



Projection of Reactive Programs onto Dataflow Engines

Master thesis submitted in partial fulfillment of the requirements for the degree of
Master of Science in Applied Sciences and Engineering: Applied Computer Science

Alexander Moerman

Promoter: Prof. Dr. Wolfgang De Meuter

Advisor: Mathijs Saey, Florian Myter and Thierry
Renaux

Academic year 2016-2017



Abstract

Abstract

Declaration of Originality

I hereby declare that this thesis was entirely my own work and that any additional sources of information have been duly cited. I certify that, to the best of my knowledge, my thesis does not infringe upon anyone's copyright nor violate any proprietary rights and that any ideas, techniques, quotations, or any other material from the work of other people included in my thesis, published or otherwise, are fully acknowledged in accordance with the standard referencing practices. Furthermore, to the extent that I have included copyrighted material, I certify that I have obtained a written permission from the copyright owner(s) to include such material(s) in my thesis and have included copies of such copyright clearances to my appendix.

I declare that this thesis has not been submitted for a higher degree to any other University or Institution.

Acknowledgements

Contents

1	Introduction	
1.1	Context	2
1.2	Goals	2
1.3	Contributions	3
1.4	Structure	3
2	Background	
2.1	Introduction	5
2.2	Reactive Programming	6
2.2.1	Example	6
2.2.2	Advantages of Reactive Programming	7
2.3	The Dataflow Model	9
2.3.1	Introduction	9
2.3.2	Tagged Token DataFlow	10
2.3.3	Example	11
2.3.4	Advantages	12
2.4	Conclusion	12
3	Language	
3.1	Introduction	13
3.2	FrDataFlow	14
3.2.1	Sample program	14
3.2.2	Evaluation without the dataflow engine	15
3.3	Conclusion	18
4	DataFlow Engine	
4.1	Introduction	19
4.2	Architecture	20
4.2.1	Components	20
4.2.2	Example program with evaluation by the dataflow engine	21
4.3	Mapping of reactive signals to dataflow engine	24
4.3.1	Problems encountered	24

4.4	Conclusion	26
5	Evaluation	
6	Future work and limitations	
6.1	Introduction	29
6.2	Dynamically creating signals	29
6.2.1	Filtering	30
6.3	Conclusion	31
7	Related work	
7.1	Introduction	33
7.2	Reactive programming	34
7.2.1	Elm	34
7.2.2	FrTime	36
7.3	Dataflow Model	38
7.3.1	Virtual machine design for the execution of languages on dataflow machines	38
7.4	Conclusion	38
8	Conclusion	
A	Your Appendix	

List of Figures

2.1	Graph of signals	7
2.2	A tagged token	10
2.3	Graph of instructions	11
3.1	The billboard as a signal graph	15
3.2	The billboard as a topologically sorted list	15
3.3	The initial state of the billboard. Green = Not stale	16
3.4	A new temperature is emitted by <code>current-temp-fahrenheit</code> . Blue = New value and not stale , Grey = Stale	16
3.5	<code>current-temp-celsius</code> gets recalculated	17
3.6	billboard-label gets recalculated	17
4.1	The interaction between the four components of the dataflow engine	20
4.2	A tagged token	21
4.3	The corresponding data flow nodes for two calls to the <i>average</i> function. Each color represents a different execution context.	22
4.4	The results of the <i>plus</i> instruction are forwarded to the <i>divide</i> instruction	22
4.5	The second invocation of the <i>plus</i> instruction finishes. All inputs are now present for the <i>divide</i> instruction for both ex- ecution contexts.	23
4.6	The first <i>divide</i> instruction is invoked. Its result is put on the token queue again.	23
4.7	The second <i>divide</i> instruction is invoked. Its result is put on the token queue again.	23
4.8	The billboard program, but the signals are now data flow nodes	24
6.1	A timeline diagram of the <i>filter</i> operator in RxJs	31
7.1	The current timestamp is based on two different computations of <i>current-milliseconds</i>	35

List of Tables

1

Introduction

Reactive programming is becoming increasingly popular. Over the past decade, we have observed a slow but steady shift away from traditional imperative methodologies towards other, more declarative paradigms. The technology landscape is moving, and with it the software development world. Web and mobile applications, the *internet of things* and now virtual reality software are dominating the conversation, and they all have one thing in common: they are driven by events. Events, callbacks and asynchronous computation have always been challenging, so it's not hard to see why reactive programming - which puts events at the forefront as first class citizens - is gaining such popularity. Its declarative style and modeling of *values over time* is a perfect fit for environments with many impulses, such as the web.

Evaluation models for this style of programming are plenty, but none of them come with free parallelism. As can be expected, research has already gone into parallelizing reactive programs (Peterson et al., 2000), but none have tried mapping these applications onto something that was designed to run parallel from the beginning: the dataflow model. This model enforces instruction execution whenever the inputs are available, contrary to the sequential model where instructions are executed one after another, which sets up the perfect conditions to run in parallel.

1.1 Context

Reactive programming nor the dataflow model are new technologies, both go back to at least the 1980s (Harel & Pnueli, 1985; Veen, 1986). While they try to solve different problems, they do share an interesting common trait: the evaluation models of both use directed graphs to orchestrate data flowing through its applications.

The core principle of reactive programming is making events a first class citizen: they can be listened to, transformed or even composed with other events, ultimately building a graph of nodes that represent these events and the data dependencies between them. When the application executes, data courses through this graph via the *reactions* of the nodes when an event is fired. One could say that the system *reacts* to every event.

The dataflow model on the other hand has a different purpose: parallelizing instructions as much as possible by isolating each instruction and executing it whenever the inputs are ready. The runtime in this scenario is responsible for tracking the inputs of each instruction and forwarding the results to other instructions that depend on it. These dependencies between instructions again form a graph. This time however, nodes in the graph represent instructions, not events. Dependencies in this graph simply indicate that one instruction takes as input the output of another.

So while reactive programming uses a graph of nodes which represent events, the dataflow model has a graph which represents instructions. When executed, data flows through these graphs and the output of a node is forwarded to nodes further down the graph. Conceptually, nodes in these graphs mean different things in the two models, but the way that they behave is undeniably similar.

1.2 Goals

The goal of this thesis is to explore the possible benefits of running a reactive language on top of a dataflow engine, more specifically the advantages with regards to parallel execution. We propose that the update mechanism necessary to support a reactive language can be completely implemented using a dataflow engine, with the aim to parallelize the updating of separate nodes in the reactive graph. This would allow us to scale a reactive program horizontally, exploiting the maximum amount of parallelism possible. Moore's law essentially states that the processing power of a single processor core doubles nearly every 2 years. The last few years however, this exponential factor has been decreasing and more focus has been going towards splitting up proces-

sors into multiple cores. To make full use of these cores though, programs have to natively support parallel execution. The purpose of this thesis is therefore to investigate the parallelization of reactive programs by using the dataflow model as a platform. Given a successful mapping from reactive programming to the dataflow model, we can prove that reactive programming is a future proof paradigm, well suited for parallel evaluation.

1.3 Contributions

In order to test our hypothesis, we present a new reactive programming language *FrDataFlow*, based on Racket with a few extra features to natively support reactive programming. Expressions in this language are evaluated by our own interpreter, which builds the aforementioned graph in the background and keeps it up to date. Rather than implementing our own update mechanism however, the reactive graph is translated to instructions for our custom dataflow engine. This is the core mechanism which will orchestrate the events and keep nodes in the graph up to date.

Furthermore, we evaluate this approach by comparing it to an implementation of the same language that does not run on a dataflow engine, but applies a more traditional evaluation model. Benchmarks are provided for both latency and throughput for both implementations. Lastly, we also investigate the scaling possibilities of *FrDataFlow* by actually running it across multiple cores simultaneously.

1.4 Structure

This dissertation is structured to provide the reader with sufficient context before the actual research and evaluation is discussed. To this end, chapter 2 provides a general background with regards to both reactive programming and the dataflow model. It succinctly covers the problems they want to solve, how they attempt to do so, the advantages of these approaches and a short example illustrating how they work.

