

Rivar: Reactive Instance Variable

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Abstract

The Functional Reactive Programming (FRP) paradigm specializes in maintaining derived variables' values. However, this task has difficulties in performing predictable behavior especially when applications grow with many code duplications and long chains of updates. While the FRP paradigm contributes to the predictability of variables' updates, the Object Oriented Programming (OOP) paradigm contributes to the predictability of code changes. In this thesis, we combine the two paradigms to promote predictability.

We use the combination of *reactive variable* from FRP and the *instance variable* from OOP, calling it *RIVar*, a shortcut to the full name *Reactive Instance Variable*. We introduce an approach and method for a single RIVar assigned with formulas by several clients. The assignment semantics adopts the meaning from FRP, to relate the variable to be updated according to the specified formula. However, in contrast to the traditional FRP, there can be several assignments to the same variable. Under the hood, RIVars observe several formulas, and infer values when and according to the latest value coming from any of the sources.

To evaluate the approach, we compare it against traditional approaches, in how they handle variables' updates, and what code-reuse options are available. In addition, we present an implementation attached with a case study. The implementation is provided as an extension library, named RIVarX, to C# programming language. The case study presents how we

separate one domain logic into sub-domains, separating a central calculation procedure. In the case study, each object manages its formulas, even when the formulas consist of variables belonging to other objects.

We expect this approach being implemented as a state management solution and ease the development of front end applications. In this process, it is expected that we will discover that the method as is is too limited to being used in real-life applications. Because the model currently provides only one method to the variable to infer values from its sources. However, with the current method, the model is handled as a decentralized solution for Multiway Dataflow Constraint Systems suited for user interfaces.

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Chapter 1

Introduction

In the field of *Functional Reactive Programming* (FRP) [4, 14] effort has been invested in implementing *reactive variables* [50] (with some variations also known as *behavior* [14], *signal* [30], *cell* [4] and also *reactive value* [12]) to automate updates. Reactive variables are variables that are recalculated in response and according to dependant variables' updates, similar to cells containing formulas in spreadsheet applications. The variables can get input (= operator) or be assigned ($:=$ operator) with an expression consisting of a set of other reactive variables. The assignment defines that the value of the variable is set to the value of the expression, and continuously re-evaluated in response to changes in the value of any of the variables appearing in the expression. For example (Figure 1.1), given two reactive variables A and B, the formula $A := B + 1$ associates the variable A with the expression $B + 1$, and the value of A changes in response to any input provided to the value of B.

In maintaining and updating the variables, we sometimes face an unpredictable behavior and even infinite loops [27]. The unpredictable behavior might exist especially when applications grow and have long chains of updates. Specifically, when adding a functionality to update one variable, where that update is part of a long chains of updates, so it might fall into an endless loop. The complexity of this task

```
1 A:=B+1
2 B=1 // A=2
3 B=6 // A=7
```

Figure 1.1: An example for using reactive variables. The formula $A:=B+1$ associates the variable A with the expression $B+1$, so that the value of A changes in response to any input provided to the value of B .

has two parts. First, the difficulties to control the data dependencies implied implicitly by event handling logic [30]. In the events paradigm, the data dependencies are not explicit because they are not directly expressed in the code, but are instead implied by the event handling logic. The event handling logic determines what happens when an event is triggered, and in this case, it sets the values of variables and updates their dependencies. The second complexity part is to separate the task into small manageable and independent tasks, for being in separated loosely-coupled components. Typically components become coupled by affecting each other's state [28], causing the task to be centralized.

The first complexity type has the solution of reactive variables, in explicitly declaring the data dependencies [30]. The second, we relate to the *Object Oriented Programming* (OOP) paradigm. This paradigm enables that different parts of the software, in the form of objects, are loosely coupled and do not depend on one another. This makes it easier to change objects without affecting the others.

In REScala and ReactiveX¹ [46] the reactive variables are part of the object interface, but implemented differently. REScala derives previous FRP implementations, in its functional style, and in using an algorithm that carefully determines the order in which to update the variables. ReactiveX derives the observer pattern. The reactive variables are implemented as events streams or observables, subscribed to input and/or other reactive variables, to update their subscribers, in a form of an iterator.

¹<https://reactivex.io>

Both alternatives have their tradeoffs, which calls for an integration of their concepts. REScala gives the *referential transparency* property [4], meaning that the same input will produce consistently the same output. This property gives REScala the power from the functional paradigm, the property of *compositionality*, to build bigger functions out of smaller ones. However, the updates are taken by a central mediator. ReactiveX is good in separation: It let to decouple formulas from the used reactive variables, to associate an expression to a reactive variables from outside of an object, and that variables are updated directly by their dependencies (without a central mediator).

In this thesis, we use the approach from the second alternative and extend it to add the benefits from the first alternative. The variables have the form of the events streams like ReactiveX. But instead of the default behavior to pass immediately any value to subscribers, and instead of a centerlized mediator used in REScala to consider the order of the updates, the variables consider the coming updates by themselves, properly ordering the updates to the subscribers.

1.1 Contribution

We introduce `RIVar`, *Reactive Instance Variable* to be consistent with both *instance variables* from OOP and *reactive variables* from FRP to support the features from both paradigms. We also provide the library `RIVarX`² with an implemented `RIVar` in C# programming language, attached with a case study.

Outline. Chapter 2 presents a background about implementing FRP under the hood. Chapter 3 presents an example to demonstrate the need for RIVars. Then in chapter 4 we present the new variant of FRP, so that reactive variables will be able to be RIVars. In chapter 5 we compare the model against the other solutions and paradigms, in handling graphs and reducing code duplication. Then in chapter 6 we

²<https://github.com/RivkaAltshuler/RIVar>, <https://www.nuget.org/packages/RIVar.RIVarX>

present RIVarX with an implementation to the example presented in chapter 3 being the case study.

Chapter 2

Background

Reactive systems is a system that get inputs and provide outputs over time. In the context of reactive variables in user interfaces or front-end development, the input and output are value changes in an input control. three existing paradigms¹ provide different approaches to implement the applications.

2.1 Events

Events is an embedded observer pattern in programming languages. Thanks to this mechanism, objects can provide consumers to register code that update variables, to be executed in the events when other variables are updated. By this technique, enterprise applications provide customers to extend the application according to their business needs, such as Microsoft Dynamics 365² do. In Microsoft Dynamics 365, developers can register custom plugins that update fields, to be re-calculated according other fields. Registering one such plugin might lead to an infinite loop of updates caused from several registered plugins. This familiar problem has the ad-hoc solution

¹<https://www.infoq.com/presentations/reactive-programming-evolution/>

²<https://learn.microsoft.com/en-us/dynamics365/>

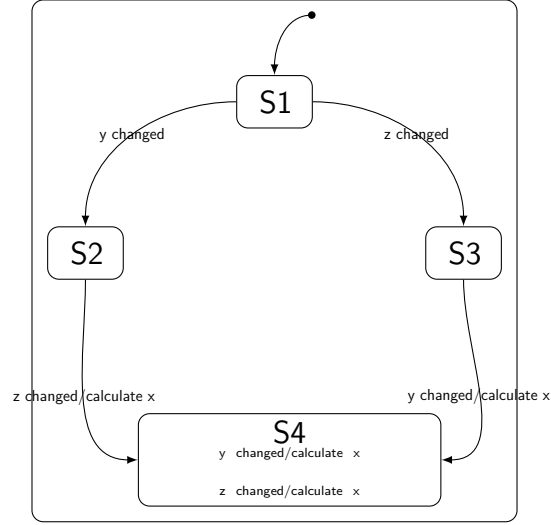


Figure 2.1: Statechart modeling the execution of $x:=y+z$

to stop the loop by the provided field named `Depth`³, containing how many times the current plugin is executed. This situation with Microsoft Dynamics 365 reflects typical situations in maintaining variables.

In order to control the updates, there is an approach used by XState⁴ and Redux [8], to model applications by logical states [24]. The events are modeled as transition between states. Actions of updates are attached to transitions to clearly control the exact state when the actions should be executed.

