Functional Reactivity: Eschewing the Imperative

An Overview of Functional Reactive Programming in the Context of Yampa

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with

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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):

- Paradigm for reactive programming in a functional setting.
- Originated from Functional Reactive Animation (Fran) (Elliott & Hudak).
- Has evolved in a number of directions and into different concrete implementations.

Related languages

FRP related to:

- Synchronous languages, like Esterel, Lucid Synchrone.
- Modeling languages, like Simulink, Modelica.

Distinct features of FRP:

- First class reactive components.
- Allows highly dynamic system structure.

FRP applications

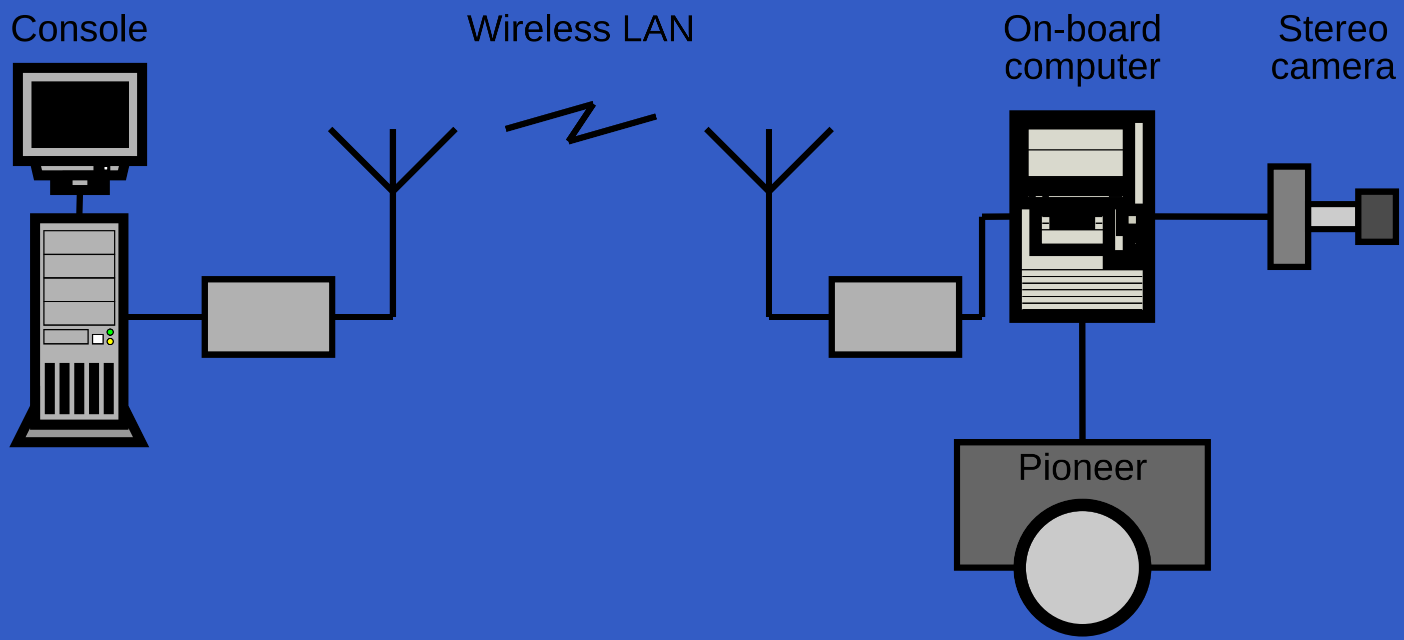
Some domains where FRP has been used:

- 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)

