-safe sinks have to detect multi-threaded access.

Library developers should not expose unsafe sinks but can use them internally in a controlled calling environment where they can ensure external synchronization of the calls that lead to `onNext`, `onComplete` and `onError` signals, in respect of the Reactive Streams specification.

Sinks.one()

This method directly construct a simple instance of `Sinks.One<T>`. This flavor of `Sinks` is viewable as a `Mono` (through its `asMono()` view method), and has slightly different `emit` methods to better convey this Mono-like semantics:

- `emitValue(T value)` generates an `onNext(value)` signal and - in most implementations - will also trigger an implicit `onComplete()`
- `emitEmpty()` generates an isolated `onComplete()` signal, intended as generating the equivalent of an empty `Mono`
- `emitError(Throwable t)` generates an `onError(t)` signal

`Sinks.one()` accepts *one* call of any of these methods, effectively generating a `Mono` that either completed with a value, completed empty or failed.

Sinks.empty()

This method directly constructs a simple instance of `Sinks.Empty<T>`. This flavor of `Sinks` is like `Sinks.One<T>`, except it doesn't offer the `emitValue` method.

As a result, it can only generates a `Mono` that completes empty or fails.

The sink is still typed with a generic `<T>` despite being unable to trigger an `onNext`, because it allows easy composition and inclusion in chains of operators that require a specific type.

Chapter 5. Kotlin support

Kotlin is a statically-typed language targeting the JVM (and other platforms), which allows writing concise and elegant code while providing very good interoperability with existing libraries written in Java.

This section describes Reactor's support for Kotlin.

Requirements

Reactor supports Kotlin 1.1+ and requires `kotlin-stdlib` (or one of its `kotlin-stdlib-jdk7` or `kotlin-stdlib-jdk8` variants).

Extensions

As of `Dysprosium-M1` (ie. `reactor-core 3.3.0.M1`), Kotlin extensions are moved to a dedicated `reactor-kotlin-extensions` module with new package names that start with `reactor.kotlin` instead of simply `reactor`.

As a consequence, Kotlin extensions in `reactor-core` module are deprecated. The new dependency's groupId and artifactId are:

```
io.projectreactor.kotlin:reactor-kotlin-extensions
```

Thanks to its great Java interoperability and to Kotlin extensions, Reactor Kotlin APIs leverage regular Java APIs and are additionally enhanced by a few Kotlin-specific APIs that are available out of the box within Reactor artifacts.

Keep in mind that Kotlin extensions need to be imported to be used. This means for example that the `Throwable.toFlux` Kotlin extension is available only if `import reactor.kotlin.core.publisher.toFlux` is imported. That said, similar to static imports, an IDE should automatically suggest the import in most cases.

For example, Kotlin reified type parameters provide a workaround for JVM generics type erasure, and Reactor provides some extensions to take advantage of this feature.

The following table compares Reactor with Java against Reactor with Kotlin and extensions:

Java	Kotlin with extensions
`Mono.just("foo")`	`"foo".toMono()`
`Flux.fromIterable(list)`	`list.toFlux()`
`Mono.error(new RuntimeException())`	`RuntimeException().toMono()`
`Flux.error(new RuntimeException())`	`RuntimeException().toFlux()`
`flux.ofType(Foo.class)`	`flux.ofType<Foo>()` or `flux.ofType(Foo::class)`
`StepVerifier.create(flux).verifyComplete()`	`flux.test().verifyComplete()`

The Reactor KDoc API lists and documents all the available Kotlin extensions.

Null Safety

One of Kotlin's key features is null safety, which cleanly deals with `null` values at compile time rather than bumping into the famous `NullPointerException` at runtime. This makes applications safer through nullability declarations and expressive "value or no value" semantics without paying the cost of wrappers such as `Optional`. (Kotlin allows using functional constructs with nullable values. See this comprehensive guide to Kotlin null-safety.)

Although Java does not let one express null safety in its type-system, Reactor now provides null safety of the whole Reactor API through tooling-friendly annotations declared in the `reactor.util.annotation` package. By default, types from Java APIs used in Kotlin are recognized as platform types for which null-checks are relaxed. Kotlin support for JSR 305 annotations and Reactor nullability annotations provide null-safety for the whole Reactor API to Kotlin developers, with the advantage of dealing with `null`-related issues at compile time.

You can configure the JSR 305 checks by adding the `-Xjsr305` compiler flag with the following options: `-Xjsr305={strict|warn|ignore}`.

For kotlin versions 1.1.50+, the default behavior is the same as `-Xjsr305=warn`. The `strict` value is required to have the Reactor API full null-safety taken into account but should be considered experimental, since the Reactor API nullability declaration could evolve even between minor releases, as more checks may be added in the future).

Nullability for generic type arguments, variable arguments, and array elements is not supported yet, but itshould be in an upcoming release. See this dicussion for up-to-date information.

Chapter 6. Testing

Whether you have written a simple chain of Reactor operators or your own operator, automated testing is always a good idea.

Reactor comes with a few elements dedicated to testing, gathered into their own artifact: `reactor-test`. You can find that project on Github, inside of the `reactor-core` repository.

To use it in your tests, you must add it as a test dependency. The following example shows how to add `reactor-test` as a dependency in Maven:

reactor-test in Maven, in `<dependencies>`

```
<dependency>
    <groupId>io.projectreactor</groupId>
    <artifactId>reactor-test</artifactId>
    <scope>test</scope>
①
</dependency>
```

① If you use the BOM, you do not need to specify a `<version>`.

The following example shows how to add `reactor-test` as a dependency in Gradle:

reactor-test in Gradle, amend the `dependencies` *block*

```
dependencies {
   testCompile 'io.projectreactor:reactor-test'
}
```

The three main uses of `reactor-test` are as follows:

- Testing that a sequence follows a given scenario, step-by-step, with `StepVerifier`.
- Producing data in order to test the behavior of downstream operators (including you own operators) with `TestPublisher`.
- In sequences that can go through several alternative `Publisher` (for example, a chain that uses `switchIfEmpty`, probing such a `Publisher` to ensure it was used (that is, subscribed to).

Testing a Scenario with `StepVerifier`

The most common case for testing a Reactor sequence is to have a `Flux` or a `Mono` defined in your code (for example, it might be returned by a method) and to want to test how it behaves when subscribed to.

This situation translates well to defining a “test scenario,” where you define your expectations in terms of events, step-by-step. You can ask and answer questions such as the following:

- What is the next expected event?

- Do you expect the `Flux` to emit a particular value?
- Or maybe to do nothing for the next 300ms?

You can express all of that through the `StepVerifier` API.

For instance, you could have the following utility method in your codebase that decorates a `Flux`:

```
public <T> Flux<T> appendBoomError(Flux<T> source) {
  return source.concatWith(Mono.error(new IllegalArgumentException("boom")));
}
```

In order to test it, you want to verify the following scenario:

> I expect this `Flux` to first emit `thing1`, then emit `thing2`, and then **produce an error** with the message, `boom`. Subscribe and **verify** these expectations.

In the `StepVerifier` API, this translates to the following test:

```
@Test
public void testAppendBoomError() {
  Flux<String> source = Flux.just("thing1", "thing2"); ①

  StepVerifier.create( ②
    appendBoomError(source)) ③
    .expectNext("thing1") ④
    .expectNext("thing2")
    .expectErrorMessage("boom") ⑤
    .verify(); ⑥
}
```

① Since our method needs a source `Flux`, define a simple one for testing purposes.

② Create a `StepVerifier` builder that wraps and verifies a `Flux`.

③ Pass the `Flux` to be tested (the result of calling our utility method).

④ The first signal we expect to happen upon subscription is an `onNext`, with a value of `thing1`.

⑤ The last signal we expect to happen is a termination of the sequence with an `onError`. The exception should have `boom` as a message.

⑥ It is important to trigger the test by calling `verify()`.

The API is a builder. You start by creating a `StepVerifier` and passing the sequence to be tested. This offers a choice of methods that let you:

- Express expectations about the next signals to occur. If any other signal is received (or the content of the signal does not match the expectation), the whole test fails with a meaningful `AssertionError`. For example, you might use `expectNext(T…)` and `expectNextCount(long)`.
- Consume the next signal. This is used when you want to skip part of the sequence or when you

want to apply a custom `assertion` on the content of the signal (for example, to check that there is an `onNext` event and assert that the emitted item is a list of size 5). For example, you might use `consumeNextWith(Consumer<T>)`.

- Take miscellaneous actions such as pausing or running arbitrary code. For example, if you want to manipulate a test-specific state or context. To that effect, you might use `thenAwait(Duration)` and `then(Runnable)`.

For terminal events, the corresponding expectation methods (`expectComplete()` and `expectError()` and all their variants) switch to an API where you cannot express expectations anymore. In that last step, all you can do is perform some additional configuration on the `StepVerifier` and then trigger the verification, often with `verify()` or one of its variants.

What happens at this point is that the `StepVerifier` subscribes to the tested `Flux` or `Mono` and plays the sequence, comparing each new signal with the next step in the scenario. As long as these match, the test is considered a success. As soon as there is a discrepancy, an `AssertionError` is thrown.

Remember the `verify()` step, which triggers the verification. To help, the API includes a few shortcut methods that combine the terminal expectations with a call to `verify()`: `verifyComplete()`, `verifyError()`, `verifyErrorMessage(String)`, and others.

Note that, if one of the lambda-based expectations throws an `AssertionError`, it is reported as is, failing the test. This is useful for custom assertions.

By default, the `verify()` method and derived shortcut methods (`verifyThenAssertThat`, `verifyComplete()`, and so on) have no timeout. They can block indefinitely. You can use `StepVerifier.setDefaultTimeout(Duration)` to globally set a timeout for these methods, or specify one on a per-call basis with `verify(Duration)`.

Better Identifying Test Failures

`StepVerifier` provides two options to better identify exactly which expectation step caused a test to fail:

- `as(String)`: Used after most `expect*` methods to give a description to the preceding expectation. If the expectation fails, its error message contains the description. Terminal expectations and `verify` cannot be described that way.
- `StepVerifierOptions.create().scenarioName(String)`: By using `StepVerifierOptions` to create your `StepVerifier`, you can use the `scenarioName` method to give the whole scenario a name, which is also used in assertion error messages.

Note that, in both cases, the use of the description or name in messages is only guaranteed for `StepVerifier` methods that produce their own `AssertionError` (for example, throwing an exception manually or through an assertion library in `assertNext` does not add the description or name to the error's message).

Manipulating Time

You can use `StepVerifier` with time-based operators to avoid long run times for corresponding tests. You can do so through the `StepVerifier.withVirtualTime` builder.

It looks like the following example:

```
StepVerifier.withVirtualTime(() -> Mono.delay(Duration.ofDays(1)))
//... continue expectations here
```

This virtual time feature plugs in a custom `Scheduler` in Reactor's `Schedulers` factory. Since these timed operators usually use the default `Schedulers.parallel()` scheduler, replacing it with a `VirtualTimeScheduler` does the trick. However, an important prerequisite is that the operator be instantiated after the virtual time scheduler has been activated.

To increase the chances that this happens correctly, the `StepVerifier` does not take a simple `Flux` as input. `withVirtualTime` takes a `Supplier`, which guides you into lazily creating the instance of the tested flux *after* having done the scheduler set up.

Take extra care to ensure the `Supplier<Publisher<T>>` can be used in a lazy fashion. Otherwise, virtual time is not guaranteed. Especially avoid instantiating the `Flux` earlier in the test code and having the `Supplier` return that variable. Instead, always instantiate the `Flux` inside the lambda.

There are two expectation methods that deal with time, and they are both valid with or without virtual time:

- `thenAwait(Duration)`: Pauses the evaluation of steps (allowing a few signals to occur or delays to run out).
- `expectNoEvent(Duration)`: Also lets the sequence play out for a given duration but fails the test if *any* signal occurs during that time.

Both methods pause the thread for the given duration in classic mode and advance the virtual clock instead in virtual mode.

`expectNoEvent` also considers the `subscription` as an event. If you use it as a first step, it usually fails because the subscription signal is detected. Use `expectSubscription().expectNoEvent(duration)` instead.

In order to quickly evaluate the behavior of our `Mono.delay` above, we can finish writing our code as follows:

```
StepVerifier.withVirtualTime(() -> Mono.delay(Duration.ofDays(1)))
    .expectSubscription() ①
    .expectNoEvent(Duration.ofDays(1)) ②
    .expectNext(0L) ③
    .verifyComplete(); ④
```

① See the preceding tip.

② Expect nothing to happen for a full day.

③ Then expect a delay that emits `0`.

④ Then expect completion (and trigger the verification).

We could have used `thenAwait(Duration.ofDays(1))` above, but `expectNoEvent` has the benefit of guaranteeing that nothing happened earlier than it should have.

Note that `verify()` returns a `Duration` value. This is the real-time duration of the entire test.

Virtual time is not a silver bullet. All `Schedulers` are replaced with the same `VirtualTimeScheduler`. In some cases, you can lock the verification process because the virtual clock has not moved forward before an expectation is expressed, resulting in the expectation waiting on data that can only be produced by advancing time. In most cases, you need to advance the virtual clock for sequences to emit. Virtual time also gets very limited with infinite sequences, which might hog the thread on which both the sequence and its verification run.

Performing Post-execution Assertions with `StepVerifier`

After having described the final expectation of your scenario, you can switch to a complementary assertion API instead of triggering `verify()`. To do so, use `verifyThenAssertThat()` instead.

`verifyThenAssertThat()` returns a `StepVerifier.Assertions` object, which you can use to assert a few elements of state once the whole scenario has played out successfully (because it also calls `verify()`). Typical (albeit advanced) usage is to capture elements that have been dropped by some operator and assert them (see the section on Hooks).

Testing the `Context`

For more information about the `Context`, see Adding a Context to a Reactive Sequence.

`StepVerifier` comes with a couple of expectations around the propagation of a `Context`:

- `expectAccessibleContext`: Returns a `ContextExpectations` object that you can use to set up expectations on the propagated `Context`. Be sure to call `then()` to return to the set of sequence expectations.
- `expectNoAccessibleContext`: Sets up an expectation that NO `Context` can be propagated up the chain of operators under test. This most likely occurs when the `Publisher` under test is not a

Reactor one or does not have any operator that can propagate the `Context` (for example, a generator source).

Additionally, you can associate a test-specific initial `Context` to a `StepVerifier` by using `StepVerifierOptions` to create the verifier.

These features are demonstrated in the following snippet:

```
StepVerifier.create(Mono.just(1).map(i -> i + 10),
                StepVerifierOptions.create().withInitialContext(Context.of("thing1",
"thing2"))) ①
                    .expectAccessibleContext() ②
                    .contains("thing1", "thing2") ③
                    .then() ④
                    .expectNext(11)
                    .verifyComplete(); ⑤
```

① Create the `StepVerifier` by using `StepVerifierOptions` and pass in an initial `Context`

② Start setting up expectations about `Context` propagation. This alone ensures that a `Context` was propagated.

③ An example of a `Context`-specific expectation. It must contain value "thing2" for key "thing1".

④ We `then()` switch back to setting up normal expectations on the data.

⑤ Let us not forget to `verify()` the whole set of expectations.

Manually Emitting with `TestPublisher`

For more advanced test cases, it might be useful to have complete mastery over the source of data, to trigger finely chosen signals that closely match the particular situation you want to test.

Another situation is when you have implemented your own operator and you want to verify how it behaves with regards to the Reactive Streams specification, especially if its source is not well behaved.

For both cases, `reactor-test` offers the `TestPublisher` class. This is a `Publisher<T>` that lets you programmatically trigger various signals:

- `next(T)` and `next(T, T…)` triggers 1-n `onNext` signals.
- `emit(T…)` triggers 1-n `onNext` signals and does `complete()`.
- `complete()` terminates with an `onComplete` signal.
- `error(Throwable)` terminates with an `onError` signal.

You can get a well behaved `TestPublisher` through the `create` factory method. Also, you can create a misbehaving `TestPublisher` by using the `createNonCompliant` factory method. The latter takes a value or multiple values from the `TestPublisher.Violation` enum. The values define which parts of the specification the publisher can overlook. These enum values include:

- `REQUEST_OVERFLOW`: Allows `next` calls to be made despite an insufficient request, without triggering an `IllegalStateException`.
- `ALLOW_NULL`: Allows `next` calls to be made with a `null` value without triggering a `NullPointerException`.
- `CLEANUP_ON_TERMINATE`: Allows termination signals to be sent several times in a row. This includes `complete()`, `error()`, and `emit()`.
- `DEFER_CANCELLATION`: Allows the `TestPublisher` to ignore cancellation signals and continue emitting signals as if the cancellation lost the race against said signals.

Finally, the `TestPublisher` keeps track of internal state after subscription, which can be asserted through its various `assert*` methods.

You can use it as a `Flux` or `Mono` by using the conversion methods, `flux()` and `mono()`.

Checking the Execution Path with `PublisherProbe`

When building complex chains of operators, you could come across cases where there are several possible execution paths, materialized by distinct sub-sequences.

Most of the time, these sub-sequences produce a specific-enough `onNext` signal that you can assert that it was executed by looking at the end result.

For instance, consider the following method, which builds a chain of operators from a source and uses a `switchIfEmpty` to fall back to a particular alternative if the source is empty:

```
public Flux<String> processOrFallback(Mono<String> source, Publisher<String> fallback)
{
    return source
            .flatMapMany(phrase -> Flux.fromArray(phrase.split("\\s+")))
            .switchIfEmpty(fallback);
}
```

You can test which logical branch of the switchIfEmpty was used, as follows:

```
@Test
public void testSplitPathIsUsed() {
    StepVerifier.create(processOrFallback(Mono.just("just a  phrase with    tabs!"),
            Mono.just("EMPTY_PHRASE")))
                .expectNext("just", "a", "phrase", "with", "tabs!")
                .verifyComplete();
}

@Test
public void testEmptyPathIsUsed() {
    StepVerifier.create(processOrFallback(Mono.empty(), Mono.just("EMPTY_PHRASE")))
                .expectNext("EMPTY_PHRASE")
                .verifyComplete();
}
```

However, think about an example where the method produces a `Mono<Void>` instead. It waits for the source to complete, performs an additional task, and completes. If the source is empty, a fallback `Runnable`-like task must be performed instead. The following example shows such a case:

```
private Mono<String> executeCommand(String command) {
    return Mono.just(command + " DONE");
}

public Mono<Void> processOrFallback(Mono<String> commandSource, Mono<Void>
doWhenEmpty) {
    return commandSource
            .flatMap(command -> executeCommand(command).then()) ①
            .switchIfEmpty(doWhenEmpty); ②
}
```

① `then()` forgets about the command result. It cares only that it was completed.

② How to distinguish between two cases that are both empty sequences?

To verify that your `processOrFallback` method does indeed go through the `doWhenEmpty` path, you need to write a bit of boilerplate. Namely you need a `Mono<Void>` that:

- Captures the fact that it has been subscribed to.
- Lets you assert that fact *after* the whole process has terminated.

Before version 3.1, you would need to manually maintain one `AtomicBoolean` per state you wanted to assert and attach a corresponding `doOn*` callback to the publisher you wanted to evaluate. This could be a lot of boilerplate when having to apply this pattern regularly. Fortunately, 3.1.0 introduced an alternative with `PublisherProbe`. The following example shows how to use it:

```
@Test
public void testCommandEmptyPathIsUsed() {
    PublisherProbe<Void> probe = PublisherProbe.empty(); ①

    StepVerifier.create(processOrFallback(Mono.empty(), probe.mono())) ②
                .verifyComplete();

    probe.assertWasSubscribed(); ③
    probe.assertWasRequested(); ④
    probe.assertWasNotCancelled(); ⑤
}
```

① Create a probe that translates to an empty sequence.

② Use the probe in place of `Mono<Void>` by calling `probe.mono()`.

③ After completion of the sequence, the probe lets you assert that it was used. You can check that is was subscribed to…

④ …as well as actually requested data…

⑤ …and whether or not it was cancelled.

You can also use the probe in place of a `Flux<T>` by calling `.flux()` instead of `.mono()`. For cases where you need to probe an execution path but also need the probe to emit data, you can wrap any `Publisher<T>` by using `PublisherProbe.of(Publisher)`.

Chapter 7. Debugging Reactor

Switching from an imperative and synchronous programming paradigm to a reactive and asynchronous one can sometimes be daunting. One of the steepest steps in the learning curve is how to analyze and debug when something goes wrong.

In the imperative world, debugging is usually pretty straightforward. You can read the stacktrace and see where the problem originated. Was it entirely a failure of your code? Did the failure occur in some library code? If so, what part of your code called the library, potentially passing in improper parameters that ultimately caused the failure?

The Typical Reactor Stack Trace

When you shift to asynchronous code, things can get much more complicated.

Consider the following stack trace:

A typical Reactor stack trace

```
java.lang.IndexOutOfBoundsException: Source emitted more than one item
    at reactor.core.publisher.MonoSingle$SingleSubscriber.onNext(MonoSingle.java:129)
    at reactor.core.publisher.FluxFlatMap$FlatMapMain.tryEmitScalar(FluxFlatMap.java
:445)
    at reactor.core.publisher.FluxFlatMap$FlatMapMain.onNext(FluxFlatMap.java:379)
    at reactor.core.publisher.FluxMapFuseable$MapFuseableSubscriber.onNext
(FluxMapFuseable.java:121)
    at reactor.core.publisher.FluxRange$RangeSubscription.slowPath(FluxRange.java:154)
    at reactor.core.publisher.FluxRange$RangeSubscription.request(FluxRange.java:109)
    at reactor.core.publisher.FluxMapFuseable$MapFuseableSubscriber.request
(FluxMapFuseable.java:162)
    at reactor.core.publisher.FluxFlatMap$FlatMapMain.onSubscribe(FluxFlatMap.java:
332)
    at reactor.core.publisher.FluxMapFuseable$MapFuseableSubscriber.onSubscribe
(FluxMapFuseable.java:90)
    at reactor.core.publisher.FluxRange.subscribe(FluxRange.java:68)
    at reactor.core.publisher.FluxMapFuseable.subscribe(FluxMapFuseable.java:63)
    at reactor.core.publisher.FluxFlatMap.subscribe(FluxFlatMap.java:97)
    at reactor.core.publisher.MonoSingle.subscribe(MonoSingle.java:58)
    at reactor.core.publisher.Mono.subscribe(Mono.java:3096)
    at reactor.core.publisher.Mono.subscribeWith(Mono.java:3204)
    at reactor.core.publisher.Mono.subscribe(Mono.java:3090)
    at reactor.core.publisher.Mono.subscribe(Mono.java:3057)
    at reactor.core.publisher.Mono.subscribe(Mono.java:3029)
    at reactor.guide.GuideTests.debuggingCommonStacktrace(GuideTests.java:995)
```

There is a lot going on there. We get an `IndexOutOfBoundsException`, which tells us that a `source emitted more than one item`.

We can probably quickly come to assume that this source is a Flux or a Mono, as confirmed by the

next line, which mentions `MonoSingle`. So it appears to be some sort of complaint from a `single` operator.