2.2 Reactive Programming

In the FRP paradigm reactive variables are defined as functions over other reactive variables, while the runtime maintains the variables' values. The runtime uses a directed acyclic graph data structure [4] to manage the updates.

accordingly, using a directed acyclic graph data structure [4]. In REScala, also instance variables can be reactive variables (i.e., objects can have reactive variables as

³<https://learn.microsoft.com/en-us/dotnet/api/microsoft.xrm.sdk.iexecutioncontext.depth?view=dataverse-sdk-latest>

⁴<https://xstate.js.org>

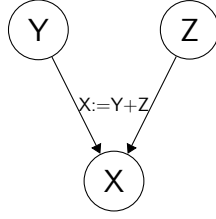


Figure 2.2: Directed acyclic graph data structure representing $X := Y + Z$

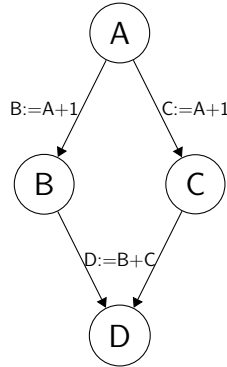


Figure 2.3: A data dependency graph that in push-based evaluation might have glitches. The nodes represent variables that should be updated either by input or by updating according to the specified function in the label. Each variable's update leads to update the dependencies. Updating A leads to updating B and C, each leads to updating D. In the first update, the value is incorrect (a glitch), because B or C has not been updated yet.

part of their interface) having such runtime to maintain them [?]. For example, the formula $X := Y + Z$ defines the reactive variable X to be a function of reactive variables Y and Z . The runtime uses a graph illustrated in Figure 2.2 to automatically maintain X . Consequently, there is no need to repeat registering to events to re-calculate variables like the illustration in Figure 2.1. The FRP paradigm has the referential transparency property [4] from being based on pure functions, with the meaning that the same input will produce consistently the same output. Consequently, the FRP paradigm provides predictability in scaling the application.

Although the high level abstraction, the events concept still exist in the paradigm [14, 29, 4, 43]. In the approach used by ReactiveX⁵ [4] and Sodium [4], functions

⁵<https://reactivex.io>

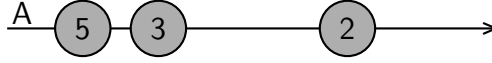


Figure 2.4: An events stream representing a varying value.

over *events streams* are declared, preserving the referential transparency property. Actually reactive variables can be represented by events streams representing the varying value over time, similar to a list [4, 50]. However, there is a big difference between the original reactive variable to this representation.

In addition to the more verbose syntax [50] achieved by events streams, the mechanism is very different. Functions over events streams are typically not handled by a special runtime with the graph data structure. Instead, the events streams are *observables*, with *operators* over them, that subscribe and produce events streams. Accordingly objects can have reactive variables as part of their interface, while the values are propagated according to the events mechanism. Generally speaking, reactive variables as events streams does no depend on the mediator exists in the original FRP, because they interact directly.

The mediator has access to all the variables and formulas, so it can provide more predictable behavior. For example, if one variable has several updates caused by a single update, such as in 2.3, that updating A leads to update B and C. In case that the variables interact directly, D will have an incorrect update named *glitch*. In contrast, a mediator has the knowledge of the special construction to handle the updates correctly. So D will be updated only when both B and C has been updated. Even though the mediator can provide more predictable behavior, there are sometimes requirements that prefer directed interaction over a mediator. For example, typical distributed applications prefer directed interacton to reduce performace.

In the FRP paradigm with the distributed settings, variables can be located in different processes or hosts [31, 51, 12]. Using solutions like XFRP [51], developers

declare functions over reactive variables, and the compiler generates a distributed application, that handles the updates according to the specified formulas.

2.2.1 Integrate with Objects

ReactiveX⁶ and REScala [46] provide reactive variables as part of the object’s interface.

Existing implementations provide two methods for assigning reactive variables externally, both have difficulties in compatibility with FRP. ReactiveX⁷ and REScala [46] provide reactive variables as standard data types, causing reactive variables being able to be assigned through an interface (by setters). However, this strategy is contrasted with the concept of reactive variables. The concept of reactive variables originates from the field of *Functional Reactive Programming* (FRP), that is based on *Functional Programming* [14]. According to FRP, the programs should “describe things that exist, rather than actions that have happened or are to happen (i.e., what is, not what does)” [14]. In contrast, in ReactiveX and REScala, an assignment causes to stop the old source, and then start to respond to new source. In general, separating the variables and expressions between interfaces and consumers seems incompatible with FRP, because reactive variables are defined by their functions over other reactive variables, or by their values over time [41].

In the second method, reactive variables are accessed externally by injecting events handlers. In events handlers, we can set inputs to reactive variables in response other reactive variables’ updates. For example, in ReactiveX the statement `A.Subscribe(val=>B.OnNext(val))` produces the meaning of `A:=B`. This method *adds* the formula in addition to the existing formulas handled by the runtime of the FRP solution. But in the current implementation, the formula is activated externally, without the advantages that the paradigm of FRP should provide. FRP aims

⁶<https://reactivex.io>

⁷<https://reactivex.io>

to provide predictability and composability. In contrast, adding formulas externally, by integration between FRP and imperative programming, might cause infinite loops [50, 4]. For example, a change in a reactive variable, might execute an event handler, causing the reactive variable to change.

(REScala is a library in Scala programming language, that supports reactive variables under the name *signals*, being part of the object interface. Instead of declaring events and invoking them when variables change, the library enables the developers to declare the data dependencies. The signals interact with the inputs of the user interfaces, because signals changes and events can be converted between each other. REScala is the result of an active research in FRP, and adopts recent updates in the field.

ReactiveX is another library, developed first in C# programming language and adopted in many others programming languages. This library implements an observable that updates its subscribers in a form of an iterator.

The values that it updates the subscribers are values that it also supports reactive variables differently, but they are also a part of the objects interface.

ReactiveX important concept is the observable which is similar to events stream.
)

2.3 Constraints

FRP shares with the paradigm of constraints systems the idea, that developers declare equations, and the runtime automates variables' updates according to the equations and input. However, they are different: FRP is about defining variables as functions over other variables, while constraints systems are about to satisfy constraints.

There are constraints systems similar to FRP that handle one-way constraints

Input	Constraints hierarchical in descending order	Solution
A=1	A=B, A=1	A=1, B=1
B=2	A=B, B=2, A=1	A=2, B=2
A=3	A=B, A=3, B=2	A=3, B=3

Table 2.1: Maintaining A and B according to the constraint $A=B$, using constraint hierarchies.

[49]. Other constraints systems like Hotdrink [17] handle two-way constraints [25, 17, 49]. Constraints systems that handle two-way constraints, by their nature, handle cycles, and allows defining multiple constraints that output to the same variable [49]. Actually, the developers declaring two-way constraints need to declare also the one-way constraints, e.g., in Figure 2.5, $A=B+C$ is attached with $A:=B+C$, $B:=A-C$ and $C:=A-B$.

The FRP runtime uses *constraints solver* to maintain the variables. The constraints solvers are algorithms developed for constraints systems to satisfy the constraints. In order to solve a set of two-way constraints, the constraints solver uses a model named *constraint hierarchies* [6]. There are cases that the algorithm cannot satisfy all the constraints, then it satisfies only those that are specified to be in a higher hierarchy. For example, having the following constraints hierarchical in the descending order $A=B$, $A=1$ and $B=2$, the constraints solver will satisfy only the first two constraints, by $A=1$ and $B=1$. In order to maintain the variables according to the constraints, as in the example in Table 2.1, the runtime maintains an added constraints derived from the variables. For each variable X containing a value x , the runtime maintain a constraint $X=x$, with hierarchical according to the order of the input.

```

1 function sum( a, b ) { return a + b; }
2 function diff( a, b ) { return a - b; }
3
4 var model = new hd.ModelBuilder()
5     .variables( {A: 0, B: 0, C: 0} )
6
7     .constraint( A, B, C )
8         .method( 'B, C -> A', sum ) // A:=B+C
9         .method( 'A, C -> B', diff ) // B:=A-C
10        .method( 'A, B -> C', diff ) // C:=A-B
11
12    .end();

```

Figure 2.5: two-way constraint $A=B+C$ implemented by Hotdrink

2.4 Conclusion

There are FRP runtimes that are based on the traditional simple methods calls, and are unpredictable. Others more predictable solutions use a mediator with the added complexity of having another layer needed to the application. There are FRP runtimes for distributed applications that do not use a mediator, but as the FRP paradigm, they support only the sets of formulas producing directed acyclic graphs.

Chapter 3

Motivating Example

The following UI application (Figure 3.1) handles drug administration. It observes the fields' change events, once a value is changed, dependant fields are calculated and presented. The application is a prototype of a small part from an existing application. The goal is to reduce the complexity existing in the traditional application.

In order to simplify the application, we separate the model to **Bag** and **Pump**. Also the UI is separated to micro-frontends [39] respectively. The architectural design is illustrated in Figure 3.1. **Pump** refers to giving **Bag**'s content. injecting medicines into a patient's bloodstream.

Drug	Concentration	VolumeOfFluid
<input type="text" value="100"/>	<input type="text" value="0.33"/>	<input type="text" value="300"/>
Dose	Duration	Rate
<input type="text" value="10"/>	<input type="text" value="10"/>	<input type="text" value="30"/>

Figure 3.1: Drug administration user interface. The user-defined values are in a regular typeface and the calculated values are in an italic typeface.

