Automated Refactoring to Reactive Programming

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***Abstract*—**

Reactive programming languages and libraries, such as ReactiveX, have been shown to significantly improve software design and have seen important industrial adoption over the last years. Asynchronous applications – which are notoriously error-prone to implement and to maintain – greatly benefit from reactive programming because they can be defined in a declarative style, which improves code clarity and extensibility.

In this paper, we tackle the problem of refactoring existing software that has been designed with traditional abstractions for asynchronous programming. We propose 2Rx, a refactoring approach to automatically convert asynchronous code to reactive programming. Our evaluation on top-starred GitHub projects shows that 2Rx is effective with common asynchronous constructs and it can provide a refactoring for 91.7% of their occurrences.

***Keywords*-refactoring; asynchronous programming; reactive programming; Java;**

I. Introduction

Asynchrony is essential for long-running tasks or computations that involve intensive CPU load or I/O, such as network communication and database access. Hence, asynchronous programming has become more and more important over the last years to allow a large class of software – Web applications (e.g., with AJAX), mobile apps, or Internet-of-Things applications – to stay responsive to user interaction and to environmental input. Also, in a number of cases like event driven scenarios, where event streams originate from touch screens, GPS, or sensors, asynchrony is the natural programming model as events can be processed concurrently [1].

Most programming languages offer means for developers to define asynchronous computations. A widespread solution is to fork concurrent asynchronous executions using basic thread/process mechanisms, e.g., with `java.lang.Thread` in Java. However, this approach is very low level and complicates the communication with the main thread. For this reason, modern programming languages provide abstractions for asynchronous computations. For example, C# provides the `async` and `await` keywords, and the Java concurrency package has been continuously enhanced through various Java releases to support high level abstractions such as Futures and the Fork/Join execution model [2]. Similarly, popular libraries provide their own constructs for asynchronous computations, such as `AsyncTask` for Android and `SwingWorker` for the Java GUI Swing library. These solutions significantly improve over low level abstractions like threads, but come with their own limitations. For example, `AsyncTask` does not easily support composition, like sequencing multiple asynchronous computations.

Recently, Reactive Programming (RP) has emerged as a programming paradigm specifically addressing software that combines events [3]. Crucially, RP allows to easily express computations on event streams that can be chained and combined using high-order functional operators. This way, each operator can be scheduled independently, providing a convenient model for asynchronous programming. As a result, RP provides means to describe asynchronous programs in a declarative way. Previous research showed that RP improves software design of reactive applications [4], [5]. Also, empirical studies indicate that RP increases the correctness of program comprehension, while requiring neither more time to analyze the program, nor advanced programming skills [6], [7]. This feature has been crucial in popularizing recent RP languages, including ELM [8], Bacon.js and Rx/ReactiveX [9] – originally developed by Microsoft – which received major attention after being adopted for the redesign of Netflix's streaming server backend.

Unfortunately, most existing software still implements asynchronous computations with traditional techniques. While the benefits of RP design are widely recognized, and new projects can easily adopt RP abstractions right away, this technology is not portable to existing software without a manual refactoring that is tedious and error-prone [10]. As a result, a number of software applications do not benefit from the design improvements provided by RP.

In this paper, we propose an approach to automatically refactoring asynchronous code to the RP style based on ReactiveX's `Observable`, which is a programming abstraction that emits events that are asynchronously handled by Observers. ReactiveX uses operators from RP to compose computations on `Observables`. Using these operators, it is straight-forward to extend asynchronous computations, thus increasing extensibility. Our methodology applies to common abstractions for defining asynchronous computations in Java, including `Future`, and Swing's `SwingWorker`. We implemented our approach in 2Rx, an extensible Eclipse refactoring plugin. Our evaluation on a number of third-party popular GitHub projects – including Apache Zookeeper, Jabref, JUnit, and Mockito – shows the broad applicability of our technique

```
1 Observable<Data> data = getDataFromNetwork();
2 data
3   .filter(d -> d != null)
4   .map(d -> d.toString() + " transformed")
5   .subscribeOn(Schedulers.computation())
6   .subscribe(d ->
7     System.out.println("onNext => " + d));
```

Fig. 1: RxJava example, adapted from ReactiveX's introduction to RP [9].

(on more than 7K projects) as well as its correctness, as the technique was able to correctly refactor 91.7% of the occurrences of asynchronous constructs (the other cases where ruled out by refactoring preconditions).

In summary, the contributions of the paper are as follows:

- We propose a technique to refactor common Java asynchronous constructs to RP.
- We design 2Rx, an extensible approach implemented as an Eclipse plugin that provides such technique for RxJava.
- We evaluate our approach with automatic testing and code inspection, showing that it is broadly applicable, it provides a large coverage of construct instances and exhibits acceptable execution time.
- We release a new large dataset of third-party projects suitable for research on asynchronous programming in Java.

In this paper, we do not address the problem of refactoring synchronous code to asynchronous code – an issue addressed elsewhere [1], [11], [12] – nor we aim at refactoring imperative programming into functional programming – which has been tackled, e.g., in [13], [14]. Also, formally proving the correctness, of refactorings is an open research question [15], [16]. As a first step, we provide supporting evidence for the soundness of our refactoring technique using standard methods like manual inspection and automated testing [1], [11], [12], [14], [17]–[25].

II. Reactive Programming for Asynchronous Applications

In this section, we first introduce ReactiveX, then we demonstrate refactoring to RP through a running example.

A. Reactive Programming in a Nutshell

ReactiveX [9] is a library for asynchronous RP that provides abstractions and operators to process and combine event streams. ReactiveX is available for several languages. In this paper, we consider the Java implementation RxJava. The main abstraction in ReactiveX is an `Observable`, which is the source of an event stream. Similar to the Observer design pattern, an `Observer` can register to an `Observable` and it can be notified of event occurrences. In addition, however, `Observables` can be chained and executed on different threads. Hence, asynchronous programs can be specified in a pipeline fashion with operators such as `map` or `filter`.