Referring to the Javadoc for the `Mono#single` operator, we see that `single` has a contract: The source must emit exactly one element. It appears we had a source that emitted more than one and thus violated that contract.

Can we dig deeper and identify that source? The following rows are not very helpful. They take us through the internals of what seems to be a reactive chain, through multiple calls to `subscribe` and `request`.

By skimming over these rows, we can at least start to form a picture of the kind of chain that went wrong: It seems to involve a `MonoSingle`, a `FluxFlatMap`, and a `FluxRange` (each gets several rows in the trace, but overall these three classes are involved). So a `range().flatMap().single()` chain maybe?

But what if we use that pattern a lot in our application? This still does not tell us much, and simply searching for `single` is not going to find the problem. Then the last line refers to some of our code. Finally, we are getting close.

Hold on, though. When we go to the source file, all we see is that a pre-existing `Flux` is subscribed to, as follows:

```
toDebug
    .subscribeOn(Schedulers.immediate())
    .subscribe(System.out::println, Throwable::printStackTrace);
```

All of this happened at subscription time, but the `Flux` itself was not declared there. Worse, when we go to where the variable is declared, we see the following:

```
public Mono<String> toDebug; //please overlook the public class attribute
```

The variable is not instantiated where it is declared. We must assume a worst-case scenario where we find out that there could be a few different code paths that set it in the application. We remain unsure of which one caused the issue.

This is kind of the Reactor equivalent of a runtime error, as opposed to a compilation error.

What we want to find out more easily is where the operator was added into the chain - that is, where the `Flux` was declared. We usually refer to that as the “assembly” of the `Flux`.

Activating Debug Mode - aka tracebacks

this section describes the easiest but also the slowest way to enable the debugging capabilities due to the fact that it captures the stacktrace on every operator. See The `checkpoint()` Alternative for a more fine grained way of debugging, and

> Production-ready Global Debugging for a more advanced and performant global option.

Even though the stacktrace was still able to convey some information for someone with a bit of experience, we can see that it is not ideal by itself in more advanced cases.

Fortunately, Reactor comes with assembly-time instrumentation that is designed for debugging.

This is done by activating a global debug mode via the `Hooks.onOperatorDebug()` method at application start (or at least before the incriminated `Flux` or `Mono` can be instantiated), as follows:

```
Hooks.onOperatorDebug();
```

This starts instrumenting the calls to Reactor operator methods (where they are assembled into the chain) by wrapping the construction of the operator and capturing a stack trace there. Since this is done when the operator chain is declared, the hook should be activated before that, so the safest way is to activate it right at the start of your application.

Later on, if an exception occurs, the failing operator is able to refer to that capture and to rework the stack trace, appending additional information.

We call this captured assembly information (and additional information added to the exceptions by Reactor in general) a **traceback**.

In the next section, we see how the stack trace differs and how to interpret that new information.

Reading a Stack Trace in Debug Mode

When we reuse our initial example but activate the `operatorStacktrace` debug feature, several things happen:

1. The stack trace, which points to subscription site and is thus less interesting, is cut after the first frame and set aside.
2. A special suppressed exception is added to the original exception (or amended if already there).
3. A message is constructed for that special exception with several sections.
4. First section will trace back to the assembly site of the operator that fails.
5. Second section will attempt to display the chain(s) that are built from this operator and have seen the error propagate
6. Last section is the original stack trace

The full stack trace, once printed, is as follows:

```
java.lang.IndexOutOfBoundsException: Source emitted more than one item
    at reactor.core.publisher.MonoSingle$SingleSubscriber.onNext(MonoSingle.java:127)
①
    Suppressed: The stacktrace has been enhanced by Reactor, refer to additional
information below: ②
Assembly trace from producer [reactor.core.publisher.MonoSingle] : ③
    reactor.core.publisher.Flux.single(Flux.java:7915)
    reactor.guide.GuideTests.scatterAndGather(GuideTests.java:1017)
Error has been observed at the following site(s): ④
    *_______Flux.single ⇢ at reactor.guide.GuideTests.scatterAndGather(GuideTests.
java:1017) ⑤
    |_ Mono.subscribeOn ⇢ at reactor.guide.GuideTests.debuggingActivated(GuideTests
.java:1071) ⑥
Original Stack Trace: ⑦
        at reactor.core.publisher.MonoSingle$SingleSubscriber.onNext(MonoSingle.java
:127)
...
⑧
...
        at reactor.core.publisher.Mono.subscribeWith(Mono.java:4363)
        at reactor.core.publisher.Mono.subscribe(Mono.java:4223)
        at reactor.core.publisher.Mono.subscribe(Mono.java:4159)
        at reactor.core.publisher.Mono.subscribe(Mono.java:4131)
        at reactor.guide.GuideTests.debuggingActivated(GuideTests.java:1067)
```

① The original stack trace is truncated to a single frame.

② This is new: We see the wrapper operator that captures the stack. This is where the traceback starts to appear.

③ First, we get some details about where the operator was assembled.

④ Second, we get a notion of operator chain(s) through which the error propagated, from first to last (error site to subscribe site).

⑤ Each operator that saw the error is mentioned along with the user class and line where it was used. Here we have a "root".

⑥ Here we have a simple part of the chain.

⑦ The rest of the stack trace is moved at the end…

⑧ …showing a bit of the operator's internals (so we removed a bit of the snippet here).

The captured stack trace is appended to the original error as a suppressed `OnAssemblyException`. There are three parts to it, but the first section is the most interesting. It shows the path of construction for the operator that triggered the exception. Here, it shows that the `single` that caused our issue was actually created in the `scatterAndGather` method.

Now that we are armed with enough information to find the culprit, we can have a meaningful look at that `scatterAndGather` method:

```
private Mono<String> scatterAndGather(Flux<String> urls) {
    return urls.flatMap(url -> doRequest(url))
            .single(); ①
}
```

① Sure enough, here is our `single`.

Now we can see what the root cause of the error was a `flatMap` that performs several HTTP calls to a few URLs but that is chained with `single`, which is too restrictive. After a short `git blame` and a quick discussion with the author of that line, we find out he meant to use the less restrictive `take(1)` instead.

We have solved our problem.

Now consider the following section in the stack trace:

```
Error has been observed at the following site(s):
```

That second part of the traceback was not necessarily interesting in this particular example, because the error was actually happening in the last operator in the chain (the one closest to `subscribe`). Considering another example might make it more clear:

```
FakeRepository.findAllUserByName(Flux.just("pedro", "simon", "stephane"))
              .transform(FakeUtils1.applyFilters)
              .transform(FakeUtils2.enrichUser)
              .blockLast();
```

Now imagine that, inside `findAllUserByName`, there is a `map` that fails. Here, we would see the following in the second part of the traceback:

```
Error has been observed at the following site(s):
    *_______Flux.map ⇢ at reactor.guide.FakeRepository.findAllUserByName
(FakeRepository.java:27)
    |_       Flux.map ⇢ at reactor.guide.FakeRepository.findAllUserByName
(FakeRepository.java:28)
    |_    Flux.filter ⇢ at reactor.guide.FakeUtils1.lambda$static$1(FakeUtils1.java:
29)
    |_ Flux.transform ⇢ at reactor.guide.GuideDebuggingExtraTests
.debuggingActivatedWithDeepTraceback(GuideDebuggingExtraTests.java:39)
    |_   Flux.elapsed ⇢ at reactor.guide.FakeUtils2.lambda$static$0(FakeUtils2.java:
30)
    |_ Flux.transform ⇢ at reactor.guide.GuideDebuggingExtraTests
.debuggingActivatedWithDeepTraceback(GuideDebuggingExtraTests.java:40)
```

This corresponds to the section of the chain(s) of operators that gets notified of the error:

1. The exception originates in the first `map`. This one is identified as a root by the `*` connector and the fact `_` are used for indentation.
2. The exception is seen by a second `map` (both in fact correspond to the `findAllUserByName` method).
3. It is then seen by a `filter` and a `transform`, which indicate that part of the chain is constructed by a reusable transformation function (here, the `applyFilters` utility method).
4. Finally, it is seen by an `elapsed` and a `transform`. Once again, `elapsed` is applied by the transformation function of that second transform.

In some cases where the same exception is propagated through multiple chains, the "root" marker `*_` allows us to better separate such chains. If a site is seen several time, there will be an `(observed x times)` after the call site information.

For instance, let us consider the following snippet:

```
public class MyClass {
    public void myMethod() {
        Flux<String> source = Flux.error(sharedError);
        Flux<String> chain1 = source.map(String::toLowerCase).filter(s -> s.length() <
4);
        Flux<String> chain2 = source.filter(s -> s.length() > 5).distinct();

        Mono<Void> when = Mono.when(chain1, chain2);
    }
}
```

In the code above, error propagates to the `when`, going through two separate chains `chain1` and `chain2`. It would lead to a traceback containing the following:

```
Error has been observed at the following site(s):
    *_____Flux.error ⇢ at myClass.myMethod(MyClass.java:3) (observed 2 times)
    |_      Flux.map ⇢ at myClass.myMethod(MyClass.java:4)
    |_   Flux.filter ⇢ at myClass.myMethod(MyClass.java:4)
    *_____Flux.error ⇢ at myClass.myMethod(MyClass.java:3) (observed 2 times)
    |_   Flux.filter ⇢ at myClass.myMethod(MyClass.java:5)
    |_ Flux.distinct ⇢ at myClass.myMethod(MyClass.java:5)
    *______Mono.when ⇢ at myClass.myMethod(MyClass.java:7)
```

We see that:

1. there are 3 "root" elements (the `when` is the true root).
2. two chains starting from `Flux.error` are visible.
3. both chains seem to be based on the same `Flux.error` source (`observed 2 times`).
4. first chain is `Flux.error().map().filter`
5. second chain is `Flux.error().filter().distinct()

A note on tracebacks and suppressed exceptions: As tracebacks are appended to original errors as suppressed exceptions, this can somewhat interfere with another type of exception that uses this mechanism: composite exceptions. Such exceptions can be created directly via `Exceptions.multiple(Throwable…)`, or by some operators that might join multiple erroring sources (like `Flux#flatMapDelayError`). They can be unwrapped into a `List` via `Exceptions.unwrapMultiple(Throwable)`, in which case the traceback would be considered a component of the composite and be part of the returned `List`. If that is somehow not desirable, tracebacks can be identified thanks to `Exceptions.isTraceback(Throwable)` check, and excluded from such an unwrap by using `Exceptions.unwrapMultipleExcludingTracebacks(Throwable)` instead.

Static exceptions: Optimizing exception handling sometimes involves reusing exceptions via pre-creating global static instances instead of creating new instances upon an exceptional state occuring. With such reused exceptions, tracebacks will start to accumulate as appended suppressed exceptions and inevitably lead to memory leaks. In most circumstances static exceptions are used in combination with disabling stacktrace capturing which is the biggest contributor to the cost of creating exceptions. However, exceptions can be created dynamically without a stack trace with only the marginal cost of memory allocation and no need for static instances. In case your code still needs to rely on static instances of exceptions, the way to avoid memory leaks with tracebacks is to disable suppression at the expense of not being able to see tracebacks if these exceptions are propagated down the reactive chain.

We deal with a form of instrumentation here, and creating a stack trace is costly. That is why this debugging feature should only be activated in a controlled manner, as a last resort.

The `checkpoint()` Alternative

The debug mode is global and affects every single operator assembled into a `Flux` or a `Mono` inside the application. This has the benefit of allowing after-the-fact debugging: Whatever the error, we can obtain additional information to debug it.

As we saw earlier, this global knowledge comes at the cost of an impact on performance (due to the number of populated stack traces). That cost can be reduced if we have an idea of likely problematic operators. However, we usually do not know which operators are likely to be problematic unless we observed an error in the wild, saw we were missing assembly information, and then modified the code to activate assembly tracking, hoping to observe the same error again.

In that scenario, we have to switch into debugging mode and make preparations in order to better observe a second occurrence of the error, this time capturing all the additional information.

If you can identify reactive chains that you assemble in your application for which serviceability is critical, you can achieve a mix of both techniques with the `checkpoint()` operator.

You can chain this operator into a method chain. The `checkpoint` operator works like the hook version but only for its link of that particular chain.

There is also a `checkpoint(String)` variant that lets you add a unique `String` identifier to the assembly traceback. This way, the stack trace is omitted and you rely on the description to identify the assembly site. `checkpoint(String)` imposes less processing cost than a regular `checkpoint`.

Last but not least, if you want to add a more generic description to the checkpoint but still rely on the stack trace mechanism to identify the assembly site, you can force that behavior by using the `checkpoint("description", true)` version. We are now back to the initial message for the traceback, augmented with a `description`, as shown in the following example:

```
Assembly trace from producer [reactor.core.publisher.ParallelSource], described as
[descriptionCorrelation1234] : ①
    reactor.core.publisher.ParallelFlux.checkpoint(ParallelFlux.java:215)
    reactor.core.publisher.FluxOnAssemblyTest
.parallelFluxCheckpointDescriptionAndForceStack(FluxOnAssemblyTest.java:225)
Error has been observed at the following site(s):
    |_  ParallelFlux.checkpoint ⇢ reactor.core.publisher.FluxOnAssemblyTest
.parallelFluxCheckpointDescriptionAndForceStack(FluxOnAssemblyTest.java:225)
```

① `descriptionCorrelation1234` is the description provided in the `checkpoint`.

The description could be a static identifier or user-readable description or a wider correlation ID (for instance, coming from a header in the case of an HTTP request).

When global debugging is enabled in conjunction with checkpoints, the global debugging traceback style is applied and checkpoints are only reflected in the "Error has been observed..." section. As a result, the name of heavy checkpoints is not visible in this case.

Production-ready Global Debugging

Project Reactor comes with a separate Java Agent that instruments your code and adds debugging info without paying the cost of capturing the stacktrace on every operator call. The behaviour is very similar to Activating Debug Mode - aka tracebacks, but without the runtime performance overhead.

To use it in your app, you must add it as a dependency.

The following example shows how to add `reactor-tools` as a dependency in Maven:

reactor-tools in Maven, in `<dependencies>`

```
<dependency>
    <groupId>io.projectreactor</groupId>
    <artifactId>reactor-tools</artifactId>
①
</dependency>
```

① If you use the BOM, you do not need to specify a `<version>`.

The following example shows how to add `reactor-tools` as a dependency in Gradle:

reactor-tools in Gradle, amend the `dependencies` block

```
dependencies {
   compile 'io.projectreactor:reactor-tools'
}
```

It also needs to be explicitly initialized with:

```
ReactorDebugAgent.init();
```

Since the implementation will instrument your classes when they are loaded, the best place to put it is before everything else in your main(String[]) method:

```
public static void main(String[] args) {
    ReactorDebugAgent.init();
    SpringApplication.run(Application.class, args);
}
```

You may also re-process existing classes with `processExistingClasses()` if you cannot run the init eagerly. For example, in JUnit5 tests from a `TestExecutionListener` or even in the class `static` initializer block:

```
ReactorDebugAgent.init();
ReactorDebugAgent.processExistingClasses();
```

Be aware that the re-processing takes a couple of seconds due to the need to iterate over all loaded classes and apply the transformation. Use it only if you see that some call-sites are not instrumented.

Limitations

`ReactorDebugAgent` is implemented as a Java Agent and uses ByteBuddy to perform the self-attach. Self-attach may not work on some JVMs, please refer to ByteBuddy's documentation for more details.

Running ReactorDebugAgent as a Java Agent

If your environment does not support ByteBuddy's self-attachment, you can run `reactor-tools` as a Java Agent:

```
java -javaagent:reactor-tools.jar -jar app.jar
```

Running ReactorDebugAgent at build time

It is also possible to run `reactor-tools` at build time. To do so, you need to apply it as a plugin for ByteBuddy's build instrumentation.

The transformation will only be applied to your project's classes. The classpath libraries will not be instrumented.

reactor-tools with ByteBuddy's Maven plugin

```
<dependencies>
    <dependency>
        <groupId>io.projectreactor</groupId>
        <artifactId>reactor-tools</artifactId>
①
        <classifier>original</classifier> ②
        <scope>runtime</scope>
    </dependency>
</dependencies>

<build>
    <plugins>
        <plugin>
            <groupId>net.bytebuddy</groupId>
            <artifactId>byte-buddy-maven-plugin</artifactId>
            <configuration>
                <transformations>
                    <transformation>
                        <plugin>
reactor.tools.agent.ReactorDebugByteBuddyPlugin</plugin>
                    </transformation>
                </transformations>
            </configuration>
        </plugin>
    </plugins>
</build>
```

① If you use the BOM, you do not need to specify a `<version>`.

② `classifier` here is important.

reactor-tools with ByteBuddy's Gradle plugin

```
plugins {
    id 'net.bytebuddy.byte-buddy-gradle-plugin' version '1.10.9'
}

configurations {
    byteBuddyPlugin
}
```

```
dependencies {
    byteBuddyPlugin(
            group: 'io.projectreactor',
            name: 'reactor-tools',
①
            classifier: 'original', ②
    )
}

byteBuddy {
    transformation {
        plugin = "reactor.tools.agent.ReactorDebugByteBuddyPlugin"
        classPath = configurations.byteBuddyPlugin
    }
}
```

① If you use the BOM, you do not need to specify a `version`.

② `classifier` here is important.

Logging a Sequence

In addition to stack trace debugging and analysis, another powerful tool to have in your toolkit is the ability to trace and log events in an asynchronous sequence.

The `log()` operator can do just that. Chained inside a sequence, it peeks at every event of the `Flux` or `Mono` upstream of it (including `onNext`, `onError`, and `onComplete` as well as subscriptions, cancellations, and requests).

A note on logging implementation

The `log` operator uses the `Loggers` utility class, which picks up common logging frameworks such as Log4J and Logback through `SLF4J` and defaults to logging to the console if SLF4J is unavailable.

The console fallback uses `System.err` for the `WARN` and `ERROR` log levels and `System.out` for everything else.

If you prefer a JDK `java.util.logging` fallback, as in 3.0.x, you can get it by setting the `reactor.logging.fallback` system property to `JDK`.

In all cases, when logging in production **you should take care to configure the underlying logging framework to use its most asynchronous and non-blocking approach** — for instance, an `AsyncAppender` in Logback or `AsyncLogger` in Log4j 2.

For instance, suppose we have Logback activated and configured and a chain like `range(1,10).take(3)`. By placing a `log()` before the `take`, we can get some insight into how it works and what kind of events it propagates upstream to the range, as the following example shows:

```
Flux<Integer> flux = Flux.range(1, 10)
                         .log()
                         .take(3);
flux.subscribe();
```

This prints out the following (through the logger's console appender):

```
10:45:20.200 [main] INFO  reactor.Flux.Range.1 - | onSubscribe([Synchronous Fuseable]
FluxRange.RangeSubscription) ①
10:45:20.205 [main] INFO  reactor.Flux.Range.1 - | request(3) ②
10:45:20.205 [main] INFO  reactor.Flux.Range.1 - | onNext(1) ③
10:45:20.205 [main] INFO  reactor.Flux.Range.1 - | onNext(2)
10:45:20.205 [main] INFO  reactor.Flux.Range.1 - | onNext(3)
10:45:20.205 [main] INFO  reactor.Flux.Range.1 - | cancel() ④
```

Here, in addition to the logger's own formatter (time, thread, level, message), the `log()` operator outputs a few things in its own format:

① `reactor.Flux.Range.1` is an automatic category for the log, in case you use the operator several times in a chain. It lets you distinguish which operator's events are logged (in this case, the `range`). You can overwrite the identifier with your own custom category by using the `log(String)` method signature. After a few separating characters, the actual event gets printed. Here, we get an `onSubscribe` call, a `request` call, three `onNext` calls, and a `cancel` call. For the first line, `onSubscribe`, we get the implementation of the `Subscriber`, which usually corresponds to the operator-specific implementation. Between square brackets, we get additional information, including whether the operator can be automatically optimized through synchronous or asynchronous fusion.

② On the second line, we can see that take limited the request to upstream to 3.

③ Then the range sends three values in a row.

④ On the last line, we see `cancel()`.

The second (2) and last lines (4) are the most interesting. We can see the `take` in action there. It leverages backpressure in order to ask the source for exactly the expected amount of elements. After having received enough elements, it tells the source no more items will be needed by calling `cancel()`. Note that if downstream had itself used backpressure, eg. by requesting only 1 element, the `take` operator would have honored that (it *caps* the request when propagating it from downstream to upstream).

Chapter 8. Exposing Reactor metrics

Project Reactor is a library designed for performance and better utilization of resources. But to truly understand the performance of a system, it is best to be able to monitor its various components.

This is why Reactor provides a built-in integration with Micrometer via the `reactor-core-micrometer` module. Introduced in the `2022.0 BOM` release, the module provides an explicit dependency to Micrometer, which allows it to offer fine-tuned APIs for metrics and observations.

Up to Reactor-Core `3.5.0`, metrics were implemented as operators that would be no-op if Micrometer wasn't on the classpath.

The `reactor-core-micrometer` APIs require the user to provide a form of *registry* explicitly instead of relying on a hardcoded global registry. When applying instrumentation to classes that have a NATIVE notion of naming or tags, these APIs will attempt to discover such elements in the reactive chain. Otherwise, the API will expect that a *prefix* for naming meters is provided alongside the registry.

Scheduler metrics

Every async operation in Reactor is done via the Scheduler abstraction described in Threading and Schedulers. This is why it is important to monitor your schedulers, watch out for key metrics that start to look suspicious and react accordingly.

The `reactor-core-micrometer` module offers a "timed" `Scheduler` wrapper that perform measurements around tasks submitted through it, which can be used as follows:

```
Scheduler originalScheduler = Schedulers.newParallel("test", 4);

Scheduler schedulerWithMetrics = Micrometer.timedScheduler(
    originalScheduler, ①
    applicationDefinedMeterRegistry, ②
    "testingMetrics", ③
    Tags.of(Tag.of("additionalTag", "yes")) ④
);
```

① the `Scheduler` to wrap

② the `MeterRegistry` in which to publish metrics

③ the prefix to use in naming meters. This would for example lead to a `testingMetrics.scheduler.tasks.completed` meter being created.

④ optional tags to add to all the meters created for that wrapping `Scheduler`

When wrapping a common `Scheduler` (eg. `Schedulers.single()`) or a `Scheduler` that is used in multiple places, only the `Runnable` tasks that are submitted through the wrapper instance returned by `Micrometer#timedScheduler` are going to be

instrumented.

See Micrometer.timedScheduler() for produced meters and associated default tags.

Publisher metrics

Sometimes it is useful to be able to record metrics at some stage in your reactive pipeline.

One way to do it would be to manually push the values to your metrics backend of choice from a custom `SignalListener` provided to the `tap` operator.

An out-of-the-box implementation is actually provided by the `reactor-core-micrometer` module, via `Micrometer#metrics` APIs. Consider the following pipeline:

```
listenToEvents()
    .doOnNext(event -> log.info("Received {}", event))
    .delayUntil(this::processEvent)
    .retry()
    .subscribe();
```

To enable the metrics for this source `Flux` (returned from `listenToEvents()`), we need to turn on the metrics collection:

```
listenToEvents()
    .name("events") ①
    .tap(Micrometer.metrics( ②
        applicationDefinedMeterRegistry ③
    ))
    .doOnNext(event -> log.info("Received {}", event))
    .delayUntil(this::processEvent)
    .retry()
    .subscribe();
```

① Every metric at this stage of the reactive pipeline will use "events" as a naming prefix (optional, defaults to `reactor` prefix).

