Implementing and Optimising Functional Reactive Programming

*Big-O Meetup, 14 Dec. 2016*

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Key idea: Don’t program one-time-step-at-a-time, but describe an evolving entity as whole.
Functional Reactive Programming (1)

- Key idea: Don’t program one-time-step-at-a-time, but describe an evolving entity as whole.
- FRP originated in Conal Elliott and Paul Hudak’s work on Functional Reactive Animation (Fran). (Highly cited 1997 ICFP paper; ICFP award for most influential paper in 2007.)
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FRP has evolved in a number of directions and into different concrete implementations.
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FRP has evolved in a number of directions and into different concrete implementations.

This talk considers Yampa: an arrows-based FRP system embedded in Haskell.
Yampa: pure and principled implementation in a pure setting.
Functional Reactive Programming (2)

- Yampa: pure and principled implementation in a pure setting.
- In particular: many algebraic laws hold.
Yampa: pure and principled implementation in a pure setting.

In particular: many algebraic laws hold.

These guide the implementation and optimisations: a theme of this talk.
FRP Applications (1)

Some domains where FRP or FRP-inspired approaches have been used:

- Robotics
- Vision
- Sound synthesis
- GUls
- Virtual Reality Environments
- Games
- Distributed Event-based Systems
FRP Applications (2)

Example: Breakout in Yampa (and SDL) on a tablet:
Take-home Game!

Or download one for free to your Android device!

Play Store: Pang-a-lambda (Keera Studios)
Arrows?

- A *notion of computation*: function-like entities that may have effects.
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- Examples:
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  - Pure functions
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  - Any function of the form \( a \rightarrow M b \) where \( M \) is a monad (the “Kleisli construction”).
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  - Pure functions
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- A number of *algebraic laws* must be satisfied: we will come back to those.
Arrows?

- A notion of computation: function-like entities that may have effects.
- Examples:
  - Pure functions
  - “Functions” with internal state
  - Conditional probabilities
  - Any function of the form $a \rightarrow M b$ where $M$ is a monad (the “Kleisli construction”).
- A number of algebraic laws must be satisfied: we will come back to those.
- Arrows due to Prof. John Hughes.
The Arrow framework (1)

Types signatures for some arrow $F$:

- $\text{arr} :: (a \rightarrow b) \rightarrow F\ a\ b$
- $\text{arr} :: (a \rightarrow b) \rightarrow F\ a\ b$
- $\text{first} :: F\ a\ b \rightarrow F\ (a, c)\ (b, c)$
- $\text{loop} :: F\ (a, c)\ (b, c) \rightarrow F\ a\ b$
The Arrow framework (2)

Some derived combinators:

\[ f \text{ *** } g \]
\[ f \&\&\& g \]

\[(***) :: F \text{ a b } \rightarrow F \text{ c d } \rightarrow F \text{ (a,c) (b,d)}\]
\n\n\n\[ (\&\&\&) :: F \text{ a b } \rightarrow F \text{ a c } \rightarrow F \text{ a (b,c)}\]
Constructing a network
Constructing a network

![Diagram with labeled nodes and arrows indicating a loop]

- first
- f
- g
- h

> > >

> > >

> > >

***
Constructing a network

Tedious way to program?
Constructing a network

Tedious way to program?

Yes, can be. But syntactic support can be provided.
Key FRP Features

Combines conceptual simplicity of the *synchronous data flow* approach with the flexibility and abstraction power of higher-order functional programming:

- Synchronous
- First class temporal abstractions
- Hybrid: mixed continuous and discrete time
- Dynamic system structure
Key FRP Features

Combines conceptual simplicity of the *synchronous data flow* approach with the flexibility and abstraction power of higher-order functional programming:

- Synchronous
- First class temporal abstractions
- Hybrid: mixed continuous and discrete time
- Dynamic system structure

(But not everything labelled “FRP” supports them all.)
Yampa (1)
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- Key concepts:
  - *Signals*: time-varying values
  - *Signal Functions*: functions on signals
  - *Switching* between signal functions
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- Key concepts:
  - **Signals**: time-varying values
  - **Signal Functions**: functions on signals
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- Programming model:
Yampa (2)

- Signal functions are the primary notion: first-class entities.
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Yampa (2)

- Signal functions are the primary notion: first-class entities.
- Signals are a secondary notion: only exist indirectly.
- This is a key aspect allowing for a fundamentally simple, pure, implementation.
- Of course, FRP does not have to be implemented purely, and many FRP implementations are indeed not pure. But keeping it pure makes it easier to get correct. Good for reference if nothing else.
Yampa?
Yampa?