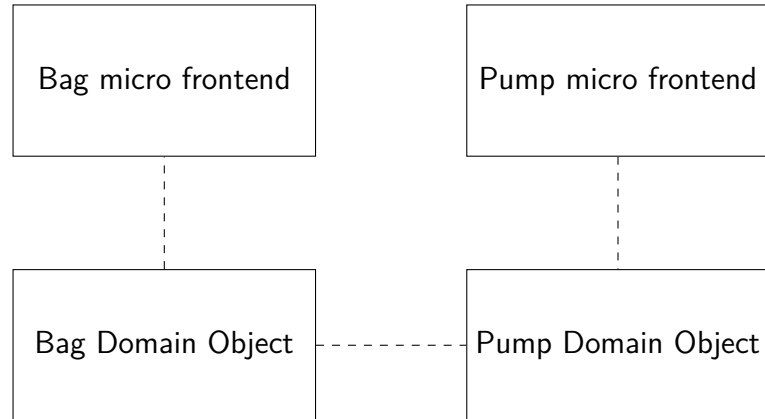


Figure 3.2: Design of the drug administration application, showcasing observer interaction through dashed lines.

3.1 Drug Administration Data Model

Pump refers to a medical device used to deliver fluids with medication into a patient's body in a controlled manner. Accordingly, we model **Pump** class with contained **IBag** representing the connected bag, containing **Drug** and **VolumeOfFluid**. **Drug** relates to amount of medication administered to a patient, (e.g. 100 mg). **VolumeOfFluid** relates to the fluid volume mixed with the drug (e.g., 300 ml). Based on the existing bag, **Pump** contains the data related to giving the bag's content over time. **Rate** relates to **VolumeOfFluid** flow administered into the patient's body per time unit (e.g., 30 ml per hour). **Dose** relates to the dosage, which is the **Drug** administered into the patient's body per time unit (e.g., 10 mg per hour). **Duration** relates to the duration from starting the injection until stopping it. According to the architectural design and as visualized in Figure 3.3, the fields in the user interface can trigger changes to **Pump** which trigger changes also to the bag. **Pump** interacts with the bag indirectly using an interface.

In order to achieve our goal to separate the drug administration model, **Pump** and its bag will be loosely coupled. The bag will be defined as an interface, and **Pump** will only send messages to it, to update **Drug** or **VolumeOfFluid**. Such as example

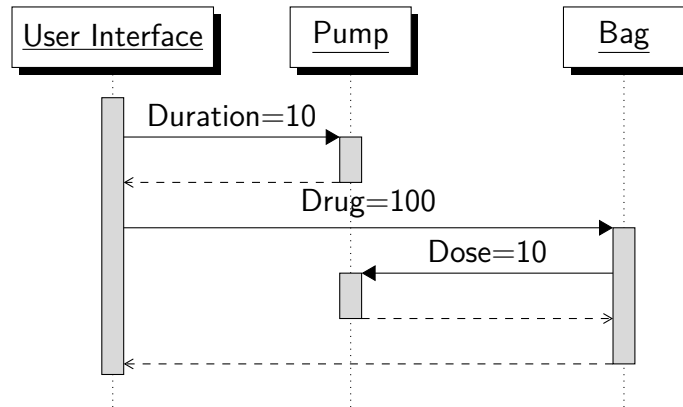


Figure 3.3: Calculation procedure spread over separated objects.

is visualized in Figure 3.3. When Pump send a message to the bag, it should not be aware of any internal information related to the bag.

Bag, in addition to **Drug** and **VolumeOfFluid**, contains also **Concentration** relating to the amount of the Drug per **VolumeOfFluid** (e.g. 0.33 mg/ml). Pump should not be aware of **Concentration**. Pump interacts with Bag by the interface it is implemented, named **IBag**. The data model and the relationships are visualized in Figure 3.4.

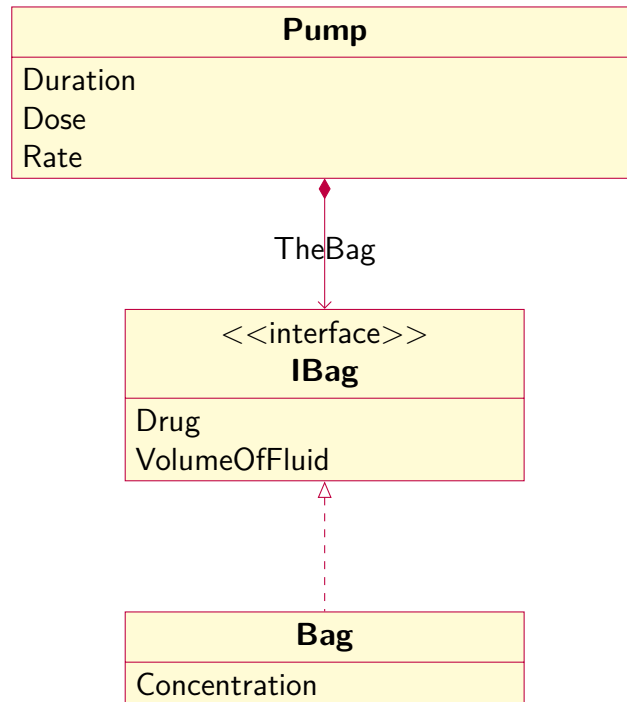


Figure 3.4: Drug administration class diagram

3.2 Unpredictable Calculation

In the original application, the calculation is centerlized. Whenever a user sets a new value to any of the fields, a calculation procedure (Figure 3.5) is executed. The procedure consists of branches according to the user-cases, in each branch there are three values being used to calculate the other values. In contrast, following the seperation, the calculations task is spread over **Pump** and **Bag**.

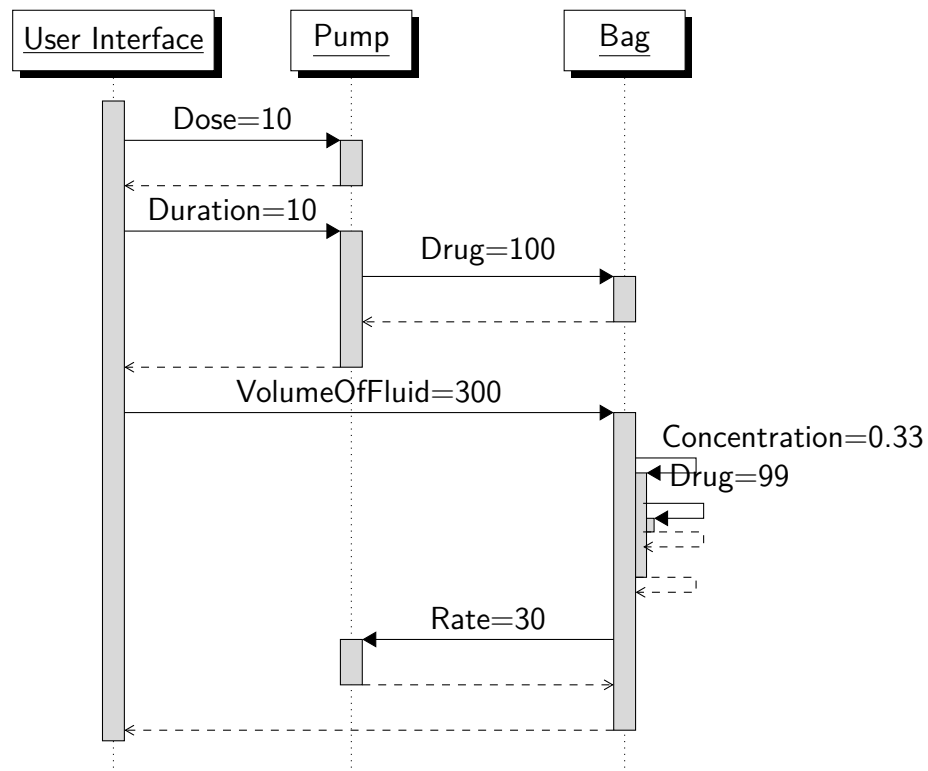
In the cenario visualized in Figure 3.6 the user sets **Dose** to 10, then **Duration**, in response **Drug** is calculated to 100. The user then sets **VolumeOfFluid** to 300, in response **Concentration** is calculated to 0.33. Then **Drug** is calculated to 99 unexpectedly.

The unpredictable change has two reasons. First, in the update of **Concentration** 100/300 was rounded, and lost information in the process. This caused **Concentration** to be calculated to 0.33, which caused **Drug** to be calculated to 99. Second, there

```
1 If edited triple is of Dose, Duration, and VolumeOfFluid
2   Drug = Dose*Duration
3   Concentration = Drug/VolumeOfFluid
4   Rate = VolumeOfFluid/Duration
5 Else If edited triple is of Drug, Dose, and Rate
6   Duration = Drug/Dose
7   VolumeOfFluid = Duration*Rate
8   Concentration = Drug/VolumeOfFluid
9 Else If edited triple is of Concentration, Volume, and Duration
10  Drug = Volume*Concentration
11  Rate = VolumeOfFluid/Duration
12  Dose = Drug/Duration
13 End If
```

Figure 3.5: Part of a centralized calculation procedure

was a cycle: **Concentration** was updated according to **Drug**, which was updated according to **Concentration**.



(The user set it to 100 and it has been changed to 99.)

Figure 3.6: Calculation procedure spread over separated objects producing unpredictable calculation.