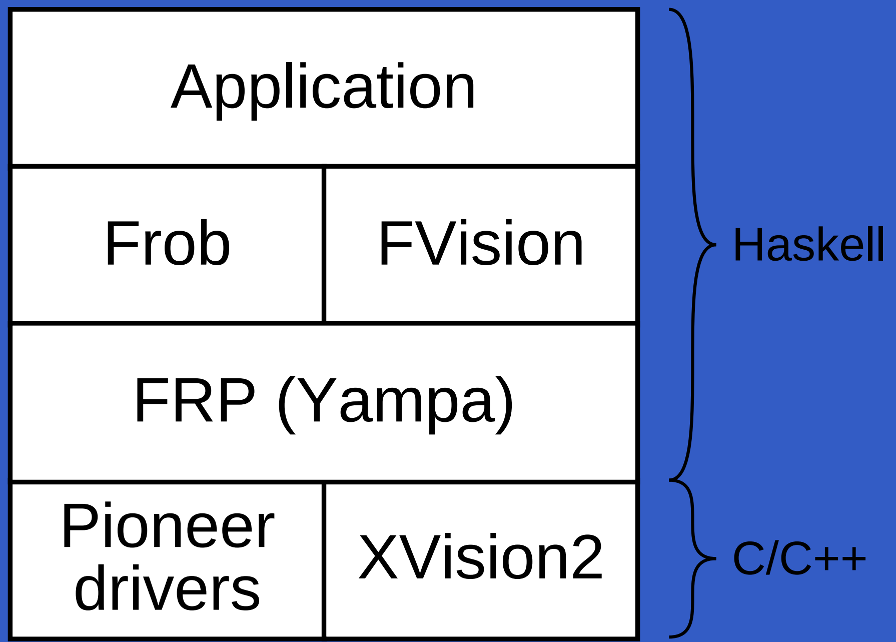
[PPDP'02, with Izzet Pembeci and Greg Hager, Johns Hopkins University]

Hardware setup:

