
To be Decided?

Bla bla bla...

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ABSTRACT

In the last few years the *** of Reactive Programming has gained much traction in the developer's community, especially with the general trend for programming languages to embrace functional programming and the shifting of today's applications towards an asynchronous approach to modeling data. The goal of this work is to shed some light to the sea of more or less informed opinions regarding what the meaning of Reactive Programming is thorough the use of Mathematics...

DEDICATION AND ACKNOWLEDGEMENTS

Here goes the dedication.

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INTRODUCTION

*The cold winds are rising in
the North... Brace yourselves,
winter is coming.*

— George R.R. Martin,
A Game of Thrones

You know
nothing John
Snow quote

With the evolution of technologies brought in by the new millennium and the exponential growth of Internet-based services targeting millions of users all over the world, the Software Engineers' community has been continuously tested by an ever growing number of challenges related to management of increasingly large amounts of user data^[6].

This phenomena is commonly referred to as Big Data. A very popular 2001 research report^[8] by analyst Doug Laney, proposes a definition of big data based on its three defining characteristics:

- *Volume*: the quantity of data applications have to deal with, ranging from small - e.g. locally maintained Databases - to large - e.g. distributed File Systems replicated among data centers.
- *Variety*: the type and structure of data, ranging from classic SQL-structured data sets to more diversified and unstructured ones such as text, images, audio and video.
- *Velocity*: the speed at which data is generated, establishing the difference between pull-based systems, where data is synchronously pulled by the consumer, and push-based systems, more suited for handling real-time data by asynchronously pushing it to its clients.

Each of these traits directly influences the way programming languages, APIs and databases are designed today. The increasing volume calls for a declarative approach to data handling as opposed to an imperative one, resulting in the developer's focus shifting from how to compute

something to what it is to be computed in the first place^[5]. The diversification of data, on the other hand, is the main drive for the research and development of noSQL approaches to data storage. Lastly, the increase in velocity fuels the need for event-driven, push-based models of computation that can better manage the high throughput of incoming data^[9].

In this context, the concept of *reactive programming* has gained much traction in the developer's community as a paradigm well-suited for the development of asynchronous event-driven applications^[2]. Unfortunately, reactive programming has been at the center of much discussion, if not confusion, with regards to its definition, properties and principles that identify it^[10].

The goal of our work is to shed light on this much discussed topic by providing a formalization of the reactive programming paradigm. We are going to do so by means of a mathematical approach in the derivation of the reactive types. We will then continue with the development of an API which builds upon the previously derived theoretical foundations and discuss how this relates to the already existing, commercial reactive libraries.

Contributions

To the best of our knowledge, we are not aware of any previous work which analyses reactive programming from a mathematical and theoretical perspective..

Many attempts have been conducted in order to formalize this concept, some more business-driven than others, such as the Reactive Manifesto, Reactive Streams. None of these precisely defines reactive programming, but in most cases result in a nice document to be presented to a company's management for adoption - lots of buzzwords, not much substance.

Write contributions

Overview

Chapter 2 starts with ... bla bla bla

Write overview

Notation & Conventions

In the exposition of our work we will use Haskell as the reference programming language.. because it's close to mathematical notation..

Write notation and conventions

REACTIVE PROGRAMMING

"It was much pleasanter at home," thought poor Alice, "when one wasn't always growing larger and smaller, and being ordered about by mice and rabbits. I almost wish I hadn't gone down the rabbit-hole – and yet – and yet – ..."

— Lewis Carol,
Alice in Wonderland

In this chapter ... bla bla bla

Write chapter introduction

1.1 The essence of Reactive Programs

The use of the term reactive program in scientific literature is dated back to the mid-sixties^[1]. A relevant and insightful definition was given by G. Berry in 1991^[3] as he describes reactive programs in relation to their dual counterparts, interactive programs:

"Interactive programs interact at their own speed with users or with other programs; from a user point of view, a time-sharing system is interactive. *Reactive*

programs also maintain a continuous interaction with their environment, but at a speed which is determined by the environment, not by the program itself.”