In chapter 3, our custom language *FrDataFlow* is presented, with an elaborate sample program displaying most of the features supported by the language. The evaluation of this example by our interpreter is then visually detailed with diagrams and corresponding explanations.

The dataflow engine is discussed in chapter 4. This is an implementation of the dataflow model that powers the update mechanism in *FrDataFlow*. A short sample is provided to show how instructions are invoked in this engine,

and how output from one instruction gets forwarded to the input argument of another. Next, the main research topic of this dissertation is presented: the mapping algorithm. This is the translation we make from the graph in reactive programming to a new graph of instructions for the dataflow engine. Encountered obstacles and corresponding workarounds are discussed.

Chapter 5 details the evaluation of our research. *** TODO ***
*** TODO ***
*** TODO ***

In chapter 6, we summarize the boundaries at which this research has drawn a line and discuss possible future improvements or extensions to our system. We do this by recognizing features provided in other reactive languages or frameworks, that are not present in FrDataFlow.

Related research topics are discussed in chapter 7. We took great inspiration from ambitious works such as Elm and FrTime, which we compare with FrDataFlow in terms of design and evaluation.

Finally, we conclude with chapter 8, which summarizes our findings of this research. *** TODO ***
*** TODO ***
*** TODO ***

2

Background

2.1 Introduction

This research builds on two existing paradigms in software development: reactive programming and the dataflow model. While intimate knowledge about these concepts is not required, a basic understanding of both will be necessary to follow the ideas and implementation of this dissertation. Reactive Programming is situated in the category of higher level software development, serving as an abstraction tool for events and reactions to those events. The dataflow model on the other hand can be considered more 'low level', providing a strategy for the implicitly parallel execution of programs.

2.2 Reactive Programming

Reactive Programming is a software development paradigm focused on reactions, i.e. the handling of external events, user interactions, etc. In this paradigm, the application state is derived from the previous state and any events that may occur, for example user interactions or current environmental factors. This deviates from more traditional approaches, where values and state can be written at any point and for any reason. In a reactive program however, the flow of dependencies is recorded as a (possibly cyclic!) directed graph, making the derivation of the application state very explicit. At the core of reactive programming are the following main concepts:

- The first-class reification of events (making events a first-class citizen)
- The composition of these events through lifted functions
- The automatic tracking of dependencies and re-evaluation by the language runtime

A number of implementations exist for reactive programming, in this thesis we will focus on the interpretation taken in FrTime (Cooper & Krishnamurthi, 2006).

2.2.1 Example

The canonical metaphor for Reactive Programming is spreadsheets, which typically track changes across input cells and automatically recompute values in other cells if the formulas they contain reference the aforementioned input cells. In essence, cells react to modifications made in other cells if their formulas depend on them. These cells are what we call *observables* or *signals* in Reactive Programming. Imagine a simple program in an imperative programming setting, as shown in listing 2.1.

```
a = b + c
```

Listing 2.1: A basic reactive program

When this statement is executed, it assigns the result of adding b and c to the variable a , mutating a in the current scope. Note that this only happens once. A snapshot is taken of the current value of b and c , to determine the new value of variable a . Of course, this assumes that the variable b and c are provided to the program.

In a reactive programming setting, a would subscribe to the values of b and c , essentially asking to be notified whenever the variables b or c change,

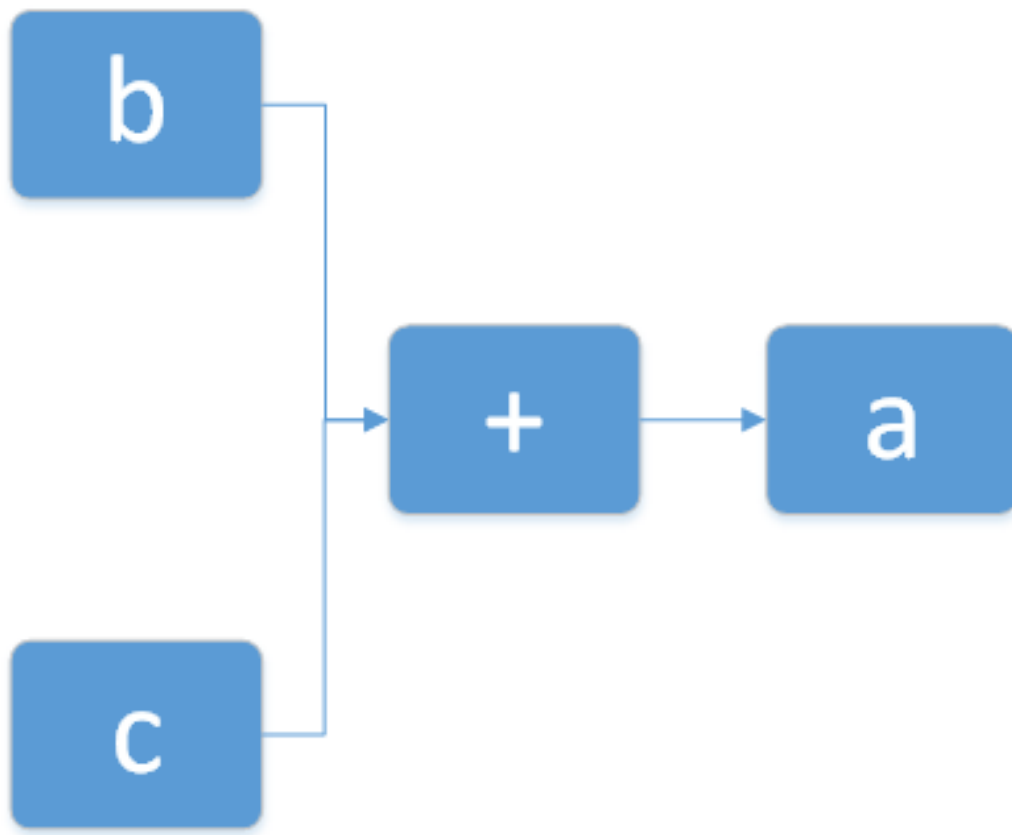


Figure 2.1: Graph of signals

at which point the value of variable *a* changes. See figure 2.1 for the reactive graph. This process repeats every time the variables *b* or *c* are modified. Note that the value of *a* is undetermined until both *b* and *c* produce a value.

The implementation of this reactive mechanism can be provided by the language itself or by a framework or library.

2.2.2 Advantages of Reactive Programming

A signal can be described as "values over time", in contrast with a variable which only holds its latest value, revealing no information about the time that value was provided or what changed it. Signals can be used to model almost any concept in software development:

- mouse movements as a signal which emits the current position in real time

- click events as a signal which emits event objects
- the results of a database query as a signal which emits only one value
- an infinite sequence as a signal which never stops emitting

Even though the underlying mechanism will still be identical to more traditional approaches (attaching event listeners to DOM events in HTML, opening and connecting to a WebSocket connection, etc.), the fact that all these concepts can be brought together under a single umbrella called *signals* allows for the modeling of higher order operators to map, combine and filter these flows of values in ways that were previously a lot harder.

2.3 The Dataflow Model

2.3.1 Introduction

The dataflow model (Johnston et al., 2004) is a paradigm focused on the parallel execution of programs. In this paradigm, instructions are seen as isolated units, which should be able to execute whenever the necessary operands have been provided. Contrary to imperative programming, instructions are not invoked by a program counter, but rather whenever all of the operands are present.

The execution of a program in the dataflow model can be represented as a direct graph of nodes where each node represents an instruction and each edge is data traveling between instructions. It is up to the dataflow engine to orchestrate inputs so that instructions are invoked when all of the input data is present. Whenever an instruction is invoked, the output is sent through to all connected instructions which depend on it.