② We use the `tap` operator combined with a `SignalListener` implementation provided in `reactor-core-micrometer` for metrics collection.

③ As with other APIs in that module, the `MeterRegistry` into which to publish metrics needs to be explicitly provided.

The detail of the exposed metrics is available in Micrometer.metrics().

Tags

In addition to the common tags described in Micrometer.metrics(), users can add custom tags to their reactive chains via the `tag` operator:

```
listenToEvents()
    .name("events") ①
    .tag("source", "kafka") ②
    .tap(Micrometer.metrics(applicationDefinedRegistry)) ③
    .doOnNext(event -> log.info("Received {}", event))
    .delayUntil(this::processEvent)
    .retry()
    .subscribe();
```

① Every metric at this stage will be identified with the "events" prefix.

② Set a custom tag "source" to value "kafka".

③ All reported metrics will have `source=kafka` tag assigned in addition to the common tags.

Please note that depending on the monitoring system you're using, using a name can be considered mandatory when using tags, since it would otherwise result in a different set of tags between two default-named sequences. Some systems like Prometheus might also require to have the exact same set of tags for each metric with the same name.

Observation

In addition to full metrics, the `reactor-core-micrometer` module offers an alternative based on Micrometer's `Observation`. Depending on the configuration and runtime classpath, an `Observation` could translate to timers, spans, logging statements or any combination.

A reactive chain can be observed via the `tap` operator and `Micrometer.observation` utility, as follows:

```
listenToEvents()
    .name("events") ①
    .doOnNext(event -> log.info("Received {}", event))
    .delayUntil(this::processEvent)
    .tap(Micrometer.observation( ②
        applicationDefinedRegistry)) ③
    .retry()
    .subscribe();
```

① The `Observation` for this pipeline will be identified with the "events" prefix.

② We use the `tap` operator with the `observation` utility, making an anonymous `observation` available to upstream operators.

③ A registry must be provided into which to publish the observation results. Note this is an `ObservationRegistry`.

The detail of the observation and its tags is provided in Micrometer.observation().

The set of meters collected with `Micrometer.observation()` differs from the set of meters that `Micrometer.metrics()` provides. `Micrometer.observation()` covers the lifecycle of an entire reactive chain, while `Micrometer.metrics()` provides some insight into individual signals within the chain. Due to the generic nature of

> `Micrometer.observation()` (like providing traces aside from metrics) it might require wrapping unitsof work, like `Mono.just(processedItem)` and observing a sub-chain using a `flatMap`-like operator.

You can also fully customize Micrometer's Observation via `Micrometer.observation(ObservationRegistry registry, Function<ObservationRegistry, Observation> observationSupplier)` with your own Observation supplier, as follows:

```
listenToEvents()
    .name("events") ①
    .doOnNext(event -> log.info("Received {}", event))
    .delayUntil(this::processEvent)
    .tap(Micrometer.observation( ②
        applicationDefinedRegistry, ③
        registry -> Observation.createNotStarted( ④
            myConvention, ⑤
            myContextSupplier, ⑥
            registry)))
    .retry()
    .subscribe();
```

① The `Observation` for this pipeline will be identified with the "events" prefix.

② We use the `tap` operator with the `observation` utility, making a custom `observation` available to upstream operators.

③ A registry must be provided into which to publish the observation results. Note this is an `ObservationRegistry`.

④ We provide our own function to create the Observation

⑤ with a custom `ObservationConvention`

⑥ and a custom `Supplier<Context>`.

Meters and tags for Reactor-Core-Micrometer module

`Micrometer.metrics()`

Below is the list of meters used by the metrics tap listener feature, as exposed via `Micrometer.metrics(MeterRegistry meterRegistry)`.

> Please note that metrics below use a dynamic `%s` prefix. When applied on a `Flux` or `Mono` that uses the `name(String n)` operator, this is replaced with `n`. Otherwise, this is replaced by the default value of `"reactor"`.

Flow Duration

> Times the duration elapsed between a subscription and the termination or cancellation of the sequence. A TerminationTags#STATUS tag is added to

> specify what event caused the timer to end (`"completed"`, `"completedEmpty"`, `"error"` or `"cancelled"`).

Metric name `%s.flow.duration` - since it contains `%s`, the name is dynamic and will be resolved at runtime. **Type** `distribution summary`.

KeyValues that are added after starting the Observation might be missing from the *.active metrics.

Table 1. Low cardinality Keys

Name	Description
`exception` *(required)*	Tag used by FLOW_DURATION when STATUS is `"error"`, to store the exception that occurred.
`status` *(required)*	The termination status: • `"completed"` for a sequence that terminates with an onComplete, with onNext(s) • `"completedEmpty"` for a sequence that terminates without any onNext before the onComplete • `"error"` for a sequence that terminates with an onError • `"cancelled"` for a sequence that has cancelled its subscription
`type` *(required)*	The type of the sequence (`"Flux"` or `"Mono"`).

Malformed Source Events

> Counts the number of events received from a malformed source (ie an onNext after an onComplete).

Metric name `%s.malformed.source` - since it contains `%s`, the name is dynamic and will be resolved at runtime. **Type** `counter`.

KeyValues that are added after starting the Observation might be missing from the *.active metrics.

Table 2. Low cardinality Keys

Name	Description
`type` *(required)*	The type of the sequence (`"Flux"` or `"Mono"`).

On Next Delay

> Measures the delay between each onNext (or between the first onNext and the onSubscribe event).

Metric name `%s.onNext.delay` - since it contains `%s`, the name is dynamic and will be resolved at runtime. **Type** `timer` and **base unit** `nanoseconds`.

KeyValues that are added after starting the Observation might be missing from the *.active metrics.

Micrometer internally uses `nanoseconds` for the baseunit. However, each backend determines the actual baseunit. (i.e. Prometheus uses seconds)

Table 3. Low cardinality Keys

Name	Description
`type` *(required)*	The type of the sequence (`"Flux"` or `"Mono"`).

Requested Amount

> Counts the amount requested to a named sequence (eg. `Flux.name(String)`) by all subscribers, until at least one requests an unbounded amount.

Metric name `%s.requested` - since it contains `%s`, the name is dynamic and will be resolved at runtime. **Type** `distribution summary`.

KeyValues that are added after starting the Observation might be missing from the *.active metrics.

Table 4. Low cardinality Keys

Name	Description
`type` *(required)*	The type of the sequence (`"Flux"` or `"Mono"`).

Subscribed

> Counts the number of subscriptions to a sequence.

Metric name `%s.subscribed` - since it contains `%s`, the name is dynamic and will be resolved at runtime. **Type** `counter`.

KeyValues that are added after starting the Observation might be missing from the *.active metrics.

Table 5. Low cardinality Keys

Name	Description
`type` *(required)*	The type of the sequence (`"Flux"` or `"Mono"`).

`Micrometer.timedScheduler()`

Below is the list of meters used by the TimedScheduler feature, as exposed via `Micrometer.timedScheduler(Scheduler original, MeterRegistry meterRegistry, String metricsPrefix)`.

Please note that metrics below use a dynamic `%s` prefix. This is replaced with the provided `metricsPrefix` in practice.

Tasks Active

> LongTaskTimer reflecting tasks currently running. Note that this reflects all types of active tasks, including tasks scheduled with a delay or periodically (each iteration being considered an active task).

Metric name `%s.scheduler.tasks.active` - since it contains `%s`, the name is dynamic and will be resolved at runtime. **Type** `long task timer`.

KeyValues that are added after starting the Observation might be missing from the *.active metrics.

Micrometer internally uses `nanoseconds` for the baseunit. However, each backend determines the actual baseunit. (i.e. Prometheus uses seconds)

Tasks Completed

> Timer reflecting tasks that have finished execution. Note that this reflects all types of active tasks, including tasks with a delay or periodically (each iteration being considered a separate completed task).

Metric name `%s.scheduler.tasks.completed` - since it contains `%s`, the name is dynamic and will be resolved at runtime. **Type** `timer`.

KeyValues that are added after starting the Observation might be missing from the *.active metrics.

Micrometer internally uses `nanoseconds` for the baseunit. However, each backend determines the actual baseunit. (i.e. Prometheus uses seconds)

Tasks Pending

> LongTaskTimer reflecting tasks that were submitted for immediate

> execution but couldn't be started immediately because the scheduler is already at max capacity. Note that only immediate submissions via Scheduler#schedule(Runnable) and Scheduler.Worker#schedule(Runnable) are considered.

Metric name `%s.scheduler.tasks.pending` - since it contains `%s`, the name is dynamic and will be resolved at runtime. **Type** `long task timer`.

KeyValues that are added after starting the Observation might be missing from the *.active metrics.

Micrometer internally uses `nanoseconds` for the baseunit. However, each backend determines the actual baseunit. (i.e. Prometheus uses seconds)

Tasks Submitted

> Counter that increments by one each time a task is submitted (via any of the schedule methods on both Scheduler and Scheduler.Worker).
>
> Note that there are actually 4 counters, which can be differentiated by the SubmittedTags#SUBMISSION tag. The sum of all these can thus be compared with the TASKS_COMPLETED counter.

Metric name `%s.scheduler.tasks.submitted` - since it contains `%s`, the name is dynamic and will be resolved at runtime. **Type** `counter`.

KeyValues that are added after starting the Observation might be missing from the *.active metrics.

Table 6. Low cardinality Keys

Name	Description
`submission.type` *(required)*	The type of submission: • `"direct"` for `Scheduler#schedule(Runnable)` • `"delayed"` for `Scheduler#schedule(Runnable,long,TimeUnit)` • `"periodic_initial"` for `Scheduler#schedulePeriodically(Runnable,long,long,TimeUnit)` after the initial delay • `"periodic_iteration"` for `Scheduler#schedulePeriodically(Runnable,long,long,TimeUnit)` further periodic iterations

`Micrometer.observation()`

Below is the list of meters used by the observation tap listener feature, as exposed via `Micrometer.observation(ObservationRegistry registry)`.

This is the ANONYMOUS observation, but you can create a similar Observation with a custom name by using the `name(String)` operator.

You can also fully customize Micrometer's Observation via `Micrometer.observation(ObservationRegistry registry, Function<ObservationRegistry, Observation> observationSupplier)` with your own Observation supplier, allowing to configure its attributes (name, contextual name, low and high cardinality keys, ...).

Anonymous

> Anonymous version of the Micrometer.observation(), when the sequence hasn't been explicitly named via e.g. Flux#name(String) operator.

Metric name `reactor.observation`. **Type** `timer`.

Metric name `reactor.observation.active`. **Type** `long task timer`.

KeyValues that are added after starting the Observation might be missing from the *.active metrics.

Micrometer internally uses `nanoseconds` for the baseunit. However, each backend determines the actual baseunit. (i.e. Prometheus uses seconds)

Table 7. Low cardinality Keys

Name	Description
`reactor.status` *(required)*	The status of the sequence, which indicates how it terminated (`"completed"`, `"completedEmpty"`, `"error"` or `"cancelled"`).
`reactor.type` *(required)*	The type of the sequence, i.e. `"Flux"` or `"Mono"`.

Chapter 9. Advanced Features and Concepts

This chapter covers advanced features and concepts of Reactor, including the following:

- Mutualizing Operator Usage
- Hot Versus Cold
- Broadcasting to Multiple Subscribers with `ConnectableFlux`
- Three Sorts of Batching
- Parallelizing Work with `ParallelFlux`
- Replacing Default `Schedulers`
- Using Global Hooks
- Adding a Context to a Reactive Sequence
- Context-Propagation Support
- Null Safety
- Dealing with Objects that Need Cleanup

9.1. Mutualizing Operator Usage

From a clean-code perspective, code reuse is generally a good thing. Reactor offers a few patterns that can help you reuse and mutualize code, notably for operators or combinations of operators that you might want to apply regularly in your codebase. If you think of a chain of operators as a recipe, you can create a "cookbook" of operator recipes.

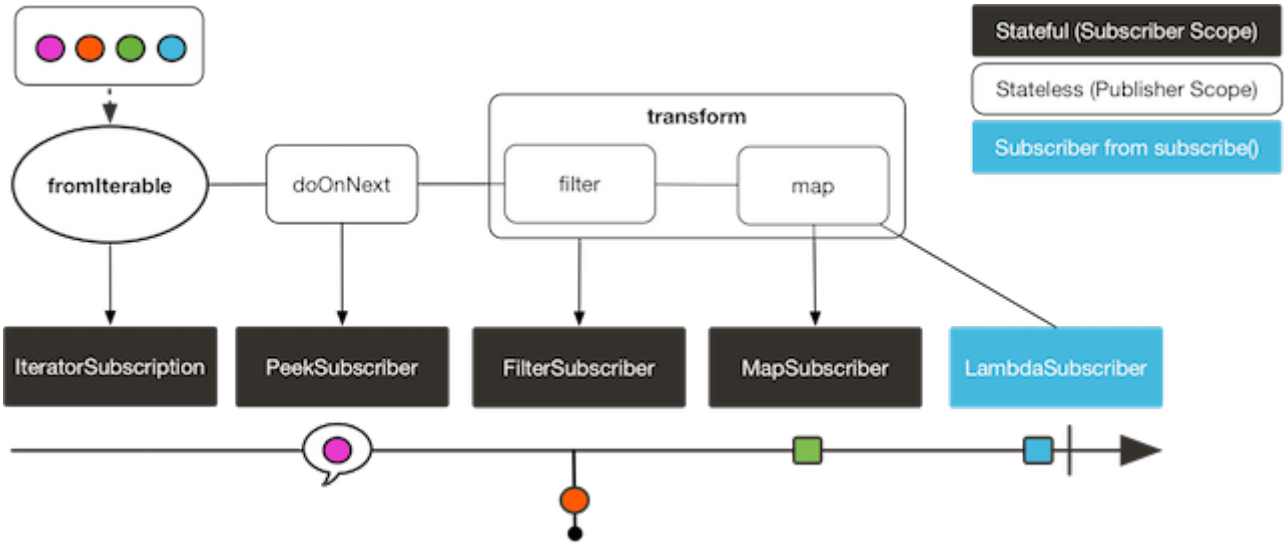
Using the `transform` Operator

The `transform` operator lets you encapsulate a piece of an operator chain into a function. That function is applied to an original operator chain at assembly time to augment it with the encapsulated operators. Doing so applies the same operations to all the subscribers of a sequence and is basically equivalent to chaining the operators directly. The following code shows an example:

```
Function<Flux<String>, Flux<String>> filterAndMap =
f -> f.filter(color -> !color.equals("orange"))
      .map(String::toUpperCase);

Flux.fromIterable(Arrays.asList("blue", "green", "orange", "purple"))
    .doOnNext(System.out::println)
    .transform(filterAndMap)
    .subscribe(d -> System.out.println("Subscriber to Transformed MapAndFilter: "+d));
```

The following image shows how the `transform` operator encapsulates flows:



The preceding example produces the following output:

```
blue
Subscriber to Transformed MapAndFilter: BLUE
green
Subscriber to Transformed MapAndFilter: GREEN
orange
purple
Subscriber to Transformed MapAndFilter: PURPLE
```

Using the `transformDeferred` Operator

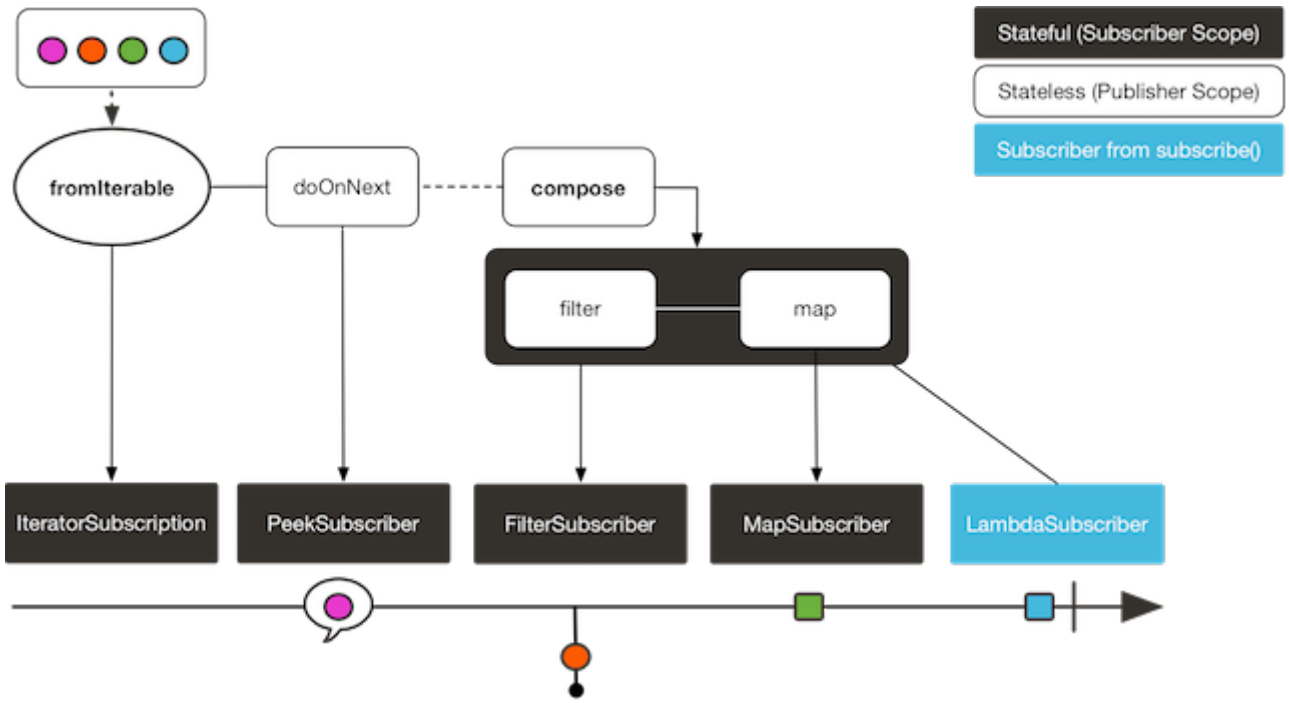
The `transformDeferred` operator is similar to `transform` and also lets you encapsulate operators in a function. The major difference is that this function is applied to the original sequence *on a per-subscriber basis*. It means that the function can actually produce a different operator chain for each subscription (by maintaining some state). The following code shows an example:

```
AtomicInteger ai = new AtomicInteger();
Function<Flux<String>, Flux<String>> filterAndMap = f -> {
    if (ai.incrementAndGet() == 1) {
return f.filter(color -> !color.equals("orange"))
        .map(String::toUpperCase);
    }
    return f.filter(color -> !color.equals("purple"))
            .map(String::toUpperCase);
};

Flux<String> composedFlux =
Flux.fromIterable(Arrays.asList("blue", "green", "orange", "purple"))
    .doOnNext(System.out::println)
    .transformDeferred(filterAndMap);

composedFlux.subscribe(d -> System.out.println("Subscriber 1 to Composed MapAndFilter
:"+d));
composedFlux.subscribe(d -> System.out.println("Subscriber 2 to Composed MapAndFilter:
"+d));
```

The following image shows how the `transformDeferred` operator works with per-subscriber transformations:



The preceding example produces the following output:

```
blue
Subscriber 1 to Composed MapAndFilter :BLUE
green
Subscriber 1 to Composed MapAndFilter :GREEN
orange
purple
Subscriber 1 to Composed MapAndFilter :PURPLE
blue
Subscriber 2 to Composed MapAndFilter: BLUE
green
Subscriber 2 to Composed MapAndFilter: GREEN
orange
Subscriber 2 to Composed MapAndFilter: ORANGE
purple
```

9.2. Hot Versus Cold

So far, we have considered that all `Flux` (and `Mono`) are the same: They all represent an asynchronous sequence of data, and nothing happens before you subscribe.

Really, though, there are two broad families of publishers: hot and cold.

The earlier description applies to the cold family of publishers. They generate data anew for each subscription. If no subscription is created, data never gets generated.

Think of an HTTP request: Each new subscriber triggers an HTTP call, but no call is made if no one is interested in the result.

Hot publishers, on the other hand, do not depend on any number of subscribers. They might start publishing data right away and would continue doing so whenever a new `Subscriber` comes in (in which case, the subscriber would see only new elements emitted *after* it subscribed). For hot publishers, *something* does indeed happen before you subscribe.

One example of the few hot operators in Reactor is `just`: It directly captures the value at assembly time and replays it to anybody subscribing to it later. To re-use the HTTP call analogy, if the captured data is the result of an HTTP call, then only one network call is made, when instantiating `just`.

To transform `just` into a cold publisher, you can use `defer`. It defers the HTTP request in our example to subscription time (and would result in a separate network call for each new subscription).

On the opposite, `share()` and `replay(…)` can be used to turn a cold publisher into a hot one (at least once a first subscription has happened). Both of these also have `Sinks.Many` equivalents in the `Sinks` class, which allow programmatically feeding the sequence.