Interactive programs concretize the idea of a pull-based model of computation, where the program - the consumer in this case - has control over the speed at which data will be requested and handled. A perfect example of an interactive program is a control-flow structure such as a for-loop iterating over a collection of data: the program is in control of the speed at which data is retrieved from the containing collection and will request the next element only after it is done handling the current one.

Reactive programs, on the contrary, embody the idea of a push-based - or event-driven - model of computation, where the speed at which the program interacts with the environment is determined by the environment rather than the program. In other words, it is now the producer of the data - i.e. the environment - who determines the speed at which events will occur whilst the program’s role reduces to that of a silent observer that will react upon receiving events. Standard example of such systems are GUI applications dealing with various events originating from user input - e.g. mouse clicks, keyboard button presses - and programs dealing with stock market, social media or any other kind of asynchronous updates.

1.2 Why Reactive Programming Matters

Considering the definition and examples of reactive programs we analyzed in the previous section, let’s now try to formalize the class of problems the reactive programming paradigm is specifically well-suited for.

The table below provides a collection of types offered by common programming languages for handling data, parameterized over two variables: the size of the data, either one or multiple values, and the way data is handled, either by synchronous or asynchronous computations^[11].

	One	Many
Sync	a	Iterable a
Async	Future a	<i>Reactive Programming</i>

Fix the table,
add caption.

The first row shows that synchronous functions come in two flavors: classic functions that return a single value of type `a` and functions that produce a collection of results of type `a`, abstracted through the `Iterable a` interface (See section 2.1). These types of functions embody the standard imperative, pull-based approach to programming, where a call to a function synchronously blocks until the result is produced.

Moving on to the second row, we encounter `Future a`, an interface representing an asynchronous computation that, at a certain point in the future, will result in a value of type `a`. Futures are generally created by supplying two callbacks together with the asynchronous computation, one to be executed in case of success and the other one in case of error.

Programming languages, however, are not as well equipped when it comes to handling asynchronous computations resulting in multiple values. The issue lies in the fact that the program's control flow is dictated by the environment rather than the program itself - i.e. inversion of control -, making it very hard to model such problems with commonly known control structures, which are optimized for sequential models of computation.

This class of problems reflects the definition of reactive programs we analyzed in the previous section, where the environment asynchronously - i.e. at its own speed - pushes multiple events to the program.

Traditional solutions typically involve developers manually trying to compose callbacks by explicitly writing CPS (continuation passing style) code^[11], resulting in what it's commonly referred to as *Callback Hell*^[4].

The reactive programming paradigm sets out to provide interfaces and abstractions to facilitate modeling the aforementioned class of problems. In the next session we will discuss and analyze various approaches and libraries attempting to implement this paradigm, motivating our need for a mathematical formalization to remove doubts and confusion.

Rewrite this part.

1.3 Reactive Programming in the Real World

Talk about FRP, Reactive Streams, Rx and other stuff. Cite survey paper Claim that Observable is dual of Iterator in order to justify the why.

1.3.1 Reactive Extensions

1.3.2 Reactive Streams

1.3.3 Functional Reactive Programming

INTO THE RABBIT HOLE: *Deriving the Observable*

"It was much pleasanter at home," thought poor Alice, "when one wasn't always growing larger and smaller, and being ordered about by mice and rabbits. I almost wish I hadn't gone down the rabbit-hole – and yet – and yet – ..."

— Lewis Carol,
Alice in Wonderland

In this chapter we are going to derive the `Observable` interface starting from its dual counterpart, the `Iterable`, which, as we have seen in Chapter 1, represents embodies the idea of a pull-based model of computation and is the commonly adopted solution to dealing with synchronous computations resulting in multiple values.

2.1 Iterables

An `Iterable` is a programming construct which enables the user to traverse a collection of data, abstracting over the underlying implementation^[7].

The interface and semantics of `Iterable`s were first introduced by the Gang of Four though their Iterator pattern^[7]; today's most used programming languages expose the `Iterable` as the

root interface in standard Collections APIs.

The `Iterable` interface is generally fixed across programming languages, with the exception of naming conventions - C# and related languages call it `IEnumerable` - and slight differences in the types, as we can see from the following definitions.