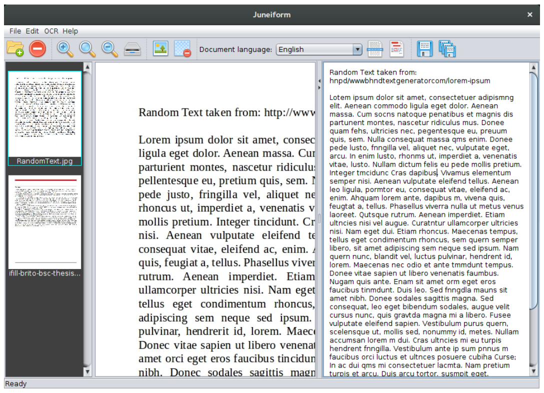

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Fig. 2: Juneiform application.

Figure 1 demonstrates this design. Initially, we obtain a stream of `Data` from the network as an `Observable` (Line 1). Next, all data that is **`null`** gets filtered out (Line 3) and the data is transformed to a `String` and `" transformed"` is appended (Line 4). The `Observable` is executed using the default scheduler (Line 5) – ReactiveX provides a multitude of schedulers to enable asynchronous operations. Finally, the result is printed to the command line (Line 7).

This approach has several advantages: the computations over the stream are *extensible* by adding new operations to the stream and *composable* via combining streams through functional operators. Since data flow gets disentangled from control flow, programs are easier to comprehend and maintain [4]–[6].

B. Refactoring an OCR Application

Figure 2 shows Juneiform [26], an application for Optical Character Recognition (OCR). In Juneiform, users load image files in the UI. The application uses asynchronous programming to load the documents and to process them in a separate thread than the UI.

1) Asynchrony in Juneiform: The document loading functionality is shown in Figure 3a. The `DocumentLoader` class, which extends `SwingWorker`, loads the images into Juneiform. The `SwingWorker` class is provided by the Swing Java GUI library to help programmers implementing asynchronous tasks. In `SwingWorker`, the asynchronous functionality is defined in the `doInBackground` method which is executed when the `execute` method is called. The `doInBackground` method can both (1) return a value after the computation has finished, and (2) publish intermediate values during its execution.

In the example, `DocumentLoader` inherits from the `SwingWorker` class (Line 2) and it assigns two type parameters. The first one is for the return type of the asynchronous call – `List<Document>` as we want to load a list of documents. The other one is for intermediate results of the asynchronous execution – `Document`, to start handling documents to the UI thread before the loading of all documents completes. When the user selects the images from

```
 1 public abstract class DocumentLoader
 2 extends SwingWorker<List<Document>, Document> {
 3
 4  private File[] files;
 5
 6
 7
 8
 9
10  protected List<Document> doInBackground()
11  throws Exception {
12   List<Document> results = ...
13   ...
14   for (File f : files) {
15    ...
16    Document d = new Document(... f ...);
17    results.add(d);
18    publish(d);
19    ...
20   }
21   return results;
22  }
23
24
25
26
27  public void load(File... files) {
28   this.files = files;
29   execute();
30  }
31  protected void process(List<Document> chunks){
32   fetchResults(chunks);
33  }
34  protected void done() {
35   ...
36   List<Document> documents = get();
37   ...
38  }
39  public abstract void fetchResult(
40   List<Document> result);
41  ...
42 }
```

(a) Original SwingWorker implementation.

```
 1 public abstract class DocumentLoader
 2  extends SWSubscriber<List<Document>, Document>{
 3
 4  private File[] files;
 5
 6  private Observable<SWEvent<List<Document>,
 7    Document>> getObservable() {
 8   Emitter<List<Document>, Document> emitter =
 9    new SWEmitter<List<Document>, Document>() {
10     protected List<Document> doInBackground()
11     throws Exception {
12      List<Document> results = ...
13      ...
14      for (File f : files) {
15       ...
16       Document d = new Document(... f ...);
17       results.add(d);
18       publish(d);
19       ...
20      }
21      return results;
22   } };
23   return Observable.fromEmitter(emitter,
24    Emitter.BackpressureMode.BUFFER);
25  }
26
27  public void load(File... files) {
28   this.files = files;
29   executeObservable();
30  }
31  protected void process(List<Document> chunks){
32   fetchResult(chunks);
33  }
34  protected void done() {
35   ...
36   List<Document> documents = get();
37   ...
38  }
39  public abstract void fetchResult(
40   List<Document> result);
41  ...
42 }
```

(b) Refactored to ReactiveX. Changes are marked.

Fig. 3: Asynchronous file loading in Juneiform.

the file chooser dialog and clicks "Open", the `load` method (Lines 27-30) of `DocumentLoader` is invoked with the selected files as arguments. The files are cached in the private `files` field (Line 28). Finally, `execute` (Line 29) invokes `doInBackground` (Line 10-22) in a background thread.

Each `Document` holds the information for an image file, e.g., name, absolute path and file content. To load the images, the program iterates through all `files`, creates a `Document` object for each of them and adds it to the `results` list. Each `Document` is sent to the UI thread as an intermediate result with the `publish` method (Line 18). Before being processed, the results are stored in a buffer (not shown). Then the callback method `process` is invoked with the buffer as argument (Line 31). The buffer is necessary as the UI thread may not be able to execute `process` before multiple results have been published. To display the selected images in the UI, the `process` method invokes the `fetchResults` method (Line 40) with the intermediate results of the asynchronous operation as argument.

The asynchronous operation ends when the `doInBackground` method returns. The return value of the `doInBackground` method, `results`, can be accessed from the `done` method using `get` (Lines 34-38). These methods are declared by the `SwingWorker` class.

2) The Refactoring: The refactoring replaces the `SwingWorker` class with ReactiveX's `Observable` introduced in Section II-A. There are three aspects to consider when refactoring `SwingWorker` to reactive code: (1) Generate emissions on each `publish` invocation – rather than only on the result – to capture the data stream nature of `SwingWorker`, such that an `Observer` in the RP implementation reacts to each emission of the `Observable`; (2) all methods available in the `SwingWorker` API must be available in the `Observer` and (3) the `Observable` must stop sending items to the `Observer` if the latter has not finished processing the last emission.