Consider two examples, one that demonstrates a cold Flux and the other that makes use of the `Sinks` to simulate a hot Flux. The following code shows the first example:

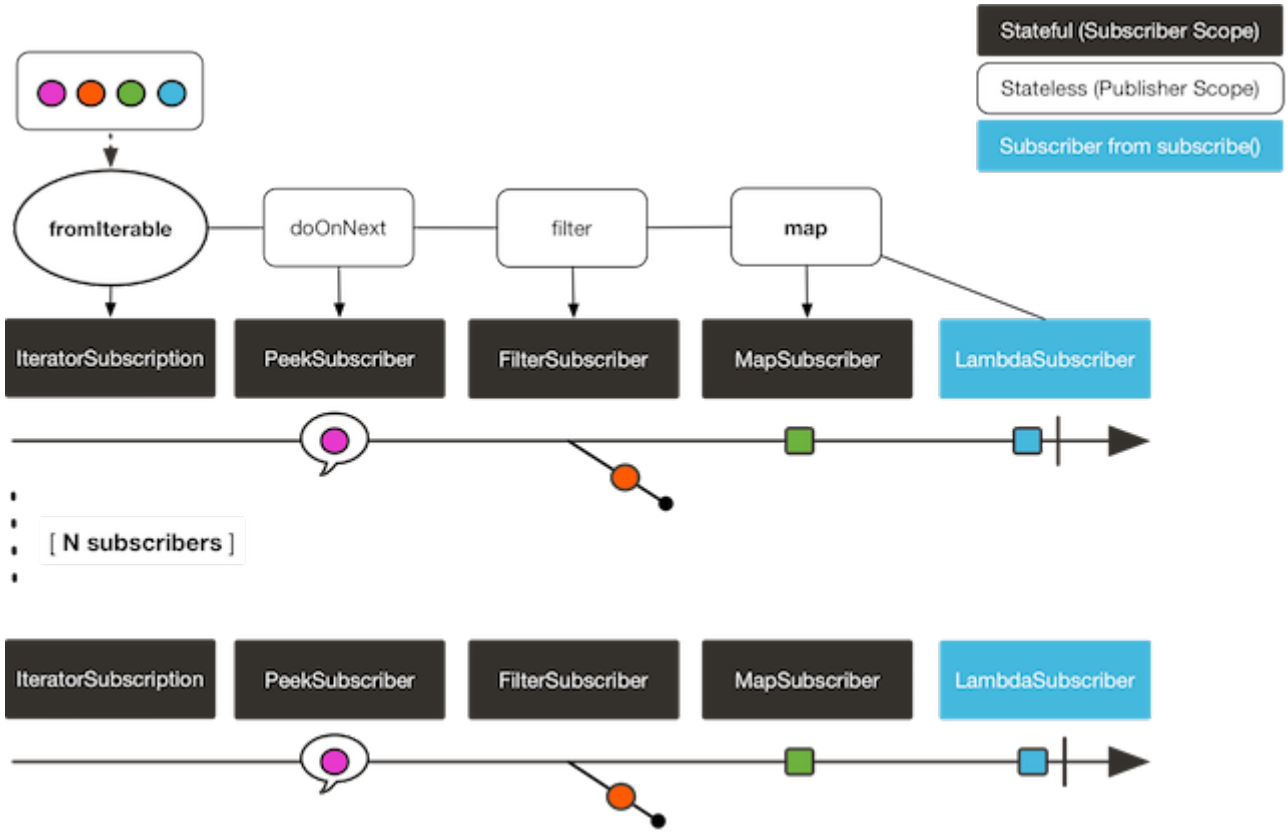
```
Flux<String> source = Flux.fromIterable(Arrays.asList("blue", "green", "orange",
"purple"))
                          .map(String::toUpperCase);

source.subscribe(d -> System.out.println("Subscriber 1: "+d));
source.subscribe(d -> System.out.println("Subscriber 2: "+d));
```

This first example produces the following output:

```
Subscriber 1: BLUE
Subscriber 1: GREEN
Subscriber 1: ORANGE
Subscriber 1: PURPLE
Subscriber 2: BLUE
Subscriber 2: GREEN
Subscriber 2: ORANGE
Subscriber 2: PURPLE
```

The following image shows the replay behavior:



Both subscribers catch all four colors, because each subscriber causes the process defined by the operators on the `Flux` to run.

Compare the first example to the second example, shown in the following code:

```
Sinks.Many<String> hotSource = Sinks.unsafe().many().multicast().directBestEffort();

Flux<String> hotFlux = hotSource.asFlux().map(String::toUpperCase);

hotFlux.subscribe(d -> System.out.println("Subscriber 1 to Hot Source: "+d));

hotSource.emitNext("blue", FAIL_FAST); ①
hotSource.tryEmitNext("green").orThrow(); ②

hotFlux.subscribe(d -> System.out.println("Subscriber 2 to Hot Source: "+d));

hotSource.emitNext("orange", FAIL_FAST);
hotSource.emitNext("purple", FAIL_FAST);
hotSource.emitComplete(FAIL_FAST);
```

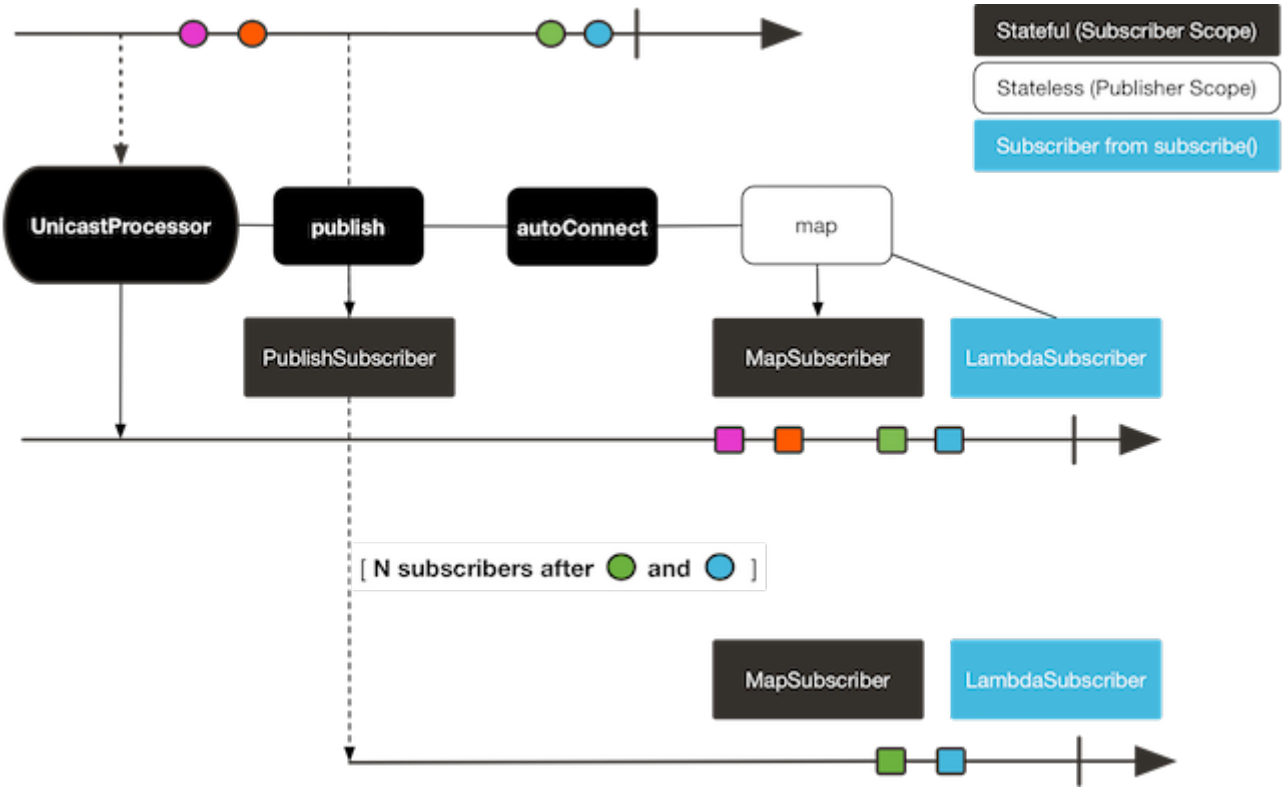
① for more details about sinks, see Sinks

② side note: `orThrow()` here is an alternative to `emitNext` + `Sinks.EmitFailureHandler.FAIL_FAST` that is suitable for tests, since throwing there is acceptable (more so than in reactive applications).

The second example produces the following output:

```
Subscriber 1 to Hot Source: BLUE
Subscriber 1 to Hot Source: GREEN
Subscriber 1 to Hot Source: ORANGE
Subscriber 2 to Hot Source: ORANGE
Subscriber 1 to Hot Source: PURPLE
Subscriber 2 to Hot Source: PURPLE
```

The following image shows how a subscription is broadcast:



Subscriber 1 catches all four colors. Subscriber 2, having been created after the first two colors were produced, catches only the last two colors. This difference accounts for the doubling of `ORANGE` and `PURPLE` in the output. The process described by the operators on this Flux runs regardless of when subscriptions have been attached.

9.3. Broadcasting to Multiple Subscribers with `ConnectableFlux`

Sometimes, you may want to not defer only some processing to the subscription time of one subscriber, but you might actually want for several of them to rendezvous and then trigger the subscription and data generation.

This is what `ConnectableFlux` is made for. Two main patterns are covered in the `Flux` API that return a `ConnectableFlux`: `publish` and `replay`.

- `publish` dynamically tries to respect the demand from its various subscribers, in terms of backpressure, by forwarding these requests to the source. Most notably, if any subscriber has a pending demand of `0`, publish pauses its requesting to the source.
- `replay` buffers data seen through the first subscription, up to configurable limits (in time and buffer size). It replays the data to subsequent subscribers.

A `ConnectableFlux` offers additional methods to manage subscriptions downstream versus subscriptions to the original source. These additional methods include the following:

- `connect()` can be called manually once you reach enough subscriptions to the `Flux`. That triggers the subscription to the upstream source.
- `autoConnect(n)` can do the same job automatically once `n` subscriptions have been made.
- `refCount(n)` not only automatically tracks incoming subscriptions but also detects when these

subscriptions are cancelled. If not enough subscribers are tracked, the source is “disconnected”, causing a new subscription to the source later if additional subscribers appear.

- `refCount(int, Duration)` adds a “grace period.” Once the number of tracked subscribers becomes too low, it waits for the `Duration` before disconnecting the source, potentially allowing for enough new subscribers to come in and cross the connection threshold again.

Consider the following example:

```
Flux<Integer> source = Flux.range(1, 3)
                           .doOnSubscribe(s -> System.out.println("subscribed to
source"));

ConnectableFlux<Integer> co = source.publish();

co.subscribe(System.out::println, e -> {}, () -> {});
co.subscribe(System.out::println, e -> {}, () -> {});

System.out.println("done subscribing");
Thread.sleep(500);
System.out.println("will now connect");

co.connect();
```

The preceding code produces the following output:

```
done subscribing
will now connect
subscribed to source
1
1
2
2
3
3
```

The following code uses `autoConnect`:

```
Flux<Integer> source = Flux.range(1, 3)
                           .doOnSubscribe(s -> System.out.println("subscribed to
source"));

Flux<Integer> autoCo = source.publish().autoConnect(2);

autoCo.subscribe(System.out::println, e -> {}, () -> {});
System.out.println("subscribed first");
Thread.sleep(500);
System.out.println("subscribing second");
autoCo.subscribe(System.out::println, e -> {}, () -> {});
```

The preceding code produces the following output:

```
subscribed first
subscribing second
subscribed to source
1
1
2
2
3
3
```

9.4. Three Sorts of Batching

When you have lots of elements and you want to separate them into batches, you have three broad solutions in Reactor: grouping, windowing, and buffering. These three are conceptually close, because they redistribute a `Flux<T>` into an aggregate. Grouping and windowing create a `Flux<Flux<T>>`, while buffering aggregates into a `Collection<T>`.

Grouping with `Flux<GroupedFlux<T>>`

Grouping is the act of splitting the source `Flux<T>` into multiple batches, each of which matches a key.

The associated operator is `groupBy`.

Each group is represented as a `GroupedFlux<T>`, which lets you retrieve the key by calling its `key()` method.

There is no necessary continuity in the content of the groups. Once a source element produces a new key, the group for this key is opened and elements that match the key end up in the group (several groups could be open at the same time).

This means that groups:

1. Are always disjoint (a source element belongs to one and only one group).

2. Can contain elements from different places in the original sequence.
3. Are never empty.

The following example groups values by whether they are even or odd:

```
StepVerifier.create(
    Flux.just(1, 3, 5, 2, 4, 6, 11, 12, 13)
        .groupBy(i -> i % 2 == 0 ? "even" : "odd")
        .concatMap(g -> g.defaultIfEmpty(-1) //if empty groups, show them
                .map(String::valueOf) //map to string
                .startWith(g.key())) //start with the group's key
    )
    .expectNext("odd", "1", "3", "5", "11", "13")
    .expectNext("even", "2", "4", "6", "12")
    .verifyComplete();
```

Grouping is best suited for when you have a medium to low number of groups. The groups must also imperatively be consumed (such as by a `flatMap`) so that `groupBy` continues fetching data from upstream and feeding more groups. Sometimes, these two constraints multiply and lead to hangs, such as when you have a high cardinality and the concurrency of the `flatMap` consuming the groups is too low.

To better understand the risks of hangs when combining `groupBy` with inappropriate operators, let's consider an example.

The following snippet groups strings by their 1st character:

```
 public static Flux<String> createGroupedFlux() {
        List<String> data = List.of("alpha", "air", "aim", "beta", "cat", "ball",
"apple", "bat", "dog", "ace");
        return Flux.fromIterable(data)
                .groupBy(d -> d.charAt(0), 5)
                .concatMap(g -> g.map(String::valueOf)
                        .startWith(String.valueOf(g.key()))
                        .map(o -> {
                            System.out.println(o);
                            return o;
                        })
                );
    }

    @Test
    public void testGroupBy() {
        StepVerifier.create(createGroupedFlux())
                .expectNext("a", "alpha", "air", "aim", "apple", "ace")
                .expectNext("b", "beta", "ball", "bat")
                .expectNext("c", "cat", "d", "dog")
                .verifyComplete();
    }
```

In the above:

- The cardinality of groups is **4** (`"a"`, `"b"`, `"c"`, and `"d"` being the group keys).
- The concurrency of `concatMap` is **1**.
- The buffer size of `groupBy` is **5** (since we defined `prefetch` as 5; by default it's 256),

```
a alpha air aim apple
```

The test gets stuck after printing these elements. Let's consider what happened.

1. Initially, `groupBy` requests 5 elements. They end up in a buffer: `"alpha", "air", "aim", "beta", "cat"`.
2. `concatMap` has concurrency of **1**. Therefore, the group with key `"a"` is the only group that gets subscribed. Out of the initial items, `"alpha", "air", "aim"` are consumed by `concatMap` and `"beta", "cat"` remain in the buffer.
3. Next, `groupBy` requests additional 3 items (2 items are already buffered). The buffer now contains `"beta", "cat", "ball", "apple", "bat"`. Out of these, `"apple"` is consumed and the rest remain in the buffer.
4. Next, `groupBy` requests for additional 1 item (4 spaces are already occupied in buffer). The buffered items are `"beta", "cat", "ball", "bat","dog"`.
5. Now, nothing in the buffer belongs to group `"a"`, hence no more consumption happens by `concatMap` and the first Flux remains not completed. `groupBy` is unable to request more data from

the publisher since its buffer size is full. The publisher faces backpressure and is not able to publish the remaining items. This results in the deadlock.

In the same example, if the data was in a slightly different order, for example:

```
"alpha", "air", "aim", "beta", "cat", "ball", "apple", "dog", "ace", "bat"
```

The same test would pass successfully: the same `concatMap` would be able to receive a complete signal, complete one group, then subscribe to next group and so on. Hence, when the pattern of data published is arbitrary, `groupBy` is likely to face a deadlock when the consumption pattern doesn't match the capacity of the `groupBy` buffer.

Windowing with `Flux<Flux<T>>`

Windowing is the act of splitting the source `Flux<T>` into *windows*, by criteria of size, time, boundary-defining predicates, or boundary-defining `Publisher`.

The associated operators are `window`, `windowTimeout`, `windowUntil`, `windowWhile`, and `windowWhen`.

Contrary to `groupBy`, which randomly overlaps according to incoming keys, windows are (most of the time) opened sequentially.

Some variants can still overlap, though. For instance, in `window(int maxSize, int skip)` the `maxSize` parameter is the number of elements after which a window closes, and the `skip` parameter is the number of elements in the source after which a new window is opened. So if `maxSize > skip`, a new window opens before the previous one closes and the two windows overlap.

The following example shows overlapping windows:

```
StepVerifier.create(
    Flux.range(1, 10)
        .window(5, 3) //overlapping windows
        .concatMap(g -> g.defaultIfEmpty(-1)) //show empty windows as -1
    )
        .expectNext(1, 2, 3, 4, 5)
        .expectNext(4, 5, 6, 7, 8)
        .expectNext(7, 8, 9, 10)
        .expectNext(10)
        .verifyComplete();
```

With the reverse configuration (`maxSize` < `skip`), some elements from the source are dropped and are not part of any window.

In the case of predicate-based windowing through `windowUntil` and `windowWhile`, having subsequent source elements that do not match the predicate can also lead to empty windows, as demonstrated in the following example:

```
StepVerifier.create(
    Flux.just(1, 3, 5, 2, 4, 6, 11, 12, 13)
        .windowWhile(i -> i % 2 == 0)
        .concatMap(g -> g.defaultIfEmpty(-1))
    )
        .expectNext(-1, -1, -1) //respectively triggered by odd 1 3 5
        .expectNext(2, 4, 6) // triggered by 11
        .expectNext(12) // triggered by 13
        // however, no empty completion window is emitted (would contain extra
matching elements)
        .verifyComplete();
```

Buffering with `Flux<List<T>>`

Buffering is similar to windowing, with the following twist: Instead of emitting *windows* (each of which is each a `Flux<T>`), it emits *buffers* (which are `Collection<T>` — by default, `List<T>`).

The operators for buffering mirror those for windowing: `buffer`, `bufferTimeout`, `bufferUntil`, `bufferWhile`, and `bufferWhen`.

Where the corresponding windowing operator opens a window, a buffering operator creates a new collection and starts adding elements to it. Where a window closes, the buffering operator emits the collection.

Buffering can also lead to dropping source elements or having overlapping buffers, as the following example shows:

```
StepVerifier.create(
    Flux.range(1, 10)
        .buffer(5, 3) //overlapping buffers
    )
        .expectNext(Arrays.asList(1, 2, 3, 4, 5))
        .expectNext(Arrays.asList(4, 5, 6, 7, 8))
        .expectNext(Arrays.asList(7, 8, 9, 10))
        .expectNext(Collections.singletonList(10))
        .verifyComplete();
```

Unlike in windowing, `bufferUntil` and `bufferWhile` do not emit an empty buffer, as the following example shows:

```
StepVerifier.create(
    Flux.just(1, 3, 5, 2, 4, 6, 11, 12, 13)
        .bufferWhile(i -> i % 2 == 0)
    )
    .expectNext(Arrays.asList(2, 4, 6)) // triggered by 11
    .expectNext(Collections.singletonList(12)) // triggered by 13
    .verifyComplete();
```

9.5. Parallelizing Work with `ParallelFlux`

With multi-core architectures being a commodity nowadays, being able to easily parallelize work is important. Reactor helps with that by providing a special type, `ParallelFlux`, that exposes operators that are optimized for parallelized work.

To obtain a `ParallelFlux`, you can use the `parallel()` operator on any `Flux`. By itself, this method does not parallelize the work. Rather, it divides the workload into "rails" (by default, as many rails as there are CPU cores).

In order to tell the resulting `ParallelFlux` where to run each rail (and, by extension, to run rails in parallel) you have to use `runOn(Scheduler)`. Note that there is a recommended dedicated `Scheduler` for parallel work: `Schedulers.parallel()`.

Compare the next two examples:

```
Flux.range(1, 10)
    .parallel(2) ①
    .subscribe(i -> System.out.println(Thread.currentThread().getName() + " -> " +
i));
```

① We force a number of rails instead of relying on the number of CPU cores.

```
Flux.range(1, 10)
    .parallel(2)
    .runOn(Schedulers.parallel())
    .subscribe(i -> System.out.println(Thread.currentThread().getName() + " -> " +
i));
```

The first example produces the following output:

```
main -> 1
main -> 2
main -> 3
main -> 4
main -> 5
main -> 6
main -> 7
main -> 8
main -> 9
main -> 10
```

The second correctly parallelizes on two threads, as shown in the following output:

```
parallel-1 -> 1
parallel-2 -> 2
parallel-1 -> 3
```

```
parallel-2 -> 4
parallel-1 -> 5
parallel-2 -> 6
parallel-1 -> 7
parallel-1 -> 9
parallel-2 -> 8
parallel-2 -> 10
```

If, once you process your sequence in parallel, you want to revert back to a “normal” `Flux` and apply the rest of the operator chain in a sequential manner, you can use the `sequential()` method on `ParallelFlux`.

Note that `sequential()` is implicitly applied if you `subscribe` to the `ParallelFlux` with a `Subscriber` but not when using the lambda-based variants of `subscribe`.

Note also that `subscribe(Subscriber<T>)` merges all the rails, while `subscribe(Consumer<T>)` runs all the rails. If the `subscribe()` method has a lambda, each lambda is executed as many times as there are rails.

You can also access individual rails or “groups” as a `Flux<GroupedFlux<T>>` through the `groups()` method and apply additional operators to them through the `composeGroup()` method.

9.6. Replacing Default `Schedulers`

As we described in the Threading and Schedulers section, Reactor Core comes with several `Scheduler` implementations. While you can always create new instances through the `new*` factory methods, each `Scheduler` flavor also has a default singleton instance that is accessible through the direct factory method (such as `Schedulers.boundedElastic()` versus `Schedulers.newBoundedElastic(…)`).

These default instances are the ones used by operators that need a `Scheduler` to work when you do not explicitly specify one. For example, `Flux#delayElements(Duration)` uses the `Schedulers.parallel()` instance.

In some cases, however, you might need to change these default instances with something else in a cross-cutting way, without having to make sure every single operator you call has your specific `Scheduler` as a parameter. An example is measuring the time every single scheduled task takes by wrapping the real schedulers, for instrumentation purposes. In other words, you might want to change the default `Schedulers`.

Changing the default schedulers is possible through the `Schedulers.Factory` class. By default, a `Factory` creates all the standard `Scheduler` through similarly named methods. You can override each of these with your custom implementation.

Additionally, the factory exposes one additional customization method: `decorateExecutorService`. It is invoked during the creation of every Reactor Core `Scheduler` that is backed by a `ScheduledExecutorService` (even non-default instances, such as those created by calls to `Schedulers.newParallel()`).

This lets you tune the `ScheduledExecutorService` to be used: The default one is exposed as a `Supplier` and, depending on the type of `Scheduler` being configured, you can choose to entirely bypass that supplier and return your own instance or you can `get()` the default instance and wrap it.

Once you create a `Factory` that fits your needs, you must install it by calling `Schedulers.setFactory(Factory)`.

Finally, there is a last customizable hook in `Schedulers`: `onHandleError`. This hook is invoked whenever a `Runnable` task submitted to a `Scheduler` throws an `Exception` (note that if there is an `UncaughtExceptionHandler` set for the `Thread` that ran the task, both the handler and the hook are invoked).

9.7. Using Global Hooks

Reactor has another category of configurable callbacks that are invoked by Reactor operators in various situations. They are all set in the `Hooks` class, and they fall into three categories:

- Dropping Hooks
- Internal Error Hook
- Assembly Hooks

Dropping Hooks

Dropping hooks are invoked when the source of an operator does not comply with the Reactive Streams specification. These kind of errors are outside of the normal execution path (that is, they cannot be propagated through `onError`).

Typically, a `Publisher` calls `onNext` on the operator despite having already called `onCompleted` on it previously. In that case, the `onNext` value is dropped. The same is true for an extraneous `onError` signal.

The corresponding hooks, `onNextDropped` and `onErrorDropped`, let you provide a global `Consumer` for these drops. For example, you can use it to log the drop and clean up resources associated with a value if needed (as it never makes it to the rest of the reactive chain).

Setting the hooks twice in a row is additive: every consumer you provide is invoked. The hooks can be fully reset to their defaults by using the `Hooks.resetOn*Dropped()` methods.

Internal Error Hook

One hook, `onOperatorError`, is invoked by operators when an unexpected `Exception` is thrown during the execution of their `onNext`, `onError`, and `onComplete` methods.

Unlike the previous category, this is still within the normal execution path. A typical example is the `map` operator with a map function that throws an `Exception` (such as division by zero). It is still possible at this point to go through the usual channel of `onError`, and that is what the operator does.

First, it passes the `Exception` through `onOperatorError`. The hook lets you inspect the error (and the

incriminating value, if relevant) and change the `Exception`. Of course, you can also do something on the side, such as log and return the original `Exception`.