Yet Another Mostly Pointless Acronym?
Yampa?

Yet Another Mostly Pointless Acronym?

Yampa is a river with long calmly flowing sections and abrupt whitewater transitions in between.

A good metaphor for hybrid systems!
Signal Functions

\[ x \rightarrow f \rightarrow y \]
Signal Functions

Intuition:
Signal Functions

Intuition:

\[ \text{Time} \approx \mathbb{R} \]
Signal Functions

Intuition:

Time $\approx \mathbb{R}$
Signal $a \approx \text{Time} \rightarrow a$
x :: Signal $T_1$
y :: Signal $T_2$
Signal Functions

Intuition:

\[
\text{Time} \approx \mathbb{R} \\
\text{Signal } a \approx \text{Time} \rightarrow a \\
x :: \text{Signal } T1 \\
y :: \text{Signal } T2 \\
\text{SF } a \ b \approx \text{Signal } a \rightarrow \text{Signal } b \\
f :: \text{SF } T1 \ T2
\]
Signal Functions

Intuition:

\[
\begin{align*}
\text{Time} & \approx \mathbb{R} \\
\text{Signal } a & \approx \text{Time } \rightarrow a \\
x & :: \text{Signal } T_1 \\
y & :: \text{Signal } T_2 \\
\text{SF } a \ b & \approx \text{Signal } a \rightarrow \text{Signal } b \\
f & :: \text{SF } T_1 \ T_2
\end{align*}
\]

Additionally, \textit{causality} required: output at time \( t \) must be determined by input on interval \([0, t]\).
Signal Functions and State

Alternative view:
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Signal functions can encapsulate *state*.

\[ \text{state}(t) \text{ summarizes input history } x(t'), \ t' \in [0, t]. \]
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\[ \text{state}(t) \text{ summarizes input history } x(t'), t' \in [0, t]. \]

From this perspective, signal functions are:

- **stateful** if \( y(t) \) depends on \( x(t) \) and \( \text{state}(t) \)
- **stateless** if \( y(t) \) depends only on \( x(t) \)
Signal Functions and State

Alternative view:

Signal functions can encapsulate \textit{state}.

\[ state(t) \text{ summarizes input history } x(t'), \ t' \in [0, t]. \]

From this perspective, signal functions are:

- \textit{stateful} if \( y(t) \) depends on \( x(t) \) and \( state(t) \)
- \textit{stateless} if \( y(t) \) depends only on \( x(t) \)

Signal functions form an arrow.
Some Basic Signal Functions

identity :: SF a a
Some Basic Signal Functions

\[
\text{identity} :: \text{SF} \ a \ a
\]

\[
\text{constant} :: b \rightarrow \text{SF} \ a \ b
\]
Some Basic Signal Functions

identity :: SF a a
constant :: b -> SF a b
iPre :: a -> SF a a
Some Basic Signal Functions

- **identity**: \( \text{SF} \ a \ a \)
- **constant**: \( b \rightarrow \text{SF} \ a \ b \)
- **iPre**: \( a \rightarrow \text{SF} \ a \ a \)
- **integral**: \( \text{VectorSpace} \ a \ s \Rightarrow \text{SF} \ a \ a \)

\[
y(t) = \int_{0}^{t} x(\tau) \, d\tau
\]
Each signal function is essentially represented by a *transition function*. Arguments:

- Time passed since the previous time step.
- The current input value.

Returns:

- A (possibly) updated representation of the signal function, the *continuation*.
- The current value of the output signal.
A basic implementation: SF (2)

type DTime = Double

data SF a b =
    SF {sfTF :: DTime -> a
        -> Transition a b}

type Transition a b = (SF a b, b)

The continuation encapsulates any internal state of the signal function. The type synonym DTime is the type used for the time deltas, > 0.
A basic impl.: reactimate (1)

The function `reactimate` is responsible for animating a signal function:
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- At each sampling point:
A basic impl.: reactimate (1)

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A basic impl.: `reactimate(1)`

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- Loops over the sampling points.
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The function \texttt{reactimate} is responsible for animating a signal function:

- Loops over the sampling points.
- At each sampling point:
  - reads input sample and time from the external environment (typically I/O action)
  - feeds sample and time passed since previous sampling into the signal function’s transition function
  - writes the resulting output sample to the environment (typically I/O action).
A basic impl.: reactimate (2)

- The loop then repeats, but uses the continuation returned from the transition function on the next iteration, thus ensuring any internal state is maintained.
A basic implementation: \texttt{arr}

\texttt{arr :: (a -> b) -> SF a b}
\texttt{arr f = sf}
\texttt{where}
\texttt{sf = SF \{sfTF = \_ a -> (sf, f a)\}}