The result of the refactoring is in Figure 3b. The `getObservable` method (Lines 7-25) creates a

```
 1 DocumentLoader loader = new DocumentLoader();
 2
 3 // Setup observable
 4 Observable<Document> observable =
 5  loader.getObservable()
 6  .flatMap(ev -> Observable.from(ev.getChunks()))
 7  .filter(doc -> doc.getName().contains(".jpg"))
 8  .subscribeOn(Schedulers.computation());
 9
10 // Display document names
11 observable
12 .observeOn(SwingScheduler.getInstance())
13 .subscribe(doc -> label.setText(doc.getName()));
14
15 // Upload document to server
16 observable
17 .observeOn(Schedulers.io())
18 .map(doc -> jpgToBitmap(doc))
19 .subscribe(doc -> uploadToDropbox(document));
20
21 // Connect observable with subscribers
22 loader.load(files);
```

Fig. 4: Extending the Juneiform application.

SWEmitter object that emits a value whenever the doInBackground method produces a result (Lines 9-22). The Observable emits values of type SWEvent. SWEvent objects carry either an intermediate value or the final result of the asynchronous computation.

SwingWorker has functionalities not available in Observable, such as starting the asynchronous operation with the execute method, or storing the current state of the execution (i.e., whether it has completed). In our approach, the SWSubscriber class implements these functionalities: In the refactored version, DocumentLoader is a subclass of SWSubscriber (Line 2). The load method remains unchanged except calling the executeObservable method (Line 29) to start the asynchronous computation instead of the execute method of the SwingWorker class. Similarly, the process method (Line 31), and the done method (Line 34) override the methods in the SWSubscriber class with the same semantics as the corresponding methods in SwingWorker. The body of all these methods remains unchanged in the refactoring. The user-defined method fetchResults (Line 40) remains unchanged as well.

3) Extending Juneiform: The refactoring described above is of limited interest *per se* – the approach in Figure 3b is arguably not better than the solution in Figure 3a. However, the refactoring is beneficial because it *enables* taking advantage of RP's support for extensibility and asynchronous programming via event stream combination.

Let's consider the case in which a developer wants to extend the Juneiform application such that (1) only files with jpg extension are loaded, (2) the GUI displays the name of the file currently processed to provide the user feedback on the loading progress, and (3) the image file is converted from jpg to Bitmap and uploaded to Dropbox for backup.

Implementing these changes in the case of Figure 3a is challenging. First, the steps in the computation exhibit dependencies (e.g., transform an image to a Bitmap and *then* upload it to Dropbox). Hence, a programmer needs to store intermediate results – hiding the logic of the processing sequence. A harder problem is that the long-running tasks in (3) should be executed in separate threads *and* processing should happen as soon as new files are available. Finally, (2) should be executed on the GUI thread to avoid race conditions on the (non-synchronized) GUI components.

These functionalities can be of course achieved with a complex combination of non-composable imperative transformations, intermediate state, asynchronous constructs for the execution on separate threads, and callbacks to achieve responsive push-based processing of new files.

Alternatively, developers can implement these features right away with RP operators such as filter. Figure 4 shows an implementation of these features that extends the refactored version from Figure 3b. First, the getObservable method retrieves the Observable (Line 5) previously defined in the DocumentLoader class. For (1) – load only jpg files – the flatMap operator applied to the Observable (Line 6) provides a stream of Documents, since the Observable produces events containing values of type List<Document>. From this stream, the filter method produces a stream with only jpg files (Line 7). These functionalities are executed in a background thread as specified by Schedulers.computation() (Line 8). For (2) – display in the GUI the name of the file currently processed – Lines 11-13 directly specify to execute this operation in the UI thread. Finally, for (3), the file is converted from jpg to Bitmap as well as uploaded to Dropbox (Lines 16-19). These operations are executed asynchronously and independently of each other – the latter executes as soon as a result from the former is available. Loading the files starts the emission (Line 22). Further extensions are also trivial to support and can be implemented adding new operators to the pipeline.

4) Discussion: We have shown that, thanks to the refactoring to RP, the asynchronous Juneiform application benefits from the advantages of RP design – extensibility and composability. The refactoring we just described requires some observations. In the example, the refactored code is slightly longer and it introduces new concepts, such as Observable or Subscriber, which may harden program comprehension for developers. However, here is no way around learning new concepts when switching to a new programming paradigm, and our target are developers who are already familiar with RP. On the other hand, automated refactoring may help novices to adapt to RP without the burden to manually introduce the new concepts in the codebase. Another potential downside is that the refactored code may not be as performant.For example, one factor that influences performance is the configuration of the scheduler for the asynchronous computations (e.g., Futures), which cannot be faithfully reproduced in the refactored code. Yet, RxJava provides access to the scheduler configuration so that the developer can easily tune the scheduling policy, e.g., by subscribing an Observable to a different scheduler.

III. 2Rx: Refactoring to Reactive Programming

We designed 2Rx, a tool that automatically refactors selected asynchronous constructs to ReactiveX. The key idea of the refactoring is to transform the values generated by asynchronous computations into an event stream that emits an event whenever a new value is generated. For example, `SwingWorker` produces (several) intermediate values and a final result, both of which can be represented as an event stream. 2Rx's refactoring strategy is to replace the asynchronous construct with a ReactiveX `Observable`. The `Observable` emits an event for each results generated by the asynchronous computation. We target two Java constructs for asynchronous programming:

- `javax.swing.SwingWorker`: `SwingWorker` is a construct defined in the Java Swing library. It asynchronously executes the code in its `doInBackground` method, which returns the result of the computation. Also, `SwingWorker` can emit intermediate values during the asynchronous execution.
- `java.util.concurrent.Future`: A future is a value that has not been computed yet, but is available eventually [27]. In Java, the `Future` interface has several implementations. Although `Future` does not emit multiple values, refactoring to RP relieves developers from handling the emission of the value explicitly and enables RP's support for functional composition and asynchronous execution.[1]

The constructs above are not the only way to define an asynchronous task. For example, a primitive way to implement asynchronous execution of long-running computations is via threads, i.e., by implementing the `java.lang.Runnable` interface or by subclassing the `java.lang.Thread` class.