Should I use a datatype instead of class?

```
1  -- Java Iterable
2  class Iterable a where
3      getIterator :: () -> IO (Iterator a)
4
5  class Iterator a where
6      hasNext :: () -> Bool
7      next    :: () -> IO a
8
9  -----
10
11 -- C# IEnumerable
12 class IEnumerable a where
13     GetEnumerator :: () -> IO (IEnumerator a)
14
15 class IEnumerator a where
16     moveNext :: () -> IO Bool
17     current  :: () -> a
```

Although the essence of the pattern is preserved in both definitions, we claim that the C# version more clearly and accurately reflects the way side effects play a role in the usage of the interface: `moveNext` contains all the side effects of walking down the underlying collection and retrieving the next value while `current` can inspect the retrieved value multiple times in a pure way. The Java version, on the other hand, embeds the side effect in the `next` function, making it impossible to inspect the current value multiple times. For this reason and without loss of generality, we will make use of the C# definition - modulo naming conventions - in the reminder of the discussion.

Mention Subscription here?


```
1 class Iterable a where
2   getIterator :: () -> IO (Iterator a)
3
4 class Iterator a where
5   moveNext :: () -> IO Bool
6   current  :: () -> a
```

The derivation that follows will require the use of a number mathematical concepts such as categorical duality, continuations, (co)products and (un)currying. We suggest the reader to get familiar with these topics before diving into the derivation. An accessible introduction to each can be found in Appendix A.

2.2 The essence of Iterables

The first step in deriving the `Observable` is to simplify our `Iterable` definition to a type that reflects its very essence; we are gonna do this by stripping the interface presented in the previous section of all the unnecessary operational features that only clutter our definition.

Let's start by taking a closer look at the `Iterator` interface; we can observe that the definition of the functions `moveNext` and `current` is equivalent to a single function which returns either a value - analogous to a `moveNext` call returning true and a subsequent invocation to `current` - or nothing - analogous to a call to `moveNext` returning false.

Before we formalize this observation with a proper type, let us notice another effect that is hidden in the current definition of `moveNext` and not made explicit by its type: the possibility for an exception to be thrown by the function's body.

By merging these considerations with the notion of coproducts and Haskell's `Maybe` type, we obtain the following definition.

```
1 class Iterable a where
2   getIterator :: () -> IO (Iterator a)
3
4 class Iterator a where
5   moveNext :: () -> IO (Either Exception (Maybe a))
```

The next step is to forget about class instances and express our interfaces as simple types.

```
1 type Iterable a = () -> IO (Iterator a)
2 type Iterator a = () -> IO (Either Exception (Maybe a))
```

Let's now go one step further and simplify our definition even more, with the purpose of understanding the real essence of an Iterable. In order to achieve this, let's forget for a moment about errors and no values returned from an iterator, i.e. let's ignore operational concerns such as exceptions and termination.

```
4 type Iterable a = () -> IO (() -> IO a)
5 type Iterator a = () -> IO a
```

An Iterable is simply a function which, when invoked, returns an Iterator and an Iterator is itself a function which returns a computation that will eventually result in a value of type `a`. In some way, we can think of an Iterator as a getter function, and of an Iterable as a getter of a getter.

Analyze the Iterator, it's covariant and it's a functor.

2.3 Observable is the dual of Iterable

As we noticed before, the way we deal with a single value in an synchronous environment is dual to the asynchronous method, flipping the arrows brings us from a function resulting in a value of type `a` to one accepting an `a`.

It seems reasonable now to apply the same concept of duality to the Iterable in order to find a possible solution to our original problem, dealing with a collection of asynchronous values.

```
1 type Iterable a = () -> IO (() -> IO a)
2 type Iterator a = () -> IO a
3
4 type Observable a = (a -> IO ()) -> IO ()
5 type Observer a = a -> IO ()
```

It is straightforward to see how duality plays out in the derivation of the new types.

This dualisation leaves us with an interface which is interesting under many point of views. First of all, to link back to the observation that an `Iterable` is a getter of a getter, we can observe that the `Observable` plays exactly the opposite role, that is, a setter of a setter, the `Observer`.