2.3.2 Tagged Token DataFlow

The dataflow model has different possible implementations, in this dissertation we solely focus on *tagged token dataflow* (Arvind & Nikhil, 1990). In this version, instruction arguments, i.e. tokens, are tagged with meta data. A token consists of the following parts, as shown in figure 2.2:

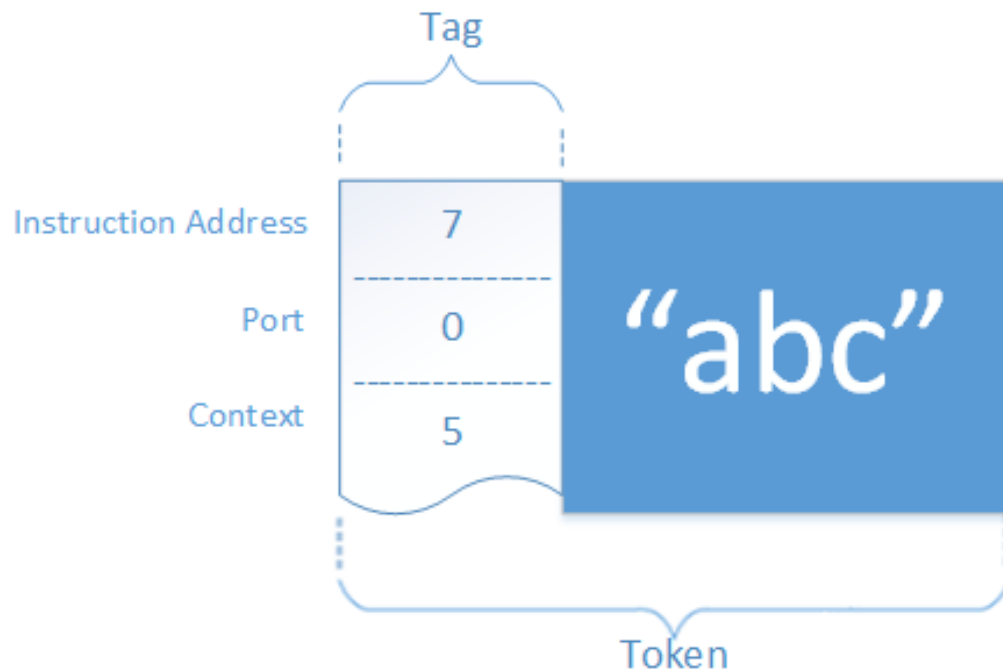


Figure 2.2: A tagged token

The value

Also called the datum, in this example "abc"

The instruction address

Uniquely identifies the instruction to be invoked

The port

Uniquely identifies the position of the token, should an instruction need multiple tokens for a single invocation.

The execution context

This uniquely identifies a function call, and is meant to distinguish instruction invocations of different function calls. This essentially allows the graph to be made reentrant.

2.3.3 Example

Imagine a simple program in an imperative programming setting, as shown in listing 2.1.

```
a = b + c  
d = a + b
```

Listing 2.2: A basic data flow program

This assumes that the variable *b* and *c* are provided to the program. In a traditional execution, the variable *a* would be set to the sum of *b* and *c* and the variable *d* would be set to the sum of *a* and *b*. Note that the sequence in which these operations are executed is of vital importance: switching the two statements would result in different values for the variable *d*!

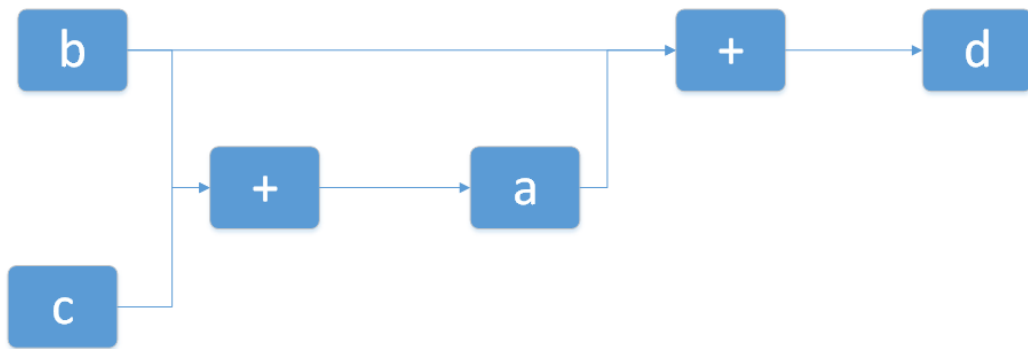


Figure 2.3: Graph of instructions

In a dataflow engine, these instructions are registered as nodes in the dependency graph, as visualized by figure 2.3. What really happens is that the values of *b* and *c* are added as tokens to the processing pipeline at application startup. The value of *b* is added as a token twice; once for the "+" instruction which computes the value of *a* and once for the "+" instruction which computes the value of *d*. When the dataflow engine spins up and starts processing data, it sends the tokens for *b* and *c* to the first "+" instruction, which is triggered because all of its inputs are present. This produces a value for *a*, which gets added as a token to the processing pipeline again as the first operand for the second "+" instruction. This instruction now also has all of its inputs present, which allows it to compute the value for variable *d* at this point.

If at any point in the future, *b* or *c* (which should be seen as the output of other instructions not shown in the sample code) produce new values, these would be enqueued again in the pipeline for further processing.

2.3.4 Advantages

The key advantage of the data flow model is that only the data dependencies of the instructions decide when an instruction can be executed. Since data flow instructions are not allowed to access or manipulate shared state, each instruction is completely isolated. This means that all dataflow instructions can be run in parallel, across different processes and even separate machines.

2.4 Conclusion

Two paradigms were presented: reactive programming and the dataflow model.

A large difference between both is that the dataflow model puts the instruction invocation at the center stage, while reactive programming puts forward signals as the core concept of its paradigm. In other words, while both systems have the notion of a dependency graph, the nodes in their graphs carry different concepts: instructions and signals respectively.

Reactive programming is targeted more towards events and reactions and shines best in environments where these things are plenty, for example in user interfaces and other places where events can come from any direction. The dataflow model on its part focuses more on the parallel execution of instructions by streaming operands to them in isolated scopes. We do however note similarities between the two, namely that they both work with an update graph that guides the data along its nodes.

3

Language

3.1 Introduction

For the purposes of this thesis, we have implemented a lightweight language called *FrDataFlow* using two different AST interpreters in Racket, supporting most of the basic constructs found in Racket. This language is based on earlier work detailed in Abelson et al. (1999). The first interpreter supports reactive patterns on top of the already existing Racket language. The second interpreter also supports the exact same language, but executes its instructions using an underlying dataflow engine. We chose to implement this custom language *FrDataFlow* (rather than a framework or library) to maintain maximum control over the inner workings and to facilitate experimentation atop the dataflow engine. The main goal was to have a reactive superset of Racket for experimental purposes during this thesis.

3.2 FrDataFlow

3.2.1 Sample program

FrDataFlow provides an environment with most Racket language constructs (defining variables, procedures, lambda, primitive operators, ...), the *lift* operator (which creates a new signal based on other signals) and some built in signals, shown in listing 3.1

```
;; A signal which emits the current seconds since 1 Jan 1970, every second
current-unix-timestamp
;; A signal which emits the current temperature from time to time
current-temp-fahrenheit
```

Listing 3.1: Built in signals

Take for example a roadside digital billboard which displays the current date and temperature. To show this information, we can derive a signal that contains the exact information that needs to be shown, using the built in signals in FrDataFlow. From the *current-unix-timestamp* signal, we can compute the date using the built in procedures *seconds->date* and *date->string*. The temperature is unfortunately in fahrenheit, so we will convert it to Celsius first. Lastly, we combine these signals into a single signal that contains the text we want to show. See listing 3.2 for the full definition of the billboard text written with FrDataFlow constructs.

```
(define (fahrenheit->celsius fahrenheit)
  (quotient (* (- fahrenheit 32) 5) 9))
(define current-temp-celsius
  (lift fahrenheit->celsius current-temp-fahrenheit))
(define current-date
  (lift seconds->date current-unix-timestamp))
(define billboard-label
  (lift
    (lambda (temperature date)
      (string-append "Temperature:~" (number->string temperature) "C°, Date:
                        " (date->string date))))
    current-temp-celsius
    current-date))
```

Listing 3.2: Billboard

This ultimately produces a signal *billboard-label* which will update every time either *current-unix-timestamp* or *current-temp-fahrenheit* produce new values. When this happens, the runtime will recalculate the values of *current-date* and *current-temp-celsius*, which in turn will trigger the update of *billboard-label*. Also note that *billboard-label* will not produce a value until both the current date and the current temperature are known.