Note: It is obvious that \texttt{arr} constructs a \textit{stateless} signal function since the returned continuation is exactly the signal function being defined, i.e. it never changes.
A basic implementation: >>>>

For >>>, we have to combine their continuations into updated continuation for the composed arrow:

\[(\ggg) \; :: \; SF \; a \; b \rightarrow \; SF \; b \; c \rightarrow \; SF \; a \; c\]

\[(SF \{sfTF = tf1\}) \ggg (SF \{sfTF=tf2\}) = SF \{sfTF = tf\}\]

where

\[tf \; dt \; a = (sf1' \ggg sf2', \; c)\]

where

\[(sf1', \; b) = tf1 \; dt \; a\]

\[(sf2', \; c) = tf2 \; dt \; b\]

Note how \textit{same} time delta is fed to both subordinate signal functions, thus ensuring \textit{synchrony}. 
A basic impl.: How to get started? (1)

What should the very first time delta be?
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- Could use 0, but that would violate the assumption of positive time deltas (time always progressing), and is a bit of a hack.
A basic impl.: How to get started? (1)

What should the very first time delta be?

• Could use 0, but that would violate the assumption of positive time deltas (time always always progressing), and is a bit of a hack.

• Instead:
  - Initial SF representation makes a first transition given just an input sample.
  - Makes that transition into a representation that expects time deltas from then on.
data SF a b =
    SF {sfTF :: a -> Transition a b}

data SF' a b =
    SF' {sfTF' :: DTime -> a
         -> Transition a b}

type Transition a b = (SF' a b, b)

SF' is internal, can be thought of as representing a “running” signal function.
The arrow identity law:

\[ \text{arr id} \triangleright\triangleright\triangleright a = a = a \triangleright\triangleright\triangleright \text{arr id} \]
The arrow identity law:

\[\text{arr id } >>> a = a = a >>> \text{arr id}\]

How can this be exploited?
Optmimizing >>>: First Attempt (1)

The arrow identity law:

\[
\text{arr id} \gggg a = a = a \gggg \text{arr id}
\]

How can this be exploited?

1. Introduce a constructor representing \textit{arr id}

\[
\text{data SF a b} = \ldots
\]

\[
| \text{SFId}
\]

| \ldots
The arrow identity law:

$\text{arr id} >>> a = a = a >>> \text{arr id}$

How can this be exploited?

1. Introduce a constructor representing $\text{arr id}$

   ```haskell
data SF a b = ...
   | SFId
   | ...
   ```

2. Make $\text{SF}$ abstract by hiding all its constructors.
3. Ensure $\text{SFId}$ only gets used at intended type:

```haskell
identity :: SF a a
identity = SFId
```
3. Ensure \texttt{SFId} only gets used at intended type:

\begin{verbatim}
identity :: SF a a
identity = SFId
\end{verbatim}

4. Define optimizing version of \texttt{>>>}: 

\begin{verbatim}
(>>>) :: SF a b -> SF b c -> SF a c
\end{verbatim}

\begin{verbatim}
... SFId >>> sf = sf
...
\end{verbatim}
Optmimizing >>>: First Attempt (2)

3. Ensure \( \text{SFId} \) only gets used at intended type:

\[
\text{identity} :: \text{SF } a \ a \\
\text{identity} = \text{SFId}
\]

4. Define optimizing version of >>>:

\[
(\text{>>>}) :: \text{SF } a \ b \to \text{SF } b \ c \to \text{SF } a \ c \\
\ldots
\]

\[
\text{SFId} \text{>>> } \text{sf} = \text{sf}
\]

\[
:: \text{SF } b \ c \neq \text{SF } a \ c
\]
The type system does not get in the way of all optimizations. For example, for:

```haskell
constant :: b -> SF a b
constant b = arr (const b)
```

the following laws can readily be exploited:

```haskell
sf >>> constant c = constant c
constant c >>> arr f = constant (f c)
```

But to do better, we need GADTs.
Generalized Algebraic Data Types

GADTs allow

- individual specification of return type of constructors
- the more precise type information to be taken into account during case analysis.
Instead of

\[
\text{data SF } a \ b = \ldots
\]

| SFId
| \ldots
Instead of

```haskell
data SF a b = ...
  | SFId
  | ...
  | :: SF a b
```

Optmimizing >>>>: Second Attempt (1)
Instead of

```
data SF a b = ... |
| SFId |
| ... |
```

we define

```
data SF a b where
...

SFId :: SF a a
...
```
Define optimizing version of >>> exactly as before:

\[ (>>>) :: SF \ a \ b \to SF \ b \ c \to SF \ a \ c \]

