Elm-style Functional Reactive Programming demystified

Sergei Winitzki

SF Types, Theorems, and Programming Languages

April 13, 2015

What is "functional reactive programming"

FRP has little to do with...

- multithreading, message-passing concurrency, "actors"
- distributed computing on massively parallel load-balanced clusters
- ma/reduce, the "reactive manifesto", (*insert latest fad here*)...

FRP is...

- **pure functions using temporal types as primitives**
  - (temporal type $\approx$ lazy stream of events)

Transformational vs. reactive programs

Transformational programs	**Reactive** programs
example: `pdflatex elm_talk.tex`	**example**: any GUI program, OS
start, run, then stop	keep running indefinitely
read some input, write some output	wait for signals, send messages
execution: sequential, parallel	"main run loop" + concurrency
difficulty: algorithms	signal/response sequences
specification: classical logic?	classical temporal logic?
verification: proof of correctness?	model checking?
synthesis: extract code from proof?	temporal logic synthesis?
type theory: intuitionistic logic	intuitionistic *temporal* logic

Difficulties in reactive programming

- Input signals may come at unpredictable times
  - Imperative updates are difficult to keep in the correct order
  - Flow of events becomes difficult to understand
- Asynchronous (out-of-order) callback logic becomes opaque
- Inverted control (“the system will call you”) obscures the flow of data
- Some concurrency is usually required (e.g. background tasks)
  - Explicit multithreaded code is hard to write and debug

Motivation for FRP

- Reactive programs work on **infinite sequences** of input/output values
- Main idea: make infinite sequences implicit, as a new "temporal" type
  - (Elm) `Signal` α — an infinite sequence of values of type α
  - alternatively, a value of type α that "changes with time"
- Reactive programs are **pure functions**
  - a GUI is a pure function of type `Signal Inputs` $\to$ `Signal View`
  - a Web server is a pure function `Signal Request` $\to$ `Signal Response`
  - all mutation is **implicit** in `Signal` α; our code is 100% immutable
    - ★ instead of updating an `x:Int`, we define a value of type `Signal Int`
  - asynchronous behavior is **implicit**: our code has no callbacks
  - concurrency / parallelism is **implicit**
    - ★ the runtime needs to provide the required scheduling of events

Elm in a nutshell

- Elm is a pure polymorphic λ-calculus with products and sums
- **Temporal type** $\Sigma\alpha$ — a time-dependent value of **ordinary** type α
- Temporal primitive terms in core Elm:

  constant: $\alpha \to \Sigma\alpha$
  map2: $(\alpha \to \beta \to \gamma) \to \Sigma\alpha \to \Sigma\beta \to \Sigma\gamma$
  foldp: $(\alpha \to \beta \to \beta) \to \beta \to \Sigma\alpha \to \Sigma\beta$
  async: $\Sigma\alpha \to \Sigma\alpha$

- **No nested** temporal types: `constant (constant x)` is ill-typed!
- Domain-specific primitive types: `Bool`, `Int`, `Float`, `String`, `View`
- Standard library with data structures, HTML, HTTP, JSON, ...
  - ...and signals `Time.every`, `Mouse.position`, `Window.dimensions`, ...
- Try Elm online at http://elm-lang.org/try

`Elm` type judgments

- Non-temporal values are used as in polymorphic λ-calculus

$$\frac{\Gamma, (x : \alpha) \vdash e : \beta}{\Gamma \vdash (\lambda x . e) : \alpha \to \beta}\ \text{Lambda} \qquad \frac{\Gamma \vdash e_1 : \alpha \to \beta \quad \Gamma \vdash e_2 : \alpha}{\Gamma \vdash e_1\, e_2 : \beta}\ \text{Apply}$$

- Temporal values have special types of the form $\Sigma\tau$
  - Here, type variables α, β,... **cannot be** of the form $\Sigma\tau$:

$$\frac{\Gamma \vdash e : \alpha}{\Gamma \vdash (\text{constant}\ e) : \Sigma\alpha}\ \text{Constant}$$

$$\frac{\Gamma \vdash m : \alpha \to \beta \to \gamma \quad \Gamma \vdash p : \Sigma\alpha \quad \Gamma \vdash q : \Sigma\beta}{\Gamma \vdash \text{map2}\ m\ p\ q : \Sigma\gamma}\ \text{Map2}$$

$$\frac{\Gamma \vdash u : \alpha \to \beta \to \beta \quad \Gamma \vdash e : \beta \quad \Gamma \vdash s : \Sigma\alpha}{\Gamma \vdash (\text{foldp}\ u\ e\ s) : \Sigma\beta}\ \text{FoldP}$$

- A value of type $\Sigma\Sigma\alpha$ is impossible in a well-typed expression!