Note that you can set the `onOperatorError` hook multiple times. You can provide a `String` identifier for a particular `BiFunction` and subsequent calls with different keys concatenates the functions, which are all executed. On the other hand, reusing the same key twice lets you replace a function you previously set.

As a consequence, the default hook behavior can be both fully reset (by using `Hooks.resetOnOperatorError()`) or partially reset for a specific `key` only (by using `Hooks.resetOnOperatorError(String)`).

Assembly Hooks

These hooks tie in the lifecycle of operators. They are invoked when a chain of operators is assembled (that is, instantiated). `onEachOperator` lets you dynamically change each operator as it is assembled in the chain, by returning a different `Publisher`. `onLastOperator` is similar, except that it is invoked only on the last operator in the chain before the `subscribe` call.

If you want to decorate all operators with a cross-cutting `Subscriber` implementation, you can look into the `Operators#lift*` methods to help you deal with the various types of Reactor `Publishers` out there (`Flux`, `Mono`, `ParallelFlux`, `GroupedFlux`, and `ConnectableFlux`), as well as their `Fuseable` versions.

Like `onOperatorError`, these hooks are cumulative and can be identified with a key. They can also be reset partially or totally.

Hook Presets

The `Hooks` utility class provides two preset hooks. These are alternatives to the default behaviors that you can use by calling their corresponding method, rather than coming up with the hook yourself:

- `onNextDroppedFail()`: `onNextDropped` used to throw a `Exceptions.failWithCancel()` exception. It now defaults to logging the dropped value at the DEBUG level. To go back to the old default behavior of throwing, use `onNextDroppedFail()`.
- `onOperatorDebug()`: This method activates debug mode. It ties into the `onOperatorError` hook, so calling `resetOnOperatorError()` also resets it. You can independently reset it by using `resetOnOperatorDebug()`, as it uses a specific key internally.

9.8. Adding a Context to a Reactive Sequence

One of the big technical challenges encountered when switching from an imperative programming perspective to a reactive programming mindset lies in how you deal with threading.

Contrary to what you might be used to, in reactive programming, you can use a `Thread` to process several asynchronous sequences that run at roughly the same time (actually, in non-blocking locksteps). The execution can also easily and often jump from one thread to another.

This arrangement is especially hard for developers that use features dependent on the threading

model being more “stable,” such as `ThreadLocal`. As it lets you associate data with a thread, it becomes tricky to use in a reactive context. As a result, libraries that rely on `ThreadLocal` at least introduce new challenges when used with Reactor. At worst, they work badly or even fail. Using the MDC of Logback to store and log correlation IDs is a prime example of such a situation.

The usual workaround for `ThreadLocal` usage is to move the contextual data, `C`, along your business data, `T`, in the sequence, by using (for instance) `Tuple2<T, C>`. This does not look good and leaks an orthogonal concern (the contextual data) into your method and `Flux` signatures.

Since version `3.1.0`, Reactor comes with an advanced feature that is somewhat comparable to `ThreadLocal` but can be applied to a `Flux` or a `Mono` instead of a `Thread`. This feature is called `Context`.

As an illustration of what it looks like, the following example both reads from and writes to `Context`:

```
String key = "message";
Mono<String> r = Mono.just("Hello")
    .flatMap(s -> Mono.deferContextual(ctx ->
         Mono.just(s + " " + ctx.get(key))))
    .contextWrite(ctx -> ctx.put(key, "World"));

StepVerifier.create(r)
            .expectNext("Hello World")
            .verifyComplete();
```

In the following sections, we cover `Context` and how to use it, so that you can eventually understand the preceding example.

This is an advanced feature that is more targeted at library developers. It requires good understanding of the lifecycle of a `Subscription` and is intended for libraries that are responsible for the subscriptions.

The `Context` API

`Context` is an interface reminiscent of `Map`. It stores key-value pairs and lets you fetch a value you stored by its key. It has a simplified version that only exposes read methods, the `ContextView`. More specifically:

- Both key and values are of type `Object`, so a `Context` (and `ContextView`) instance can contain any number of highly divergent values from different libraries and sources.
- A `Context` is immutable. It exposes write methods like `put` and `putAll` but they produce a new instance.
- For a read-only API that doesn’t even expose such write methods, there’s the `ContextView` superinterface since 3.4.0
- You can check whether the key is present with `hasKey(Object key)`.
- Use `getOrDefault(Object key, T defaultValue)` to retrieve a value (cast to a `T`) or fall back to a default one if the `Context` instance does not have that key.

- Use `getOrEmpty(Object key)` to get an `Optional<T>` (the `Context` instance attempts to cast the stored value to `T`).
- Use `put(Object key, Object value)` to store a key-value pair, returning a new `Context` instance. You can also merge two contexts into a new one by using `putAll(ContextView)`.
- Use `delete(Object key)` to remove the value associated to a key, returning a new `Context`.

When you create a `Context`, you can create pre-valued `Context` instances with up to five key-value pairs by using the static `Context.of` methods. They take 2, 4, 6, 8 or 10 `Object` instances, each couple of `Object` instances being a key-value pair to add to the `Context`.

Alternatively you can also create an empty `Context` by using `Context.empty()`.

Tying a `Context` to a `Flux` and Writing

To make a `Context` be useful, it must be tied to a specific sequence and be accessible by each operator in a chain. Note that the operator must be a Reactor-native operator, as `Context` is specific to Reactor.

Actually, a `Context` is tied to each `Subscriber` in a chain. It uses the `Subscription` propagation mechanism to make itself available to each operator, starting with the final `subscribe` and moving up the chain.

In order to populate the `Context`, which can only be done at subscription time, you need to use the `contextWrite` operator.

`contextWrite(ContextView)` merges the `ContextView` you provide and the `Context` from downstream (remember, the `Context` is propagated from the bottom of the chain towards the top). This is done through a call to `putAll`, resulting in a NEW `Context` for upstream.

You can also use the more advanced `contextWrite(Function<Context, Context>)`. It receives a copy of the `Context` from downstream, lets you put or delete values as you see fit, and returns the new `Context` to use. You can even decide to return a completely different instance, although it is really not recommended (doing so might impact third-party libraries that depend on the `Context`).

Reading a `Context`, through the `ContextView`

Once you have populated a `Context`, you may want to peek into it at runtime. Most of the time, the responsibility of putting information into the `Context` is on the end user's side, while exploiting that information is on the third-party library's side, as such libraries are usually upstream of the client code.

The read oriented operators allow to obtain data from the `Context` in a chain of operators by exposing its `ContextView`:

- to access the context from a source-like operator, use `deferContextual` factory method
- to access the context from the middle of an operator chain, use

`transformDeferredContextual(BiFunction)`

- alternatively, when dealing with an inner sequence (like inside a `flatMap`), the `ContextView` can be materialized using `Mono.deferContextual(Mono::just)`. Usually though, you might want to perform meaningful work directly within the defer's lambda, eg. `Mono.deferContextual(ctx -> doSomethingAsyncWithContextData(v, ctx.get(key)))` where `v` is the value being flatMapped.

In order to read from the `Context` without misleading users into thinking one can write to it while data is running through the pipeline, only the `ContextView` is exposed by the operators above. In case one needs to use one of the remaining APIs that still require a `Context`, one can use `Context.of(contextView)` for conversion.

Simple `Context` Examples

The examples in this section are meant as ways to better understand some of the caveats of using a `Context`.

We first look back at our simple example from the introduction in a bit more detail, as the following example shows:

```
String key = "message";
Mono<String> r = Mono.just("Hello")
    .flatMap(s -> Mono.deferContextual(ctx ->
         Mono.just(s + " " + ctx.get(key)))) ②
    .contextWrite(ctx -> ctx.put(key, "World")); ①

StepVerifier.create(r)
            .expectNext("Hello World") ③
            .verifyComplete();
```

① The chain of operators ends with a call to `contextWrite(Function)` that puts `"World"` into the `Context` under a key of `"message"`.

② We `flatMap` on the source element, materializing the `ContextView` with `Mono.deferContextual()` and directly extract the data associated to `"message"` and concatenate that with the original word.

③ The resulting `Mono<String>` emits `"Hello World"`.

The numbering above versus the actual line order is not a mistake. It represents the execution order. Even though `contextWrite` is the last piece of the chain, it is the one that gets executed first (due to its subscription-time nature and the fact that the subscription signal flows from bottom to top).

In your chain of operators, the relative positions of where you write to the `Context` and where you read from it matters. The `Context` is immutable and its content can only be seen by operators above it, as demonstrated in the following example:

```
String key = "message";
Mono<String> r = Mono.just("Hello")
    .contextWrite(ctx -> ctx.put(key, "World")) ①
    .flatMap( s -> Mono.deferContextual(ctx ->
        Mono.just(s + " " + ctx.getOrDefault(key, "Stranger")))); ②

StepVerifier.create(r)
            .expectNext("Hello Stranger") ③
            .verifyComplete();
```

① The `Context` is written to too high in the chain.

② As a result, in the `flatMap`, there is no value associated with our key. A default value is used instead.

③ The resulting `Mono<String>` thus emits `"Hello Stranger"`.

Similarly, in the case of several attempts to write the same key to the `Context`, the relative order of the writes matters, too. Operators that read the `Context` see the value that was set closest to being under them, as demonstrated in the following example:

```
String key = "message";
Mono<String> r = Mono
    .deferContextual(ctx -> Mono.just("Hello " + ctx.get(key)))
    .contextWrite(ctx -> ctx.put(key, "Reactor")) ①
    .contextWrite(ctx -> ctx.put(key, "World")); ②

StepVerifier.create(r)
            .expectNext("Hello Reactor") ③
            .verifyComplete();
```

① A write attempt on key `"message"`.

② Another write attempt on key `"message"`.

③ The `deferContextual` only saw the value set closest to it (and below it): `"Reactor"`.

In the preceding example, the `Context` is populated with `"World"` during subscription. Then the subscription signal moves upstream and another write happens. This produces a second immutable `Context` with a value of `"Reactor"`. After that, data starts flowing. The `deferContextual` sees the `Context` closest to it, which is our second `Context` with the `"Reactor"` value (exposed to the user as a `ContextView`).

You might wonder if the `Context` is propagated along with the data signal. If that was the case, putting another `flatMap` between these two writes would use the value from the top `Context`. But this is not the case, as demonstrated by the following example:

```
String key = "message";
Mono<String> r = Mono
    .deferContextual(ctx -> Mono.just("Hello " + ctx.get(key))) ③
    .contextWrite(ctx -> ctx.put(key, "Reactor")) ②
    .flatMap( s -> Mono.deferContextual(ctx ->
        Mono.just(s + " " + ctx.get(key)))) ④
    .contextWrite(ctx -> ctx.put(key, "World")); ①

StepVerifier.create(r)
            .expectNext("Hello Reactor World") ⑤
            .verifyComplete();
```

① This is the first write to happen.

② This is the second write to happen.

③ The top context read sees second write.

④ The `flatMap` concatenates the result from initial read with the value from the first write.

⑤ The `Mono` emits `"Hello Reactor World"`.

The reason is that the `Context` is associated to the `Subscriber` and each operator accesses the `Context` by requesting it from its downstream `Subscriber`.

One last interesting propagation case is the one where the `Context` is also written to inside a `flatMap`, as in the following example:

```
String key = "message";
Mono<String> r = Mono.just("Hello")
    .flatMap( s -> Mono
        .deferContextual(ctxView -> Mono.just(s + " " + ctxView.get(key)))
    )
    .flatMap( s -> Mono
        .deferContextual(ctxView -> Mono.just(s + " " + ctxView.get(key)))
        .contextWrite(ctx -> ctx.put(key, "Reactor")) ①
    )
    .contextWrite(ctx -> ctx.put(key, "World")); ②

StepVerifier.create(r)
            .expectNext("Hello World Reactor")
            .verifyComplete();
```

① This `contextWrite` does not impact anything outside of its `flatMap`.

② This `contextWrite` impacts the main sequence's `Context`.

In the preceding example, the final emitted value is `"Hello World Reactor"` and not "Hello Reactor World", because the `contextWrite` that writes `"Reactor"` does so as part of the inner sequence of the second `flatMap`. As a consequence, it is not visible or propagated through the main sequence and the first `flatMap` does not see it. Propagation and immutability isolate the `Context` in operators that create intermediate inner sequences such as `flatMap`.

Full Example

Now we can consider a more real life example of a library reading information from the `Context`: a reactive HTTP client that takes a `Mono<String>` as the source of data for a `PUT` but also looks for a particular Context key to add a correlation ID to the request's headers.

From the user perspective, it is called as follows:

```
doPut("www.example.com", Mono.just("Walter"))
```

In order to propagate a correlation ID, it would be called as follows:

```
doPut("www.example.com", Mono.just("Walter"))
    .contextWrite(Context.of(HTTP_CORRELATION_ID, "2-j3r9afaf92j-afkaf"))
```

As the preceding snippets show, the user code uses `contextWrite` to populate a `Context` with an `HTTP_CORRELATION_ID` key-value pair. The upstream of the operator is a `Mono<Tuple2<Integer, String>>` (a simplistic representation of an HTTP response) returned by the HTTP client library. So it effectively passes information from the user code to the library code.

The following example shows mock code from the library's perspective that reads the context and "augments the request" if it can find the correlation ID:

```
static final String HTTP_CORRELATION_ID = "reactive.http.library.correlationId";

Mono<Tuple2<Integer, String>> doPut(String url, Mono<String> data) {
  Mono<Tuple2<String, Optional<Object>>> dataAndContext =
      data.zipWith(Mono.deferContextual(c -> ①
          Mono.just(c.getOrEmpty(HTTP_CORRELATION_ID))) ②
      );

  return dataAndContext.<String>handle((dac, sink) -> {
      if (dac.getT2().isPresent()) { ③
        sink.next("PUT <" + dac.getT1() + "> sent to " + url +
            " with header X-Correlation-ID = " + dac.getT2().get());
      }
      else {
        sink.next("PUT <" + dac.getT1() + "> sent to " + url);
      }
        sink.complete();
      })
      .map(msg -> Tuples.of(200, msg));
}
```

① Materialize the `ContextView` through `Mono.deferContextual` and…

② within the defer, extract a value for the correlation ID key, as an `Optional`.

③ If the key was present in the context, use the correlation ID as a header.

The library snippet zips the data `Mono` with `Mono.deferContextual(Mono::just)`. This gives the library a `Tuple2<String, ContextView>`, and that context contains the `HTTP_CORRELATION_ID` entry from downstream (as it is on the direct path to the subscriber).

The library code then uses `map` to extract an `Optional<String>` for that key, and, if the entry is present, it uses the passed correlation ID as a `X-Correlation-ID` header. That last part is simulated by the `handle`.

The whole test that validates the library code used the correlation ID can be written as follows:

```
@Test
public void contextForLibraryReactivePut() {
  Mono<String> put = doPut("www.example.com", Mono.just("Walter"))
      .contextWrite(Context.of(HTTP_CORRELATION_ID, "2-j3r9afaf92j-afkaf"))
      .filter(t -> t.getT1() < 300)
      .map(Tuple2::getT2);

  StepVerifier.create(put)
              .expectNext("PUT <Walter> sent to www.example.com" +
                  " with header X-Correlation-ID = 2-j3r9afaf92j-afkaf")
              .verifyComplete();
}
```

9.9. Context-Propagation Support

Since 3.5.0, Reactor-Core embeds support for the `io.micrometer:context-propagation` SPI. This library is intended as a means to easily adapt between various implementations of the concept of a Context, of which `ContextView`/`Context` is an example, and between `ThreadLocal` variables as well.

`ReactorContextAccessor` allows the Context-Propagation library to understand Reactor `Context` and `ContextView`. It implements the SPI and is loaded via `java.util.ServiceLoader`. No user action is required, other than having a dependency on both reactor-core and `io.micrometer:context-propagation`. The `ReactorContextAccessor` class is public but shouldn't generally be accessed by user code.

Reactor-Core supports two modes of operation with `io.micrometer:context-propagation`:

- the **default** (limited) mode,
- and the **automatic** mode, enabled via `Hooks.enableAutomaticContextPropagation()`. Please note that this mode applies only to new subscriptions, so it is recommended to enable this hook when the application starts.

Their key differences are discussed in the context of either writing data to Reactor `Context`, or accessing `ThreadLocal` state that reflects the contents of the `Context` of currently attached `Subscriber` for reading.

Writing to `Context`

Depending on the individual application, you might either have to store already populated `ThreadLocal` state as entries in the `Context`, or might only need to directly populate the `Context`.

`contextWrite` Operator

When the values meant to be accessed as `ThreadLocal` are not (or do not need to be) present at the time of subscription, they can immediately be stored in the `Context`:

```
// assuming TL is known to Context-Propagation as key TLKEY.
static final ThreadLocal<String> TL = new ThreadLocal<>();

// in the main Thread, TL is not set

Mono.deferContextual(ctx ->
  Mono.delay(Duration.ofSeconds(1))
      // we're now in another thread, TL is not explicitly set
      .map(v -> "delayed ctx[" + TLKEY + "]=" + ctx.getOrDefault(TLKEY, "not found") +
", TL=" + TL.get()))
.contextWrite(ctx -> ctx.put(TLKEY, "HELLO"))
.block(); // returns "delayed ctx[TLKEY]=HELLO, TL=null" in default mode
          // returns "delayed ctx[TLKEY]=HELLO, TL=HELLO" in automatic mode
```

`contextCapture` Operator

This operator can be used when one needs to capture `ThreadLocal` value(s) at subscription time and reflect these values in the Reactor `Context` for the benefit of upstream operators.

In contrast to the manual `contextWrite` operator, `contextCapture` uses the `context-propagation` API to obtain a `ContextSnapshot` and then uses that snapshot to populate the Reactor `Context`.

As a result, if there were any `ThreadLocal` values during subscription phase, for which there is a registered `ThreadLocalAccessor`, their values would now be stored in the Reactor `Context` and visible at runtime in upstream operators.

```
// assuming TL is known to Context-Propagation as key TLKEY.
static final ThreadLocal<String> TL = new ThreadLocal<>();

// in the main Thread, TL is set to "HELLO"
TL.set("HELLO");

Mono.deferContextual(ctx ->
  Mono.delay(Duration.ofSeconds(1))
      // we're now in another thread, TL is not explicitly set
      .map(v -> "delayed ctx[" + TLKEY + "]=" + ctx.getOrDefault(TLKEY, "not found") +
", TL=" + TL.get()))
.contextCapture() // can be skipped in automatic mode when a blocking operator follows
.block(); // returns "delayed ctx[TLKEY]=HELLO, TL=null" in default mode
          // returns "delayed ctx[TLKEY]=HELLO, TL=HELLO" in automatic mode
```

In the **automatic** mode, blocking operators, such as `Flux#blockFirst()`, `Flux#blockLast()`, `Flux#toIterable()`, `Mono#block()`, `Mono#blockOptional()`, and relevant overloads, all perform `contextCapture()` transparently, so in most cases it is not necessary to add it.

Accessing `ThreadLocal` state

Starting from Reactor-Core 3.5.0, `ThreadLocal` state is restored in a limited set of operators. We call this behaviour the **default** (limited) mode. In 3.5.3, a new mode was added, the **automatic** mode, which provides access to `ThreadLocal` values throughout the reactive chain.

Reactor-Core performs `ThreadLocal` state restoration using the values stored in `Context` and `ThreadLocalAccessor` instances registered in `ContextRegistry` that match by key.

Default mode operators for snapshot restoration: `handle` and `tap`

In the **default** mode, both `Flux` and `Mono` variants of `handle` and `tap` will have their behavior slightly modified if the Context-Propagation library is available at runtime.

Namely, if their downstream `ContextView` is not empty they will assume a context capture has occurred (either manually or via the `contextCapture()` operator) and will attempt to restore ThreadLocals from that snapshot transparently. Any ThreadLocals for keys that are missing in the `ContextView` are left untouched.

These operators will ensure restoration is performed around the user-provided code, respectively:

- `handle` will wrap the `BiConsumer` in one which restores `ThreadLocal`s
- `tap` variants will wrap the `SignalListener` into one that has the same kind of wrapping around each method (this includes the `addToContext` method)

The intent is to have a minimalistic set of operators transparently perform restoration. As a result we chose operators with rather general and broad applications (one with transformative capabilities, one with side-effect capabilities)

```
//assuming TL is known to Context-Propagation.
static final ThreadLocal<String> TL = new ThreadLocal<>();

//in the main thread, TL is set to "HELLO"
TL.set("HELLO");

Mono.delay(Duration.ofSeconds(1))
  //we're now in another thread, TL is not set yet
  .doOnNext(v -> System.out.println(TL.get()))
  //inside the handler however, TL _is_ restored
  .handle((v, sink) -> sink.next("handled delayed TL=" + TL.get()))
  .contextCapture()
  .block(); // prints "null" and returns "handled delayed TL=HELLO"
```

Automatic mode

In the **automatic** mode, all operators restore `ThreadLocal` state across `Thread` boundaries. In contrast, in the **default** mode only selected operators do so.

`Hooks.enableAutomaticContextPropagation()` can be called upon application start to enable the **automatic** mode. Please note that this mode applies only to new subscriptions, so it is recommended to enable this hook when the application starts.

It is not an easy task to achieve, as the Reactive Streams specification makes reactive chains `Thread` -agnostic. However, Reactor-Core does its best to control sources of `Thread` switches and perform snapshot restoration based on the Reactor `Context`, which is treated as the source of truth for `ThreadLocal` state.

While the **default** mode limits the `ThreadLocal` state only to the user code executed as arguments to the chosen operators, the **automatic** mode allows `ThreadLocal` state to cross operator boundaries. This requires proper cleanup to avoid leaking the state to unrelated code which reuses the same `Thread`. This requires to treat absent keys in the `Context` for registered instances of `ThreadLocalAccessor` as signals to clear the corresponding `ThreadLocal` state. This is especially important for an empty `Context`, which clears all state for registered `ThreadLocalAccessor` instances.

Which mode should I choose?

Both **default** and **automatic** modes have an impact on performance. Accessing `ThreadLocal` variables can impact a reactive pipeline significantly. If the highest scalability and performance is the goal, more verbose approaches for logging and explicit argument passing can be considered instead of relying on `ThreadLocal` state. If access to established libraries in the space of Observability, such as Micrometer and SLF4J, which use `ThreadLocal` state for convenience to provide meaningful production grade features is an understood compromise, the choice of the mode is yet another compromise to make. The **automatic** mode, depending on the flow of your application and the amount of operators used, can be either better or worse than the **default** mode. The only recommendation that can be given is to measure how your application behaves and what

scalability and performance characteristics you obtain when presented with a load you expect.

9.10. Dealing with Objects that Need Cleanup

In very specific cases, your application may deal with types that necessitate some form of cleanup once they are no longer in use. This is an advanced scenario — for, example when you have reference-counted objects or when you deal with off-heap objects. Netty's `ByteBuf` is a prime example of both.