...
Define optimizing version of >>> exactly as before:

```haskell
(>>>>) :: SF a b -> SF b c -> SF a c

SFId >>> sf = sf
```
Optmimizing >>>: Second Attempt (2)

Define optimizing version of >>> exactly as before:

\[(\llll) \::\ SF\ a\ b\ \rightarrow\ SF\ b\ c\ \rightarrow\ SF\ a\ c\]

...\[SFId\ \llll \ sf = \ sf\]

...\[::\ SF\ a\ a\]
Define optimizing version of >>> exactly as before:

\[(>>>) \colon SF \ a \ b \to SF \ b \ c \to SF \ a \ c\]

\[
\begin{align*}
\text{SFIId} & \to \text{sf} = \text{sf} \\
:: \text{SF} \ a \ a & \to :: \text{SF} \ a \ c
\end{align*}
\]
Other Ways? Statically?

- Other (typed) approaches include keeping coercion functions around as “evidence” for use at runtime (Hughes 2004). But imposes an overhead.
Other Ways? Statically?

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- When network structure is static, optimizations can be carried out once and for all. But Yampa networks may evolve over time.
Other Ways? Statically?

- Other (typed) approaches include keeping coercion functions around as “evidence” for use at runtime (Hughes 2004). But imposes an overhead.
- When network structure is static, optimizations can be carried out once and for all. But Yampa networks may evolve over time.

\[
\text{arr } g \ggg \text{switch (\ldots)} (\_ \rightarrow \text{arr } f) \\
\text{switch} \quad \text{arr } g \ggg \text{arr } f = \text{arr} (f \ . \ g)
\]
Laws Exploited for Optimizations

General arrow laws:

\[
(f \ggg g) \ggg h = f \ggg (g \ggg h) \\
arr (g \cdot f) = arr f \ggg arr g \\
arr id \ggg f = f \\
f = f \ggg arr id
\]

Laws involving \texttt{const} (the first is Yampa-specific):

\[
sf \ggg arr (\texttt{const} k) = arr (\texttt{const} k) \\
arr (\texttt{const} k) \ggg arr f = arr (\texttt{const}(f k))
\]
Causal Commutative Arrows

- The Yampa arrow satisfies additional laws: in particular it is *commutative*, meaning ordering between signal functions composed in parallel is irrelevant.
Causal Commutative Arrows

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- This can be exploited (Liu, Cheng, Hudak 2009) to define a **Causal Commutative Normal Form (CCNF)** for *switch-free* networks.
The Yampa arrow satisfies additional laws: in particular it is **commutative**, meaning ordering between signal functions composed in parallel is irrelevant.

This can be exploited (Liu, Cheng, Hudak 2009) to define a **Causal Commutative Normal Form (CCNF)** for **switch-free** networks.

Essentially CCNF is a **Mealy Machine**.
Causal Commutative Arrows

• The Yampa arrow satisfies additional laws: in particular it is *commutative*, meaning ordering between signal functions composed in parallel is irrelevant.

• This can be exploited (Liu, Cheng, Hudak 2009) to define a *Causal Commutative Normal Form (CCNF)* for *switch-free* networks.

• Essentially CCNF is a *Mealy Machine*.

• Not exploited in Yampa, but this optimization has been used to obtain performance gains of two orders of magnitude (over Yampa-like performance).
data SF a b where
SFArr ::
    (DTime -> a -> (SF a b, b))
    -> FunDesc a b
    -> SF a b
SF CpAXA ::
    (DTime -> a -> (SF a d, d))
    -> FunDesc a b -> SF b c -> FunDesc c d
    -> SF a d
SF ::
    (DTime -> a -> (SF a b, b))
    -> SF a b
data FunDesc a b where
    FDI :: FunDesc a a
    FDC :: b -> FunDesc a b
    FDG :: (a -> b) -> FunDesc a b
data FunDesc a b where
  FDI :: FunDesc a a
  FDC :: b -> FunDesc a b
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data FunDesc a b where
  FDI :: FunDesc a a
  FDC :: b -> FunDesc a b
  FDG :: (a -> b) -> FunDesc a b

Recovering the function from a FunDesc:

fdFun :: FunDesc a b -> (a -> b)
fdFun FDI = id
fdFun (FDC b) = const b
fdFun (FDG f) = f
data FunDesc a b where
  FDI :: FunDesc a a
  FDC :: b -> FunDesc a b
  FDG :: (a -> b) -> FunDesc a b