*Elm operational semantics

- Non-temporal expressions are evaluated **eagerly** in pure λ-calculus
- The runtime will cache all values to avoid recomputation

*Elm operational semantics

- Example
- *I work after the boss comes by and until the phone rings*:

```
let after_until w (b,r) = (w or b) and not r in
  foldp after_until false (boss, phone)
```

GUI building: "Hello, world" in Elm

- The value called main will be visualized by the runtime

```
import Graphics.Element (..)
import Text (..)
import Signal (..)

text : Element
text = plainText "Hello, World!"

main : Signal Element
main = constant text
```

Typical program structure in Elm

- A state machine:

  `update: Command → State → State`

- A rendering function:

  `draw: State → View`

- A manager that merges the required input signals into one:
  - may use `Mouse`, `Keyboard`, `Time`, `HTML` stuff, etc.

  `merge_inputs: Signal Command`

- Program boilerplate:

```
init_state : State
main : Signal View
main = map draw $ foldp update init_state merge_inputs
```

*Asynchrony and concurrency in `Elm`

- Long-running computations will delay signal updates
- Solutions: 1. Caching of all results. 2. Using `async`

Some limitations of `Elm`-style FRP

- No recursion of any kind
- No higher-order signals: $\Sigma(\Sigma\alpha)$ is disallowed by the type system
- No distinction between continuous time and discrete time
- The signal processing logic is fully specified statically
- No constructors for signals
    - Impossible to implement the “dining philosophers”!

`Elm` cannot do “dining philosophers”

- “Dining philosophers”: need to simulate a philosopher who thinks for a random time and then eats for a random time
- Can a signal value `p : Signal Unit` update at random times?
  - No! There is no way to delay the update times of a signal **at runtime**.
  - `Time.delay: Int`$\to \Sigma\alpha \to \Sigma\alpha$ cannot use a time-varying delay value
  - `Time.every: Int`$\to \Sigma$`Int` also requires a fixed delay value
  - Cannot lift `Time.every` into Σ`Int`$\to \Sigma\Sigma$`Int` to achieve variable delay

The JavaScript backend for `Elm`

Features:

- Good support for HTML/CSS, HTTP requests, JSON
- Good performance of caching views
- Transparent, declarative modeling of data

Limitations:

- No implementation for `async` and no concurrency
- Ordinary recursion may generate invalid JavaScript
- The lack of recursive signals is compensated by *ad hoc* primitives

*Possible extensions

- Recursive definitions for signals
- Monadic signal combinators
- Signal constructors

Part 2. Temporal logic and FRP

This part of the talk is optional.

- Reminder (Curry-Howard): temporal logic expressions will be our types
- We only need to control the **order** of events: no “hard real-time”
- How to understand temporal logic:
  - classical propositional logic ≈ Boolean arithmetic
  - intuitionistic propositional logic ≈ same but without **true** / **false** dichotomy
  - (linear-time) temporal logic ≈ Boolean arithmetic for *infinite sequences*
  - intuitionistic temporal logic ≈ same but without **true** / **false** dichotomy
- In other words:
  - a temporal type represents a **single infinite sequence** of values

Boolean arithmetic: notation

- Classical propositional (Boolean) logic: T, F, $a \vee b$, $a \wedge b$, $\neg a$, $a \rightarrow b$
- A notation better adapted to school-level arithmetic: 1, 0, $a+b$, ab, a'
- The only "new rule" is $1+1=1$
- Define $a \rightarrow b = a' + b$
- Some identities:

$$\begin{gathered}0a=0, \quad 1a=a, \quad a+0=a, \quad a+1=1, \\ a+a=a, \quad aa=a, \quad a+a'=1, \quad aa'=0, \\ (a+b)'=a'b', \quad (ab)'=a'+b', \quad \left(a'\right)'=a \\ a\left(b+c\right)=ab+ac, \quad \left(a+b\right)\left(a+c\right)=a+bc\end{gathered}$$

Boolean arithmetic: example

Of the three suspects A, B, C, only one is guilty of a crime.
Suspect A says: "B did it". Suspect B says: "C is innocent."
The guilty one is lying, the innocent ones tell the truth.

$$\phi = \left(ab'c' + a'bc' + a'b'c\right)\left(a'b + ab'\right)\left(b'c' + bc\right)$$

Simplify: expand the brackets, omit aa', bb', cc', replace $aa = a$ etc.:

$$\phi = ab'c' + 0 + 0 = ab'c'$$

The guilty one is A.

Propositional linear-time temporal logic (LTL)

- We work with *infinite boolean sequences* ("linear time")
  Boolean operations:

$$a = [a_0, a_1, a_2, ...]\,; \quad b = [b_0, b_1, b_2, ...]\,;$$
$$a + b = [a_0 + b_0, a_1 + b_1, ...]\,;\ a' = \left[a'_0, a'_1, ...\right]\,;\ ab = [a_0 b_0, a_1 b_1, ...]$$

  Temporal operations:

$$\begin{aligned} &\text{(Next)} && \mathbf{N}a = [a_1, a_2, ...] \\ &\text{(Sometimes)} && \mathbf{F}a = [a_0 + a_1 + a_2 + ...,\ a_1 + a_2 + ...,\ ...] \\ &\text{(Always)} && \mathbf{G}a = [a_0 a_1 a_2 a_3 ...,\ a_1 a_2 a_3 ...,\ a_2 a_3 ...,\ ...] \end{aligned}$$