3.3 Summary

We tried to separate an application unsuccessfully. The calculations are defined separately in `Pump` and `Bag`. Also the runtime is separated, managing the updates on top of the objects' interactions (standard calls). But the resulted calculations does not fit the requirements.

Chapter 4

Approach and Method

4.1 ?????????

The name RIVar refers to Reactive Instance Variable. This special variable is similar to a *reactive* variable and an *instance* variable. Similar to reactive variables, the variables can be updated directly by external inputs, and also by transitive updates according to assigned expressions. The variables has the two assignment forms: `:=` to associate expressions and `=` to provide input. Similar to instance variables, the variables are associated to objects of the OOP paradigm. Accordingly, the updates are executed by direct interactions by synchronous method calls. In addition, The assignment behaves similar to instance variables (or their *setters*, that are objects' methods used to assign instance variables) in that the variables can be assigned from outside of objects.

Objects can expose a well-defined interface for assigning the variables. Therefore, services can expose variables for their clients to assign. This includes subclasses that can assign variables belonging to the superclass (specialization interface). The assignment relates the variable to be updated according to the specified formula. In executing a formula, we say that the formula is added to the existing formulas that

```

1  class DrugAdministration{
2      RIVar<double> Drug, Volume
3      RIVar<double> Concentration:=Drug/VolumeOfFluid
4  }
5
6  void Main(){
7      DrugAdministration administration=new DrugAdministration()
8      administration.Drug=50
9      administration.Volume=100 // administration.Concentration=0.5
10     administration.Drug=25 // administration.Concentration=0.25
11 }

```

Figure 4.1: `DrugAdministration` class contains the variables `Drug`, `Volume` and `Concentration`. The class contains a formula (line 3) defining `Concentration` to be re-evaluated whenever `Drug` or `Volume` is updated. Then once an instance of `DrugAdministration` is created (line 7), any change to its `Drug` or its `Volume` causes its `Concentration` to re-evaluate.

the runtime maintain.

When executing the formula, the formula is handled by the runtime.

Executed formulas means that the runtime update the varia

Consequently, formulas are unconditionally added. The semantics to add the formula, fits well with the conceptual specialization (subtyping) [54], making the derived class only extending the base class. However added formulas sometimes complicates the calculations.

In the next sections we introduce a new variant of FRP that supports complex calculations. The updates are taken with two fundamentals. First, we use only synchronous method calls from the basic objects framework. Second, we satisfy the *referential transparency* property related to FRP [4], i.e., the same input will produce consistently the same output. We provide the property using the formulation of the guarantee [17]: “the same sequence of events produces the same results, regardless of the timing of those events”.

```

1  class ExtendedDrugAdministration {
2      IDrugAdministration drugAdministration
3      ExtendedDrugAdministration(DrugAdministration drugAdministration){
4          this.drugAdministration=drugAdministration
5      }
6      drugAdministration.Drug:=
          ↪ drugAdministration.Concentration*drugAdministration.VolumeOfFluid
7  }

```

Figure 4.2: A reactive instance variables assigned externally with a formula.

```

1  class ExtendedDrugAdministration:DrugAdministration {
2      RIVar<double> Dose, Rate, Duration
3      Drug:=Dose*Duration
4
5  }

```

Figure 4.3: Specialization Interface

4.2 The Computational Model

This section provides a new variant of FRP in high level, that follows the approach's fundamentals. We describe this as a computation model. The computation model comprises the basic items used in FRP applications, the problem description model, that is the style or method used to represent an FRP application, and the execution model, which present the process of how the FRP application is executed according to the specification.

4.2.1 Basic Items

There are three basic items: reactive variables, operators and assignments. reactive variables are the typical *continuous* [14] variables representing real world variables in the problem domain, independent of time. Operator is a lifted function, such that a function over values are lifted to being over reactive variables: the constructed

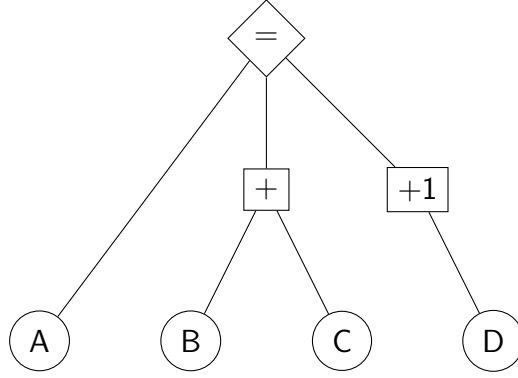


Figure 4.4: An assignment operator over reactive variables.

expression continuously reflects the varying value calculated from the reactive variables. Assignment over reactive variables would be a *lifted* assignment, such that an assigned reactive variable should reflect the assigned expression continuously.

4.2.2 Problem Description Model

The reactive variables, operators and assignments are used to build FRP applications. A FRP application has the functional style, in such that any statement is just like declaring functions over reactive variables. Unlike the functional paradigm there may be *several-assignments*, i.e., several formulas in which their target variable is pointed to the same variable.

Nevertheless, the case of several assignments is interpreted as a single assignment operator over the variable and assigned expressions in the various statements. For example, as seen in Figure 4.4, the two statements of a FRP application $A := B + C$ and $A := D + 1$, produces the function $\text{"="}(\text{"="}(A, B + C), D)$.

The n-ary assignment operator should be equivalent to a composite of several binary assignments. For example, $\text{"="}(A, (B + C), D)$ behaves the same as $\text{"="}(\text{"="}(A, B + C), D)$ (Figure 4.5). In this sense, $A := B + C$ refers to $\text{"="}(A, B + C)$, then $A := D$ accumulates the meaning to $\text{"="}(\text{"="}(A, B + C), D)$.

In addition to the FRP application, there is also the *FRP application consumer*,

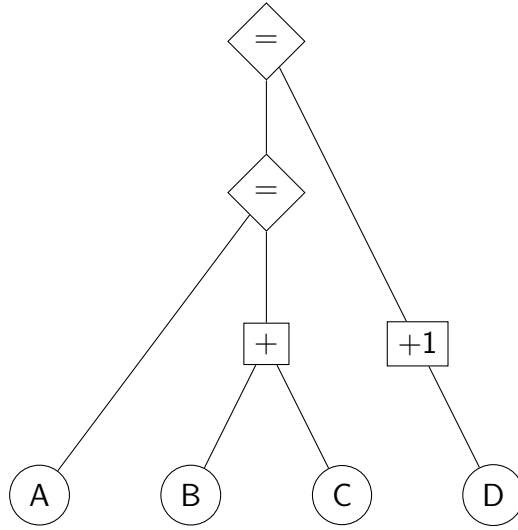


Figure 4.5: A composition of binary assignments

unless it, the FRP application is useless. The FRP application is effectful only when it is connected to external events of inputs, and also the external events of outputs are observed. So, the role of the FRP application consumer is to trigger events, feeding the reactive variables with values, and observe the reactive variables by being subscribed to their events.

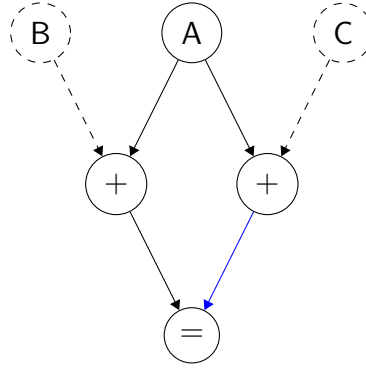
In this scope, we just use statements of the form `Var=input` to trigger a single event of an external input. For example, `A=1` refers to that the reactive variable `A` has just being updated by an external input to the value of 1.

4.2.3 Execution Model

An external input, caused a variable's value to change, causes a depth-first search (DFS) traversal on the graph starting from this variable's node. In the traversal, the dependant variables would update according to the new input.

The DFS traversal is caused by synchronous calls process: whenever an element's value is changed, it makes recursive synchronous calls to elements depending on it, calculating their new values.

The result of a DFS of the graph can be described in terms of a spanning tree of



*Dotted Lines (in contrast to the solid lines) refers to that it is not part of the spanning graph of the vertices reached during the search.

Figure 4.6: A special edge in DFS to an assignment element

the vertices reached during the search. The traversal and updates are simple while edges are *tree edges*, however we should consider also the *special* edges (back edges, cross edges and forward edges). Reactive variables will always be visited through tree edges going from an assignment, so we should consider only assignments and operators.

For operators, the special edges reminds the glitch issue [31, 3]. The root element's change causes two (or more) visits in the elements that have the special edge, while only the last produced a correct calculation. However if the graph contains cycles, it is not simple to identify what is the last visit. So, we use a *model of order* and will ignore visits with less updated value than the existing one.

For assignments, in the first glance it does not make sense having a special edge, because it seems to be defined conflicts. However, as in Figure 4.6, any element in the spanning graph is supposed to depend on other variables from the graph. That's why each visit represents not only the current external input but also the preceding external inputs affected the other dependant variables. According to the model of order, the visit representing the latest external inputs, should be the correct calculation.