In order to ensure proper cleanup of such objects, you need to account for it on a `Flux`-by-`Flux` basis, as well as in several of the global hooks (see Using Global Hooks):

- The `doOnDiscard` `Flux`/`Mono` operator
- The `onOperatorError` hook
- The `onNextDropped` hook
- Operator-specific handlers

This is needed because each hook is made with a specific subset of cleanup in mind, and users might want (for example) to implement specific error-handling logic in addition to cleanup logic within `onOperatorError`.

Note that some operators are less adapted to dealing with objects that need cleanup. For example, `bufferWhen` can introduce overlapping buffers, and that means that the discard "local hook" we used earlier might see a first buffer as being discarded and cleanup an element in it that is in a second buffer, where it is still valid.

For the purpose of cleaning up, **all these hooks MUST be IDEMPOTENT**. They might on some occasions get applied several times to the same object. Unlike the `doOnDiscard` operator, which performs a class-level `instanceOf` check, the global hooks are also dealing with instances that can be any `Object`. It is up to the user's implementation to distinguish between which instances need cleanup and which do not.

The `doOnDiscard` Operator or Local Hook

This hook has been specifically put in place for cleanup of objects that would otherwise never be exposed to user code. It is intended as a cleanup hook for flows that operate under normal circumstances (not malformed sources that push too many items, which is covered by `onNextDropped`).

It is local, in the sense that it is activated through an operator and applies only to a given `Flux` or `Mono`.

Obvious cases include operators that filter elements from upstream. These elements never reach the next operator (or final subscriber), but this is part of the normal path of execution. As such, they are passed to the `doOnDiscard` hook. Examples of when you might use the `doOnDiscard` hook include the following:

- `filter`: Items that do not match the filter are considered to be "discarded."
- `skip`: Skipped items are discarded.
- `buffer(maxSize, skip)` with `maxSize < skip`: A "dropping buffer" — items in between buffers are discarded.

But `doOnDiscard` is not limited to filtering operators, and is also used by operators that internally queue data for backpressure purposes. More specifically, most of the time, this is important during cancellation. An operator that prefetches data from its source and later drains to its subscriber upon demand could have un-emitted data when it gets cancelled. Such operators use the `doOnDiscard` hook during cancellation to clear up their internal backpressure `Queue`.

Each call to `doOnDiscard(Class, Consumer)` is additive with the others, to the extent that it is visible and used by only operators upstream of it.

The `onOperatorError` hook

The `onOperatorError` hook is intended to modify errors in a transverse manner (similar to an AOP catch-and-rethrow).

When the error happens during the processing of an `onNext` signal, the element that was being emitted is passed to `onOperatorError`.

If that type of element needs cleanup, you need to implement it in the `onOperatorError` hook, possibly on top of error-rewriting code.

The `onNextDropped` Hook

With malformed `Publishers`, there could be cases where an operator receives an element when it expected none (typically, after having received the `onError` or `onComplete` signals). In such cases, the unexpected element is "dropped" — that is, passed to the `onNextDropped` hook. If you have types that need cleanup, you must detect these in the `onNextDropped` hook and implement cleanup code there as well.

Operator-specific Handlers

Some operators that deal with buffers or collect values as part of their operations have specific handlers for cases where collected data is not propagated downstream. If you use such operators with the type(s) that need cleanup, you need to perform cleanup in these handlers.

For example, `distinct` has such a callback that is invoked when the operator terminates (or is cancelled) in order to clear the collection it uses to judge whether an element is distinct or not. By default, the collection is a `HashSet`, and the cleanup callback is a `HashSet::clear`. However, if you deal with reference-counted objects, you might want to change that to a more involved handler that would `release` each element in the set before calling `clear()` on it.

9.11. Null Safety

Although Java does not let you express nullness markers with its type system yet, Project Reactor's codebase is annotated with JSpecify annotations to declare the nullability of its APIs, fields, and related type usages. Reading the JSpecify user guide is highly recommended in order to get familiar with those annotations and semantics.

The primary goal of this null-safety arrangement is to prevent a `NullPointerException` from being thrown at runtime via build time checks and to use explicit nullability as a way to express the possible absence of value. It is useful in Java by leveraging nullability checkers such as NullAway or IDEs supporting JSpecify annotations such as IntelliJ IDEA and Eclipse (the latter requiring manual configuration). In Kotlin, JSpecify annotations are automatically translated to Kotlin's null safety.

Annotating libraries with JSpecify annotations

As of Reactor Core 3.8.0, the Project Reactor codebase leverages JSpecify annotations to expose null-safe APIs and to check the consistency of those nullability declarations with NullAway as part of its build. It is recommended for each library depending on Reactor Core and Project Reactor portfolio projects to do the same.

Leveraging JSpecify annotations in applications

Developing applications with IDEs that support nullness annotations will provide warnings in Java and errors in Kotlin when the nullability contracts are not honored, allowing application developers to refine their null handling to prevent a `NullPointerException` from being thrown at runtime.

Optionally, application developers can annotate their codebase and use build plugins like NullAway to enforce null-safety at the application level during build time.

Guidelines

The purpose of this section is to share some proposed guidelines for explicitly specifying the nullability of Reactor-related libraries or applications.

JSpecify

Defaults to non-null

A key point to understand is that the nullness of types is unknown by default in Java and that non-null type usage is by far more frequent than nullable usage. In order to keep codebases readable, we typically want to define by default that type usage is non-null unless marked as nullable for a specific scope. This is exactly the purpose of `@NullMarked` which is typically set in Project Reactor projects at the package level via a `package-info.java` file, for example:

```
@NullMarked
package reactor.core;
```

```
import org.jspecify.annotations.NullMarked;
```

Explicit nullability

In `@NullMarked` code, nullable type usage is defined explicitly with `@Nullable`.

A key difference between JSpecify `@Nullable` / `@NonNull` annotations and most other variants is that the JSpecify annotations are meta-annotated with `@Target(ElementType.TYPE_USE)`, so they apply only to type usage. This impacts where such annotations should be placed, either to comply with related Java specifications or to follow code style best practices. From a style perspective, it is recommended to embrace the type-use nature of those annotations by placing them on the same line as and immediately preceding the annotated type.

For example, for a field:

```
private @Nullable String field;
```

Or for method parameters and method return types:

```
public @Nullable String buildMessage(@Nullable String message,
                                     @Nullable Throwable cause) {
    // ...
}
```

When overriding a method, JSpecify annotations are not inherited from the original method. That means the JSpecify annotations should be copied to the overriding method if you want to override the implementation and keep the same nullability semantics.

`@NonNull` and `@NullUnmarked` should rarely be needed for typical use cases.

Arrays and varargs

With arrays and varargs, you need to be able to differentiate the nullness of the elements from the nullness of the array itself. Pay attention to the syntax defined by the Java specification which may be initially surprising. For example, in `@NullMarked` code:

- `@Nullable Object[] array` means individual elements can be `null` but the array itself cannot.
- `Object @Nullable [] array` means individual elements cannot be `null` but the array itself can.
- `@Nullable Object @Nullable [] array` means both individual elements and the array can be `null`.

Generics

JSpecify annotations apply to generics as well. For example, in `@NullMarked` code:

- `List<String>` means a list of non-null elements (equivalent of `List<@NonNull String>`)

- `List<@Nullable String>` means a list of nullable elements

Things are a bit more complicated when you are declaring generic types or generic methods. See the related JSpecify generics documentation for more details.

Reactor's `Flux` and `Mono` do not support nullable type parameters (such as `Flux<@Nullable T>` or `Mono<@Nullable T>`) since `null` signals are not permitted. However, note that `Mono#block()`, `Flux#blockFirst()` and similar methods have a signature that permits a `null` return value to represent the absence of a value upon completion (for example `@Nullable T block()`).

The nullability of generic types and generic methods is not yet fully supported by NullAway.

Nested and fully qualified types

The Java specification also enforces that annotations defined with `@Target(ElementType.TYPE_USE)` – like JSpecify's `@Nullable` annotation – must be declared after the last dot (`.`) within inner or fully qualified type names:

- `Sinks.@Nullable Many`
- `io.micrometer.context.ContextSnapshot.@Nullable Scope`

NullAway

Configuration

The recommended configuration is:

- `NullAway:OnlyNullMarked=true` in order to perform nullability checks only for packages annotated with `@NullMarked`.

Optionally, it is possible to set `NullAway:JSpecifyMode=true` to enable checks on the full JSpecify semantics, including annotations on arrays, varargs, and generics. Be aware that this mode is still under development and requires JDK 22 or later (typically combined with the `--release` Java compiler flag to configure the expected baseline). It is recommended to enable the JSpecify mode only as a second step, after making sure the codebase generates no warning with the recommended configuration mentioned previously in this section.

Warnings suppression

There are a few valid use cases where NullAway will incorrectly detect nullability problems. In such cases, it is recommended to suppress related warnings and to document the reason:

- `@SuppressWarnings("NullAway.Init")` at field, constructor, or class level can be used to avoid unnecessary warnings due to the lazy initialization of fields.
- `@SuppressWarnings("NullAway") // Dataflow analysis limitation` can be used when NullAway dataflow analysis is not able to detect that the path involving a nullability problem will never happen.

- `@SuppressWarnings("NullAway") // Lambda` can be used when NullAway does not take into account assertions performed outside of a lambda for the code path within the lambda.
- `@SuppressWarnings("NullAway") // Reflection` can be used for some reflection operations that are known to return non-null values even if that cannot be expressed by the API.
- `@SuppressWarnings("NullAway") // Well-known map keys` can be used when `Map#get` invocations are performed with keys that are known to be present and when non-null related values have been inserted previously.
- `@SuppressWarnings("NullAway") // Overridden method does not define nullability` can be used when the superclass does not define nullability (typically when the superclass comes from an external dependency).
- `@SuppressWarnings("NullAway") // See github.com/uber/NullAway/issues/1075` can be used when NullAway is not able to detect type variable nullness in generic methods.

Migrating from Reactor null-safety annotations

Reactor null-safety annotations `@Nullable`, `@NonNull`, `@NonNullApi`, and `@NonNullFields` in the `reactor.util.annotation`package were introduced in Project Reactor when JSpecify did not exist, and the best option at that time was to leverage meta-annotations from JSR 305 (a dormant but widespread JSR). They are deprecated as of Reactor Core 3.8.0 in favor of JSpecify annotations, which provide significant enhancements such as properly defined specifications, a canonical dependency with no split-package issues, better tooling, better Kotlin integration, and the capability to specify nullability more precisely for more use cases.

A key difference is that the deprecated null-safety annotations, which follow JSR 305 semantics, apply to fields, parameters, and return values; while JSpecify annotations apply to type usage. This subtle difference is pretty significant in practice, since it allows developers to differentiate between the nullness of elements and the nullness of arrays/varargs as well as to define the nullness of generic types.

That means array and varargs null-safety declarations have to be updated to keep the same semantics. For example `@Nullable Object[] array` with Reactor annotations needs to be changed to `Object @Nullable [] array` with JSpecify annotations. The same applies to varargs.

It is also recommended to move field and return value annotations closer to the type and on the same line, for example:

- For fields, instead of `@Nullable private String field` with Spring annotations, use `private @Nullable String field` with JSpecify annotations.
- For method return types, instead of `@Nullable public String method()` with Spring annotations, use `public @Nullable String method()` with JSpecify annotations.

Also, with JSpecify, you do not need to specify `@NonNull` when overriding a type usage annotated with `@Nullable` in the super method to "undo" the nullable declaration in null-marked code. Just declare it unannotated, and the null-marked defaults will apply (type usage is considered non-null unless explicitly annotated as nullable).

Chapter 10. Appendices

10.1. Which operator do I need?

In this section, if an operator is specific to Flux or Mono, it is prefixed and linked accordingly, like this: Flux#fromArray. Common operators have no prefix, and links to both implementations are provided, for example: `just` (Flux|Mono). When a specific use case is covered by a combination of operators, it is presented as a method call, with a leading dot and parameters in parentheses, as follows: `.methodCall(parameter)`.

I want to deal with:

- Creating a New Sequence…
- Transforming an Existing Sequence
- Peeking into a Sequence
- Filtering a Sequence
- Handling Errors
- Working with Time
- Splitting a Flux
- Going Back to the Synchronous World
- Multicasting a Flux to several Subscribers

Creating a New Sequence…

- that emits a `T`, and I already have: `just` (Flux|Mono)
  - …from an Optional<T>: Mono#justOrEmpty(Optional<T>)
  - …from a potentially `null` T: Mono#justOrEmpty(T)
- that emits a `T` returned by a method: `just` (Flux|Mono) as well
  - …but lazily captured: use Mono#fromSupplier or wrap `just` (Flux|Mono) inside `defer` (Flux|Mono)
- that emits several `T` I can explicitly enumerate: Flux#just(T…)
- that iterates over:
  - an array: Flux#fromArray
  - a collection or iterable: Flux#fromIterable
  - a range of integers: Flux#range
  - a Stream supplied for each Subscription: Flux#fromStream(Supplier<Stream>)
- that emits from various single-valued sources such as:
  - a Supplier<T>: Mono#fromSupplier

    - a task: Mono#fromCallable, Mono#fromRunnable
    - a CompletableFuture<T>: Mono#fromFuture
- that completes: `empty` (Flux|Mono)
- that errors immediately: `error` (Flux|Mono)
    - ...but lazily build the Throwable: `error(Supplier<Throwable>)` (Flux|Mono)
- that never does anything: `never` (Flux|Mono)
- that is decided at subscription: `defer` (Flux|Mono)
- that depends on a disposable resource: `using` (Flux|Mono)
- that generates events programmatically (can use state):
    - synchronously and one-by-one: Flux#generate
    - asynchronously (can also be sync), multiple emissions possible in one pass: Flux#create (Mono#create as well, without the multiple emission aspect)

Transforming an Existing Sequence

- I want to transform existing data:
    - on a 1-to-1 basis (eg. strings to their length): `map` (Flux|Mono)
        - ...by just casting it: `cast` (Flux|Mono)
        - ...in order to materialize each source value's index: Flux#index
    - on a 1-to-n basis (eg. strings to their characters): `flatMap` (Flux|Mono) + use a factory method
    - on a 1-to-n basis with programmatic behavior for each source element and/or state: `handle` (Flux|Mono)
    - running an asynchronous task for each source item (eg. urls to http request): `flatMap` (Flux|Mono) + an async Publisher-returning method
        - ...ignoring some data: conditionally return a Mono.empty() in the flatMap lambda
        - ...retaining the original sequence order: Flux#flatMapSequential (this triggers the async processes immediately but reorders the results)
        - ...where the async task can return multiple values, from a Mono source: Mono#flatMapMany
- I want to add pre-set elements to an existing sequence:
    - at the start: Flux#startWith(T...)
    - at the end: Flux#concatWithValues(T...)
- I want to aggregate a Flux: (the `Flux#` prefix is assumed below)
    - into a List: collectList, collectSortedList
    - into a Map: collectMap, collectMultiMap
    - into an arbitrary container: collect
    - into the size of the sequence: count

    - by applying a function between each element (eg. running sum): reduce
        - ...but emitting each intermediary value: scan
    - into a boolean value from a predicate:
        - applied to all values (AND): all
        - applied to at least one value (OR): any
        - testing the presence of any value: hasElements *(there is a Mono equivalent in hasElement)*
        - testing the presence of a specific value: hasElement(T)
- I want to combine publishers...
    - in sequential order: Flux#concat or `.concatWith(other)` (Flux|Mono)
        - ...but delaying any error until remaining publishers have been emitted: Flux#concatDelayError
        - ...but eagerly subscribing to subsequent publishers: Flux#mergeSequential
    - in emission order (combined items emitted as they come): Flux#merge / `.mergeWith(other)` (Flux|Mono)
        - ...with different types (transforming merge): Flux#zip / Flux#zipWith
    - by pairing values:
        - from 2 Monos into a Tuple2: Mono#zipWith
        - from n Monos when they all completed: Mono#zip
    - by coordinating their termination:
        - from 1 Mono and any source into a Mono<Void>: Mono#and
        - from n sources when they all completed: Mono#when
        - into an arbitrary container type:
            - each time all sides have emitted: Flux#zip (up to the smallest cardinality)
            - each time a new value arrives at either side: Flux#combineLatest
    - selecting the first publisher which...
        - produces a *value* (`onNext`): `firstWithValue` (Flux|Mono)
        - produces *any signal*: `firstWithSignal` (Flux|Mono)
    - triggered by the elements in a source sequence: switchMap (each source element is mapped to a Publisher)
    - triggered by the start of the next publisher in a sequence of publishers: switchOnNext
- I want to repeat an existing sequence: `repeat` (Flux|Mono)
    - ...but at time intervals: `Flux.interval(duration).flatMap(tick -> myExistingPublisher)`
- I have an empty sequence but...
    - I want a value instead: `defaultIfEmpty` (Flux|Mono)
    - I want another sequence instead: `switchIfEmpty` (Flux|Mono)

- I have a sequence but I am not interested in values: `ignoreElements` (Flux.ignoreElements() | Mono.ignoreElement())
  - ...and I want the completion represented as a Mono<Void>: `then` (Flux | Mono)
  - ...and I want to wait for another task to complete at the end: `thenEmpty` (Flux | Mono)
  - ...and I want to switch to another Mono at the end: Mono#then(mono)
  - ...and I want to emit a single value at the end: Mono#thenReturn(T)
  - ...and I want to switch to a Flux at the end: `thenMany` (Flux | Mono)
- I have a Mono for which I want to defer completion...
  - ...until another publisher, which is derived from this value, has completed: Mono#delayUntil(Function)
- I want to expand elements recursively into a graph of sequences and emit the combination...
  - ...expanding the graph breadth first: `expand(Function)` (Flux | Mono)
  - ...expanding the graph depth first: `expandDeep(Function)` (Flux | Mono)

Peeking into a Sequence

- Without modifying the final sequence, I want to:
  - get notified of / execute additional behavior (sometimes referred to as "side-effects") on:
    - emissions: `doOnNext` (Flux | Mono)
    - completion: Flux#doOnComplete, Mono#doOnSuccess (includes the result, if any)
    - error termination: `doOnError` (Flux | Mono)
    - cancellation: `doOnCancel` (Flux | Mono)
    - "start" of the sequence: `doFirst` (Flux | Mono)
      - this is tied to Publisher#subscribe(Subscriber)
    - post-subscription : `doOnSubscribe` (Flux | Mono)
      - `Subscription` acknowledgment after `subscribe`
      - this is tied to Subscriber#onSubscribe(Subscription)
    - request: `doOnRequest` (Flux | Mono)
    - completion or error: `doOnTerminate` (Flux | Mono)
      - but **after** it has been propagated downstream: `doAfterTerminate` (Flux | Mono)
    - any type of signal, represented as a Signal: `doOnEach` (Flux | Mono)
    - any terminating condition (complete, error, cancel): `doFinally` (Flux | Mono)
  - log what happens internally: `log` (Flux | Mono)
- I want to know of all events:
  - each represented as Signal object:
    - in a callback outside the sequence: `doOnEach` (Flux | Mono)

        - instead of the original onNext emissions: `materialize` (Flux|Mono)
            - ...and get back to the onNexts: `dematerialize` (Flux|Mono)
    - as a line in a log: `log` (Flux|Mono)

Filtering a Sequence

- I want to filter a sequence:
    - based on an arbitrary criteria: `filter` (Flux|Mono)
        - ...that is asynchronously computed: `filterWhen` (Flux|Mono)
    - restricting on the type of the emitted objects: `ofType` (Flux|Mono)
    - by ignoring the values altogether: `ignoreElements` (Flux.ignoreElements() |Mono.ignoreElement())
    - by ignoring duplicates:
        - in the whole sequence (logical set): Flux#distinct
        - between subsequently emitted items (deduplication): Flux#distinctUntilChanged
- I want to keep only a subset of the sequence:
    - by taking N elements:
        - at the beginning of the sequence: Flux#take(long)
            - ...requesting an unbounded amount from upstream: Flux#take(long, false)
            - ...based on a duration: Flux#take(Duration)
            - ...only the first element, as a Mono: Flux#next()
        - at the end of the sequence: Flux#takeLast
        - until a criteria is met (inclusive): Flux#takeUntil (predicate-based), Flux#takeUntilOther (companion publisher-based)
        - while a criteria is met (exclusive): Flux#takeWhile
    - by taking at most 1 element:
        - at a specific position: Flux#elementAt
        - at the end: .takeLast(1)
            - ...and emit an error if empty: Flux#last()
            - ...and emit a default value if empty: Flux#last(T)
    - by skipping elements:
        - at the beginning of the sequence: Flux#skip(long)
            - ...based on a duration: Flux#skip(Duration)
        - at the end of the sequence: Flux#skipLast
        - until a criteria is met (inclusive): Flux#skipUntil (predicate-based), Flux#skipUntilOther (companion publisher-based)
        - while a criteria is met (exclusive): Flux#skipWhile

    - by sampling items:
        - by duration: Flux#sample(Duration)
            - but keeping the first element in the sampling window instead of the last: sampleFirst
        - by a publisher-based window: Flux#sample(Publisher)
        - based on a publisher "timing out": Flux#sampleTimeout (each element triggers a publisher, and is emitted if that publisher does not overlap with the next)
- I expect at most 1 element (error if more than one)...
    - and I want an error if the sequence is empty: Flux#single()
    - and I want a default value if the sequence is empty: Flux#single(T)
    - and I accept an empty sequence as well: Flux#singleOrEmpty

Handling Errors

- I want to create an erroring sequence: `error` (Flux|Mono)...
    - ...to replace the completion of a successful Flux: `.concat(Flux.error(e))`
    - ...to replace the **emission** of a successful Mono: `.then(Mono.error(e))`
    - ...if too much time elapses between onNexts: `timeout` (Flux|Mono)
    - ...lazily: `error(Supplier<Throwable>)` (Flux|Mono)
- I want the try/catch equivalent of:
    - throwing: `error` (Flux|Mono)
    - catching an exception:
        - and falling back to a default value: `onErrorReturn` (Flux|Mono)
        - and swallowing the error (ie. complete): `onErrorComplete` (Flux|Mono)
        - and falling back to another Flux or Mono: `onErrorResume` (Flux|Mono)
        - and wrapping and re-throwing: `.onErrorMap(t -> new RuntimeException(t))` (Flux|Mono)
    - the finally block: `doFinally` (Flux|Mono)
    - the using pattern from Java 7: `using` (Flux|Mono) factory method
- I want to recover from errors...
    - by falling back:
        - to a value: `onErrorReturn` (Flux|Mono)
        - to a completion ("swallowing" the error): `onErrorComplete` (Flux|Mono)
        - to a Publisher or Mono, possibly different ones depending on the error: Flux#onErrorResume and Mono#onErrorResume
    - by retrying...
        - ...with a simple policy (max number of attempts): `retry()` (Flux|Mono), `retry(long)` (Flux|Mono)
        - ...triggered by a companion control Flux: `retryWhen` (Flux|Mono)

        - ...using a standard backoff strategy (exponential backoff with jitter): `retryWhen(Retry.backoff(…))` (Flux | Mono) (see also other factory methods in Retry)
- I want to deal with backpressure "errors" (request max from upstream and apply the strategy when downstream does not produce enough request)...
    - by throwing a special IllegalStateException: Flux#onBackpressureError
    - by dropping excess values: Flux#onBackpressureDrop
        - ...except the last one seen: Flux#onBackpressureLatest
    - by buffering excess values (bounded or unbounded): Flux#onBackpressureBuffer
        - ...and applying a strategy when bounded buffer also overflows: Flux#onBackpressureBuffer with a BufferOverflowStrategy

Working with Time

- I want to associate emissions with a timing measured...
    - ...with best available precision and versatility of provided data: `timed` (Flux | Mono)
        - Timed<T>#elapsed() for Duration since last `onNext`
        - Timed<T>#timestamp() for Instant representation of the epoch timestamp (milliseconds resolution)
        - Timed<T>#elapsedSinceSubcription() for Duration since subscription (rather than last onNext)
        - can have nanoseconds resolution for elapsed Durations
    - ...as a (legacy) Tuple2<Long, T>...
        - since last onNext: `elapsed` (Flux | Mono)
        - since the dawn of time (well, computer time): `timestamp` (Flux | Mono)
- I want my sequence to be interrupted if there is too much delay between emissions: `timeout` (Flux | Mono)
- I want to get ticks from a clock, regular time intervals: Flux#interval
- I want to emit a single `0` after an initial delay: static Mono.delay.
- I want to introduce a delay:
    - between each onNext signal: Mono#delayElement, Flux#delayElements
    - before the subscription happens: `delaySubscription` (Flux | Mono)

Splitting a Flux

- I want to split a Flux<T> into a `Flux<Flux<T>>`, by a boundary criteria:
    - of size: window(int)
        - ...with overlapping or dropping windows: window(int, int)
    - of time window(Duration)
        - ...with overlapping or dropping windows: window(Duration, Duration)

    - of size OR time (window closes when count is reached or timeout elapsed): windowTimeout(int, Duration)
    - based on a predicate on elements: windowUntil
        - ……emitting the element that triggered the boundary in the next window (`cutBefore` variant): .windowUntil(predicate, true)
        - …keeping the window open while elements match a predicate: windowWhile (non-matching elements are not emitted)
    - driven by an arbitrary boundary represented by onNexts in a control Publisher: window(Publisher), windowWhen
- I want to split a Flux<T> and buffer elements within boundaries together…
    - into List:
        - by a size boundary: buffer(int)
            - …with overlapping or dropping buffers: buffer(int, int)
        - by a duration boundary: buffer(Duration)
            - …with overlapping or dropping buffers: buffer(Duration, Duration)
        - by a size OR duration boundary: bufferTimeout(int, Duration)
        - by an arbitrary criteria boundary: bufferUntil(Predicate)
            - …putting the element that triggered the boundary in the next buffer: .bufferUntil(predicate, true)
            - …buffering while predicate matches and dropping the element that triggered the boundary: bufferWhile(Predicate)
        - driven by an arbitrary boundary represented by onNexts in a control Publisher: buffer(Publisher), bufferWhen
    - into an arbitrary "collection" type `C`: use variants like buffer(int, Supplier<C>)
- I want to split a Flux<T> so that element that share a characteristic end up in the same sub-flux: groupBy(Function<T,K>) TIP: Note that this returns a `Flux<GroupedFlux<K, T>>`, each inner GroupedFlux shares the same `K` key accessible through key().