3.2.2 Evaluation without the dataflow engine

For the initial version of FrDataFlow, the metacircular interpreter in Racket was extended to natively support signals. Note that this does **not** include any mapping to the dataflow engine yet. How the example program is evaluated and how the signals are kept up to date by this initial version of the runtime will now be described in detail.

Preprocessing

When this program is evaluated, FrDataFlow will dynamically build the signal graph by registering dependent signals as children on each signal. This means that, when a *lift* function is invoked, it will register the newly created signal as a child in every signal that is referenced. Figure 3.1 is a visualization of this graph for the example given in listing 3.2.

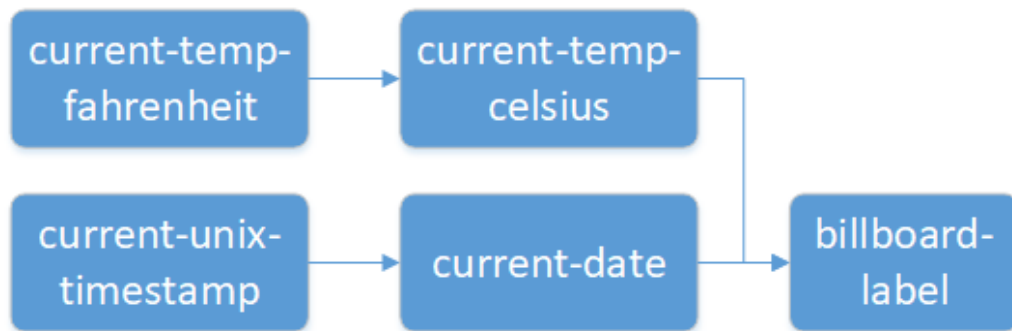


Figure 3.1: The billboard as a signal graph

Secondly, FrDataFlow will topologically sort this graph into a list, which means each signal appears later in the list than the signals it depends on. In other words, the position of a signal in this list indicates that it can be a child to signals that come before it, and that its children must come after it in the list. This allows FrDataFlow to simply loop over this topologically sorted list from start to finish, ensuring that signals are updated in the correct order.

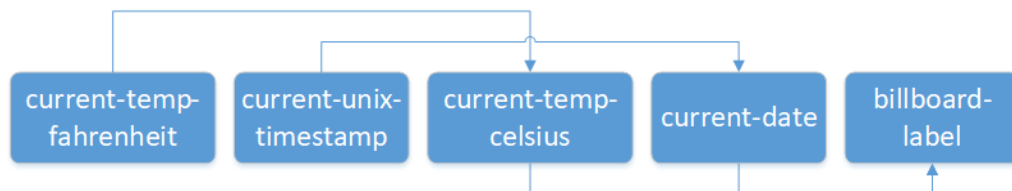


Figure 3.2: The billboard as a topologically sorted list

The update loop

To implement the update behavior, each signal has a boolean flag indicating if it is stale or not. Upon startup of the runtime, FrDataFlow initializes a never ending update loop which loops over the topologically sorted list (as shown in figure 3.2), skipping any signals which are not stale. If it encounters a stale signal, the lambda function that was provided during the creation of the signal will be called with the latest values of the parent signals. The signal is flagged as no longer being stale, and its direct children are flagged as stale immediately. Take for example an update of the current temperature. We start with a situation where the current date and temperature are already known and shown on the billboard, so the state of the signal graph looks like what is shown in figure 3.3. Note that built in signals (i.e. source signals) in FrDataFlow do not have a staleness flag, because they are kept up to date in separate background loops. For example, a standalone infinite loop keeps the *current-seconds* signal up to date by updating its value every second.

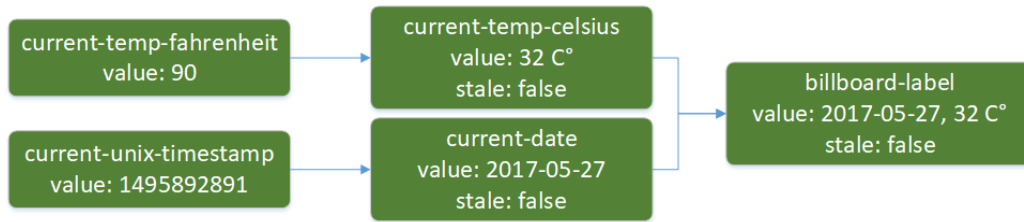


Figure 3.3: The initial state of the billboard. **Green = Not stale**

When the new temperature is observed, the direct children of *current-temp-fahrenheit* are flagged as stale, as shown in figure 3.4.

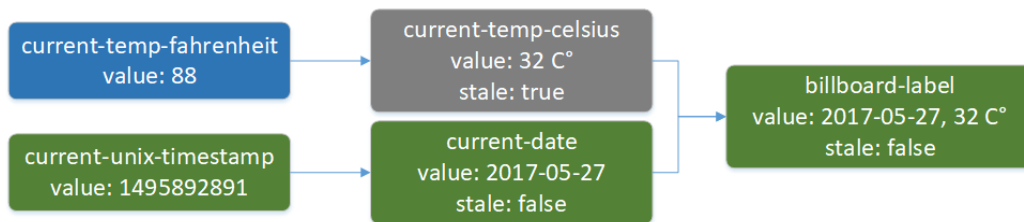


Figure 3.4: A new temperature is emitted by current-temp-fahrenheit. **Blue = New value and not stale**, **Grey = Stale**

The update loop sees that the signal has gone stale, recalculates what its value should be using the value of *current-temp-fahrenheit* and removes the stale flag when its work is done. However, it also immediately flags *billboard-*

label as stale, because it is registered as a child of *current-temp-celsius*, as shown in figure 3.5.

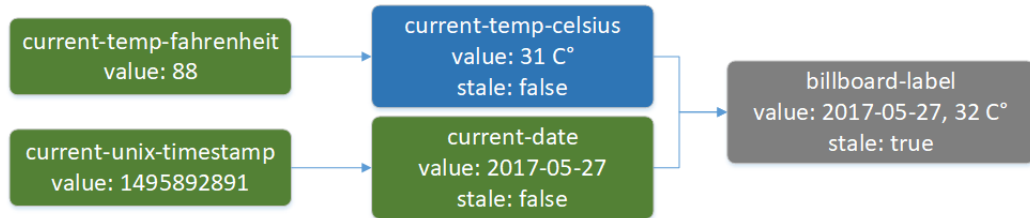


Figure 3.5: *current-temp-celsius* gets recalculated

When the update loop moves further down the topologically sorted list, it sees that *billboard-label* is stale now. It grabs the latest values from *current-temp-celsius* and *current-date* and calls the lambda that was used to create *billboard-label*, setting the stale flag to false when it is done. The final result is shown in figure 3.6. At this point, the update loop starts over again, repeating ad infinitum. Every time, the loop checks if a signal is stale and repeats the update process as described above. If no signals are stale, it keeps looping until that changes.

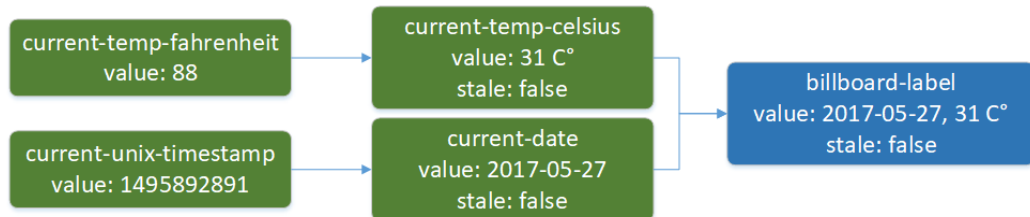


Figure 3.6: *billboard-label* gets recalculated

3.3 Conclusion

In this chapter the reactive language FrDataFlow was presented with samples and diagrams of its implementation. It is built as a metacircular evaluator that takes a core subset of the Racket language and extends it with some reactive concepts. FrDataFlow evaluates these expressions in a simulated runtime that forwards statements to the real underlying Racket implementation.