X (external input)	Value=8	timestamps: {1}
Y (external input)	Value=2	timestamps: {2}
D (external input)	Value=1	timestamps: {3}
$Z1 = X*Y$	Value=16	timestamps: {1,2}
$Z2 = X+D$	Value=9	timestamps: {1,3}
$V=Z1+Z2$	Value=25	timestamps: {1,2,3}

Table 4.1: Values' Timestamps

{1}	<	{2}
{1,2}	<	{1,3}
{1}	>	{1,2}

Table 4.2: Comparing Timestamps Set

4.3 The Model of Order

The external events are sequential. Each event has a timestamp (an incremental natural number) as X, Y and D in Table 4.1. Then a value inferred by other values has several timestamps, the ones that the value is based on (Z1 and Z2 in Table 4.1). Transitively, a value derived from other values has the timestamps produced from the union operation on the timestamps of the values it is derived from (V in Table 4.1). For the sake of simplicity, timestamps are uniformly represented as sets containing one or more timestamps.

Any value can be compared against any other value according to their timestamps set. Greater timestamps, as the first two lines in Table 4.2 are indicators to more recent events. However, if the set is a superset, as in the third line in Table 4.2, then it is a recursive update, so considered as not being more updated.

4.4 Computation with the Stream Model

Essentially there are two principals. First, variable's low level abstraction is an observable stream of values representing its varying value. Second, a single variable can have several sources (from being an input variable while having one or more

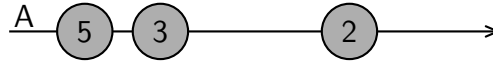


Figure 4.7: Illustrating a stream of values representing the varying value of a variable. The axis represents the time, and whenever the value is changed, there is a circle with the new value. The visualized stream presents a variable **A** updated to 5, then 3, then after a longer period 2.

assignments, or just from having several assignments).

4.4.1 Observable Stream

In addition to the reactive variable's continuous abstraction, there is also the discrete stream abstraction. Because even when a reactive variable represents a real-world variable in high level, in computers reactive variables' actual values cannot continuously provided. For example, temperature depends on an actual stream of discrete events, being sampled by a thermometer.

Similar in UI applications, the logic may be in terms of continuously update fields according to other fields. Many times, UI application observe fields' change events, once a value is changed, dependant fields are calculated and presented. The fields change events feed reactive variables (as observable variables), and the fields updates are from subscribing to reactive variables (as latent variables).

A reactive variable, and any other element in the FRP application, is a stream of values represeting its varying value. The stream can be described as in Figure 4.7. The x axis represents the time, and whenever the value is changed, there is a circle with the new value.

4.4.2 Several Sources

A variable with more than one source refers to having several streams of samples contributing to inferre its values. This is similar to situations when several devices

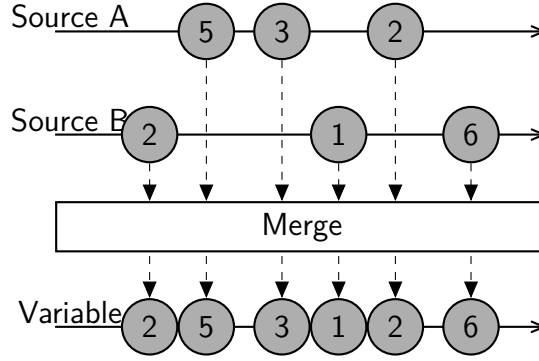


Figure 4.8: A variable varying value inferred from several sources.

sample a single real-world variable.

In this thesis, the values are inferred according to the time: whenever a new value exists in any of the sources, the value would be propagated to the target variable. Taking values from several sources according to the time, is equivalent to the merge function over streams (as in Figure 4.8).

The assignment element is a function over streams that should produce a single stream, with the meaning of inferring the value, by merging the streams. Therefore, the assignment element will be referred to, as the *merge* function.

4.4.3 Execution Model

The elements of the FRP application, as an events stream, or an observable, emits values to subscribers [35], based on the *observer* and *iterator* patterns [19]. Each operator and assignment provides its subscribers *a single values stream based on several values streams* which it is subscribed to. It tracks its input values from the inputs streams it is subscribed to, calculating and *deciding* what values to notify its subscribers; some inputs might be with an incorrect order or redundant updates due to cycles or glitches [31].

There are two stages. First, evaluating the statements. Second, reacting to the FRP application consumer, i.e., updating and triggering variables according to ex-

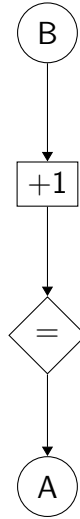


Figure 4.9: Formula $A := B + 1$ over reactive variables A and B

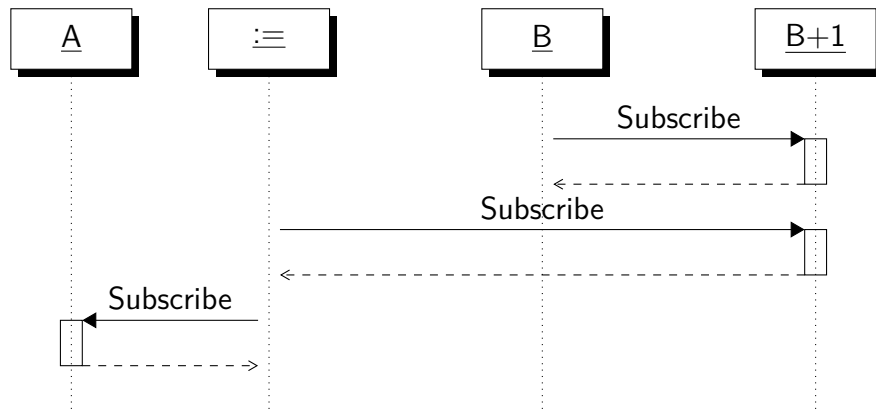


Figure 4.10: Evaluating the formula $A := B + 1$

ternal events. In the first stage of evaluation, the elements subscribe to each other according to the problem described. In the second stage, the connected elements update each other, by calling each other's `OnNext`, whenever they need to update. For example, the statement $A := B + 1$ described in Figure 4.9, is evaluated as in Figure 4.10, then as in Figure 4.11, when the UI updates B with the value 2 causing the elements update each other.

, and

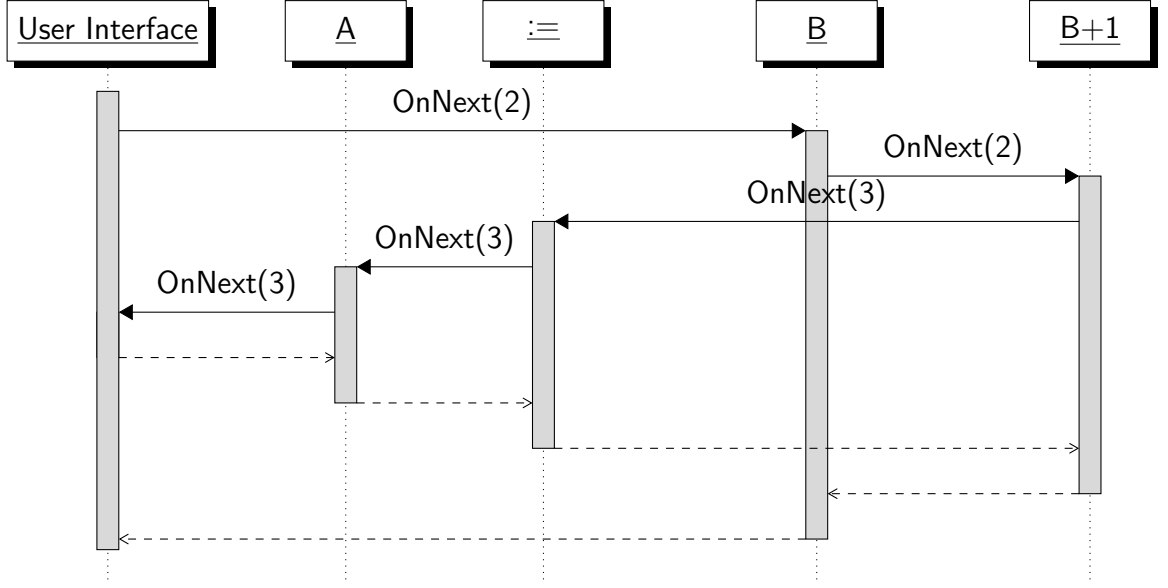


Figure 4.11: Propagation on the formula $A := B + 1$

4.4.4 Executing the Assignments

Executing the assignment statements accumulates merged streams. The execution is sequentially, with the imperative style, line by line. For example, the statement $A := B + C$ is executed as $A = \text{merge}(A, B + C)$. The next statement $A := D + 1$ is executed as $A = \text{merge}(A, D + 1)$ according to the current value of A . So that the execution if the two statements behaves as $A = \text{merge}(\text{merge}(A, B + C), D + 1)$.