This brings us to another interesting observation, the `Iterable` embodies the idea of pull collections, the `Iterable` will give us a new `Iterator` whenever we ask for it and the `Iterator`, in turn, will provide us with the next value whenever we decide to pull one from it. Dually, the `Observable` interface embodies the idea of push collections: we push a callback, the `Observer`, inside the `Observable`, which, in turn, will push a value into the `Observer` whenever one becomes available.

From here we can take two roads, one is to analyze further the type that we obtained and see what its properties are and what we can understand from it; the second road is to un-simplify its definition and augment it so as to arrive to a usable API for handling asynchronous collections. We will start with the first.

For those who are familiar with functional programming it will not be hard to see how the `Observable` type resembles a function written in continuation passing style.

```
1 cont      :: (a -> r) -> r
2 observable :: (a -> IO ()) -> IO ()
```

We can easily observe how an `Observable` is nothing more than a CPS function where the result type `r` is instantiated to `IO ()`.

This observation opens up a great deal of mathematics properties and laws that we can prove about observables.

First of all, let's convince ourselves that a CPS function, and therefore an `Observable`, truly embodies a push based model of computation. The very definition of continuation tells us that a continuation represents the "rest of the computation"; when looking at it from an observable prospective, the continuation, i.e. the observer, is the function that specifies what needs to happen to a value, whenever this becomes available, that is, whenever the observable pushes it to the observer. Since the continuation can be called multiple times, it is easy to see how this structure lets us deal with multiple values that are might come in at different times in the future.

Note how an observable is "paused" until it receives an observer to which it can push the values it produces. This comes precisely from the definition of CPS function, i.e. a suspended computation

which, given another function as argument, the continuation, will produce the final result.

Therefore an observable is a suspended computation that will start producing values once we pass in an observer, the continuation that will specify what happens to a value once it is computed. The observable will call the observer every time it produces a value.

2.4 Observables are Continuations

Talk about the interface that we want to get, even a minimal one now and explain how this relates to the cont monad, e.g. `subscribe = ContT`. Introduce the `ContT` monad and show the minimal reference implementation.

Our goal is now to start from this theoretical explanation of a push based collection and build a usable API. In the previous section we observed how and `Observable` is a particular case of the continuation monad where the result type is a computation which has `unit` as a result type. The Haskell language provides a monad construct for expressing continuations as well as a monad transformer in order to stack continuations on top of other monads. A monad transformer is exactly what we need in order to express our continuations resulting in `IO`.

```
1 type Observable a = ContT () IO a
2 type Observer a = a -> IO ()
```

Our API will also need to provide functions to create as well as start the `Observable` stream.

```
1 -- Simply wraps the function :: (a -> IO ()) -> IO ()
2 -- inside the Observable datatype
3 observable :: (Observer a -> IO ()) -> Observable a
4 observable = ContT
5
6 -- Runs the Observable by providing the continuation - i.e. the Observer -
7 -- that will handle the asynchronous data.
8 subscribe :: Observable a -> Observer a -> IO ()
9 subscribe = runContT
```

We can already notice how This should come as no surprise after our discussion regarding the connection between `Observables` and the Continuation monad. Conversely, these equivalences should justify even more the use of this model of computation for reactive programming.

At this point we have all the necessary tools to create and run an Observable

```
1 let obs = observable $ \obr ->
2   do obr 1
3     obr 2
4     obr 3
5
6 subscribe obs print
7
8 output>
9 1
10 2
11 3
```

The example above is a toy example, let's try with a more realistic one such that we can show that our basic implementation of rx based on continuations works just as well as a full blown one in terms of handling asynchronous data.

Put the actual demo that listens to keyboard presses. In the example, press 3 times and see that all the events are handled and none are lost.

```
13 obs = observable $ \obr -> do
14   passiveMotionCallback $= Just (\p -> obr p)
15
16 main :: IO ()
17 main = do
18   (_progName, _args) <- getArgsAndInitialize
19   _window <- createWindow "Hello World"
20   subscribe obs print
21   mainLoop
```

Elaborate better this part. Ask Erik for input.