2Rx does not support refactoring threads, because threads are not only used for asynchronous computations, but also for, e.g., parallel execution and scheduling. Threads expose a general interface to programmers which enables executing any computation in the thread. The communication with other threads takes place through shared state. Crucially, threads do not provide a well-defined interface for asynchronous computations that return values, making them unsuitable for refactoring to RP as there is no return value that can be processed by the `Observable` chain. Unfortunately, the cases in which threads express proper asynchronous computations are hard to distinguish because assignment to shared state can equally be due to thread communication in a concurrent application or to synchronization among parallel tasks – without the programmer intention being explicit.

Many modern libraries/languages provide dedicated support for asynchronous computations, like C#'s `async/wait`, Java's `java.util.concurrent.Future`, and Scala's `Async`, substantially deprecating the use of raw threads for concurrency. Our approach targets these cases.

[1]For this reason, RxJava already provides a `fromFuture` method to convert a `Future` into an `Observable`.

For the `java.util.concurrent.Executors` class, considerations similar to those made above for Threads apply. The class provides an API to submit asynchronous computations and to decouple task submission from the mechanics of running the task, i.e., thread use and scheduling. Yet, in some cases, the `Executors` class produces Java `Futures`. In the cases where the return value is used by the rest of the program, hence the future object is available, 2Rx performs the refactoring for `java.util.concurrent.Future`.

A. Refactoring Asynchronous Constructs

In this section, we provide an overview of our refactoring approach for each asynchronous construct.

1) SwingWorker: Refactoring `SwingWorker` to `Observable` requires to consider two major differences between the two constructs: (1) `SwingWorker` does not only emit a final result, but also intermediate results *with a different type*, and (2) `SwingWorker` keeps track of the current status of the computation – if it is still running or if it has already finished. To achieve the functionalities of `SwingWorker` with `Observable`, we implemented an extension to ReactiveX consisting of three helper classes (Figure 3b): `SWEmitter` emits an event for each call to the `publish` method and for the final result (Line 8); `SWSubscriber` implements the `SwingWorker` API on top of the emitter (Line 2); `SWEvent` is the type of events produced by the `Observable`, holding either an intermediate or a final result (Line 7). These three classes are added to the project's class path during the refactoring.

The actual refactoring consists of replacing `SwingWorker` with `SWSubscriber`. The `SwingWorker` definition is split into two parts by 2Rx. (1) The `Observable` is wrapped around the `SWEmitter` class to support further asynchronous computations. (2) The `SWSubscriber` class subscribes to the `Observable` and provides the `SwingWorker` API. The body of the `SwingWorker` class is then rewritten such that the `doInBackground` method is placed in the `SWEmitter`. The other methods remain unchanged.

2) Java Futures: Figure 5a shows the use of a `Future` in conjunction with an `ExecutorService` to schedule asynchronous tasks. The example is taken from Elasticsearch [28], a distributed search engine.

First, the `ExecutorService` is initialized (Line 1), and a list of `Future` is created (Line 3). A task is submitted to the `ExecutorService` (Line 7). The task is defined in the `call` method of `Callable` (Lines 9-15) which returns a `Future` for the task result that is then added to the list. In the example, the task waits for the result of another executor and retrieves the result – the `List<T>` returned by the `Future` (Line 14). The task is executed asynchronously, i.e., it does not block the execution of the main thread. The computation only blocks when the result of the `Future` is retrieved to store it in a list of results (Line 20).

Figure 5b shows the refactored version. The initialization of the `ExecutorService` does not change (Line 1). The list now stores `Observable` instead of `Future` (Line 3). An

```
1 ExecutorService pool = ...
2 List<Future<List<T>>> list =
3  new ArrayList<Future<List<T>>>();
4
5 for (int i = 0; i < numTasks; i++) {
6  list.add(
7   pool.submit(new Callable<List<T>>() {
8    @Override
9    public List<T> call() throws Exception {
10    List<T> results = new ArrayList<T>();
11    latch.await();
12    while(count.decrementAndGet() >= 0) {
13     results.add(executor.run()); }
14    return results;
15   }
16 })); }
17 ...
18
19 for (Future<List<T>> future : list) {
20   results.addAll(future.get()); }
```

(a) Original code.

```
1 ExecutorService pool = ...
2 List<Observable<List<T>>> list =
3  new ArrayList<Observable<List<T>>>();
4
5 for (int i = 0; i < numTasks; i++) {
6  list.add(Observable.fromFuture(
7   pool.submit(new Callable<List<T>>() {
8    @Override
9    public List<T> call() throws Exception {
10    List<T> results = new ArrayList<T>();
11    latch.await();
12    while(count.decrementAndGet() >= 0) {
13     results.add(executor.run()); }
14    return results;
15   }
16  }), Schedulers.computation() )); }
17 ...
18
19 for (Observable<List<T>> future : list) {
20   results.addAll(future.blockingSingle() ); }
```

(b) Refactored code. Changes are marked.

Fig. 5: Refactoring Java `Future`. Code extracted from the Elasticsearch search engine [28].

`Observable` is created from the same `Callable` that was submitted to the executor (Lines 9-15). The `Observable` uses a `Scheduler` (Line 16) to run asynchronously. Note that the `Future` is still executed according to the `ExecutorService` – only the `Observable` operates on the `Scheduler`.

3) Discussion: The drawback of the helper classes used in the `SwingWorker` refactoring is that they are an extension to the ReactiveX library, while a clean refactoring should be based on ReactiveX only. Helper classes enable refactoring more cases, as they take over some of the responsibility of preserving the functionality during the refactoring. But, helper classes also complicate the code introducing additional classes and functionalities. We believe that the satisfactory refactoring results for Java `Future` do not justify the loss of such clean approach for those cases.

B. Checking Preconditions

Before applying a refactoring, it is crucial to check whether certain conditions (*refactoring precondition* [29]) are satisfied to guarantee that the refactoring is possible and the result is correct. Figure 6 shows a problematic case. The original code is in Figure 6a. Two futures are created (Line 1 and 4). The first future does not use the standard Future interface but the `Future` subclass `ScheduledFuture`, on which the `cancel` method is invoked (Line 9). This configuration leads to a non-refactorable `Future` instance, because (1) `Observable` does not support the equivalent of a `cancel` method in the `Future` class, and (2) the `ScheduledFuture` subclass provides additional functionalities that are not supported by a refactoring that targets `Future`. The precondition check finds non-refactorable `Future` instances and excludes them from the refactoring.