Executing the merge, is not by creating a new stream to produce values whenever there is a value in any of the two sources. Instead, as seen in the example in Figure 4.12, we use the existing stream of the variable, and produce the merge by “adding” the missing values according to the other source. In order to add the missing values, the assignment/merge operator need to track the two sources, and do comparison according to our model of order.

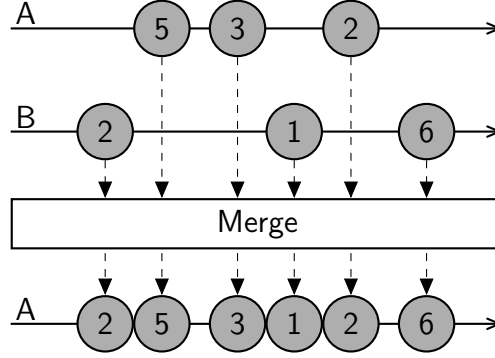


Figure 4.12: $A = \text{merge}(A, B)$

4.5 Summary

According to our approach, the variables are interacted by traditional messages from the objects containing them. Therefore, in the implemented solution of FRP, a mediator is not allowed. Instead, we use a push model, such that a variable synchronously calls its derived variables whenever it has a new value. In addition, any dependency produced from any formula, is supported.

In order to cover all types of dependency graphs, we provide semantics to the assignment operator. An assignment refers to adding more source to get values to the variable, therefore a variable infer its values over time from all the sources provided. As a result, the assignments and operators have a similarity in that they may produce a single stream by several input streams.

We provide an order model to handle the time issue, because the *visit time* of the DFS traversal is insufficient for visits caused from the same event (simultaneous events [4]). Therefore, values are attached with information to discover their time.

We use the order model as the algorithm used in the assignment operator, how to choose the values among the input streams. Consequently, whenever there is a new value from any of the sources, it is pushed to the target variable. This makes the similarity stronger between the assignments and operators.

Chapter 5

Evaluation

The idea of combining reactive variables from FRP to being instance variables in OOP is not new. REScala and ReactiveX has also reactive variable being an instance variable. Anyway, the new model has several additional properties:

- The model depends only on the basic objects, as a tidy interface to clients, consisting of instance variables and methods. ReactiveX is also based on the basic objects, however it does not have the referential transparency (as in the next property), therefore produces non predictable results in case of cycles and merges [4].
- The model has the referential transparency property, such that each of the variables has a function declaring its stream of values according to the input provided. This property is basic in FRP, however according to REScala, it requires a mediator to observe and update the variables, not just the objects model, as the previous property.
- The model corresponds to the concept of inheritance with subtyping. Because assigning a variable that belongs to a base class, *adds* a dependency. This is in contrast to REScala and ReactiveX, there the same action *replaces* a dependency.

In the next sections we will evaluate the results. Our evaluation presents the code duplication aspect (Section §5.1). Our method to handle any graph is also evaluated by comparing between our method and other solutions about special graphs (Section §5.2). At last we give a brief glance about our method compared to the paradigm of constraints systems (Section §5.3).

5.1 Code Reuse

Code reuse, *DRY* (Don't Repeat Yourself) or *SSOT* (Single Source of Truth. By not repeating code, there is no inconsistent behavior, each piece of logic has only one source of truth) are obvious principles in programming. In this section, we presents three types of code repetition being removed by the new method. In the presentation, we refer to the used abstraction mechanisms and compare to the traditional methods.

5.1.1 Repeating Updates

Derived from the FRP paradigm, we abstract away the need to update variables in response to dependant variables' updates. As mentioned in ??, The FRP paradigm maintain formulas automatically, so that there is no need to repeat registering to events to re-calculate variables. In the events paradigm, developers need to update variables in the events when other variables are updated. In case that a variable is updated according to several variables, we should register to all the relevant events to call to the variable to update. For example, as in Figure 2.1, in order that \mathbf{x} will contain the value of $\mathbf{y}+\mathbf{z}$ whenever \mathbf{y} or \mathbf{z} is updated, we should calculate \mathbf{x} in two events handlers. We provide the abstraction mechanism so that the developers don't have to repeat on the code, they only need to declare $\mathbf{x}:=\mathbf{y}+\mathbf{z}$.

5.1.2 Repeating Variables

In the FRP paradigm by nature, several reactive variables are declared to represent a single real world variable. Because reactive variables are the functions they represent. In other words, once there is a function to calculate a varying value, usually a new reactive variable is declared. In contrast, we use the principal of several assignments, such that a single reactive variable is assigned to several functions. As a result, our method use a mechanism to not duplicate variables.

5.1.2.1 Example

In the example, we demonstrate a development process. We use a bold font style to indicate for code, that it is changed compared to the previous step. The process is about the two variables **Amount** and **Alert**, the first refers to medication amount administered to a patient, and the second refers to whether the application should alert about abnormal medication amount. The following formula relates **Alert** and **Amount**, so that **Alert**'s value be automatically according to the value of **Amount**

```
Amount=FromInput()  
Alert=IsAbnormal(Amount)
```

The doctor may administer the **Concentration** and **Volume**, then the amount will be calculated by as product, thefore the code will be changed:

```
AmountByInput=FromInput()  
AmountByConcentrationAndVolume=Concentration*Volume  
Alert=Or(IsAbnormal(AmountByInput), IsAbnormal(AmountByConcentration  
↪ AndVolume))
```

The doctor may administer by setting **Dose** and **Duration**, then the medication amount will be calculated by **Dose*Duration**. In such a case, we should again update the code:

```
AmountByInput=FromInput()  
AmountByConcentrationAndVolume=Concentration*Volume  
    ↪ AmountByDoseAndDuration=Dose*Duration  
Alert=Or(IsAbnormal(AmountByInput),  
IsAbnormal(AmountByConcentrationAndVolume),  
IsAbnormal(AmountByDoseAndDuration)))
```

It can be seen, that whenever **Amount** need more values source, then we should update the assignment to **Alert**. If we forget to update (as may happen in large complex applications), there become inconsistencies between **Amount** and **Alert**.

Implementing by the new method The should be an alert if the amount is abnormal, therefore the following formula relates **Alert** and **Amount**, so that **Alert**'s value be automatically according to the value of *Amount*

```
Amount=FromInput()  
Alert=IsAbnormal(Amount)
```

The doctor may administer the **Concentration** and **Volume**, then the amount will be calculated by as product. It is enough to only add the code:

```
Amount=Concentration*Volume
```

The doctor may administer by setting **Dose** and **Duration**, then the medication amount will be calculated by **Dose*Duration**. It is enough to only add the code:

`Amount=Dose*Duration`

Nothing about variable `Alert` need updates, therefore there is no chance of consistency problem between the variables' values.

5.1.3 Repeating Solutions

The new method also provides an abstraction mechanism to not repeat on *solutions*. As mentioned in sections 5.1.1 and 5.1.2, the new method provides an abstraction mechanism to not repeat on updates and variables. However, we are not the first to provide such an abstraction mechanism. As mentioned in ??, in constraints systems, several constraints can output to the same variable, while constraints are such like formulas in FRP. Anyway, solutions created by constraints systems cannot be reused and extended with more constraints, without to change the original solution, because the constraints systems handle the updates using a central constraints solver. In contrast, with the new method, solutions can be reused, because our new variant of FRP provides adding formulas to existing solutions.

We derive from OOP the ability to reuse solutions. Before OOP, in order to reuse solutions, the developer has two alternatives: either to use an existing solution to the new client, or to copy-and paste it. The first alternative might cause unexpected changes to existing clients, because the developer might change the solution to the new client, affecting other clients unexpectedly. The second alternative produce code duplication. In the second alternative, the duplicated code is related to a common logic, if it is changed in one solution, there might be an inconsistency in the behavior. OOP provides the inheritance and composition mechanisms to reuse existings solution without to duplicate and without to change existing solutions.

The inheritance and composition mechanisms are actually not simple to use. It is expected that the new code will not change the original behavior, however even

if the code is specified only in the service or in the subclass, it might change the original behavior [13]. When assigning reactive instance variables through a service or a specialization interface (subclass assign a reactive variable of its base class), in REScala and ReactiveX, it *replaces* a dependency, then it *changes* the original behavior. In our method it *adds* the dependency, then it only *extends* the original behavior.

5.2 Special Graphs

In Chapter 4 we presented the new model that provides adding and supporting any formula. In order to support any formula, the model need to handle special graphs. In this section we compare the model against the traditional methods, in the way they handle glitches (Section §5.2.1), cycles (Section §5.2.3) and several-assignments (Section §5.2.2).

5.2.1 Glitch

As mentioned in Section §??, a variable might have several updates caused by a single update, e.g., in 2.3, updating A leads to update B and C, each of them lead to update D. The updates that are not the last update, are incorrect, and called *glitch*. This is handled by doing topological sorting [3], so each of the variables will be updated after all its dependencies have already been updated. But we cannot use this method for two reasons.