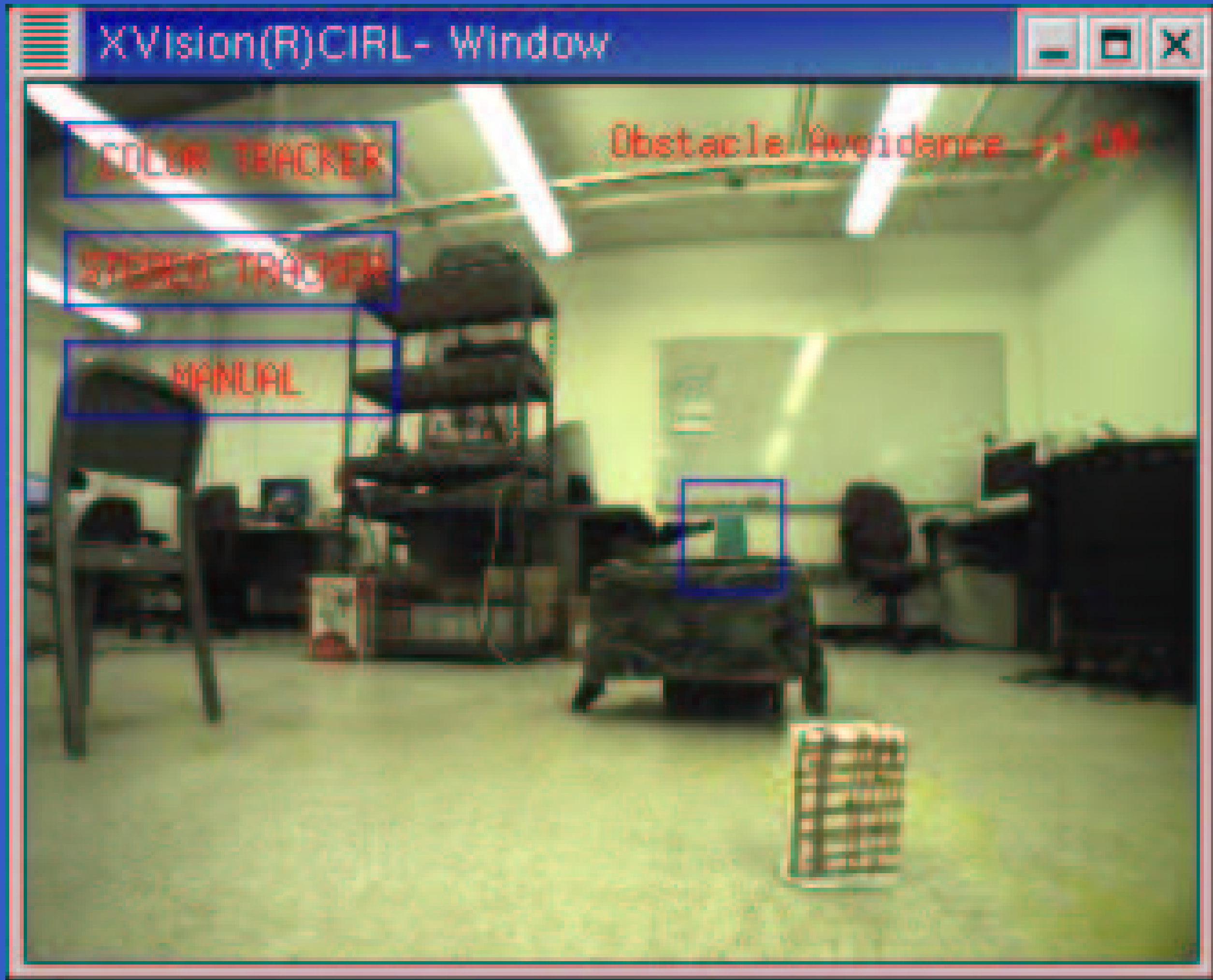


Example: Robotics (2)

Software architecture:



Example: Robotics (3)



Yampa

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

- Embedding in Haskell; i.e. a Haskell library.
- Arrows used as the basic structuring framework.
- Advanced switching constructs allows for highly dynamic system structure.

Yampa?

Yampa?

Yet
Another
Mostly
Pointless
Acronym

Yampa?

Yet
Another
Mostly
Pointless
Acronym

???

Yampa?

Y et
A nother
M ostly
P ointless
A cronym

???

No . . .

Yampa?

Yampa is a river . . .

Yampa?

. . . with long calmly flowing sections . . .

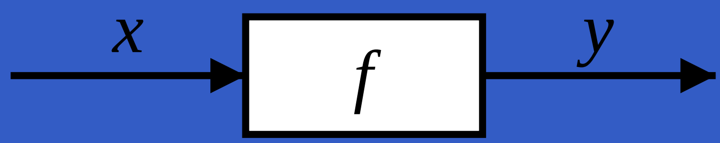
Yampa?

. . . and abrupt whitewater transitions in between.

A good metaphor for hybrid systems!

Signal functions

Key concept: ***functions on signals***.



Intuition:

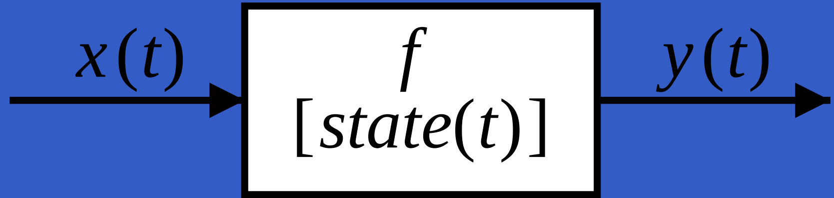
$$\texttt{Signal}\ \alpha \approx \texttt{Time} \rightarrow \alpha$$
$$x :: \texttt{Signal T1}$$
$$y :: \texttt{Signal T2}$$
$$f :: \texttt{Signal T1} \rightarrow \texttt{Signal T2}$$

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: `SF` α β $\approx$ `Signal` α $\rightarrow$ `Signal` β