This language can be used to model reactive data flows and provides a built in update loop to manage the data dependencies between signals. It does this by intelligently looping over the signals while being aware of the dependencies between them. New signals can be created by deriving from other signals and a lift function which produces a single value based on the values of the parent signals.

4

DataFlow Engine

4.1 Introduction

In this chapter, a dataflow engine is presented based on the work detailed in Saey et al. (2017). This engine is designed to support parallel execution of instructions by queuing all operands to instructions and executing these in a scope agnostic way. Tagged token dataflow is an extension to the data flow model where tags are used to distinguish the execution context of tokens, i.e. multiple invocations of the same instruction with different execution contexts, for example calling the same function twice. For the purposes of this thesis, a lightweight version of this engine has been implemented in Racket to facilitate the mapping process from FrDataFlow. Furthermore, we implemented a mapping layer that translates reactive signals to data flow instructions. Even though there were some mismatches that needed to be addressed, reactive programs can now be expressed in FrDataFlow and evaluated atop the dataflow engine.

4.2 Architecture

4.2.1 Components

The dataflow engine consists of four core components:

The token queue

This contains the tokens that need to be processed. A token has a value and meta data about which instruction it needs to be sent to.

The matching memory

This stores the operands per instruction and per context.

The execution unit

This unit will actually invoke the instructions with its operands

The tokenizer

When an instruction has been invoked, its output again is wrapped in a token and put on the token queues, which is done by the tokenizer.

The interaction between these four components can be seen in figure 4.1. What the dataflow engine essentially does is continuously pull tokens from the queue, send it through the matching memory which calls the execution unit. This will invoke the instruction with its operands, pass on the result to the tokenizer which will wrap it in a token and put it on the queue again.

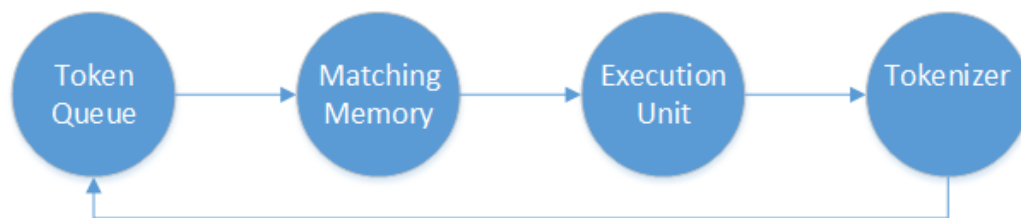


Figure 4.1: The interaction between the four components of the dataflow engine

For clarity, figure 4.2 is repeated here (from the Background chapter) to reiterate the structure of a token.

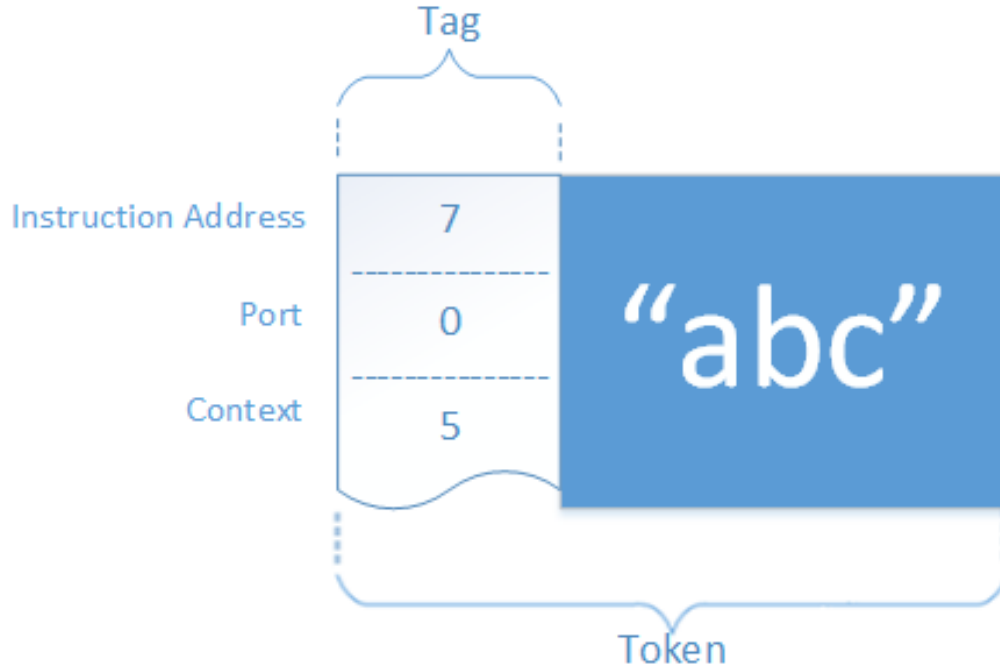


Figure 4.2: A tagged token

4.2.2 Example program with evaluation by the dataflow engine

Take for example a non reactive sample program which computes the average of two numbers, as shown in listing 4.1

```
(define (average x y)
  (/ (+ x y) 2))

(average 2 6)
(average 1 5)
```

Listing 4.1: Computing the average of two numbers

This program computes the average of two numbers twice using different arguments. When this program gets evaluated in the data flow engine, the four arguments and the 2s from the division by two are added to the token queue, containing information about which execution context they belong to

and what should happen with the result. In this example, the 2 and 6 belong to the same execution context, while 1 and 5 will belong to a different one.



Figure 4.3: The corresponding data flow nodes for two calls to the *average* function. Each color represents a different execution context.

In figure 4.3 we see the arguments queued up against the *plus* instruction. Colors indicate the execution context. At this point, the token queue consists of 2, 6, 1, 5 and two 2s. These values are all wrapped in a token containing meta data, i.e. the tag.



Figure 4.4: The results of the *plus* instruction are forwarded to the *divide* instruction

Since all inputs are present for the first invocation, the *plus* instruction gets invoked, as shown in figure 4.4. This adds a new token to the queue: 8. This result will serve as the input of the *divide* instruction. The next thing that happens in figure 4.5 is the same step for 1 and 5.

Note that the tags are very important here, otherwise the engine would not be aware which inputs belong to the same invocation. There is no guarantee that tokens will always be enqueued in the correct order.

In the end, when the *divide* instruction has also completed, its results are pushed into the token queue again, as shown by figure 4.6 and 4.7. This allows further processing of the data, but is outside the scope of this example.



Figure 4.5: The second invocation of the *plus* instruction finishes. All inputs are now present for the *divide* instruction for both execution contexts.



Figure 4.6: The first *divide* instruction is invoked. Its result is put on the token queue again.

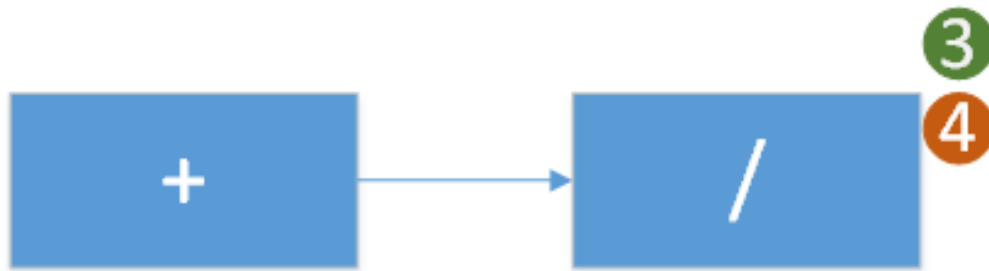


Figure 4.7: The second *divide* instruction is invoked. Its result is put on the token queue again.