It is worth noting that rx in itself is not at all async in handling data unless we use schedulers, although it does handle async data. This is a common misconception, even if you have a single thread that doesn't mean you cannot handle async data, actually you are async because the

control flow isn't linear. Naturally, the thing is that certain queries (the ones that don't use schedulers) will simply block your single thread and prevent other things from happening.

This demo shows exactly this, even though the processing of the data is synchronous, the data itself, being mouse movements, is inherently async.

At this point in the discussion we have a working implementation of a push based collection purely derived from the underlying theory of duality and continuations. The next step in augmenting out library is to note that continuations are monads and, being the Observable an instance of the continuation monad, it is itself a monad. This observation comes with great benefits, we can get mathematical laws - the monad laws - proven for free for our structure and, from a more practical point of view, we get functions defined for free for the Observable: `fmap` (from Functor), `flatMap` and `return`.

Say more on the monad laws, even if they are trivially proved.

We will soon see how the implementation of these functions will change and move from the standard one the moment we start moving towards a more operational implementation for real world use.

OUT OF THE RABBIT HOLE: *Towards a usable API*

Start from the minimal reference implementation, add exceptions and termination, explain how flatmap changes and lastly add subscription and talk about cancellation and the contract.

Up until now we have analyzed the essence of the Observable, leaving out the operational concerns that would come up when our goal is to design a usable API. Now we will slowly and step by step re-introduce these concerns in order to go from a theoretical definition of Observables to a more operational and therefore usable one.

Remember how, at the beginning of our discussion, we greatly simplified the Iterable interface in order to derive a type that represents the essence of an Iterable. We later applied the duality principle from category theory in order to derive the Observable. Now, we want to walk the simplification path backwards and, step by step, re-introduce all that we simplified before in order to arrive to a usable API.

3.1 Termination and Error Handling

The first thing we want to re-introduce is handling exceptions and termination of a stream. Where an Iterable can return a value, terminate or throw an exception when we ask for a value, and Observable, being it's dual, can produce one or more values, terminate or throw an exception when it is subscribed to.

A more appropriate type for our interface is then the following.

```

4 type Observable a = ContT () IO (Either Error (Maybe a))
5 type Observer a = Either Error (Maybe a) -> IO ()

```

Remove this Event shit and move to the custom type directly? Not sure, I like the discussion on bind.

Now, this code is not exactly the definition of readable; let's apply some good design skills to make it more pleasant to the eye without changing it's meaning.

```

4 -- datatype representing Either Error (Maybe a)
5 data Event a =
6     OnNext a
7     | OnError SomeException
8     | OnCompleted
9
10 type Observable a = ContT () IO (Event a)
11 type Observer a = Event a -> IO ()

```

Although this might not look like a big change, it greatly influences the design of our API. We are, in fact, changing our instantiation of the continuation monad to an input type that is not `a` anymore, but `Event a`. On the other hand, our type variable for `Observable` is still `a`. This is not an issue per se, but it has one big consequence: the `flatMap` function that we inherit from the continuation monad is not the one that we want to expose from our API anymore. The types differ like so.

```

13 -- bind inherited from the Continuation monad
14 (>>=) :: Observable a -> (Event a -> Observable b) -> Observable b
15
16 -- bind that we would like to expose from our API
17 flatmap :: Observable a -> (a -> Observable b) -> Observable b

```

This has many implications, first of all, we are gonna need to implement `flatMap` by ourselves.. see todo below...

It has now come the time to move away from an implementation of `Observable` as a type synonym. We have already seen how the current implementation using `Event a` does not allow

for a correspondence between `>=` operations; this will only create confusion in the future. The next step is then to define our own observable type, which will clearly be really similar to the Continuation monad and subsequently prove that it is itself a monad.

```
newtype Observable a = Observable { subscribe :: Observer a -> IO () }
data Observer a = Observer
  { onNext      :: a -> IO ()
  , onError     :: SomeException -> IO ()
  , onCompleted :: IO ()
  }
}
```

With this implementation we have eliminated the materialisation of the event types. The Observer is now not a single function from `Event a -> IO ()` but a collection of 3 continuations that will be used inside the observable depending on the type of the event. It is clear that this implementation of Observable has not changed in functionality from the previous one using the Continuation Monad, it has just dematerialized the 3 types of events in 3 functions which handle them.