Signal functions in Yampa

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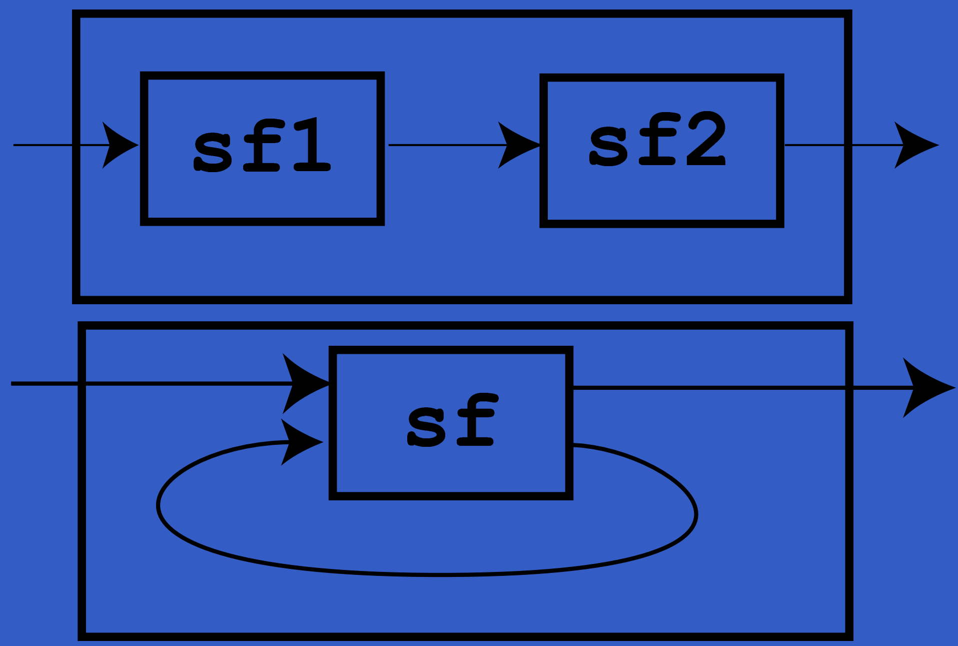
- Signals are ***not*** first class entities: they only exist indirectly through signal functions.

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 ]`

pat_1 `<-` $sfexp_1$ `-<` exp_1

pat_2 `<-` $sfexp_2$ `-<` exp_2

`...`

pat_n `<-` $sfexp_n$ `-<` exp_n

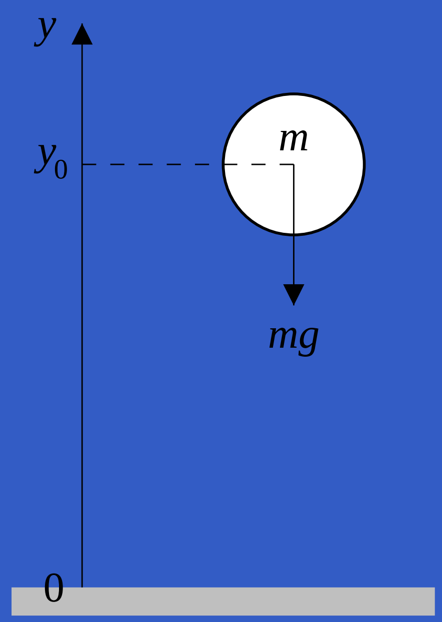
`returnA -<` exp

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"?

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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.