Going Back to the Synchronous World

Note: all of these methods except Mono#toFuture will throw an UnsupportedOperatorException if called from within a Scheduler marked as "non-blocking only" (by default parallel() and single()).

- I have a Flux<T> and I want to:
    - block until I can get the first element: Flux#blockFirst
        - …with a timeout: Flux#blockFirst(Duration)
    - block until I can get the last element (or null if empty): Flux#blockLast
        - …with a timeout: Flux#blockLast(Duration)
    - synchronously switch to an Iterable<T>: Flux#toIterable

    - synchronously switch to a Java 8 Stream<T>: Flux#toStream
- I have a Mono<T> and I want:
    - to block until I can get the value: Mono#block
        - ...with a timeout: Mono#block(Duration)
    - a CompletableFuture<T>: Mono#toFuture

Multicasting a Flux to several Subscribers

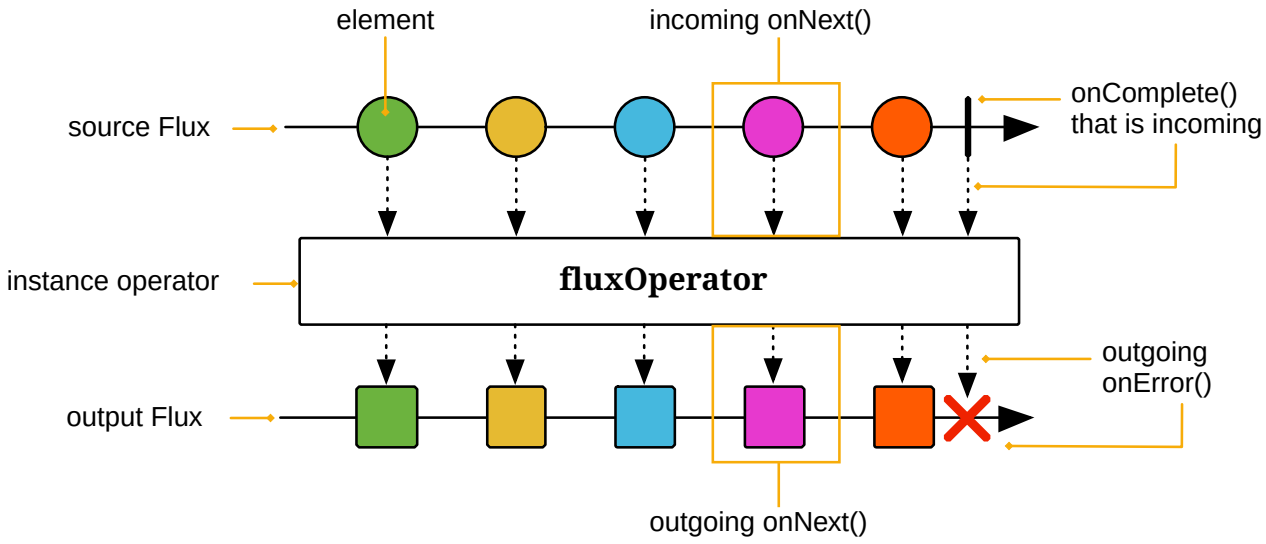
- I want to connect multiple Subscriber to a Flux:
    - and decide when to trigger the source with connect(): publish() (returns a ConnectableFlux)
    - and trigger the source immediately (late subscribers see later data): `share()` (Flux|Mono)
    - and permanently connect the source when enough subscribers have registered: .publish().autoConnect(n)
    - and automatically connect and cancel the source when subscribers go above/below the threshold: .publish().refCount(n)
        - ...but giving a chance for new subscribers to come in before cancelling: .publish().refCount(n, Duration)
- I want to cache data from a Publisher and replay it to later subscribers:
    - up to `n` elements: cache(int)
    - caching latest elements seen within a Duration (Time-To-Live): `cache(Duration)` (Flux|Mono)
        - ...but retain no more than `n` elements: cache(int, Duration)
    - but without immediately triggering the source: Flux#replay (returns a ConnectableFlux)

10.2. How to read marble diagrams?

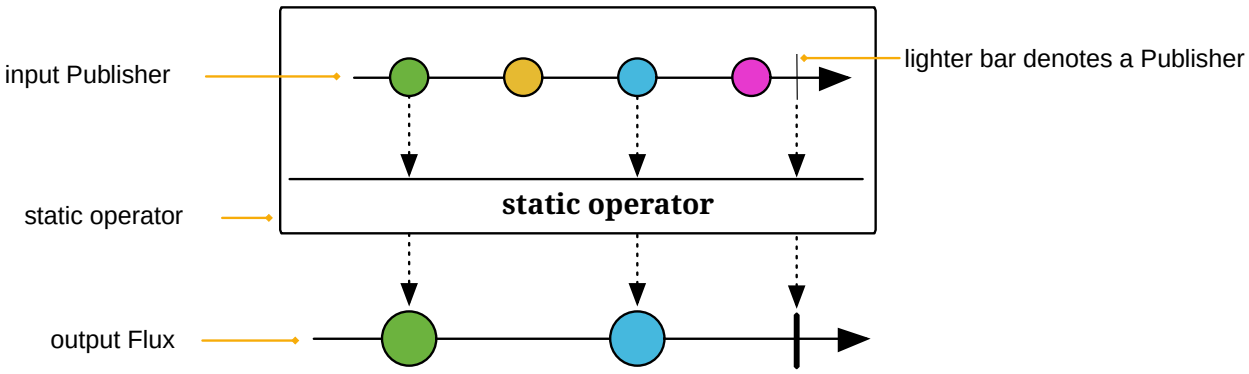
When we introduced `Flux` and `Mono`, we showed an example of a "marble diagram". These are found throughout the javadoc in order to explain the behavior of an operator in a more visual way.

In this section we'll dig a little deeper into the conventions used by the Reactor documentation for these marble diagrams. First, let's see how the most common patterns of operators are represented.

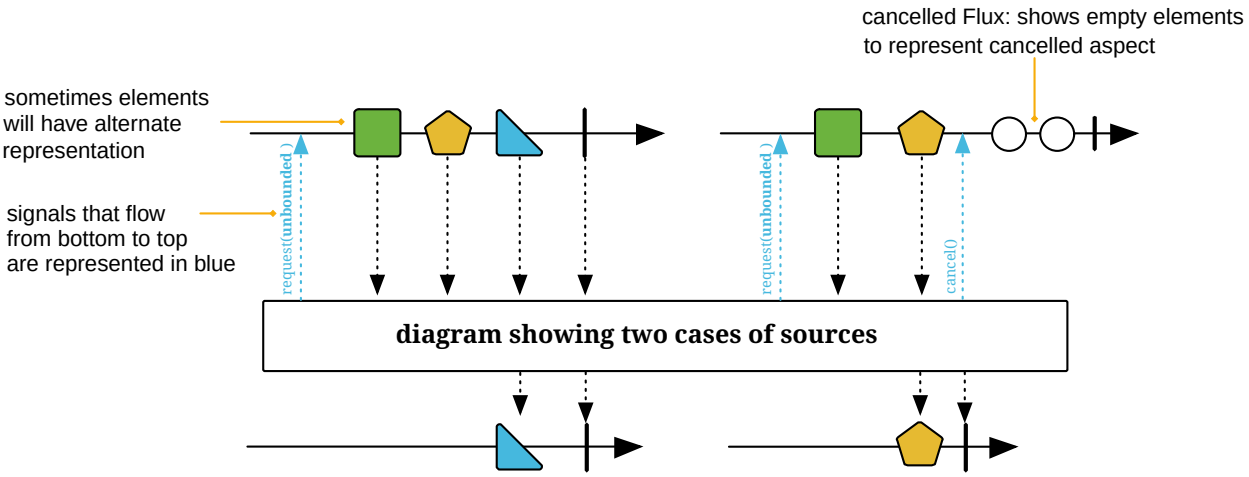
Some operators are instance methods: their output is produced by calling a method on a source `Flux` instance (like `Flux<T> output = source.fluxOperator()`):



Other operators are static methods. They can still take a source as an input parameter, like in `Flux<T> output = Flux.merge(sourceFlux1, sourcePublisher2)`. These are represented like below:

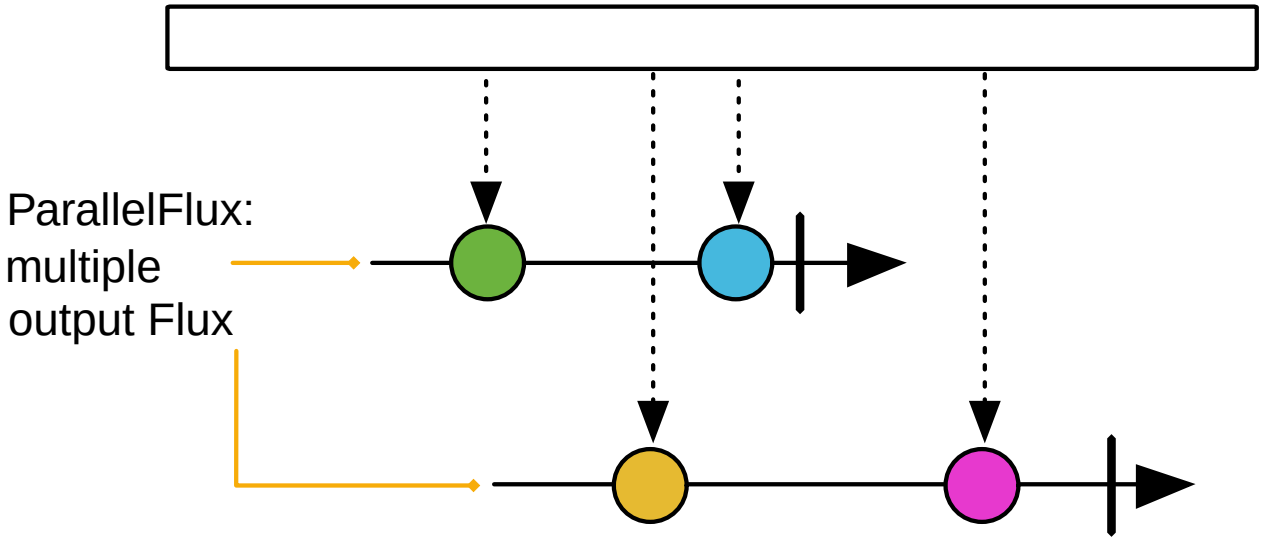


Note that sometimes we represent multiple variants or behaviors depending on the operator's input, in which case there's a single operator "box", but the source and output variants are separated like below:

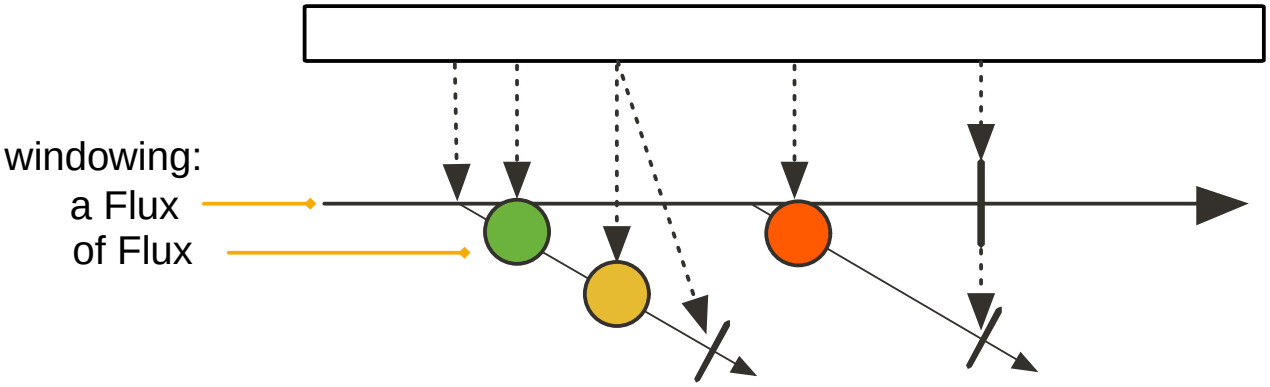


These are the basic cases, yet some operators display slightly more advanced patterns.

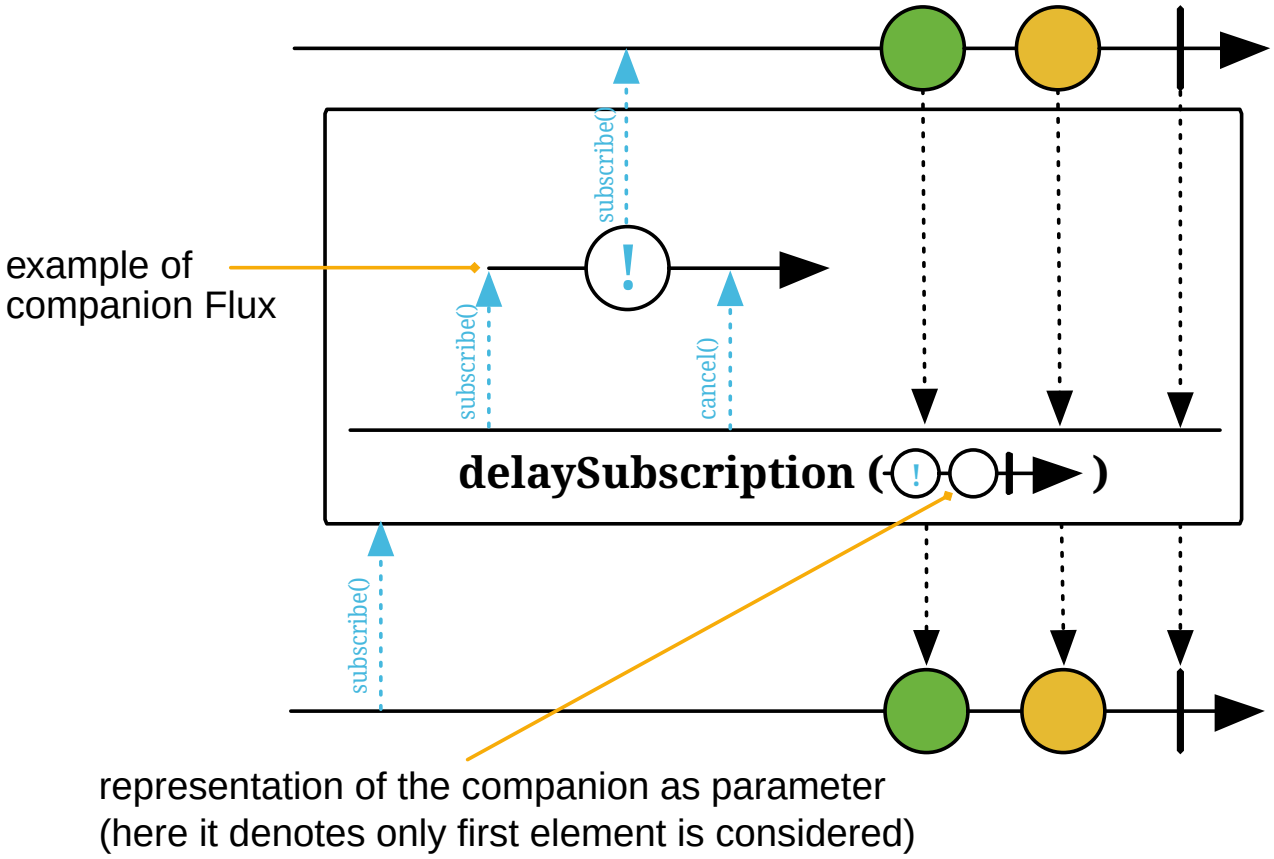
For instance, `ParallelFlux` creates multiple rails so they have multiple output `Flux`. These are represented one below the other, like in the following diagram:



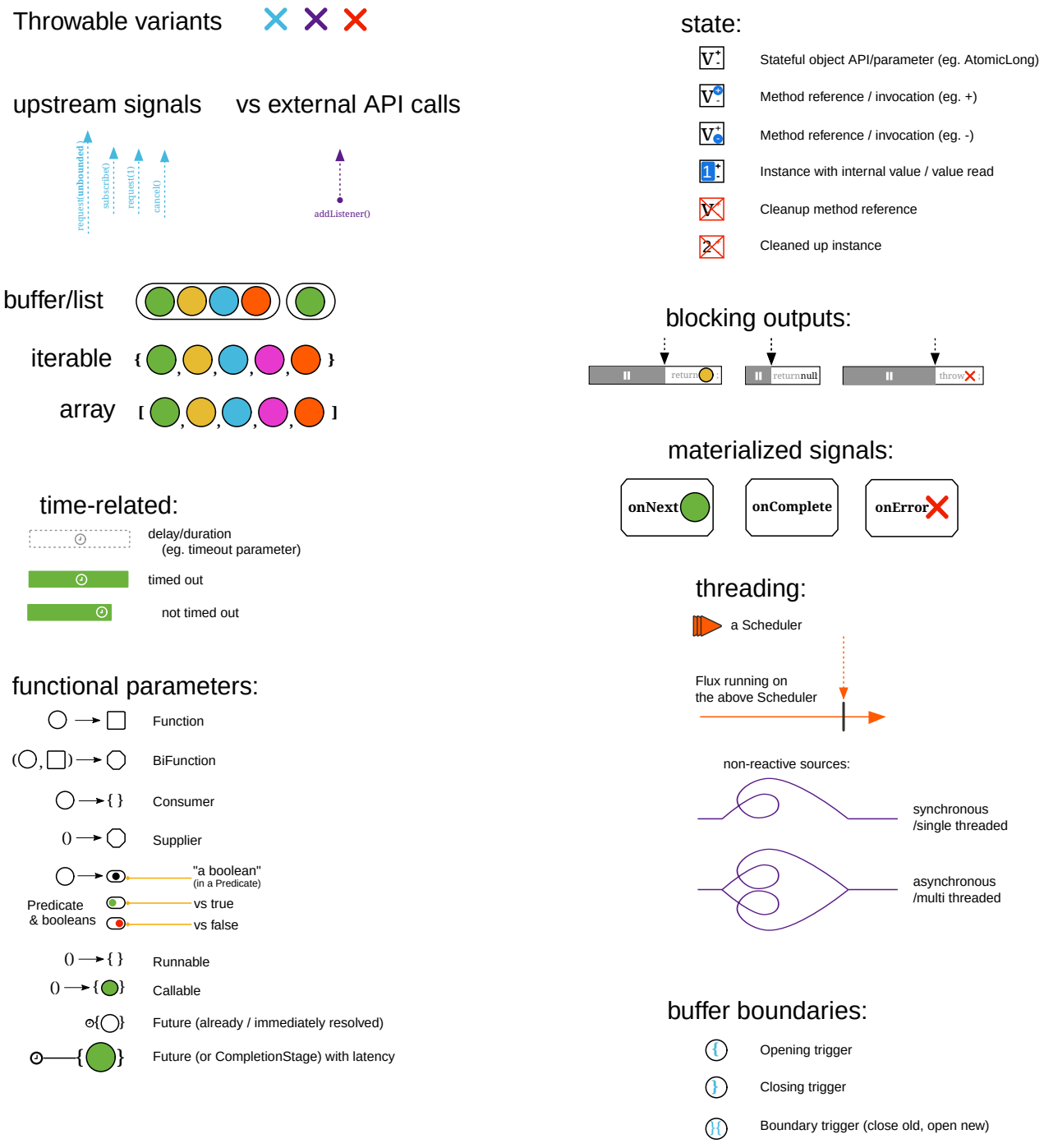
Windowing operators produce a `Flux<Flux<T>>`: the main `Flux` notifies of each window opening, while inner `Flux` represent the windows content and termination. Windows are represented as branching out of the main `Flux`, like in the following diagram:



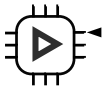
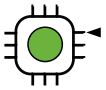
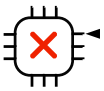
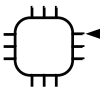
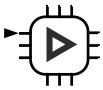
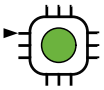
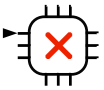
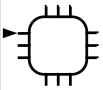
Sometimes, operators take a "companion publisher" as input (a `Flux`, `Mono` or arbitrary Reactive Stream `Publisher`). Such companion publishers help to customize the operator's behavior, which will use some of the companion's signals as trigger for its own internal behavior. They are represented like in the following diagram:

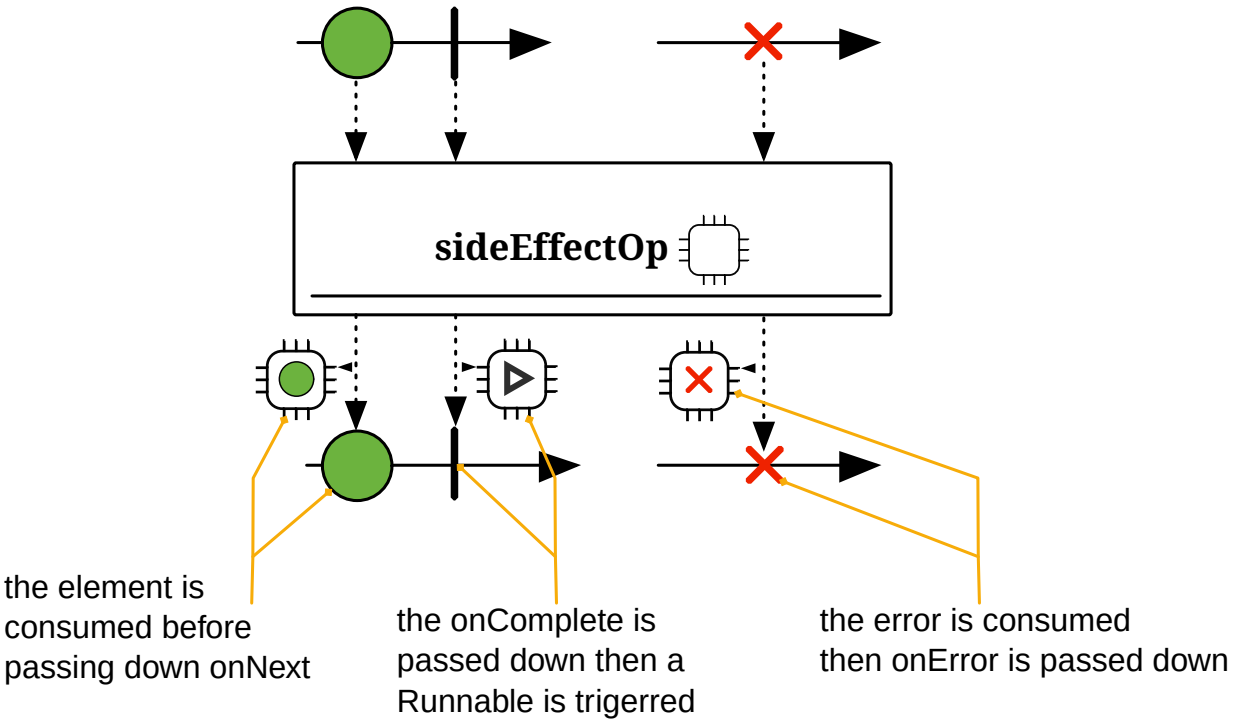


Now that we've seen the most common operator patterns, let's show the graphical representation of all the different signals, events and elements that can occur in a `Flux` or `Mono`:



Finally, in the same vein we have the graphical representation of *side effects*, which occur alongside the Reactive Stream signals:

Runnable	Consumer (onNext)	Consumer (onError)	misc	
				as parameter
				*concrete side effects occurring BEFORE passing down signal*
				*concrete side effects occurring AFTER passing down signal*



10.3. FAQ, Best Practices, and "How do I...?

This section covers the following content:

- How Do I Wrap a Synchronous, Blocking Call?
- I Used an Operator on my `Flux` but it Doesn't Seem to Apply. What Gives?
- My `Mono` `zipWith` or `zipWhen` is never called
- Using `zip` along with empty-completed publishers
- How to Use `retryWhen` to Emulate `retry(3)`?
- How can I use `retryWhen` for Exponential Backoff?
- How Do I Ensure Thread Affinity when I Use `publishOn()`?
- What Is a Good Pattern for Contextual Logging? (MDC)

How Do I Wrap a Synchronous, Blocking Call?

It is often the case that a source of information is synchronous and blocking. To deal with such sources in your Reactor applications, apply the following pattern:

```
Mono blockingWrapper = Mono.fromCallable(() -> { ①
    return /* make a remote synchronous call */ ②
});
blockingWrapper = blockingWrapper.subscribeOn(Schedulers.boundedElastic()); ③
```

① Create a new `Mono` by using `fromCallable`.

② Return the asynchronous, blocking resource.

③ Ensure each subscription happens on a dedicated worker from `Schedulers.boundedElastic()`.

You should use a `Mono`, because the source returns one value. You should use `Schedulers.boundedElastic`, because it creates a dedicated thread to wait for the blocking resource without impacting other non-blocking processing, while also ensuring that there is a limit to the amount of threads that can be created, and blocking tasks that can be enqueued and deferred during a spike.

Note that `subscribeOn` does not subscribe to the `Mono`. It specifies what kind of `Scheduler` to use when a subscribe call happens.

Also, note that `subscribeOn` operator should immediately follow the source and any further operators are defined after the `subscribeOn` wrapper.

I Used an Operator on my `Flux` but it Doesn't Seem to Apply. What Gives?

Make sure that the variable you `.subscribe()` to has been affected by the operators you think should have been applied to it.

Reactor operators are decorators. They return a different instance that wraps the source sequence and add behavior. That is why the preferred way of using operators is to *chain* the calls.

Compare the following two examples:

without chaining (incorrect)

```
Flux<String> flux = Flux.just("something", "chain");
flux.map(secret -> secret.replaceAll(".", "*")); ①
flux.subscribe(next -> System.out.println("Received: " + next));
```

① The mistake is here. The result is not attached to the `flux` variable.

without chaining (correct)

```
Flux<String> flux = Flux.just("something", "chain");
flux = flux.map(secret -> secret.replaceAll(".", "*"));
flux.subscribe(next -> System.out.println("Received: " + next));
```

The following sample is even better (because it is simpler):

with chaining (best)

```
Flux.just("something", "chain")
    .map(secret -> secret.replaceAll(".", "*"))
    .subscribe(next -> System.out.println("Received: " + next));
```

The first version outputs the following:

```
Received: something
Received: chain
```

The two other versions output the expected values, as follows:

```
Received: *********
Received: *****
```

My `Mono` `zipWith` or `zipWhen` is never called

Consider the following example:

```
myMethod.process("a") // this method returns Mono<Void>
        .zipWith(myMethod.process("b"), combinator) //this is never called
        .subscribe();
```

If the source `Mono` is either `empty` or a `Mono<Void>` (a `Mono<Void>` is empty for all intents and purposes), some combinations are never called.

This is the typical case for any transformer such as the `zip` static method or the `zipWith` `zipWhen` operators, which (by definition) need an element from each source to produce their output.

Using data-suppressing operators on sources of `zip` is thus problematic. Examples of data-suppressing operators include `then()`, `thenEmpty(Publisher<Void>)`, `ignoreElements()` and `ignoreElement()`, and `when(Publisher…)`.

Similarly, operators that use a `Function<T,?>` to tune their behavior, such as `flatMap`, need at least one element to be emitted for the `Function` to have a chance to apply. Applying these on an empty (or `<Void>`) sequence nevers produce an element.

You can use `.defaultIfEmpty(T)` and `.switchIfEmpty(Publisher<T>)` to replace an empty sequence of `T` with a default value or a fallback `Publisher<T>` (respectively), which could help avoid some of these situations. Note that this does not apply to `Flux<Void>`/`Mono<Void>` sources, as you can only switch to another `Publisher<Void>`, which is still guaranteed to be empty. The following example uses `defaultIfEmpty`:

use `defaultIfEmpty` *before* `zipWhen`

```
myMethod.emptySequenceForKey("a") // this method returns empty Mono<String>
        .defaultIfEmpty("") // this converts empty sequence to just the empty String
        .zipWhen(aString -> myMethod.process("b")) //this is called with the empty
String
        .subscribe();
```

Using `zip` along with empty-completed publishers

When using the `zip` operator along with empty-completed publishers (i.e., publishers completing without emitting an item), it is important to be aware of the following behavior.

Consider the following test case:

```
    @Test
    public void testZipEmptyCompletionAllSubscribed() {
        AtomicInteger cnt = new AtomicInteger();
        Mono<Integer> mono1 = Mono.create(sink -> {
            cnt.incrementAndGet();
            sink.success();
        });
        Mono<Integer> mono2 = Mono.create(sink -> {
            cnt.incrementAndGet();
            sink.success();
        });
        Mono<Integer> zippedMono = Mono.zip(mono1, mono2, (v1, v2) -> v1);
        zippedMono.subscribe();
        assertEquals(2, cnt.get());
    }
```

While in this case the resulting `zippedMono` subscribes to both `mono1` and `mono2`, such behaviour is not guaranteed for all cases. For instance, consider the following test case:

```
    @Test
    public void testZipEmptyCompletionOneSubscribed() {
        AtomicInteger cnt = new AtomicInteger();
        Mono<Integer> mono1 = Mono.create(sink -> {
            cnt.incrementAndGet();
            sink.success();
        });
        Mono<Integer> mono2 = Mono.create(sink -> {
            cnt.incrementAndGet();
            sink.success();
        });
        Mono<Integer> mono3 = Mono.create(sink -> {
            cnt.incrementAndGet();
            sink.success();
        });
        Mono<Integer> zippedMono = Mono.zip(mono1, Mono.zip(mono2, mono3, (v1, v2) ->
v1), (v1, v2) -> v1);
        zippedMono.subscribe();
        assertEquals(1, cnt.get());
    }
```

In this case upon empty completion of `mono1`, `zippedMono` completes immediately and does not

subscribe to `mono2` and `mono3`.

Therefore, in cases where `zip` operator is used to combine empty-completed publishers, it is not guaranteed that the resulting publisher will subscribe to all the empty-completed publishers.

If it is necessary to keep the semantics as shown in the second test case and to ensure subscription to all the publishers to be zipped, consider using `singleOptional` operator, as demonstrated in the test case below:

```
@Test
public void testZipOptionalAllSubscribed() {
    AtomicInteger cnt = new AtomicInteger();
    Mono<Integer> mono1 = Mono.create(sink -> {
        cnt.incrementAndGet();
        sink.success();
    });
    Mono<Integer> mono2 = Mono.create(sink -> {
        cnt.incrementAndGet();
        sink.success();
    });
    Mono<Integer> mono3 = Mono.create(sink -> {
        cnt.incrementAndGet();
        sink.success();
    });
    Mono<Optional<Integer>> zippedMono =
            Mono.zip(
                    mono1.singleOptional(),
                    Mono.zip(mono2.singleOptional(), mono3.singleOptional(), (v1, v2)
-> v1),
                    (v1, v2) -> v1);
    zippedMono.subscribe();
    assertEquals(3, cnt.get());
}
```

How to Use `retryWhen` to Emulate `retry(3)`?

The `retryWhen` operator can be quite complex. Hopefully the following snippet of code can help you understand how it works by attempting to emulate a simpler `retry(3)`:

```
AtomicInteger errorCount = new AtomicInteger();
Flux<String> flux =
        Flux.<String>error(new IllegalArgumentException())
                .doOnError(e -> errorCount.incrementAndGet())
                .retryWhen(Retry.from(companion -> ①
                        companion.map(rs -> { ②
                            if (rs.totalRetries() < 3) return rs.totalRetries(); ③
                            else throw Exceptions.propagate(rs.failure()); ④
                        })
                ));
```

① We customize `Retry` by adapting from a `Function` lambda rather than providing a concrete class

② The companion emits `RetrySignal` objects, which bear number of retries so far and last failure

③ To allow for three retries, we consider indexes < 3 and return a value to emit (here we simply return the index).

④ In order to terminate the sequence in error, we throw the original exception after these three retries.

How can I use `retryWhen` for Exponential Backoff?

Exponential backoff produces retry attempts with a growing delay between each of the attempts, so as not to overload the source systems and risk an all-out crash. The rationale is that, if the source produces an error, it is already in an unstable state and is not likely to immediately recover from it. So blindly retrying immediately is likely to produce yet another error and add to the instability.

Since `3.3.4.RELEASE`, Reactor comes with a builder for such a retry, to be used with `Flux#retryWhen`: `Retry.backoff`.

The following example showcases a simple use of the builder, with hooks logging message right before and after the retry attempt delays. It delays retries and increases the delay between each attempt (pseudocode: delay = 100ms * 2^attempt_number_starting_at_zero):

```
AtomicInteger errorCount = new AtomicInteger();
Flux<String> flux =
Flux.<String>error(new IllegalStateException("boom"))
        .doOnError(e -> { ①
            errorCount.incrementAndGet();
            System.out.println(e + " at " + LocalTime.now());
        })
        .retryWhen(Retry
                .backoff(3, Duration.ofMillis(100)).jitter(0d) ②
                .doAfterRetry(rs -> System.out.println("retried at " + LocalTime.now()
+ ", attempt " + rs.totalRetries())) ③
                .onRetryExhaustedThrow((spec, rs) -> rs.failure()) ④
        );
```

① We will log the time of errors emitted by the source and count them.

② We configure an exponential backoff retry with at most 3 attempts and no jitter.

③ We also log the time at which the retry happens, and the retry attempt number (starting from 0).

④ By default, an `Exceptions.retryExhausted` exception would be thrown, with the last `failure()` as a cause. Here we customize that to directly emit the cause as `onError`.

When subscribed to, this fails and terminates after printing out the following:

```
java.lang.IllegalStateException: boom at 00:00:00.0
retried at 00:00:00.101, attempt 0 ①
java.lang.IllegalStateException: boom at 00:00:00.101
retried at 00:00:00.304, attempt 1 ②
java.lang.IllegalStateException: boom at 00:00:00.304
retried at 00:00:00.702, attempt 2 ③
java.lang.IllegalStateException: boom at 00:00:00.702
```

① First retry after about 100ms

② Second retry after about 200ms

③ Third retry after about 400ms

How Do I Ensure Thread Affinity when I Use `publishOn()`?

As described in Schedulers, `publishOn()` can be used to switch execution contexts. The `publishOn` operator influences the threading context where the rest of the operators in the chain below it run, up to a new occurrence of `publishOn`. So the placement of `publishOn` is significant.

Consider the following example:

```
Sinks.Many<Integer> dataSinks = Sinks.many().unicast().onBackpressureBuffer();
Flux<Integer> source = dataSinks.asFlux();
source.publishOn(scheduler1)
      .map(i -> transform(i))
      .publishOn(scheduler2)
      .doOnNext(i -> processNext(i))
      .subscribe();
```

The `transform` function in `map()` is run on a worker of `scheduler1`, and the `processNext` method in `doOnNext()` is run on a worker of `scheduler2`. Each subscription gets its own worker, so all elements pushed to the corresponding subscriber are published on the same `Thread`.

You can use single-threaded schedulers to ensure thread affinity for different stages in the chain or for different subscribers.

What Is a Good Pattern for Contextual Logging? (MDC)

Most logging frameworks allow contextual logging, letting users store variables that are reflected in the logging pattern, generally by way of a `Map` called the MDC ("Mapped Diagnostic Context"). This is

one of the most recurring use of `ThreadLocal` in Java, and as a consequence this pattern assumes that the code being logged is tied in a one-to-one relationship with a `Thread`.

That might have been a safe assumption to make before Java 8, but with the advent of functional programming elements in the Java language things have changed a bit…

Let's take the example of an API that was imperative and used the template method pattern, then switched to a more functional style. With the template method pattern, inheritance was at play. Now in its more functional approach, higher order functions are passed to define the "steps" of the algorithm. Things are now more declarative than imperative, and that frees the library to make decisions about where each step should run. For instance, knowing which steps of the underlying algorithm can be parallelized, the library can use an `ExecutorService` to execute some of the steps in parallel.

One concrete example of such a functional API is the `Stream` API introduced in Java 8 and its `parallel()` flavor. Logging with a MDC in a parallel `Stream` is not a free lunch: one need to ensure the MDC is captured and reapplied in each step.

The functional style enables such optimizations, because each step is thread-agnostic and referentially transparent, but it can break the MDC assumption of a single `Thread`. The most idiomatic way of ensuring any kind of contextual information is accessible to all stages would be to pass that context around through the composition chain. During the development of Reactor we encountered the same general class of problem, and we wanted to avoid this very hands-down and explicit approach. This is why the `Context` was introduced: it propagates through the execution chain as long as `Flux` and `Mono` are used as the return value, by letting stages (operators) peek at the `Context` of their downstream stage. So instead of using `ThreadLocal`, Reactor offers this map-like object that is tied to a `Subscription` and not a `Thread`.

Now that we've established that MDC "just working" is not the best assumption to make in a declarative API, how can we perform contextualized log statements in relation to events in a Reactive Stream (`onNext`, `onError`, and `onComplete`)?

This entry of the FAQ offers a possible intermediate solution when one wants to log in relation to these signals in a straightforward and explicit manner. Make sure to read the Adding a Context to a Reactive Sequence section beforehand, and especially how a write must happen towards the bottom of the operator chain for operators above it to see it.

To get contextual information from the `Context` to the MDC, the simplest way is to wrap logging statements in a `doOnEach` operator with a little bit of boilerplate code. This boilerplate depends on both the logging framework/abstraction of your choice and the information you want to put in the MDC, so it has to be in your codebase.

The following is an example of such a helper function around a single MDC variable and focused on logging `onNext` events, using Java 9 enhanced `Optional` API:

```
public static <T> Consumer<Signal<T>> logOnNext(Consumer<T> logStatement) {
    return signal -> {
        if (!signal.isOnNext()) return; ①
        Optional<String> toPutInMdc = signal.getContextView().getOrEmpty(
"CONTEXT_KEY"); ②

        toPutInMdc.ifPresentOrElse(tpim -> {
            try (MDC.MDCCloseable cMdc = MDC.putCloseable("MDC_KEY", tpim)) { ③
                logStatement.accept(signal.get()); ④
            }
        },
        () -> logStatement.accept(signal.get())); ⑤
    };
}
```

① `doOnEach` signals include `onComplete` and `onError`. In this example we're only interested in logging `onNext`

② We will extract one interesting value from the Reactor `Context` (see the The `Context` API section)

③ We use the `MDCCloseable` from SLF4J 2 in this example, allowing try-with-resource syntax for automatic cleanup of the MDC after the log statement is executed

④ Proper log statement is provided by the caller as a `Consumer<T>` (consumer of the onNext value)

⑤ In case the expected key wasn't set in the `Context` we use the alternative path where nothing is put in the MDC

Using this boilerplate code ensures that we are good citizens with the MDC: we set a key right before we execute a logging statement and remove it immediately after. There is no risk of polluting the MDC for subsequent logging statements.

Of course, this is a suggestion. You might be interested in extracting multiple values from the `Context` or in logging things in case of `onError`. You might want to create additional helper methods for these cases or craft a single method that makes use of additional lambdas to cover more ground.

In any case, the usage of the preceding helper method could look like the following reactive web controller:

```
@GetMapping("/byPrice")
public Flux<Restaurant> byPrice(@RequestParam Double maxPrice, @RequestHeader(required
= false, name = "X-UserId") String userId) {
    String apiId = userId == null ? "" : userId; ①

    return restaurantService.byPrice(maxPrice))
                .doOnEach(logOnNext(r -> LOG.debug("found restaurant {} for ${}", ②
                    r.getName(), r.getPricePerPerson())))
                .contextWrite(Context.of("CONTEXT_KEY", apiId)); ③
}
```

① We need to get the contextual information from the request header to put it in the `Context`

② Here we apply our helper method to the `Flux`, using `doOnEach`. Remember: operators see `Context` values defined below them.

③ We write the value from the header to the `Context` using the chosen key `CONTEXT_KEY`.

In this configuration, the `restaurantService` can emit its data on a shared thread, yet the logs will still reference the correct `X-UserId` for each request.

For completeness, we can also see what an error-logging helper could look like:

```
public static Consumer<Signal<?>> logOnError(Consumer<Throwable> errorLogStatement) {
    return signal -> {
        if (!signal.isOnError()) return;
        Optional<String> toPutInMdc = signal.getContextView().getOrEmpty(
"CONTEXT_KEY");

        toPutInMdc.ifPresentOrElse(tpim -> {
            try (MDC.MDCCloseable cMdc = MDC.putCloseable("MDC_KEY", tpim)) {
                errorLogStatement.accept(signal.getThrowable());
            }
        },
        () -> errorLogStatement.accept(signal.getThrowable()));
    };
}
```

Nothing much has changed, except for the fact that we check that the `Signal` is effectively an `onError`, and that we provide said error (a `Throwable`) to the log statement lambda.

Applying this helper in the controller is very similar to what we've done before:

```
@GetMapping("/byPrice")
public Flux<Restaurant> byPrice(@RequestParam Double maxPrice, @RequestHeader(required
= false, name = "X-UserId") String userId) {
    String apiId = userId == null ? "" : userId;

    return restaurantService.byPrice(maxPrice))
                .doOnEach(logOnNext(v -> LOG.info("found restaurant {}", v))
                .doOnEach(logOnError(e -> LOG.error("error when searching restaurants",
e)) ①
                .contextWrite(Context.of("CONTEXT_KEY", apiId));
}
```

① In case the `restaurantService` emits an error, it will be logged with MDC context here

10.4. Reactor-Extra

The `reactor-extra` artifact contains additional operators and utilities that are for users of `reactor-core` with advanced needs, or incubating operators.

As this is a separate artifact, you need to explicitly add it to your build. The following example shows how to do so in Gradle:

```
dependencies {
     compile 'io.projectreactor:reactor-core'
     compile 'io.projectreactor.addons:reactor-extra' ①
}
```

① Add the reactor extra artifact in addition to core. See Getting Reactor for details about why you do not need to specify a version if you use the BOM, usage in Maven, and other details.

`TupleUtils` and Functional Interfaces

The `reactor.function` package contains functional interfaces that complement the Java 8 `Function`, `Predicate`, and `Consumer` interfaces, for three to eight values.

`TupleUtils` offers static methods that act as a bridge between lambdas of these functional interfaces to a similar interface on the corresponding `Tuple`.

This lets you easily work with independent parts of any `Tuple`, as the following example shows:

```
.map(tuple -> {
  String firstName = tuple.getT1();
  String lastName = tuple.getT2();
  String address = tuple.getT3();

  return new Customer(firstName, lastName, address);
});
```

You can rewrite the preceding example as follows:

```
.map(TupleUtils.function(Customer::new)); ①
```

① (as `Customer` constructor conforms to `Function3` functional interface signature)

Math Operators With `MathFlux`

The `reactor.math` package contains a `MathFlux` specialized version of `Flux` that offers mathematical operators, including `max`, `min`, `sumInt`, `averageDouble`, and others.

Schedulers

Reactor-extra comes with the `ForkJoinPoolScheduler` (in the `reactor.scheduler.forkjoin` package): it uses the Java `ForkJoinPool` to execute tasks.