  Other notation (from modal logic):

$$\mathbf{N}a \equiv \bigcirc a;\ \mathbf{F}a \equiv \Diamond a;\ \mathbf{G}a \equiv \Box a$$

- Weak Until: $p\mathbf{U}q =$ "p holds from now on until q first becomes true"

$$p\mathbf{U}q = q + p\mathbf{N}\left(q + p\mathbf{N}\left(q + ...\right)\right)$$

Temporal logic redux

- LTL as type theory: do we use $\mathbf{N}\alpha$, $\mathbf{F}\alpha$, $\mathbf{G}\alpha$ as new types?
- Are they to be functors, monads, ...?
- What is the operational semantics? (I.e., how to compile this?)

Interpreting values typed by LTL

- What does it mean to have a value x of type, say, $\mathbf{G}(\alpha \to \alpha\mathbf{U}\beta)$??
    - $x : \mathbf{N}\alpha$ means that $x : \alpha$ will be available *only* at the *next* time tick (x is a **deferred value** of type α)
    - $x : \mathbf{F}\alpha$ means that $x : \alpha$ will be available at *some* future tick(s) (x is an **event** of type α)
    - $x : \mathbf{G}\alpha$ means that a (different) value $x : \alpha$ is available at *every* tick (x is an **infinite stream** of type α)
    - $x : \alpha\mathbf{U}\beta$ means a **finite stream** of α that may end with a β
- Some *temporal axioms* of intuitionistic LTL:

$$
\begin{aligned}
&\text{(deferred apply)} \quad \mathbf{N}\,(\alpha \to \beta) \to (\mathbf{N}\alpha \to \mathbf{N}\beta)\,;\\
&\text{(streamed apply)} \quad \mathbf{G}\,(\alpha \to \beta) \to (\mathbf{G}\alpha \to \mathbf{G}\beta)\,;\\
&\text{(generate a stream)} \quad \mathbf{G}\,(\alpha \to \mathbf{N}\alpha) \to (\alpha \to \mathbf{G}\alpha)\,;\\
&\text{(read infinite stream)} \quad \mathbf{G}\alpha \to \alpha\mathbf{N}(\mathbf{G}\alpha)\\
&\text{(read finite stream)} \quad \alpha\mathbf{U}\beta \to \beta + \alpha\mathbf{N}(\alpha\mathbf{U}\beta)
\end{aligned}
$$

Elm as an FRP language

- λ-calculus with type $\mathbf{G}\alpha$, primitives map2, foldp, async

  $$\begin{aligned}
  \texttt{map2} &: (\alpha \to \beta \to \gamma) \to \mathbf{G}\alpha \to \mathbf{G}\beta \to \mathbf{G}\gamma \\
  \texttt{foldp} &: (\alpha \to \beta \to \beta) \to \beta \to \mathbf{G}\alpha \to \mathbf{G}\beta \\
  \texttt{async} &: \mathbf{G}\alpha \to \mathbf{G}\alpha
  \end{aligned}$$

- (map2 makes **G** an applicative functor)
- async is a special *scheduling instruction*
- Limitations:
  - Cannot have a type $\mathbf{G}(\mathbf{G}\alpha)$, also not using **N** or **F**
  - Cannot construct temporal values by hand
  - This language is an *incomplete* Curry-Howard image of LTL!

Conclusions and outlook

- There are some languages that implement FRP in various *ad hoc* ways
- The ideal is not (yet) reached

*Conclusions and outlook

- The ideal is not (yet) reached

Abstract

In my day job, most bugs come from imperatively implemented reactive programs. FRP is a declarative approach that promises to solve my problems.

FRP can be defined as a λ-calculus with types given by a propositional intuitionistic linear-time temporal logic (LTL). Although the `Elm` language uses only a subset of LTL, it achieves high expressivity for GUI programming. I discuss the current limitations of `Elm` and outline some possible extensions. I will also briefly review the motivations behind and the connections between temporal logic, FRP, and `Elm`.

My talk will be understandable to anyone familiar with Curry-Howard and functional programming. (The first part of the talk does not rely on temporal logic or Curry-Howard.)

Suggested reading

E. Czaplicki, S. Chong. Asynchronous FRP for GUIs. (2013)
E. Czaplicki. Concurrent FRP for functional GUI (2012).
M. F. Dam. Lectures on temporal logic. Slides: Syntax and semantics of LTL, A Hilbert-style proof system for LTL
E. Bainomugisha, et al. A survey of reactive programming (2013).
W. Jeltsch. Temporal logic with Until, Functional Reactive Programming with processes, and concrete process categories. (2013).
A. Jeffrey. LTL types FRP. (2012).
D. Marchignoli. Natural deduction systems for temporal logic. (2002). – See Chapter 2 for a natural deduction system for modal and temporal logics.