To summarize, the dataflow engine processes tokens in the queue, invokes instructions whenever all of its inputs in one execution context are present and re-enqueues the results of those invocations. Separate function calls are distinguished using tags that denote the execution context.

4.3 Mapping of reactive signals to dataflow engine

To execute our reactive signals on the dataflow engine, a translation step was required to simulate the update loop using the described mechanisms in the dataflow engine. When we represent reactive programming as a graph, the nodes are signals while the vertices denote dependencies between them. In the dataflow model, the nodes are instructions and the vertices are data being passed in to them. Therefore, our mapping layers creates data flow nodes for every signal, where the arguments passed in are the parent signal values. When a new value is produced, a token is generated for every child that is subscribed to it.

Taking our example from the Language chapter, we have the following reactive program in figure 4.8.

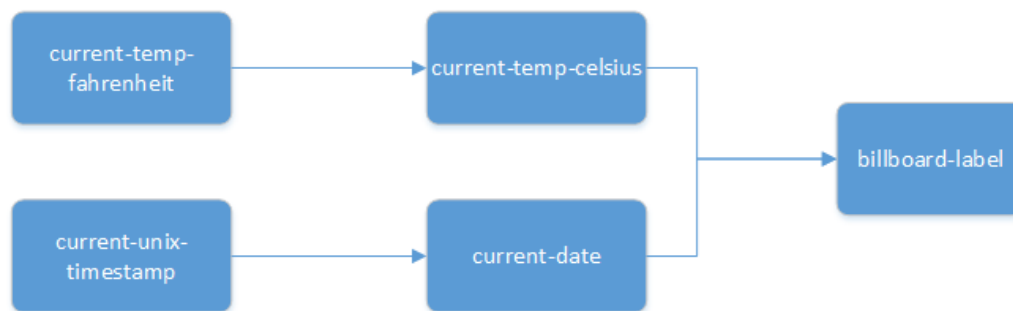


Figure 4.8: The billboard program, but the signals are now data flow nodes

This program behaves exactly the same as the reactive version, the only difference being that it is now running atop a dataflow engine.

4.3.1 Problems encountered

The consumption of arguments in the data flow model

Problem description

In reactive programs, signals with a dependency to two or more parent signals are updated whenever at least one of their parents emits a new value. This boils down to the signal functioning as a mapping of the latest values of its parents. Taking our example, this means that when the current temperature changes, the billboard will update immediately, even if the current date has not changed at all. Similarly, the billboard label updates when the date changes, even if the temperature has not emitted a new value.

In the dataflow engine, an instruction that gets invoked consumes its tokens. This is problematic, because when the current temperature emits a new value, it produces a new token. The dataflow engine will assign this token to the billboard label node, but will keep waiting until the current date produces another token as well before invoking the billboard label again. This means that a signal which is now mapped as a dataflow node does not update until ALL of its parents have emitted new values. This was the biggest mismatch between reactive programming and the data flow model.

Solution description

To simulate the same behavior as reactive signals in the data flow model, we had to figure out a way to retrieve the latest values of other parent signals when a new token arrives. Although each signal has references to all of its parents, it was not advisable to just read out the latest values and generate extra tokens for the other parents as well. This is because a strict requirement of the dataflow model is that nodes must be processed in isolation and cannot access shared state. This would break our potential for parallelism, because it should be presumed that these dataflow nodes live in and are invoked on separate processes and even machines. The whole premise of the data flow model is that nodes are only allowed to access the incoming data from the tokens (and the execution context).

The best option that remained was therefore to simulate new signal emissions for all the source signals (signals without parents that get updated by the runtime outside the update loop) whenever one of the source signals emits. Since there is no language support for filtering, throttling or dynamically manipulating the flow of data through the graph, it can be safely assumed that emitting new values from the source signals will ripple through the entire graph, causing all nodes to be updated in the same order. In practice, this meant that whenever a new temperature is sent out, the current seconds also pushes a value out at the same time. The necessary tokens are put on the queue at the same time, simulating the behavior we originally wanted: whenever one parent emits, the other parents do too.

The evaluation of all instructions in the data flow model

Problem description

The data flow engine is actually designed to execute all instructions found in the code, from the highest level abstractions to the lowest primitive operators. The mapping engine was originally designed this way to completely translate not only the signals, but also the statements found in their call-

backs to data flow nodes. This meant complete buy-in into the dataflow model, in the hopes of achieving maximum parallelism. However, there is a large mismatch between the traditional Racket language and the dataflow engine: returning values. Whenever a procedure is executed in Racket, it must return a value. In the data flow model, this concept does not exist. Output from instructions is simply enqueued and is not accessible outside the dataflow runtime. Secondly, procedures in Racket carry around with them lexically scoped environments, allowing the use of closures to capture variables or other state that is not enclosed in the body of the procedure definition. Again, this violated the core principles of the dataflow engine, which meant we had to scale down the extent to which we made use of the dataflow engine.

Solution description

Instead of completely buying into the dataflow engine, we only used its model to implement our reactive signal graph. When parents emit their values, a callback is executed for the signal to update its value. This callback is actually executed inside the interpreter, using the lexical scope assigned to the procedure, without any knowledge or awareness of its presence inside the dataflow engine. While this has the downside of reduced parallelism, it does improve correctness. Of course, it's impossible to prevent mutating global state or generally causing side effects in these callbacks, but a foolproof mechanism was not the intent of this experiment.

4.4 Conclusion

In this chapter, we presented a tagged token dataflow engine. This is a runtime that enqueues arguments to instructions and executes these in parallel. When interpreting code in the FrDataFlow language, the reactive signals are mapped to dataflow nodes in the engine using a custom mapping layer. During this process, mismatches between reactive programming and the dataflow model are tackled. For example, all source signals emit new values whenever one of them has a new value, to avoid signals waiting in the dataflow engine for inputs from all their parents. Secondly, since return values are not supported in the dataflow engine, the decision was made to only model signals as dataflow instructions and leave the rest of the code execution inside the original interpreter code. In the end, we have a reactive system running atop a parallel dataflow engine, triggering updates in the correct way whenever a parent signal emits.

5

Evaluation

6

Future work and limitations

6.1 Introduction

In this chapter we present the limitations and possible improvements of FrDataFlow. The current implementation is rather limited in its functionality because we wanted to focus on the mapping layer and the possibilities of parallelization using the dataflow engine. However, multiple improvements can still be made. The signal graphs that can be made in FrDataFlow are still static, e.g. it does not allow the dynamic creation of new signals, the filtering of values or just generally manipulating the timing of value propagation. Every signal always has to emit a value for every set of incoming values. While this already allows for a rich set of programs, these manipulations would be necessary to implement any non trivial program using FrDataFlow.

6.2 Dynamically creating signals

One of the common patterns in reactive programming is the dynamic creation of new signals based on some state or external input. Imagine a button which starts a timer. When this button is pressed, a timer should start running and continuously update the screen with the elapsed time.

First of all, this button can be represented as a signal of clicks. Every click is essentially an event, which in terms of reactive programming can be represented as an event being emitted by a signal.

A timer is also a perfect fit for a signal: it is a signal that continuously emits the current elapsed seconds. The tricky part however is that we only want to create this timer when the button is pressed. That means we want to lift the button signal and create a new timer signal only when it is pressed. Maybe another button click stops the timer, or starts a second one, but that is outside the scope of this example.

This pattern of dynamically creating signals is quite common in reactive programming, and unfortunately impossible in FrDataFlow today. A possible improvement would be to enable this, which would mean the signal would have to be added to the topologically sorted signals and be translated to a dataflow node. This would also mean that any existing dataflow nodes upon which this new signal depends would have to be updated to also generate tokens for this new node. Similarly, upon destroying signals, this node and all the references to it would have to be updated. The requirement for a static graph is currently one of the limitations of the dataflow model we use, but it would technically be possible, although it would introduce a considerable amount of bookkeeping overhead.