First, topological sorting is possible only when the dependency graph has no cycles, in contrast to our conception that every dependency is possible. Second, topological sorting means managing the variables centrally, in contrast to the concept of objects managing their variables on their own. The need to manage the updates with a decentralized settings reminds the distributed settings.

The decentralized and distributed share the property that it is not applicable to have “global centralized knowledge about the topology of the dependency structure” [12]. However, they are not distinct. Whereas distributed settings have challenges related to the network. FRP with decentralized settings is more about respecting encapsulation. Therefore, and because we support cycles, adapting existing algorithms becomes irrelevant most of the times.

We use the strategy like in the distributed settings, to attach data to the values [51, 43]. However we avoid the situation in the distributed settings, that the data about variables is public. The data becomes public, because the glitch is handled by tracking variables’ versions, and because information about variables’ versions is attached with the values.

Our order model reminds the order of *updates* described in the distributed system model [31]. In our order model, an incorrect (glitch) value (update), is considered as less than an existing value, so it is ignored. For example, in the dependency graph of 2.3, D with timestamps set $\{1\}$, getting an update depending on updated B $\{2\}$ and not updated C $\{1\}$, produces timestamps set $\{1,2\}$ that is a superset of the existing timestamps $\{1\}$. According to the order model, a superset is not considered greater so it is ignored.

Our model seems to solve only types of glitches (among [31]) caused from a single update for a single variable. This should satisfy many applications. Actually, for UI application, glitch may be not a problem, because a temporary incomplete calculation is replaced very fast with the updated values. Anyway, for more strict requirements, such like requiring several synced variables, there is a possible solution named *source unification* [51, 57], to declare a variable deriving the variables.

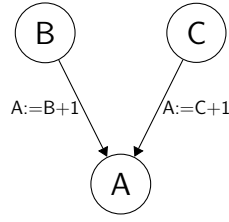


Figure 5.1: Several Assignments

5.2.2 Several Assignments

Our model supports variables depending on several expressions such as in Figure 5.1, while in runtime values are inferred according to time, i.e., the variable's current value depends on the recent input events.

FRP In FRP, a reactive variable *is* the expression it is related to. The assignment operator is related to the imperative paradigm, not to the functional paradigm. However, in languages where the assignment symbol is used in the context of functional programming, the assignment symbol connects a function body to its name. Similarly in FRP, a formula $A := \text{Var}$ declares A as a function that its body is Var . Adding statement such as $A := \text{Tar}$, is not suitable to the paradigm. In terms of reactive variables we cannot relate several sources to a single variable so we are forced to use the events abstraction.

In ReactiveX and Sodium, several streams can be merged into one stream by the use of an operator named **Merge**. ReactiveX merges the streams based on the time according the runtime traversal order, which is unpredictable [4]. Sodium provides predictability by forcing the user to define how to merge the streams. Namely, no general predictable merge has been provided.

If the developer needs to specify the correct order, it is in contrast to the functional paradigm. The functional paradigm was meant to eliminate handling time. If the developer needs to handle time, it is not clear whether the paradigm outperforms

the alternative paradigm, in which time is handled by the use of states and events [2]. Our model handles the merge problem providing the developers the high level abstraction without to handle time.

Events In simple cases our model reminds the behavior when using events: when several events handlers calculate a single variable, the variable's value is according to the latest triggered event.

Constraints As described in Section §??, constraints systems like HotDrink solve the constraints according to the hierarchy derived from the order of the input. Consequently the produced behavior is the same as our new model. It is true that the constraints system handles two-way constraints while our model handles one-way constraints. However, as said in the section, the two-way constraints are declared and handled by one-way constraints.

5.2.3 Cycles

In the FRP paradigm, where FRP runtimes are developed, There are two opposing methods about cycles. In one method, cycles are avoided, because the paradigm derived from the functional paradigm, with the referential transparency property [4]. In addition, avoiding cycles is a necessary condition to algorithms to handle glitches [31, 3]. According to the second method, forbidding cycles makes FRP unacceptably weak, because many applications have cycles by their nature [9, 41]. Following the approach that cycles are avoided, there is an approach that the needed dependency graph is dynamically changed [17].

FRP runtimes that support cycles uses various techniques to stop arisen loops. Terminating when it closes a cycle [49], adding to the language a special operator to inform the runtime when to break the cycle [9], stop after a number of iterations, stop if the value has not changed, or changed only less than a threshold (available in

Microsoft Excel ¹). The various methods caused from the unknown, that a repeating update is either needed because previous update was a glitch, or that it is unneeded because the repeating update is caused from a cycle.

Our model provides the semantics described in ?? : cycles are resulted from variables with more than one source. Those variables are updated whenever there is a newer value from any of the sources. Technically, loops are terminated, because values caused from cycles are not newer. However, we are not the first to handle cycles, as said in Section §??, constraints systems that handle two-way constraints handle cycles by their nature [49]. Nevertheless, the model treats the meaning issue about cycles more explicitly.

5.3 Constraints System

In this section, we compare our method to Hotdrink mentioned in Section §??. As mentioned in Section §?? and ??, FRP and so our method are similar to Hotdrink in that they share declare equations, providing runtime automates to automate variables' updates, they support cycles and several assignments, and that they handle the variables' values according to the order of the input. Our method is different from Hotdrink in that it is a *decenterlized* constraints system, and that it handles one-way constraints.

decenterlized constraints system Hotdrink needs for each input, to run against the entire constraints and existing values, to generate a new dependency graph according to the variables' existing values. This algorithm is executed by a mediator coupling the entire variables and dependencies. As mentioned in 5.1.3, this design causes applications to not being reused. In other words, Hotdrink can be used only to

¹<https://support.microsoft.com/en-us/office/remove-or-allow-a-circular-reference-8540bd0f-6e97-4483-bcf7-1b49cd50d123>

building monolith applications [32]. In contrast, our method provides a decentrelized constraints system, the variables observe their sources and update their values by regular objects' messages. Consequently, by nature, relations between variables can be specified, even when variables are located in different components.

one-way constraints Hotdrink handles two-way constraints while our method handle one-way constraints. As explained in Section §??, the two-way constraints need attached one-way constraints, that are the *methods* [17] to satisfy the two-way constraints. Consequently, with the two methods, the developer needs to specify one-way constraints. However, it has been augmented that it is more correct to specify two-way constraints, because several one-way constraints defined separately might define inconsistent requirements [49]. We leave this for future work. For this stage we provide two arguments to the claim. First, according to the motivating example, we need the option to write the one-way constraints separately. Second, the method should be used in a programming language that supports OOP. Consequently, it should not be hard to implement a wrapper class `Constraint` containing one-way constraints given as arguments.

Chapter 6

Implementation

In this chapter we present an implementation to the model presented in Chapter 4, attached with a small case study based on the motivating example from Chapter 3. The model is implemented as a lightweight .NET library to C# developers named RIVarX¹, based on ReactiveX².

6.1 RIVarX

When implementing RIVarX, we started from adding extensions methods to existing types of ReactiveX. The model can be fully implemented by only add extensions. Only to provide a more user friendly syntax, we defined the class named **RIVar** providing this type explicity. The main features we developed are to provide our model. The features are: (1) assignment operator, (2) order model and (3) operators.

6.1.1 ReactiveX

ReactiveX provides observable streams which has already been presented as being reactive variables [50]. ReactiveX has two useful operators to implement latent vari-

¹<https://github.com/RivkaAltshuler/RIVar>, <https://www.nuget.org/packages/RIVar.RIVarX>

²<https://reactivex.io>

ables: `Select`³ and `CombineLatest`⁴. The default behavior is that values are pushed to subscribers synchronously, just like the required push model described in 4.2.3. Consequently, FRP applications can be easily developed. For example, FRP application with the statements `B:=D+1` and `A:=B+C` can be implemented by the statements `B=D.Select(x=>x+1)` and `A=B.CombineLatest(C,(x,y)=>x+y)`.

6.1.2 The Main Features

Assignment Operator The default assignment copies values bit by bit. Therefore, in the context of FRP applications, the assignment just makes the target variable to point on the constructed expressions, disconnecting from the old referenced expression if exists. The traditional assignment cannot be overridden, therefore RIVarX implements an alternative assignment function named `Set`. `Set` uses the new approach to add the expression in addition to existing expressions.

The `Set` method has two arguments: a reference to the target and the reference to the assigned expression. When `Set` is called, it subscribes to the two streams, so that for each signal from the assigned expression, it will compare to the signal produced latest in the target. Signal that is greater refers to a signal that is later. Therefore, any signal coming from the expression, that is greater than the latest signal in the target, is pushed to the target.

Order Model The default order model just based on the *visit time* of the DFS traversal, and is insufficient for visits caused from the same event (simultaneous events [4]).

Therefore, RIVar is implemented as an observable of type named `Signal`. The `Signal` type represents timed information about a phenomenon [42]. `Signal` imple-

³<https://reactivex.io/documentation/operators/map.html>(in other programming languages it is named `map`)

⁴<https://reactivex.io/documentation/operators/combinelatest.html>

ments `Comparable` interface to abstract items that can be compared between each other. Each signal (`Signal`'s instance) contains an array of timestamps that are used in comparisons.

