Yampa: Functional Reactive Programming for Systems with Dynamic Structure

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Reactive programming

Reactive systems:

- input arrives incrementally while system is running
- output is generated in response to input in an interleaved fashion

(Contrast ***transformational systems***.)

The notions of

- time
- time-varying entities, ***signals***

are inherent.

Functional Reactive Programming

Functional Reactive Programming (FRP)

- Framework for reactive programming in a functional setting.
- Systems described by mapping ***signals*** to ***signals***.
- Supports hybrid systems (continuous and discrete time).
- Supports systems with evolving structure.
- Originated from Functional Reactive Animation (Fran) (Elliott & Hudak).

Related languages

FRP related both to modeling and synchronous dataflow languages:

- Modeling Languages:
  - Simulink
  - Ptolemy II
  - Modelica
- Synchronous languages:
  - Esterel
  - Lustre
  - Lucid Synchrone
- . . .

FRP applications

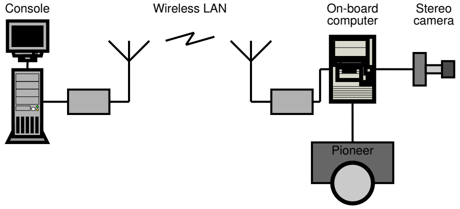
Some domains where FRP has been used:

- Graphical Animation (Fran: Elliott, Hudak)
- Robotics (Frob: Peterson, Hager, Hudak, Elliott, Pembeci, Nilsson)
- Vision (FVision: Peterson, Hudak, Reid, Hager)
- GUIs (Fruit: Courtney)
- Hybrid modeling (Nilsson, Hudak, Peterson)

Example: Robotics (1)

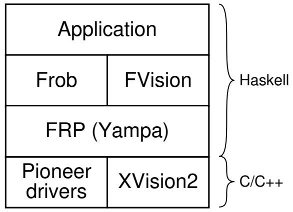
[PPDP'02, with Izzet Pembeci and Greg Hager, Johns Hopkins University]

Hardware setup:



Example: Robotics (2)

Software architecture:



Example: Robotics (3)

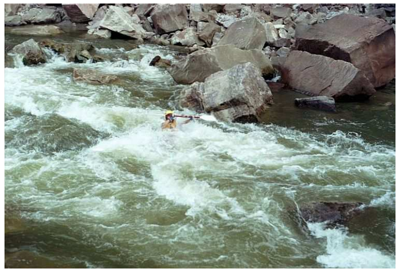
Yampa

The most recent Yale FRP implementation is called ***Yampa***:

- Embedding in Haskell; i.e. a Haskell library.
- Clear separation between signals and functions on signals.
- Arrows used as the basic structuring framework.
- Advanced switching constructs allows for description of systems with highly dynamic structure.

Yampa?

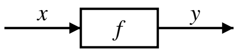
Yampa is a river with long calmly flowing sections and abrupt whitewater transitions in between.



A good metaphor for hybrid systems!

Signal functions

Key concept: functions on signals.



Intuition:

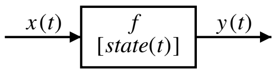
$$\begin{array}{l} \texttt{Signal}\ \alpha \approx \texttt{Time} \rightarrow \alpha \\ x\ \texttt{::}\ \texttt{Signal T1} \\ y\ \texttt{::}\ \texttt{Signal T2} \\ f\ \texttt{::}\ \texttt{Signal T1} \rightarrow \texttt{Signal T2} \end{array}$$

Additionally: ***causality*** requirement.

Signal functions and state

Alternative view:

Functions on signals can encapsulate state.



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

Functions on signals are either:

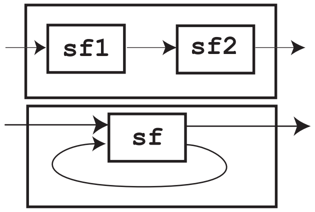
- ***Stateful***: $y(t)$ depends on $x(t)$ and $state(t)$
- ***Stateless***: $y(t)$ depends only on $x(t)$

Signal functions in Yampa

- Signal functions are ***first class entities***. Intuition: $\texttt{SF}\ \alpha\ \beta \approx \texttt{Signal}\ \alpha \rightarrow \texttt{Signal}\ \beta$
- Signals are ***not*** first class entities: they only exist indirectly through signal functions.
- The strict separation between signals and signal functions distinguishes Yampa from earlier FRP implementations.