6.2.1 Filtering

Another common practice is filtering of signals, only letting values through which satisfy a certain predicate. Our current implementation of FrDataFlow models signals as a mapping function which takes a set of inputs and produces a new value for every updated set. Filtering would introduce the possibility of not propagating a value at all if certain criteria are not met. In essence, a signal would no longer provide a lambda that has to return a value, but a lambda that can push values into a type of sink when it wants to. This refactoring would allow for a whole category of powerful constructs, such as taking only the first n values, throttling signals, etc.

An example visualization of the filter function in RxJs can be seen in figure 6.1.

We see at the top a signal which produces a stream of numbers. If we

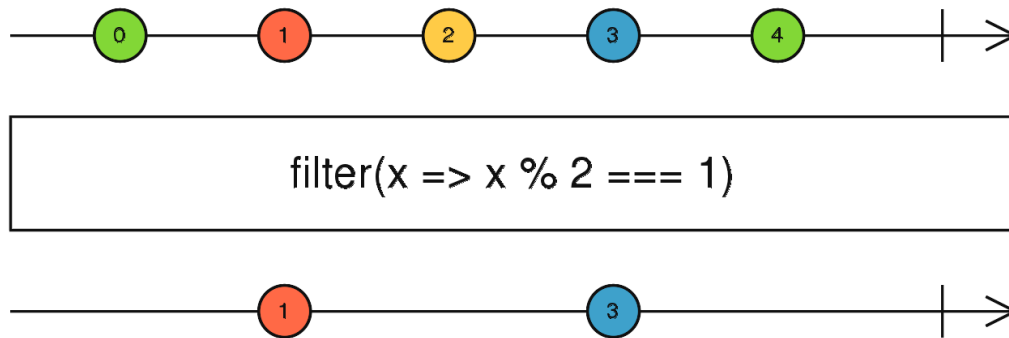


Figure 6.1: A timeline diagram of the *filter* operator in RxJs

create a new signal that filters these numbers using the filter function, we get a new stream of numbers that only contains those that satisfied the predicate. When the number 0 is pushed into the signal lambda, it does not propagate it into the sink of the child signal, which means the value does not go through.

To implement this pattern in our mapping layer, we would have to ensure that dataflow nodes don't always have to produce new tokens when they are invoked, and a way for nodes to indicate when this should happen or not. However, there is no technical reason why the dataflow engine should not be able to handle this: it is simply the presence of tokens that determines which nodes are invoked, so not emitting these tokens would essentially implement the filtering behavior we have described.

6.3 Conclusion

In this chapter we have shown how FrDataFlow is still a basic language that does not support some powerful concepts such as the dynamic creation of signals or the filtering of values. If these concepts were to be introduced, they would allow for an implementation of most of the techniques commonly found in other reactive libraries or languages.

This initial version of FrDataFlow has focused mostly on the practical mapping layer from reactive programming to the dataflow model. There are however no immediate technical shortcomings that should prevent us from implementing the modifications presented in this chapter.

7

Related work

7.1 Introduction

In this chapter, we introduce a few related works and papers that align with concepts described in this dissertation. The language Elm for example describes in detail the challenges of functional reactive programming, tackling many of the same problems and describing similar solutions as encountered in FrDataFlow. Despite the similarities, the difference in platforms (Elm has to adhere to the limitations of the JavaScript execution engine in browsers, while FrDataFlow is constrained to the limits of the Racket runtime) has a significant impact on the potential to parallelization. Another source of inspiration was FrTime, a DrScheme implementation of reactive patterns with some subtle yet powerful differences. Its focus lies more on the implicit transformation of regular programs to reactive programs, while FrDataFlow remains very explicit about the existence of signals.

Finally, we discuss the virtual machine design of the dataflow engine that FrDataFlow uses to execute its instructions. This VM builds on the principles of tagged token dataflow and provides a platform upon which the reactive nodes in FrDataFlow are scheduled and executed.

7.2 Reactive programming

7.2.1 Elm

In 2012, Evan Czaplicki wrote his dissertation on Elm (Czaplicki, 2012), a functional reactive programming language for the web. In this paper, he presents a new language *Elm* that supports concurrent functional programming for the web. Elm is compiled down to JavaScript using a compiler written in Haskell and promises to produce no runtime errors when everything compiles. Most of the reactive programming concepts in FrDataFlow were actually heavily inspired by Elm, such as *signals* and the *lift* function. Another concept inspired by Elm is signal graphs: reactive primitives as nodes and value flows as edges. Of course, source signals are a bit different in the web. For example, Elm provides source signals that represent mouse clicks, mouse positions or generally any kind of DOM event which is captured by the standard library. In the isolated, experimental little world of FrDataFlow, primitive source signals other than the current time were hard to come by.

Order of events

Looking at a signal graph, it is easy to imagine the parallel execution of the nodes. However, the order of events is very important. Take for example the signal graph shown in figure 7.1.

If a new value appears for *current-milliseconds* (the number of milliseconds since 1 Jan 1970), we compute the current date and current time separately, to combine these two data points into a single label called *timestamp-label*. Imagine now that the computation of the current time takes significantly longer than the computation of the current date. In fact, we can contemplate that the derivation of the time would actually need to derive the date first, and then use the remaining milliseconds from midnight to determine the time. Of course, depending on the date and the timezone, this could result in different clock times. This leads us to conclude that the calculation of *current-time* is slower than *current-date*.

Now imagine that these computations are run in parallel and that their outputs are piped to the timestamp label as fast as the hardware allows it. If the date is so much faster to process, it becomes possible that the timestamp label starts receiving more than one *current-date* for every *current-time*, leading to situations where the date and time that are shown do not both trace back to the same value of *current-milliseconds* they were derived from.

In Elm, this problem was fixed by the introduction of a global event

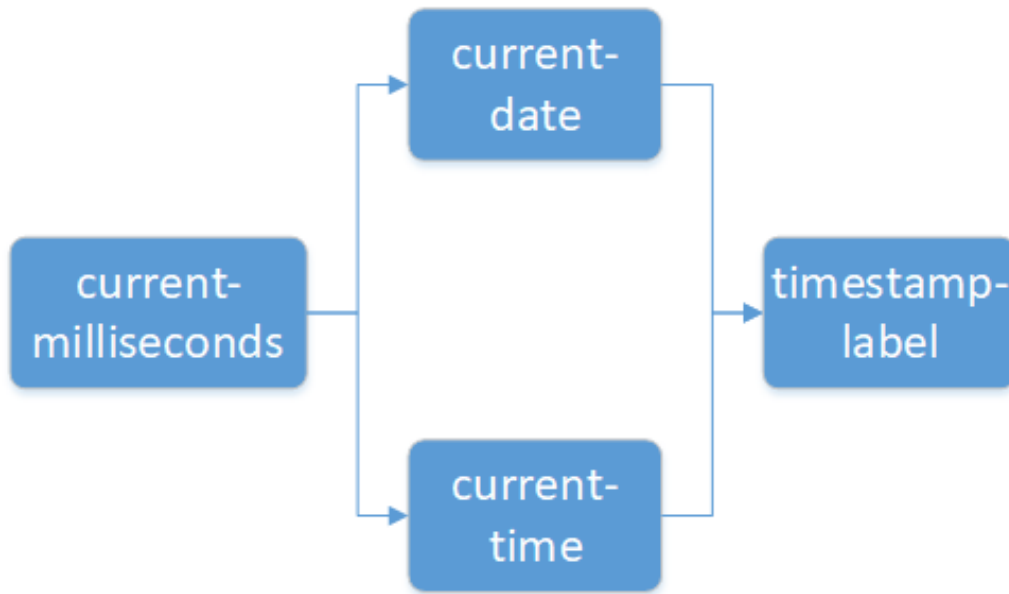


Figure 7.1: The current timestamp is based on two different computations of *current-milliseconds*

dispatcher, which imposes a few constraints on the signal graph update loop:

- Signals with more than one parent must wait for all parents to produce a value before recomputation happens. This is the same approach taken in FrDataFlow.
- When source signals emit a new value, all nodes receive that event and pass forward a "nothing changed" notification. In FrDataFlow, the approach is to simply push the current value.