The refactored code is in Figure 6b. Because of the problem above, the first `Future` is not refactored (Line 1) and our tool issues a warning for it. The second `Future` instance passes the precondition check as, contrary to the first `Future`, it uses the default `Future` interface and it only calls the `get` method. The refactoring for this instance is correct (Line 4 and 7). The example demonstrates the need for flow-sensitive source code analysis in 2RX, e.g., to find out on which instances `cancel` is invoked, and to selectively reject refactoring those instances.

Our preconditions are defined to disallow using functionalities of asynchronous constructs that can not be translated into corresponding functionalities of `Observable`. We define similar preconditions as Yin and Dig [30]: Asynchronous constructs are only used by executing and retrieving their result, and subclasses are disallowed. Preconditions are defined on *occurrences* of asynchronous constructs. An occurrence is the coherent usage of a construct. For example, in Figure 6, there are two occurrences of `Future`. Concretely, we define three preconditions for our refactoring approach. Occurrences where at least one precondition is not satisfied are excluded from the refactoring.

- *The asynchronous computation is not cancelled.* ReactiveX provides no way to cancel asynchronous computations of `Observables`, but only to unsubscribe an observer (which does not cancel the running computation).
- *The state of an asynchronous execution is not retrieved.* Asynchronous constructs often provide ways to directly retrieve the current state of an asynchronous execution, e.g., `Future.isDone()` checks whether an asynchronous computation has completed. `Observables` lack such functionality.
- *The asynchronous construct is not used through a subclass that provides additional functionalities.* This case includes classes specific to a single project, as well as unsupported library constructs like, e.g., `ScheduledFuture` from Figure 6.

```
ScheduledFuture<Void> cleanup =
  executor.schedule(...);
...
Future<String> futureResult =
  executor.submit(...);
...
String result = futureResult.get();
...
cleanup.cancel(false);
```

(a) Original code.

```
ScheduledFuture<Void> cleanup =
  executor.schedule(...);
...
Observable<String> futureResult =
  Observable.fromFuture(executor.submit(...));
...
String result = futureResult.blockingSingle() ;
...
cleanup.cancel(false);
```

(b) Refactored code. Changes are marked.

Fig. 6: Precondition example. Code extracted from the DropWizard RESTful Web service framework.

C. Implementation

We designed 2Rx as an Eclipse plugin for refactoring Java projects. The plugin consists of an extensible core that provides Eclipse integration and an API for the basic functionalities required by all refactorings. The API allows retrieving the AST of a compilation unit, performing static data flow analyses, identifying a specific Java construct, manipulating the AST, and outputting the refactored code. We implemented an extension for the two asynchronous constructs in Section III, Java `Future` and `SwingWorker`. Each extension uses the API to search for a specific construct and to implement the associated transformation. We have implemented an automatic precondition checker for both the constructs currently supported. The checker is based on a flow-sensitive static analysis on Java source code [31]. The extensible architecture simplifies adding new refactorings for other constructs, which is ongoing work.

IV. Evaluation

In this section, we evaluate our refactoring approach. First, we define our research questions.

A. Research Questions

Our evaluation answers the following research questions. First, we want to evaluate which fraction of all asynchronous constructs available in Java can be targeted by 2Rx.

> **Q1 (Applicability)**: Which fraction of asynchronous constructs used in real-world projects is supported by 2Rx?

Second we want to know, among the occurrences of asynchronous constructs supported by 2Rx, how many cases satisfy the preconditions that 2Rx requires to perform the refactoring and lead to refactored code that is correct and achieves the same functionality of the original code.

> **Q2 (Correctness)**: How many occurrences of the supported asynchronous constructs can 2Rx correctly refactor?

Finally, we want to ensure that our refactoring tool is usable, e.g., the refactoring process must complete in a *reasonable* time even for *large* projects.

> **Q3 (Efficiency)**: Is 2Rx fast enough to be usable by developers?

Next we present the methodology for creating the datasets to evaluate our work. Finally, we present the answer to the research questions above, e.g., the evaluation results on applicability, correctness and efficiency of our solution.

B. Methodology

In the following, we describe the methodology to answer the research questions.

1) Global Dataset: First, we identified the asynchronous constructs that are used in Java. We looked for documentation and tutorials that introduce asynchronous programming in Java and we considered the documentation of frameworks, such as Spring [32], which provide asynchronous constructs to users. Further, we talked to other researchers and developers, personally and over StackOverflow, about which asynchronous constructs they use. With this process, we have identified the 14 asynchronous constructs listed in Table I. We used Boa [33] – a language and infrastructure for mining software repositories – to identify projects that contain these constructs. Boa provides a snapshot of all public GitHub projects from 2015, consisting of 380,125 projects. We considered the 275,879 projects containing Java source files. We found 46,208 Java projects that contain at least one asynchronous construct.

The *global dataset* is composed of GitHub open-source projects that use one of the constructs above. We identified projects containing an asynchronous construct by searching for the class name and the corresponding import in the AST. We also searched for classes that are created by the factory classes `akka.dispatch.Futures` and `java.util.concurrent.Executors`, such as `Future`, `Executor`, `ExecutorService` and `ScheduledExecutorService`, respectively. For the class `javax.enterprise.concurrent.ManagedTask`, we also considered projects that use one of the associated classes `ManagedExecutorService` or `ManagedScheduledExecutorService`. This approach ensures that we find constructs that are adopted in the project even if they do not appear syntactically in the code (e.g., in case they are returned by a method call and used without assigning them to an intermediate variable). We used the global dataset to evaluate applicability of our methodology.

2) Refactoring Dataset: We filtered the global dataset to select relevant projects for each of the two constructs supported by 2Rx, generating the *refactoring dataset*.