Switching

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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
```

The basic switch

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Initial SF with event source

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```
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    SF a (b, Event c)
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```

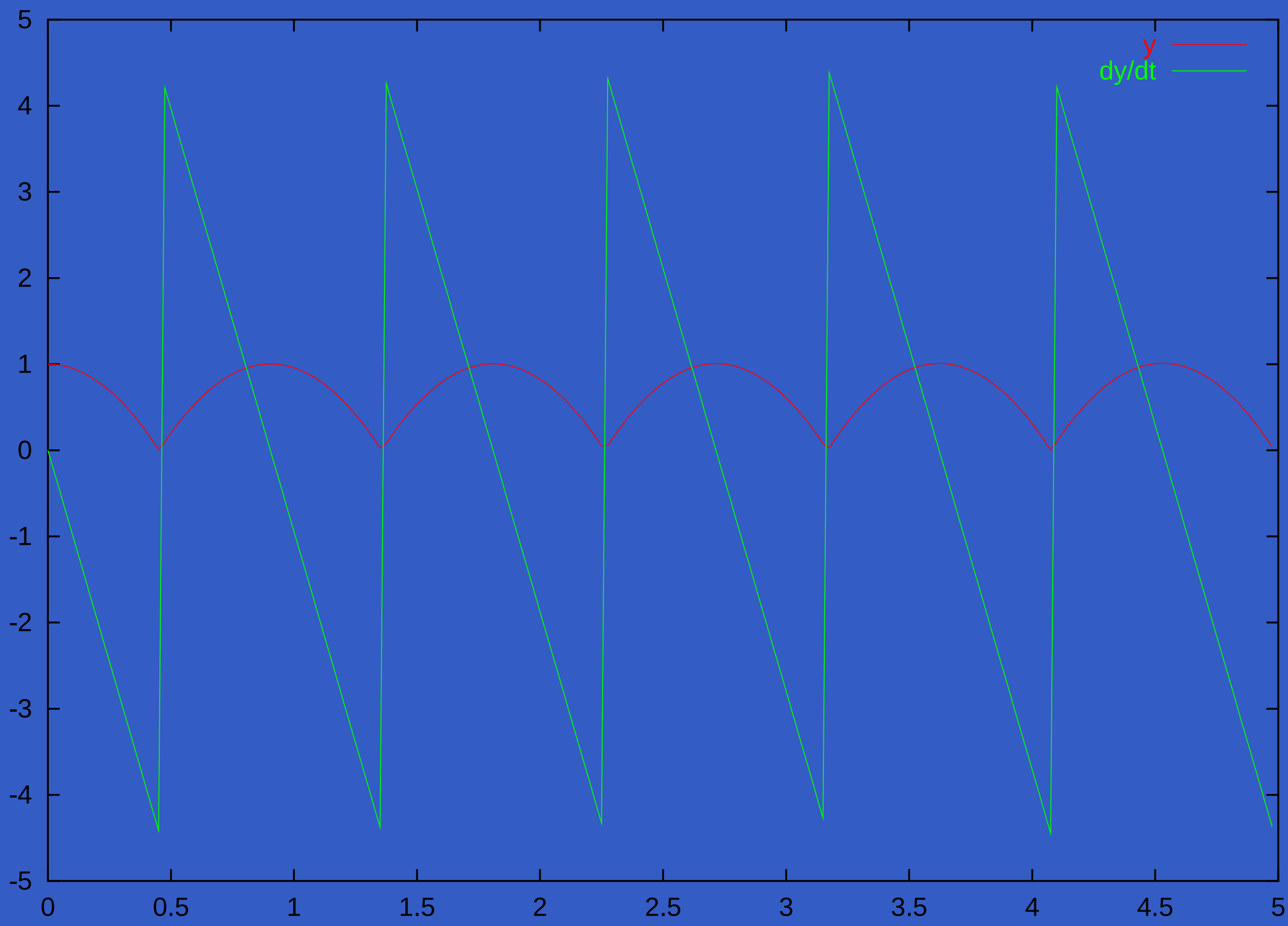
Function yielding SF to switch into

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)
```