Describing systems

Systems are described by combining signal functions into larger signal functions:



Yampa and arrows

Yampa uses John Hughes' ***arrow*** framework: Signal functions are arrows.

Core signal function combinators:

- `arr :: (a -> b) -> SF a b`
- `>>> :: SF a b -> SF b c -> SF a c`
- `first :: SF a b -> SF (a,c) (b,c)`
- `loop :: SF (a,c) (b,c) -> SF a b`

Enough to express any conceivable "wiring".

The arrow syntactic sugar

Using the basic combinators directly is often very cumbersome. Ross Paterson's syntactic sugar for arrows provides a convenient alternative:

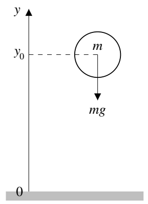
```
proc pat -> do [ rec ]
    pat1 <- sfexp1 -< exp1
    pat2 <- sfexp2 -< exp2
    ...
    patn <- sfexpn -< expn
    returnA -< exp
```

Also: `let pat = exp` $\equiv$ `pat -< arr id -< exp`

Some basic signal functions

- ```
  identity :: SF a a
  identity = arr id -- semantics
  ```
- ```
  constant :: b -> SF a b
  constant b = arr (const b) -- semant
  ```
- ```
  integral :: VectorSpace a s->SF a a
  ```
- ```
  time :: SF a Time
  time = constant 1.0 >>> integral
  ```
- ```
  (^<<) :: (b->c) -> SF a b -> SF a c
  f (^<<) sf = sf >>> arr f
  ```


A bouncing ball



$$\begin{aligned} y &= y_0 + \int \dot{y}\, \mathrm{d}t \\ \dot{y} &= \int -9.81 \end{aligned}$$

On impact:

$$\dot{y} = -\dot{y}(t-)$$

(fully elastic collision)
  ```

Modelling the bouncing ball: part 1

Free-falling ball:

```
type Pos = Double
type Vel = Double

fallingBall ::
    Pos -> Vel -> SF () (Pos, Vel)
fallingBall p0 v0 = proc () -> do
    v <- (v0 +) ^<< integral -< -9.81
    p <- (p0 +) ^<< integral -< v
    returnA -< (p, v)
```


Events

Conceptually, ***discrete-time*** signals are only defined at discrete points in time, often associated with the occurrence of some ***event***.

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`)`.

We often want to associate information with an event occurrence:

```
tag :: Event a -> b -> Event b
```


Some basic event sources

- `never :: SF a (Event b)`
- `now :: b -> SF a (Event b)`
- `after :: Time -> b -> SF a (Event b)`
- `repeatedly :: Time -> b -> SF a (Event b)`
- `edge :: SF Bool (Event ())`

Stateful event suppression

- `notYet :: SF (Event a) (Event a)`
- `once :: SF (Event a) (Event a)`

Modelling the bouncing ball: part 2

Detecting when the ball goes through the floor:

```
fallingBall' ::
    Pos -> Vel
    -> SF () ((Pos,Vel), Event (Pos,Vel))
fallingBall' p0 v0 = proc () -> do
    pv@(p, _) <- fallingBall p0 v0 -< ()
    hit       <- edge              -< p <= 0
    returnA -< (pv, hit `tag` pv)
```


Switching

Q: How and when do signal functions "start"?

A:
- ***Switchers*** "apply" a signal functions to its input signal at some point in time.
- This creates a "running" signal function ***instance***, which often replaces the previously running instance.

Switchers thus allow systems with ***varying structure*** to be described.

The basic switch

Idea:

- Allows one signal function to be replaced by another.
- Switching occurs on the first occurrence of the switching event source.

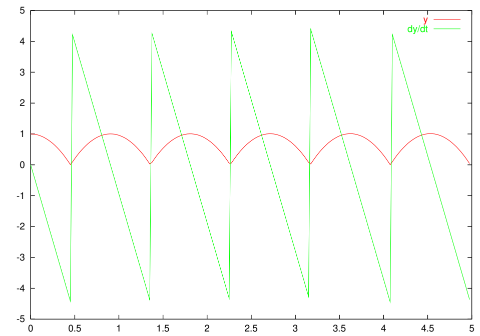
```
switch ::
   SF a (b, Event c)
   -> (c -> SF a b)
   -> SF a b
```


Modelling the bouncing ball: part 3

Making the ball bounce:

```
bouncingBall :: Pos -> SF () (Pos, Vel)
bouncingBall p0 = bbRec p0 0.0
  where
    bbRec p0 v0 =
      switch (fallingBall' p0 v0) $ \(p,v) ->
      bbRec p (-v)
```

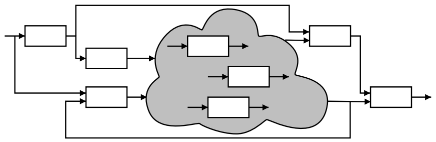

Simulation of bouncing ball



Highly dynamic system structure?

Basic switch allows one signal function to be replaced by another.

- What about more general structural changes?



- What about state?

The challenge

George Russel said on the Haskell GUI list:

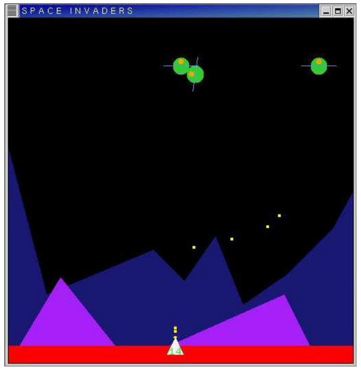
> "... Things like getting an alien spaceship to move slowly downward, moving randomly to the left and right, and bouncing off the walls, turned out to be a major headache. Also I think I had to use 'error' to get the message out to the outside world that the aliens had won. ..."

What was wrong?

Possible reasons for George Russel's reaction:

- Original reactive animation systems like Fran and FAL lacked crucial features, like dynamic collections of signal functions.
  Yampa attempts to address this [Haskell Workshop '02]
- Not many examples of good FRP code around.
  [Haskell Workshop '03]

The game



Describing the alien behavior (1)

```
type Object = SF ObjInput ObjOutput

alien :: RandomGen g =>
  g -> Position2 -> Velocity -> Object
alien g p0 vyd = proc oi -> do
  rec
    -- Pick a desired horizontal position
    rx   <- noiseR (xMin, xMax) g -< ()
    smpl <- occasionally g 5 ()   -< ()
    xd   <- hold (point2X p0) -< smpl `tag` rx
    ...
```


Describing the alien behavior (2)

```
    ...
    -- Controller
    let axd = 5 * (xd - point2X p)
              - 3 * (vector2X v)
        ayd = 20 * (vyd - (vector2Y v))
        ad  = vector2 axd ayd
        h   = vector2Theta ad
    ...
```


Describing the alien behavior (3)

```
    ...
    -- Physics
    let a = vector2Polar
              (min alienAccMax
                   (vector2Rho ad))
              h
    vp  <- iPre v0     -< v
    ffi <- forceField -< (p, vp)
    v   <- (v0 ^+^) ^<< impulseIntegral
             -< (gravity ^+^ a, ffi)
    p   <- (p0 .+^) ^<< integral -< v
    ...
```

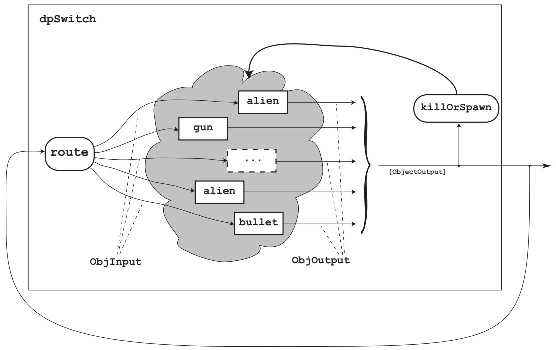

Describing the alien behavior (4)

```
    ...
    -- Shields
    sl  <- shield -< oiHit oi
    die <- edge   -< sl <= 0

  returnA -< ObjOutput
               ooObsObjState = oosAlien p h v,
               ooKillReq     = die,
               ooSpawnReq    = noEvent