First, we filtered out all projects that do not contain one of the two constructs supported by 2Rx: `SwingWorker`, and Java `Future`. Out of the 46,208 Java projects in the global dataset, we found a total of 7,133 projects that use at least one of the two supported constructs; 5,718 projects use Java `Future` and 1,651 projects use `Swingworker` (236 projects use both). Next, we removed projects that do not use one of the popular build tools Maven [34] or Ant [35] to – at least partially – automate the evaluation, as we automatically tested the refactored code as well as checked whether the refactored code compiles. We identified projects that use a build tool based on the respective build file, i.e., `pom.xml` for Maven and `build.xml` for Ant. We ended up with 4,652 projects for `Future` and 1,118 projects for `SwingWorker`.

On GitHub, projects can be starred by other users to follow their updates. We used GitHub stars as a metric for the popularity of a project [36]. As stars are not included in the Boa dataset, we counted them checking the respective online GitHub project. We took the projects for `Future` and `SwingWorker` and sorted them by their number of GitHub stars. Then, we took the top 10 ranked projects that we were able to compile, resulting in the *refactoring dataset*. As we use the Boa 2015 dataset, some projects required dependencies that were no longer available. We filtered out these projects as we were not able to compile them. For `Future`, this is the case for 5 projects, for `SwingWorker`, it is the case for 16 projects. The datasets that we created are available to researchers interested in studying Java asynchronous constructs.

3) Automatic Test Generation: To evaluate the correctness of the refactorings, we ran unit tests for each project. We assume that, when the unit tests pass before as well as after the refactoring, the refactoring does not change the functionality of the code. Unfortunately, for many projects, existing tests provided in the project already failed even with the original code, or did not cover the refactored code. For this reason, we opted for automatic test generation to create tests for exactly the parts of the code that were refactored.

To automatically test the refactored code, we implemented a framework based on Randoop [37]. The generated tests capture the behavior of the original code, and are run again on the refactored code to ascertain that programs are behaviorally equivalent to the original code. Automatic test generation to assess correct refactorings has been used before, e.g., by Soares et al. [38]. Formal verification of the correctness of refactorings is a very recent research direction [16].

To ensure that test generation remains feasible for large projects, the testing framework accurately generates tests only for methods changed by the refactoring. When the refactoring changes the signature of a method, i.e., name, parameter or return types, the framework generates tests for methods that call the changed method. The same holds for methods that are not directly accessible, e.g., because they are private. Methods that are nondeterministic or have side-effects across method calls (such as writing/reading from a file) are not amenable for automated testing, because calls to the same method result in different behaviors. The framework detects nondeterministic methods by recognizing varying test results for those methods. All tests for nondeterministic methods are discarded.

TABLE I: Asynchronous constructs in Java – global dataset.

For each asynchronous construct, the absolute number of projects (Column *total*) and the percentage over all projects that use at least one asynchronous construct (Column %) is given. Projects can contain multiple asynchronous constructs.

Constructs	total	%
`java.lang.Thread`	40,988	14.86%
`java.util.concurrent.Executors`	11,708	4.24%
`java.util.concurrent.Future`	5,718	2.07%
`javax.swing.SwingWorker`	1,651	0.60%
`java.util.concurrent.FutureTask`	1,372	0.50%
`com.google....ListenableFuture`	295	0.11%
`javafx.concurrent.Task`	163	0.06%
`akka.dispatch.Futures`	122	0.04%
`java.util.concurrent.ForkJoinTask`	92	0.03%
`javax.ejb.AsyncResult`	82	0.03%
`javax.ws.rs.container.AsyncResponse`	31	0.01%
`javax.enterprise.concurrent.ManagedTask`	19	0.01%
`java.util.concurrent.CompletableFuture`	7	<0.01%
`org.springframework.scheduling.annotation.Async`	1	<0.01%
Projects with asynchronous constructs	46,208	16.75%
All Java projects	275,879	100.00%

4) Evaluation Methodology: For Q1 (Applicability), we determined the most common asynchronous constructs used by developers in the global dataset and reported which percentage of them is supported by 2Rx. For Q2 (Correctness), we checked which fraction of the occurrences of asynchronous constructs in the refactoring dataset are correctly refactored by 2Rx. Correctness is evaluated by checking that the project still compiles after the refactoring and by executing the generated tests. For compilation and testing, we use the Boa 2015 version of the projects. We only considered occurrences that 2Rx actually refactors, i.e., occurrences that are not rejected by the preconditions. For Q3 (Efficiency), we measured the time that 2Rx requires to refactor a project. This time includes parsing the source code and constructing the AST, finding the appropriate constructs, analyzing them, and generating the refactored code.

C. Results

Table I and Table II summarize the evaluation results from, respectively, the global dataset and from the refactoring dataset. We describe the tables and then we refer to them to answer our research questions.

In Table I, for each construct, we show the total and relative number of projects where the construct is used. We found a total of 46,208 projects that use at least one asynchronous construct. Table II provides the results of the refactoring for each asynchronous construct in the refactoring dataset.

*a) **Q1** (Applicability):* Table I shows that `Thread` and `Executor` are the two most used asynchronous constructs in Java. Similar to `Thread`, the `Executor` interface can be used for arbitrary concurrent computations, usually via its `ExecutorService` extension. However, contrary to `Thread`, `Executor` provides an API to submit

TABLE II: Refactoring popular GitHub projects – refactoring dataset.

Column *Stars* shows the number of stars (i.e., "followers") on GitHub. Column *cond* shows how many occurrences pass (*y*) or violate (*n*) the preconditions, respectively. Column *time* indicates how long it takes to refactor the whole project. *LOC* are the lines of code, and *files* the number of source files in the pre-refactored project both measured with CLOC [39]. Columns `c?` and `t?` indicate whether the refactored program has been successfully compiled or tested, respectively. ✓ indicates that the compilation/testing was successful, and ∅ in the `t?` column indicates that the automatic test generation failed.

Stars	Project	cond		Time (ms)	LOC	files	c?	t?
		y	n					
3058	Zookeeper	8	0	16,051	83,956	671	✓	∅
1777	Disunity	1	0	7,733	5,720	113	✓	✓
1285	Gitblit	3	0	13,378	63,910	415	✓	✓
661	OptaPlanner	2	0	31,138	60,219	946	✓	∅
565	Jabref	1	0	20,756	93,268	698	✓	✓
486	Nodebox	2	0	9,926	32,244	283	✓	✓
150	ATLauncher	1	0	5,941	46,292	348	✓	∅
109	CookieCadger	4	0	1,976	4,415	18	✓	✓
89	PIPE	3	0	13,676	73,597	732	✓	✓
70	BurpSentinel	3	0	1,056	10,217	132	✓	✓

(a) SwingWorker.