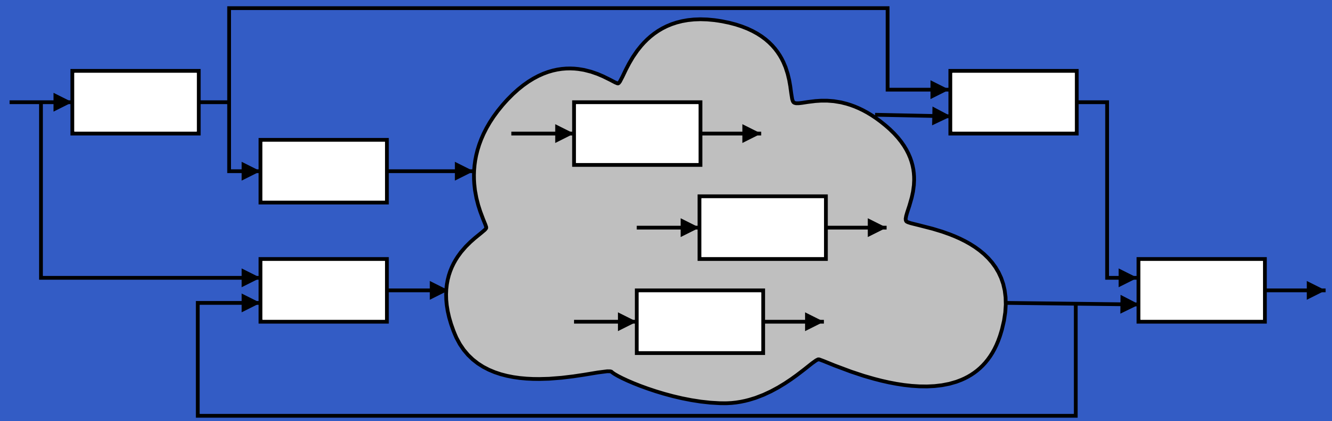
Simulation of bouncing ball



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:

> “I have to say I’m very sceptical about things like Fruit which rely on reactive animation, ever since I set our students an exercise implementing a simple space-invaders game in such a system, and had no end of a job producing an example solution. . . .

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. . . .

The challenge

George Russel said on the Haskell GUI list:

> My suspicion is that reactive animation works very nicely for the examples constructed by reactive animation folk, but not for my examples.”

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
...
```

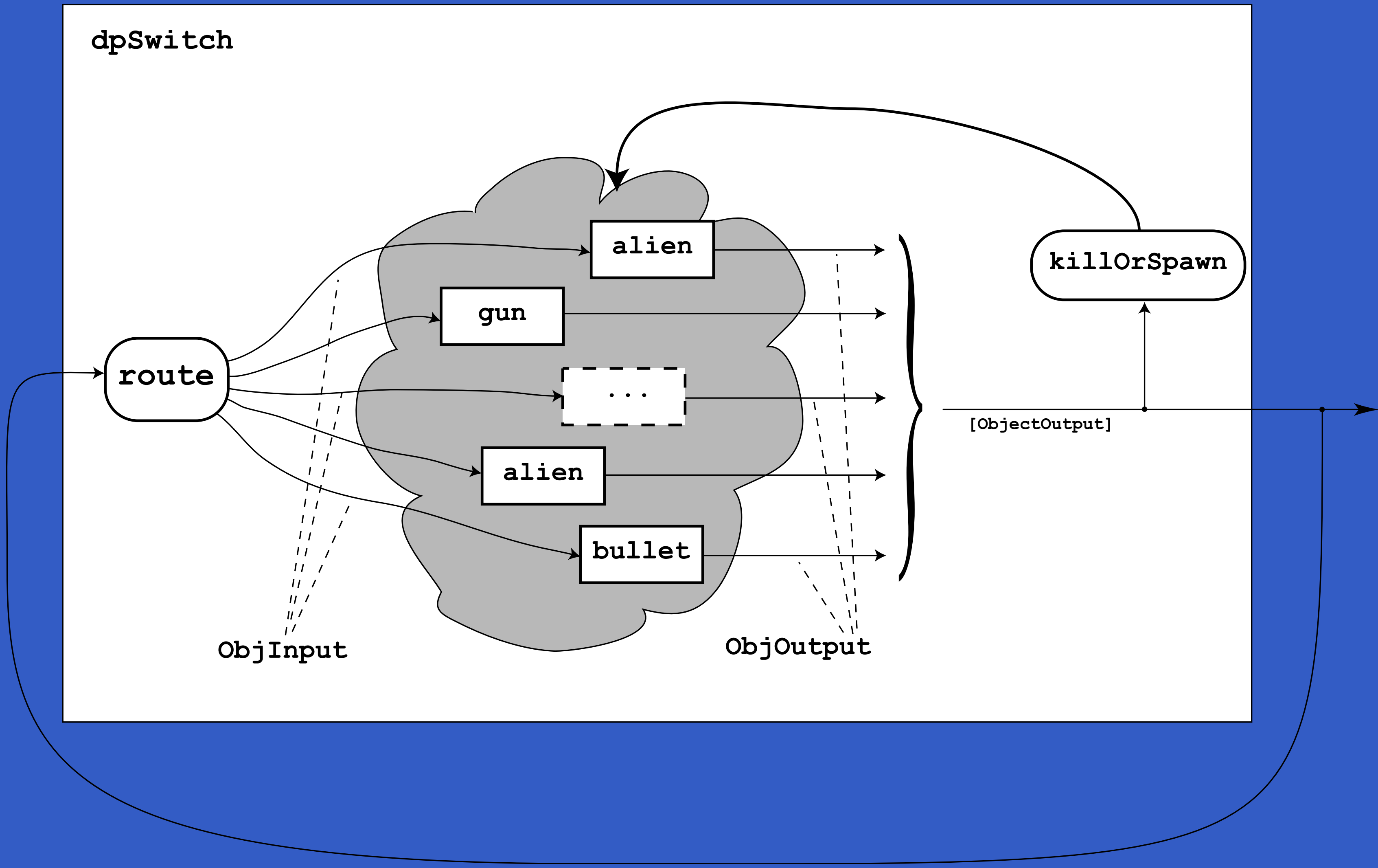
Describing the alien behavior (4)