Parallelization

In Elm, the constraints of the platform are slightly different. The JavaScript runtime does not really provide native parallelization¹, so while the language itself could perfectly support parallelism, unfortunately its platform does not.

¹Web workers exist, which were designed offload work in background threads. However, they come with two rather expensive limitations, the first being that messages between workers must be primitive data types, so there is no support for passing along functions with closures, only simple messages such as strings or numbers. Secondly, these web workers directly map to operating system threads, making them quite expensive to set up and tear down. The end result is that these workers are not a good fit for the small, atomic computations we are dealing with in reactive nodes.

Elm does provide some workarounds for when the synchronous nature of its node processing causes performance bottlenecks, namely asynchronous updates. This keyword decouples a subset of the graph from the main graph and allows it to update independently, avoiding the situation where it would have to wait for long running synchronous updates. However, this is still purely a data correctness and timing feature and unfortunately does not tackle the lack of parallelization support.

In fact, the paper does mention a possible solution to run Elm programs in parallel: if closures can be avoided somehow (for example by compiling to an intermediate language which explicitly lists the used captured variables) and if functions are passed as strings (and then dynamically interpreted inside the workers), web workers could technically provide a parallel execution mechanism. It was not considered worthwhile though, because of the amount of overhead to orchestrate this and the possible security ramifications.

7.2.2 FrTime

Another project that is closely related to FrDataFlow is *FrTime*. This is a reactive programming language that implicitly implements signals for primitive operators. The idea is that applications written in regular Scheme could be switched over to FrTime to introduce reactive programming without having to rewrite the code. Contrary to FrDataFlow, expressions in FrTime do not require explicit use of the lift operator, but are implicitly used when any of the primitive operators are used. For full effect, FrTime provides a REPL (Read Eval Print Loop) console which takes expressions and immediately prints the result. There is an extra feature though: values which are signals keep getting updated in the history. When for example the plus operator is applied to a fixed number and the current seconds, this creates a signal which continuously updates with the result, inside the console. Rather than evaluating the expression and returning a signal like in FrDataFlow, FrTime immediately returns a value and keeps updating that value, even inside the REPL history.

```
> seconds
1496651429
> (even? seconds)
#f
> (+ 10 seconds)
1496651439
```

Listing 7.1: REPL in FrTime

See the listings 7.1 and 7.2. In the first sample, some commands are entered into the REPL and their output is shown below each command.

Note that the listing 7.2 simply shows exactly the same screen from listing 7.1 but 5 seconds later. It is not revealed to the user that the expressions he is using are built with signals that update in the background. It only becomes clear, as time goes by, that these values automatically update in the REPL.

```
> seconds
1496651434
> (even? seconds)
#t
> (+ 10 seconds)
1496651444
```

Listing 7.2: REPL in FrTime, 5 seconds later

Push-driven evaluation

A major difference between FrTime and FrDataFlow is its update model. FrDataFlow implements what is called a push driven evaluation. This means that parent signals - or producers, as FrTime calls them - have references to their children (dependents in FrTime). When a parent signal gets updated, it can follow along the edges of its dependencies to ripple the change forward in the graph. Since child signals do not hold references to their parents, closures are used during the signal construction process to capture references to these parents in the callback procedure.

In FrDataFlow, callbacks and closures are not an essential part of the update mechanism. All signals are stored in a topologically sorted graph, where each signal can access its parents and children. When a new value propagates through the graph, the update loop simply grabs the necessary information from the parent signals to provide to the child.

FrTime's callback model in combination with their queue based update algorithm actually comes with a string of performance problems, which they try to address by *lowering* Burchett et al. (2007) their operators, essentially collapsing multiple operations into one to reduce overhead and to minimize the graph size. Although this considerably improves execution time, it unfortunately also reduces parallelization opportunities by growing the size of one signal node. In FrDataFlow, no such optimizations are considered.

7.3 Dataflow Model

7.3.1 Virtual machine design for the execution of languages on dataflow machines

In Saey et al. (2017), a virtual machine design is presented to execute instructions on dataflow machines. This VM tries to offer a framework in which the principles of tagged token dataflow are strictly adhered to, while allowing full access to the tokens and execution context from within a single dataflow node, i.e. an operation. This allows the creation of operations which can manipulate the destination they send data to, enabling conditional statements and dynamic flow in general. To enable closures, operations also receive access to the active working memory of the current context. In short, this design is intended to support all common flows expected in a high level language, such as function calls, closures, recursion, exception handling, etc.

A Python implementation of this design is DVM (Saey et al., 2014), by the same author. This virtual machine applies the rules and principles described earlier and provides a platform upon which dataflow instructions can be run in a custom language called *DIS*.

For FrDataFlow, a lightweight variant of this engine has been implemented in Racket, to avoid the overhead of having to communicate between Racket and Python. Instead of interpreting DIS commands, the dataflow primitives are modeled as Racket tuples or values and natively fed into the engine.

7.4 Conclusion

In this chapter, we presented other research that closely relates to and strongly inspired FrDataFlow. Elm, the web programming language with a strong focus on FRP, introduced many of the same concepts also applied in FrDataFlow. FrTime has similar semantics, but chose to hide its internals more from the end user. For the execution of our signal nodes, we applied the virtual machine design of DVM in Racket to map our reactive nodes as dataflow operations.

8

Conclusion



Your Appendix

Bibliography

- Abelson, H., Sussman, G. J., & Sussman, J. (1999). *Structure and Interpretation of Computer Programs* (Second ed.). London, UK, UK: McGraw-Hill Book Company.
- Arvind, K., & Nikhil, R. S. (1990, March). Executing a Program on the MIT Tagged-Token Dataflow Architecture. *IEEE Trans. Comput.*, 39(3), 300–318. doi: 10.1109/12.48862
- Burchett, K., Cooper, G. H., & Krishnamurthi, S. (2007). Lowering: A Static Optimization Technique for Transparent Functional Reactivity. In *Proceedings of the 2007 ACM SIGPLAN Symposium on Partial Evaluation and Semantics-based Program Manipulation* (pp. 71–80). New York, NY, USA: ACM. doi: 10.1145/1244381.1244393
- Cooper, G. H., & Krishnamurthi, S. (2006, March). Embedding Dynamic Dataflow in a Call-by-Value Language. In *Programming Languages and Systems* (pp. 294–308). Springer, Berlin, Heidelberg. doi: 10.1007/11693024_20
- Czaplicki, E. (2012). *Elm: Concurrent FRP for functional GUIs*.
- Harel, D., & Pnueli, A. (1985). On the Development of Reactive Systems. In *Logics and Models of Concurrent Systems* (pp. 477–498). Springer, Berlin, Heidelberg. doi: 10.1007/978-3-642-82453-1_17
- Johnston, W. M., Hanna, J. R. P., & Millar, R. J. (2004, March). Advances in Dataflow Programming Languages. *ACM Comput. Surv.*, 36(1), 1–34. doi: 10.1145/1013208.1013209
- Observable / RxJS API Document*. (2017, June). <http://reactivex.io/rxjs/class/es6/Observable.js~Observable.html>.
- Peterson, J., Trifonov, V., & Serjantov, A. (2000, January). Parallel Functional Reactive Programming. In *Practical Aspects of Declarative*

- Languages* (pp. 16–31). Springer, Berlin, Heidelberg. doi: 10.1007/3-540-46584-7_2
- Saey, M., De Koster, J., B. Sartor, J., & De Meuter, W. (2017). An Extensible Virtual Machine Design for the Execution of High-level Languages on Tagged-token Dataflow Machines.
- Saey, M., Prof. Dr. De Meuter, W., Dr. Vandriessche, Y., & Dr. Marr, S. (2014). *Towards a Full Dataflow Stack: A Research Infrastructure for the Exploration of Dataflow Execution Models* (masters). Free University Brussels.
- Veen, A. H. (1986, December). Dataflow Machine Architecture. *ACM Comput. Surv.*, 18(4), 365–396. doi: 10.1145/27633.28055