Stars	Project	cond		Time (ms)	LOC	files	c?	t?
		y	n					
23495	Elasticsearch	4	0	261,132	370,006	3,595	✓	✓
6152	JUnit	1	0	4,577	24,218	375	✓	✓
5820	DropWizard	2	1	48,910	17,708	361	✓	✓
4871	Mockito	2	0	104,409	52,871	822	✓	∅
4790	Springside4	0	2	8,266	20,293	199	✓	✓
4424	Titan	1	3	116,117	40,301	531	✓	∅
3774	AsyncHttpClient	105	0	15,402	29,739	344	✓	∅
3327	Graylog2Server	0	5	47,839	138,663	2,014	✓	✓
3018	Java Websocket	0	1	1,653	5,117	52	✓	✓
2840	B3log	0	1	16,217	14,635	173	✓	✓

(b) Java Future.

asynchronous computations which return a Java `Future`. We are able to refactor these occurrences of `Future` with 2Rx. These occurrences are already included in the projects using `Futures` in Table I. Java `Future`, i.e., the `java.util.concurrent.Future` interface, provided in the Java standard library, is the next most used construct. Standard ways to create a `Future` are either through `ExecutorService` – as we already mentioned – or by directly instantiating one of the various `Future` implementations: `FutureTask`, `SwingWorker` and `AsyncResult` implement the `Future` interface. The other constructs are responsible for the remaining asynchronous computations.

2Rx provides refactoring support for `SwingWorker`, and `java.util.concurrent.Future` as well as `FutureTask`. `FutureTask` is an implementation of the `Future` interface that does not add any further functionality. For this reason, 2Rx is able to refactor this construct. As already discussed (Section III), `Thread` and `Executor` are excluded from the refactoring because they express computations that are not suitable for the RP model. As a result, 2Rx targets a total of 7,552 projects, which is ∼2.7% of all projects, and ∼16.3% of all projects that contain at least one asynchronous construct. We conclude that 2Rx is applicable to some of the most used Java constructs for asynchronous computations.

*b) **Q2** (Correctness):* Table II presents the refactoring dataset with the amount of asynchronous constructs refactored for each project and the results of the automatic testing. As described in Section III-B, the code needs to fulfill refactoring preconditions to ensure that the refactoring can be applied correctly. We evaluate the correctness of the refactoring by checking that the refactored code (1) can be compiled (ensuring that the refactoring produces valid Java), and (2) passes the automatically generated tests.

In the `SwingWorker` case (Table IIa), all occurrences of asynchronous constructs pass the preconditions. Compilation after refactoring succeeds for every project. Automatic test generation fails for 3 projects. The reason is that the methods under test are within inner classes, hence it is not possible to automatically generate tests with Randoop (Section IV-B3). For the other projects, all tests succeed.

In the case of `Future` (Table IIb), we were able to refactor ∼89.8% of the occurrences. As mentioned in Section III-B, the precondition check excludes asynchronous constructs that are (1) subclasses of `Future`, that are (2) cancelled via `Future.cancel()`, or that (3) retrieve the state of the asynchronous computation via `Future.isCancelled()` or `Future.isDone()`. The precondition check rejects 13 occurrences, where 6 are cancelled, 6 are subclasses, and 1 is both. The compilation of all projects succeeds after refactoring, but the automatic test generation fails for 3 projects, because of inaccessible methods and abstract classes. For the other 7 projects, tests are generated successfully and the tests succeed.

The evaluation shows that the use of helper classes in the case of `SwingWorker` allows us to perform significantly more refactorings than in the case of `Future` for which no helper classes are used. In summary, 2Rx is capable of refactoring ∼91.7% of cases. All refactored cases can be compiled correctly. For 6 projects, the automatic test generation failed, but for the other projects, all tests are executed successfully.

*c) **Q3** (Efficiency):* At last, we discuss the efficiency of our approach. We present the run time for each refactoring in Table II. The times were measured on an Intel Core i5-7200U, with 16 GB memory running Linux Kernel 4.15.

On average, our approach requires ∼366 ms/1K LOC for `SwingWorker`, and ∼1121 ms/1K LOC for Java `Future`. The `SwingWorker` refactoring is faster than the `Future` refactoring, because the precondition analysis of `Future` is more involved, since the helper classes in the `SwingWorker` refactoring obviate the need of preconditions. The upper bound of the refactoring time, the Elasticsearch project in the Java `Future` refactorings, requires ∼261 seconds. This relatively high amount of time is due to the size and the complexity of the code base. The Elasticsearch project consists of a total of 3,602 compilation units, and 261,132 LOC. We still consider this time acceptable, as the refactoring only has to be done once for the entire project: It is faster than the time that would be required for a programmer to find the 4 asynchronous constructs and to manually refactor them. For smaller projects, the refactoring is faster and only takes a few seconds.

V. Threats to validity

In this section, we discuss the threats to the validity [40] of our work.

1) Internal Validity: The results of the evaluation of correctness rely on our testing framework described in Section IV-B3. The framework generates extensive tests that increase the confidence in the behavioral equivalence of the original code and of the refactored code. Testing is, however, by definition not complete and it could be that some differences are not detected. To mitigate this threat, we also inspected all refactorings manually and found them correct. The manual inspection has been done independently by two scientific staff members not involved in the project and by the authors. When necessary, we investigated conflicts in the inspection by manually writing small code examples which capture the essence of the inspected code. We then tested that, after refactoring, the examples behave the same as before. It is possible that refactored methods cannot be tested directly, because, e.g., methods are not accessible or the refactoring changes a methods signature. For this reason, the test generation framework creates tests for methods that call the refactored methods. This approach increases the number of methods that can be tested. Some refactoring cases, however, cannot be automatically tested, because they rely on nondeterministic methods. In these cases, the evaluation of the refactoring has to rely on manual inspection and on ensuring that the project compiles correctly. Nondeterministic methods are detected by the testing framework and are excluded from the automatic test generation. In summary, we use the automated testing approach *to increase our confidence* in the soundness of our work, rather than relying on it. There exist *ad hoc* testing techniques that specifically target certain refactorings [41], but none of them directly apply to the refactorings used in this paper, opening an interesting direction for future work.