```
    ...
    -- 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.

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)
```

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Routing function

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    -> SF a (col c)
```

Initial collection

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```

Event source

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```

Function yielding SF to switch into

Routing

Idea:

- The routing function decides which parts of the input to pass to each running signal function instance.

Routing

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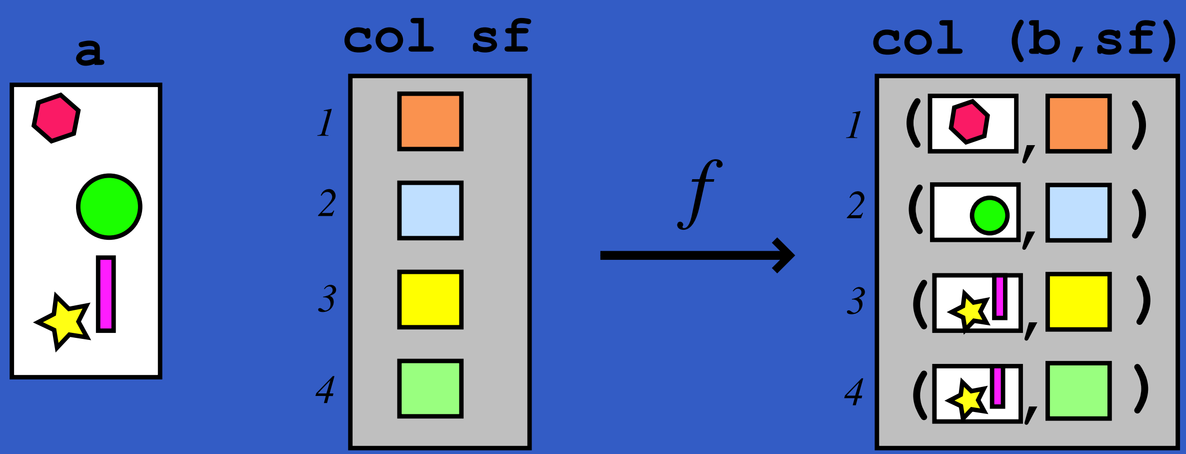
- The routing function decides which parts of the input to pass to each running signal function instance.
- It achieves this by pairing a projection of the input with each running instance:



The 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 functional 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`

Why not imperative, then?

If state is so important, why not stick to imperative/object-oriented programming where we have “state for free”?

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- Yampa retains all advantages of declarative programming:
  - High abstraction level.
  - Referential transparency facilitates formal reasoning.

Why not imperative, then?

If state is so important, why not stick to imperative/object-oriented programming where we have “state for free”?

- Yampa retains all advantages of declarative programming:
  - High abstraction level.
  - Referential transparency facilitates formal reasoning.
- Synchronous approach avoids “event-call-back soup”, meaning robust, easy-to-understand semantics.

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`