  where
    v0 = zeroVector
```


Overall game structure

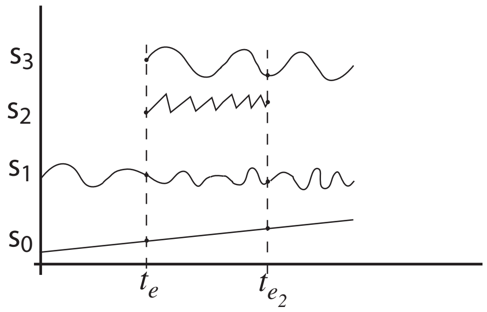


Dynamic signal function collections

Idea:

- Switch over ***collections*** of signal functions.
- On event, “freeze” running signal functions into collection of signal function ***continuations***, preserving encapsulated ***state***.
- Modify collection as needed and switch back in.

Dynamic signal function collections



dpSwitch

Need ability to express:

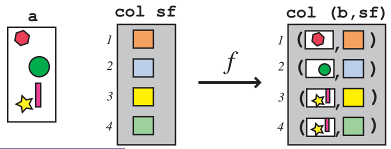
- How input routed to each signal function.
- When collection changes shape.
- How collection changes shape.

```
dpSwitch :: Functor col =>
    (forall sf . (a -> col sf -> col (b,sf)))
    -> col (SF b c)
    -> SF (a, col c) (Event d)
    -> (col (SF b c) -> d -> SF a (col c))
    -> SF a (col c)
```


Routing

Idea:

- The routing function decides which parts of the input to pass to each running signal function instance.
- It achieves this by pairing a projection of the input with each running instance:



The routing function type

Universal quantification over the collection members:

```
Functor col =>
  (forall sf . (a -> col sf -> col (b,sf)))
```

Collection members thus ***opaque***:

- Ensures only signal function instances from argument can be returned.
- Unfortunately, does not prevent duplication or discarding of signal function instances.

The game core

```
gameCore :: IL Object
            -> SF (GameInput, IL ObjOutput)
                  (IL ObjOutput)
gameCore objs =
  dpSwitch route
           objs
           (arr killOrSpawn >>> notYet)
           (\sfs’ f -> gameCore (f sfs’))
```


Closing the feedback loop (1)

```
game :: RandomGen g =>
  g -> Int -> Velocity -> Score ->
  SF GameInput ((Int, [ObsObjState]),
                Event (Either Score Score))
game g nAliens vydAlien score0 = proc gi -> do
  rec
    oos <- gameCore objs0 -< (gi, oos)
  score     <- accumHold score0
                    -< aliensDied oos
  gameOver <- edge -< alienLanded oos
  newRound <- edge -< noAliensLeft oos
  ...
```


Closing the feedback loop (2)

```
  ...
  returnA -< ((score,
               map ooObsObjState
                   (elemsIL oos)),
              (newRound ‘tag‘ (Left score))
              ‘lMerge‘ (gameOver
                        ‘tag‘ (Right score)))
  where
    objs0 =
      listToIL
        (gun (Point2 0 50)
         : mkAliens g (xMin+d) 900 nAliens)
```


Other approaches?

Transition function operating on world model with explicit state (e.g. Asteroids by Lüth):

- Model snapshot of world with ***all*** state components.
- Transition function takes input and current world snapshot to output and the next world snapshot.

One could also use this technique ***within*** Yampa to avoid switching over dynamic collections.

Why use Yampa, then?

- Yampa provides a lot of functionality for programming with time-varying values:
  - captures common patterns
  - packaged in a way that makes reuse very easy
- Yampa allows state to be nicely encapsulated by signal functions:
  - avoids keeping track of all state globally
  - adding more state is easy and usually does not imply any major changes to type or code structure

State in `alien`

Each of the following signal functions used in `alien` encapsulate state:

- `noiseR`
- `occasionally`
- `hold`
- `iPre`
- `forceField`
- `impulseIntegral`
- `integral`
- `shield`
- `edge`

Drawbacks of Yampa?

- Choosing the right switch can be tricky.
- Subtle issues concerning when to use e.g. `iPre`, `notYet`.
- Syntax could be improved (with specialized pre-processor).

Related work (1)

- First-Order Systems: no dynamic collections
  - Esterel [Berry 92], Lustre [Caspi 87], Lucid Synchrone [Caspi 00], SimuLink, RT-FRP [Wan, Taha, Hudak 01]
- Fudgets [Carlsson and Hallgren 93, 98]
  - Continuation capture with `extractSP`
  - Dynamic Collections with `dynListF`
  - No synchronous bulk update

Related work (2)

- Fran [Elliott and Hudak 97, Elliott 99]
  - First class ***signals***.
  - But dynamic collections?
- FranTk [Sage 99]
  - Dynamic collections, but only via `IO` monad.

Obtaining Yampa

Yampa 0.9 is available from

http://www.haskell.org/yampa