Operators The `Select` and `CombineLatest` produce verbose syntax in building FRP applications [50]. Furthermore, the `CombineLatest` operator uses the default order model.

Therefore, we developed `Lift` function, to lift functions over values to functions over `RVars` (implemented as observable streams). `Lift` has two overloads that are wrapper functions to `Select` and `CombineLatest`. The one that wraps `CombineLatest`, before calling to `CombineLatest`, filters out values that are less updated than their previous values.

6.2 Using `RVarX`

The interface provided by `RVarX` uses `ReactiveX` combined with the new implemented interface. The new type `RVar`, in addition to the operations introduced in 6.1.2, has the observation operations, because it implements an interface named `ISubject` derived from `IObserver` and `IObservable`. A complete usage example is listed in Figure 6.1 in the form of a unit test.

Declaring `RVars` `RVars` are declared parameterized with the type of values it should contain, as in (lines 6 to 8) in Figure 6.1.

Functions over `RVars` The developer needs to implement the function over values, and then lift it to be over `RVars`. For example, the function `plus` specified in line 9 is lifted to be over `RVars` `Y` and `Z` by `plus.Lift(Y, Z)`. The `Lift` method returns an expression to be assigned.

```

1 [TestMethod]
2 public void SimpleUsage()
3 {
4     //Construction
5     int result = 0;
6     var X = new RVar<int>();
7     var Y = new RVar<int>();
8     var Z = new RVar<int>();
9     Func<int, int, int> plus = (op1, op2) => op1 + op2;
10    X.Set(plus.Lift(Y, Z));
11    X.Subscribe(new observer<int>(i => { result = i; }));
12
13    //Action
14    Y.OnNext(2);
15    Z.OnNext(3);
16
17    //Test
18    Assert.AreEqual(5, result);
19 }

```

Figure 6.1: Using RVarX

Assigning The method `Set` is used for assignments. The argument is of type `Expression` produced by the `Lift` method. Consequently line 10 implements $X := Y + Z$.

Providing input $Y=2$ is implemented by `Y.OnNext(2)` (lines 14 and 15)

Get the output RVars are observed to get its value's changes by calling to `Subscribe`. In the example in Figure 6.1, we update a local variable with the observed value (line 11) to verify it against the expected value (line 18).

6.3 The Case Study

We implemented the motivating example by using RVarX⁵. As in Figure 6.2, `Pump` is a class depending on the interface `IBag`, containing `Drug` and `VolumeOfFluid` typed

⁵<https://github.com/RivkaAltshuler/RVar/tree/main/CaseStudies/DrugAdministration>

as `RIVar`. `Pump` depends on `IBag` by containing the class variable `TheBag` typed as `IBag`. Based on the existing bag, `Pump` contains `Rate`, `Dose` and `Duration` also typed as `RIVar`. In the constructor of `Pump` we define formulas to calculate the accessible variables. `Bag` class is independently implemented deriving from `IBag`.

`Bag` and `Pump` does not depend on each other, according to the *Dependency Inversion Principle* (DIP): “high level modules should not depend on low level modules; both should depend on abstractions” [33]. Also in runtime, `Bag` has a consistent behavior when connected or unconnected to `Pump`. Unless `Pump` has input, the connected `Pump` has no effect on `Bag`. This is simulated in Figure 6.3: line 4 has no effect on the outcome. Similarly, if we had an inheritance instead of the composition, such that `Bag` is the base class and `Pump` is the subclass. Then, according to the *Liskov Substitution Principle* [33], objects of a `Bag` can be replaced by objects of a `Pump` without any effect.

In Figure ?? we introduced a micro-frontend design. Accordingly, we developed loosely coupled components that can be developed, built and deployed independently. The bootstrap is introduced in Figure 6.4. `UserControl_Bag` is like the bag micro frontend, `UserControl_Pump` is like the pump micro frontend. `UserControl_Bag` and `UserControl_Pump` implements the UI and are connected to `Bag` and `Pump` respectively.

The UI components are connected to the model objects (`Bag` and `Pump`) in such that whenever a user changes a field’s value, it produces an input to the related variable, causing other variables to be calculated, producing updates in their related fields. The UI components also provide the functionality to indicate calculated values, just like in Figure 4.1. In addition, The UI components append to a log file any value change. In Figure 6.5, we introduce the log output of the cenario introduced in Figure 3.6, except the unexpected update.

```

1 public class Pump
2 {
3     public RVar<decimal> Rate = new RVar<decimal>();
4     public RVar<decimal> Dose = new RVar<decimal>();
5     public RVar<decimal> Duration = new RVar<decimal>();
6
7     IBag TheBag;
8
9     public Pump(IBag bag)
10    {
11        TheBag = bag;
12
13        Dose.Set(TheBag.Amount.Div(Duration));
14        Rate.Set(TheBag.Volume.Div(Duration));
15
16        Duration.Set(TheBag.Amount.Div(Dose));
17        Duration.Set(TheBag.Volume.Div(Rate));
18
19        TheBag.Amount.Set(Duration.Mul(Dose));
20        TheBag.Volume.Set(Duration.Mul(Rate));
21    }
22 }

```

Figure 6.2: Class Pump

```

1 decimal result = 0;
2 var bag = new Bag();
3 bag.Concentration.Subscribe(new observer(o => result = o));
4 var pump = new Pump(bag); // this line has no effect
5 bag.Amount.OnNext(100);
6 bag.Volume.OnNext(200);
7 Assert.AreEqual(0.5, result);

```

Figure 6.3: Bag in runtime

```

1 var bag = new Bag();
2 var pump = new Pump(bag);
3 var bagUserControl = new UserControl_Bag(bag);
4 var pumpUserControl = new UserControl_Pump(pump);

```

Figure 6.4: Bootstrap of the drug administration components

Dose_Control:10
Dose_Control: 10 <1>
Duration_Control:10
Drug_Control: 100 <2,1>
Drug_Control:100
Drug_Control: 100 <2,3>
Dose_Control: 10 <3,2>
Drug_Control: 100 <3>
Duration_Control: 10 <2>
Volume_Control:300
Drug_Control: 100.00 <3,4>
Volume_Control: 300.00 <2,3,4>
Rate_Control: 30.00 <3,4,2>
Rate_Control:30.00
Volume_Control: 300.00 <2,5>
Rate_Control: 30.00 <5>
Volume_Control: 300.00 <3,4>
Concentration_Control: 0.33 <3,4>
Volume_Control: 300 <4>

Figure 6.5: Log for the cenario of Figure 3.6

Chapter 7

Conclusion

This thesis handles the task to perform predictable behavior when applications grow with many code duplications and long chains of updates. Therefore we combine the OOP paradigm with the FRP paradigm. The OOP contributes the predictability to changing code, while the FRP contributes the predictability in the variables' updates.

We described our model by introducing RIVar as a special type of variable, being a reactive and instance variable, with an assignment specification. A single variable can be assigned by several clients, with the semantics that the variable's value can be provided from several sources, while the variable observes its sources by itself. The variables use an order model, to update consistently according to the latest produced input.

To evaluate the model, we compared it to previous paradigms and solutions and also implemented it as a library with an attached case study. In the comparison, we compared the model to REScala and ReactiveX providing an investigation on how we derive properties from OOP and FRP. We then showed how the model outperforms the previous paradigms in terms of code reuse, while handling correctly any dependency graph. We also compared the model to constraints systems, and provided a presentation to the model to being as a decentralized constraints system.

7.1 Future Work

We expect this approach being implemented as a state management solution and ease the development of front end applications. In the area of front end, the state management is separated from the other parts of the development. There are various solutions to handle the role ¹. Each solution has its maintenance and behavior limitations. our model should be ease in the maintenance, but the behavior is limited to inferring values according to the latest value coming from any of the sources.

There are additional options to be researched for reactive variables to infer their values. We think about the *equality tests* [41], in which values with no change are ignored. In addition, it might be that values should be rejected, in case that they are conflicted with another source, such case need the abstraction to be extended. In addition, we should check about integrating several semantics options.

¹<https://docs.flutter.dev/development/data-and-backend/state-mgmt/options>

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תקציר

משתנה מופע ריאקטיבי (Reactive Instance Variable), או בקיצור RIVar, הוא שילוב של משתנה ריאקטיבי (Reactive Variable) מן הפרדיגמה של תכנות ריאקטיבי-פונקציונאלי (FRP), יחד עם משתנה מופע (Instance Variable) מן הפרדיגמה של תכנות מונחה עצמים (OOP). בדומה למשתנה ריאקטיבי, ניתן להגדיר לו חישוב אוטומטי ע"י קישור לביטוי. בדומה למשתנה מופע, הוא יכול להיות חלק מממשק (Interface).

משתנה מופע ריאקטיבי

חיבור על מחקר

לשם מילוי חלקי של הדרישות לקבלת התואר
מגיסטר למדעים במדעי-המחשב



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