2) External Validity: Another threat to validity is whether our results can be generalized. The projects considered for the evaluation are open-source projects available on GitHub. We considered projects that have a high amount of stars (followers) which is on one hand an indication of popularity, but also of a certain code quality [36]. The refactoring dataset contains software applications that belong to different domains, including a distributed database (Titan), a computer game launcher (ATLauncher) and a testing framework (JUnit). In addition, since we adopt projects *in the wild* for our evaluation, we consider codebases developed by different teams, which promises variety in coding style. In particular, manual inspection showed a diverse usage of asynchronous constructs, e.g., `Future` is used with `Executor`, custom implementations, or as part of collections, amongst others.

These considerations increase our confidence that the results presented in this paper generalize to most Java projects that include the supported asynchronous constructs.

VI. Related Work

We organize related work into languages for functional reactive programming, recent results on refactoring techniques, and approaches to refactor existing software to asynchronous execution.

1) Reactive Programming: Functional reactive programming has been introduced in the Fran [42] animation system. Over the last years, abstractions from FRP – such as event streams, time-changing values and combinators to support their modular composition – have been introduced in a number of extensions of mainstream languages. These include Bacon.js [43] (Javascript), Flapjax [5] (Javascript), FrTime [4] (Scheme), REScala [44] (Scala), Scala.React [45] (Scala), and RxJava [9] (Java). Such approaches differ, among the other features, in the abstractions they support (e.g., event streams and behaviors [4], [5], [44], or events only [9], [43]) as well as in the consistency guarantees they provide (e.g., glitch-freedom [4], [5], [44], eventual consistency [9], [43] or multiple consistency levels [46]). Some approaches (e.g., [44]) use synchronous RP. For a complete overview of RP the reader can refer to the survey by Bainomugisha et al. [3].

Tool support for reactive programming is still in an early stage, with recent proposals to support interactive debugging [47], [48].

2) Refactoring: Refactoring refers to the process of modifying a program – usually to improve the quality of the code – such that the behavior remains the same [29], [49]. In a broader sense, refactoring can also change nonfunctional requirements of programs, e.g., performance. Studies have shown that refactoring can improve maintainability [50] and reusability [51] of existing software. Unfortunately, despite the availability of dedicated tools, developers tend to apply changes manually to fulfill the new requirements [52].

Operationally, refactoring consists of a series of transformations after checking that the refactoring candidate satisfies some preconditions. If any step in the sequence fails, all the transformations already done should be rolled back [53].

Due to space reasons, it is not possible to provide a complete overview of previous research on refactoring. We only focus on recent work in representative areas. Wloka et al. propose a refactoring to transform global state of Java programs to thread-local state, where possible, to introduce parallelism [17]. Schäfer et al. [18] propose a refactoring from Java's built-in locks to a lock implementation that can be fine-tuned to improve performance. Schäfer et al. [54] found that many refactorings are not safe for concurrent code and propose a technique to make refactoring concurrent Java source code more reliable. Tsantalis et al. propose to use Java 8 lambda expressions to refactor clones with (small) behavioral differences [19].

Other recent refactoring approaches target introducing Java 8 default methods into legacy software [20], automatic detection of refactorings for object-oriented models [21], clone refactoring [22], as well as performance improvement [23] using a database with an ad hoc representation of source code. Liebig at al. [55] address refactoring with preprocessor directives and propose an approach to preserve the behavior of all variants. Meng at al. propose to use refactoring for clone removal [56]. Jongwook et al. investigate scripting refactorings to retrofit design patterns in Java [57]. LAMBDAFICATOR [14] is a tool that – motivated by the new features of Java 8 – converts anonymous inner classes to lambda expressions and converts for-loops that iterate over Collections to high-order functions. None of these works tackles the issue of refactoring existing applications to RP.

3) Refactoring Asynchronous Code: The line of work by Dig and colleagues, addressed the issue of refactoring asynchronous code in the context of mobile applications. This line of research starts from the observation that most available documentation focuses on creating asynchronous apps from scratch rather than on refactoring existing synchronous code. Hence not enough tools are available to support developers to perform the refactoring [1].

With Asynchronizer [11], developers select certain statements of a program and the tool creates an `AsyncTask` which executes the selected code asynchronously. A static analysis informs the programmer in case the generated code introduces data races.

Lin et al. [24] found that many developers use the wrong construct when dealing with the GUI: in Android, the asynchronous construct `IntentService` is more efficient than `AsyncTask` which uses shared-memory. Lin et al. developed ASYNCDROID, a tool for refactoring `AsyncTask` into `IntentService`.

Okur et al. [12], propose a tool to refactor asynchronous C# programs based on two components. ASYNCIFIER transforms legacy code that uses callbacks into code that uses the built-in `async/await` constructs. CORRECTOR recognizes performance anti-patterns and issues like deadlocks of `async/await` constructs. The tool corrects most cases of undesirable behavior found through an empirical study based on GitHub public repositories.

Brodu at al. [25], propose a tool to transform callbacks to Dues – a construct similar to Promises [27], [58] – based on the observation that callbacks lead to code that is hard to understand – an issue known as *Callback Hell* [59].

All these approaches either (1) introduce asynchronous execution for otherwise sequential code [11], or (2) refactor asynchronous code to use more specific constructs (e.g., `async/await` [12], `IntentService` [24], Promises [25]). Our approach is complementary to (1) as it can refactor applications to RP after asynchronous execution has been introduced. Conceptually, our approach targets the output of (1) and (2) to convert it to RP.

VII. Conclusion

In this paper, we presented a method to refactor asynchronous programming constructs to RP. We implemented an Eclipse plugin which automates the refactorings and we evaluated it on popular third-party projects from GitHub.

The results show that our tool correctly refactors some common constructs for asynchronous programming in Java. We are currently extending 2Rx to support more constructs and improve its applicability. We hope that, equipped with 2Rx, more and more programmers can bring the design benefits of RP to their projects.

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