The next step is to make Observable a monad

```
instance Monad Observable where
  return a = observable (\obr -> onNext obr a)
  o >>= f = ...
```

The return function is the exact same as in the continuation monad, with the only difference that we have now 3 continuations to choose from instead of a single one.

Bind, on the other hand, is completely different from the Cont monad implementation; in this case ...

finish the discussion

The only thing left to do now is to prove the monad laws to show that Observable really is a monad.

```
19 -- Monad Laws
20 -- return a >>= k = k a
21 -- m >>= return = m
22 -- m >>= (x -> k x >>= h) = (m >>= k) >>= h
```

We mentioned before how the bind from Cont differs from our in the Observable. Below I will show that in this implementation it corresponds to a function lift that ...

Talk about lift = >= in Cont.

By using lift we can transform streams and implement operators...

Modify keyboard press example from before to handle errors and termination. Point to later discussion regarding the rx contract, since now we can detect termination and errors but there is no guarantee that nothing will come after we receive them, i.e. that we abide the contract.

PUT THE CONTRACT HERE????

3.2 Schedulers

Up until now our discussion on push based collections has not mentioned time. This might seem strange, especially when coming from and FRP background, where continuous time and functions are at the foundations of the theory.

- Elaborate on orthogonality of time. - Discuss how rx is synch by itself and how we need to add concurrency in order not to have it blocking. - Discuss the different possible levels of concurrency - Discuss how this affects the implementation of operators: levels of safety - Discuss how threadpool scheduler breaks monad laws.

Ask Erik
about this.

3.3 Subscriptions

With error handling and termination, our implemmentation starts getting more and more usable. We now want to add a mechanism that will allow us to stop an observable stream from the outside (as opposed to waiting for an onCompleted) whenever we don't require it's data anymore.

In order to achieve this we will use a new datatype, Subscription. The idea is that the subscribe function will return a Subscription to the user who will later be able to call unsubscribe on it and stop the stream associated to it from producing any more values.

Talk about the best effort in canceling work and eventual consistency with the contract.

A Subscription in itself is nothing more than an IO action to perform once we stop an observable stream. Naturally, to make it usable in a real setting, we are gonna need to augment it more information: first, we will need a way to test whether the subscription is unsubscribed or not. The easiest way to do this is to use mutable state and store a boolean value with every Subscription. Moreover, some operators

discuss children subscriptions

Note that from now on, in order to allow our implementation to be usable, we will make use not only of functional language features, but of imperative ones as well. This will be done in situations in which it makes sense from an understandability point of view. There's no shame in using all our tools and being a purist is not always the best way.

Probably better to put what follows somewhere else, right after we leave the theory for example.

Note that, even though the Observable's theoretical foundation is strictly functional, the road to make it usable is full of obstacles that are better tackled using imperative features, i.e. state. As much as I personally prefer a functional approach to programming, I will favor the solution that most clearly and easily solves the problem, be that functional or imperative.

```
1 type Subscription = IO ()
```

Our goal now is to implement a cancellation mechanism that would stop the Observable. This will be achieved by calling a function unsubscribe, which will prevent, from that moment on, any events to be signaled to any subscribed observer.

This is achieved by wrapping the user supplied observer to the subscribe function with an internal one which adds this functionality and forwards all accepted events to the supplied one.

the code for safe observer.

```
25     OnNext a
26   | OnError SomeException
27   | OnCompleted
28
29   --we can remove returning the subscription to the outside
30   --since the behaviour is reproducible with operators
31   --e.g. subject+takeUntil
32   subscribe :: Observable a -> Observer a -> IO Subscription
33   subscribe obs obr = do
34     s <- createSubscription (print "unsubscribed")
35     let
36       safeObr = observer safeOnNext safeOnError safeOnCompleted
37       safeOnNext a = do
38         b <- isUnsubscribed s
39         when (not b) $ obr (OnNext a)
40       safeOnError e = do
```

As a design decision, when unsubscribe is called on an observable subscription, the observable sequence will make a best effort attempt to stop all outstanding work. This means that any queued work that has not been started will not start. Any work that is already in progress might still complete as it is not always safe to abort work that is in progress. Results from this work will not be signaled to any previously subscribed observer instances.