Recovering the function from a FunDesc:

fdFun :: FunDesc a b -> (a -> b)
fdFun FDI = id
fdFun (FDC b) = const b
fdFun (FDG f) = f
fdComp :: FunDesc a b -> FunDesc b c -> FunDesc a c
fdComp FDI fd2 = fd2
fdComp fd1 FDI = fd1
fdComp (FDC b) fd2 = FDC ((fdFun fd2) b)
fdComp _ (FDC c) = FDC c
fdComp (FDG f1) fd2 = FDG (fdFun fd2 . f1)
Yampa models \textit{discrete-time} signals by lifting the \textit{range} of continuous-time signals:

\begin{verbatim}
data Event a = NoEvent | Event a

Discrete-time signal = Signal (Event α).
\end{verbatim}
Events

Yampa models *discrete-time* signals by lifting the *range* of continuous-time signals:

```
data Event a = NoEvent | Event a
```

*Discrete-time signal* = `Signal (Event α)`.

Consider composition of pure event processing:

```
f :: Event a -> Event b
g :: Event b -> Event c
```

```
arr f >>> arr g
```

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Additional function descriptor:

```haskell
data FunDesc a b where
  ...

  FDE :: (Event a -> b) -> b
  -> FunDesc (Event a) b
```
Additional function descriptor:

data FunDesc a b where

... FDE :: (Event a -> b) -> b

-> FunDesc (Event a) b
Optimizing Event Processing (1)

Additional function descriptor:

```
data FunDesc a b where
  ...
  FDE :: (Event a -> b) -> b
  -> FunDesc (Event a) b
```

Extend the composition function:

```
fdComp (FDE f1 f1ne) fd2 =
  FDE (f2 . f1) (f2 f1ne)
where
  f2 = fdFun fd2
```
Optimizing Event Processing (2)

Extend the composition function:

\[
\text{fdComp} \ (\text{FDG}\ f1)\ (\text{FDE}\ f2\ f2ne) = \text{FDG}\ f
\]

where

\[
f\ a = \\
\text{case}\ f1\ a\ \text{of}\\
\text{NoEvent} \rightarrow f2ne\\
f1a \rightarrow f2\ f1a
\]
Extend the composition function:

\[
\text{fdComp } (\text{FDG } f1) (\text{FDE } f2 \ f2ne) = \text{FDG } f
\]

where

\[
f a = \begin{cases} 
\text{NoEvent} & \rightarrow f2ne \\
 f1a & \rightarrow f2 \ f1a 
\end{cases}
\]
A general stateful event processor:

\[
\text{ep} :: (c \rightarrow a \rightarrow (c, b, b)) \rightarrow c \rightarrow b \\
\rightarrow \text{SF} (\text{Event } a) \ b
\]
Optimizing Stateful Event Processing

A general stateful event processor:

\[
\text{ep} :: (c \rightarrow a \rightarrow (c, b, b)) \rightarrow c \rightarrow b \\
\rightarrow \text{SF (Event a) b}
\]

Composes nicely with stateful and stateless event processors!
A general stateful event processor:

\[
\text{ep} :: (c \to a \to (c, b, b)) \to c \to b \\
\quad \to \text{SF (Event } a) \ b
\]

Composes nicely with stateful and stateless event processors!

Introduce explicit representation:

\[
data \text{ SF } a \ b \ \text{where} \\
\ldots
\]\n
\[
\text{SFEP} :: \ldots \\
\quad \to (c \to a \to (c, b, b)) \to c \to b \\
\quad \to \text{SF (Event } a) \ b
\]
Cause for Concern

Code with GADT-based optimizations is getting large and complicated:

- Many more cases to consider.
- Larger size of signal function representation.
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Is the result really a performance improvement?
Cause for Concern

Code with GADT-based optimizations is getting large and complicated:

- Many more cases to consider.
- Larger size of signal function representation.

Is the result really a performance improvement? A number of Micro Benchmarks were carried out to verify that individual optimizations worked as intended, including:

- Space Invaders
- MIDI Event Processor
Benchmark 1: Space Invaders
Benchmark 2: MIDI Event Processor

High-level model of a MIDI event processor programmed to perform typical duties:
The MEP4
## Results

<table>
<thead>
<tr>
<th>Benchmark</th>
<th>$T_U$ [s]</th>
<th>$T_O$ [s]</th>
<th>$T_O/T_U$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space Inv.</td>
<td>0.95</td>
<td>0.86</td>
<td>0.93</td>
</tr>
<tr>
<td>MEP</td>
<td>19.39</td>
<td>10.31</td>
<td>0.48</td>
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Most important gains:

- Insensitive to bracketing.
- A number of “pre-composed” combinators no longer needed, thus simplifying the Yampa API (and implementation).
- Much better event processing.