Motivation for children subscriptions: some operators will create inner observables and therefore will need to unsubscribe from them when the outer observable is unsubscribed from.

On why using `Cont () (StateT Subscription IO) (Event a)` wouldn't work: it would be perfect in order to thread Subscriptions throughout execution making it usable inside operators, since the call to the continuation would return a state which would then be sequenced by `»=`. This method fails with schedulers, in particular `newThread` since the state of the action executed on the new thread would be disconnected from the threading mentioned above. The other thread would get a state but it would not know what to do with it and would not have any ways to connect it to the original one passed by the subscribe. Another way is to use `mapStateT` to map the IO action that will result from the state to an action on the other thread. Again, this method won't work,

On the motivation for a Subscription: it is needed so the user can cancel work at any time.

This implies that a scheduler is used. If this is not the case the subscription will be returned synchronously after the execution of the whole stream. It will therefore be already unsubscribed and calling unsubscribe will be a NoOp. In the case that we actually use schedulers then we can unsubscribe from anywhere in our program.

Now the question is the following: can we reproduce the behaviour of unsubscribe with operators so that we can eliminate subscriptions altogether? That is, we can hide them to the outside and use them only inside the stream, we still need them but we don't necessarily need to return them when we subscribe. The behaviour can be easily replaced by the use of `takeUntil(Observable a)` where we pass in a subject that will be signaled when we want to stop the stream. The `takeUntil` operator fires events from the upstream up until the point in which we signal the subject, then stops the stream and unsubscribes.

With this approach we seemingly lose one thing, i.e. the ability to specify what happens at unsubscription time; this functionality can simply be regained by a subscribe function that takes the unsubscribe action as a parameter and runs it when the stream is unsubscribed.

3.4 The Reactive Contract

Begins a section.

3.4.1 Subsection

Begins a subsection.

TODO LIST

■ You know nothing John Snow quote	1
■ Write contributions	2
■ Write overview	2
■ Write notation and conventions	2
■ Write chapter introduction	3
■ Fix the table, add caption.	4
■ Rewirte this part.	5
■ Should I use a datatype instead of class?	8
■ Mention Subscription here?	8
■ Talk about the interface that we want to get, even a minimal one now and explain how this relates to the cont monad, e.g. subscribe = ContT. Introduce the ContT monad and show the minimal reference implementation.	12
■ Put the actual demo that listens to keyboard presses. In the example, press 3 times and see that all the events are handled and none are lost.	13
■ Elaborate better this part. Ask Erik for input.	13
■ Say more on the monad laws, even if they are trivially proved.	14
■ Start from the minimal reference implementation, add exceptions and termination, explain how flatmap changes and lastly add subscription and talk about cancellation and the contract.	15
■ Remove this Event shit and move to the custom type directly? Not sure, I like the discussion on bind.	16

■ finish the discussion	17
■ Talk about lift = »= in Cont.	18
■ Modify keyboard press example from before to handle errors and termination. Point to later discussion regarding the rx contract, since now we can detect termination and errors but there is no guarantee that nothing will come after we receive them, i.e. that we abide the contract.	18
■ Ask Erik about this.	18
■ Talk about the best effort in canceling work and eventual consistency with the contract.	18
■ discuss children subscriptions	19
■ Probably better to put what follows somewhere else, right after we leave the theory for example.	19
■ the code for safe observer.	19
■ Motivation for children subscriptions: some operators will create inner observables and therefore will need to unsubscribe from them when the outer observable is unsubscribed from.	20

**APPENDIX A**

Begins an appendix

A.1 Duality**A.2 Continuation Passing Style****A.3 Product and Sum Types****A.4 Currying and Uncurrying**

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