MGS 2005
Functional Reactive Programming

Lecture 1:
Introduction to FRP, Yampa, and Arrows

Henrik Nilsson

School of Computer Science and Information Technology
University of Nottingham, UK

Outline

- Brief introduction to FRP and Yampa
- Signal functions
- Arrows

Reactive programming

Reactive systems:

- Input arrives ***incrementally*** while system is running.
- Output is generated in response to input in an interleaved and ***timely*** fashion.

Contrast ***transformational systems***.

The notions of

- time
- time-varying values, or ***signals***

are inherent and central for reactive systems.

Functional Reactive Programming

What is 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.

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)

Key FRP features

- First class reactive components.
- Synchronous: all system parts operate in synchrony.
- Support for hybrid (mixed continuous and discrete time) systems.
- Allows dynamic system structure.

Related languages and paradigms

FRP related to:

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

Yampa

What is ***Yampa***?

- The most recent Yale FRP implementation. People:
  - Antony Courtney
  - Paul Hudak
  - Henrik Nilsson
  - John Peterson
- A Haskell ***combinator library***, a.k.a. ***Domain-Specific Embedded Language*** (DSEL).

Yampa

What is *Yampa*?

- Structured using ***arrows***.
- ***Continuous-time*** signals (conceptually)
- Option type ***Event*** to handle discrete-time signals.
- Advanced ***switching constructs*** to describe systems with dynamic structure.

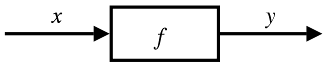
Yampa?

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

A good metaphor for hybrid systems!

Signal functions (1)

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



Intuition:

Signal α $\approx$ Time$\rightarrow\alpha$
x :: Signal T1
y :: Signal T2
f :: Signal T1 $\rightarrow$Signal T2

Signal functions (2)

Additionally, ***causality*** required: output at time t must be determined by input on interval $[0, t]$.

Signal functions are said to be

- ***pure*** or ***stateless*** if output at time t only depends on input at time t
- ***impure*** or ***stateful*** if output at time t depends on input over the interval $[0, t]$.

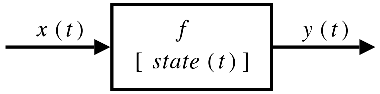
Signal functions in Yampa

- ***Signal functions*** are ***first class entities***.
  Intuition: `SF` α $\beta \approx$ `Signal` $\alpha \rightarrow$ `Signal` β
- ***Signals*** are ***not*** first class entities: they only exist indirectly through signal functions.

Signal functions and state

Alternative view:

Signal functions can encapsulate ***state***.



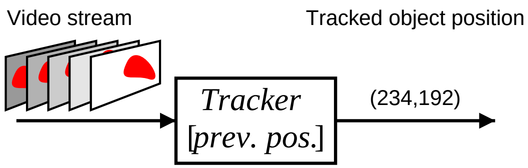
$state(t)$ summarizes input history $x(t')$, $t' \in [0, t]$.
Thus, really a kind of ***process***.

From this perspective, signal functions are:

- ***stateful*** if $y(t)$ depends on $x(t)$ and $state(t)$
- ***stateless*** if $y(t)$ depends only on $x(t)$

Example: Video tracker

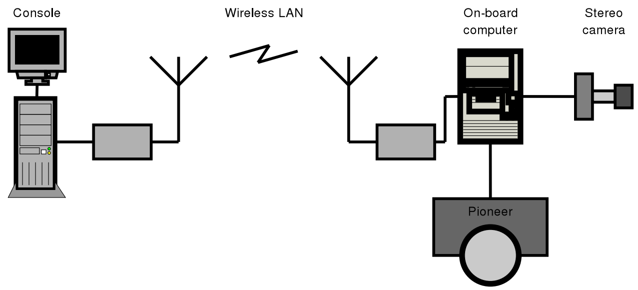
Video trackers are typically stateful signal functions:



Example: Robotics (1)

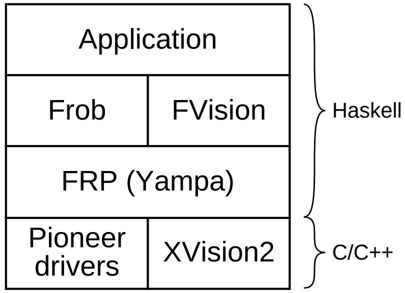
[PPDP'02, with Izzet Pembeci and Greg Hager, Johns Hopkins University]

Hardware setup:



Example: Robotics (2)

Software architecture:

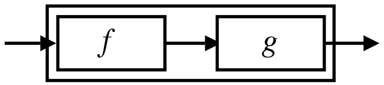


Example: Robotics (3)

Yampa and Arrows (1)

In Yampa, systems are described by combining signal functions (forming new signal functions).

For example, serial composition:

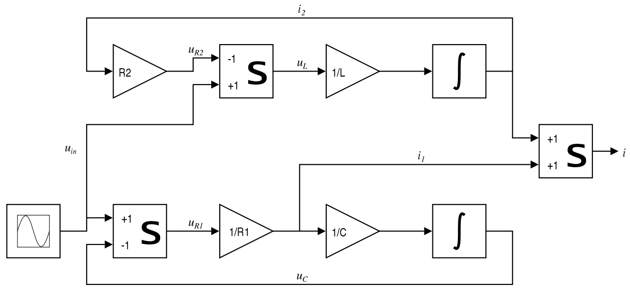


A *combinator* can be defined that captures this idea:

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


Yampa and Arrows (2)

But systems can be complex:



How many and what combinators do we need to be able to describe arbitrary systems?

Yampa and Arrows (3)

John Hughes' ***arrow*** framework:

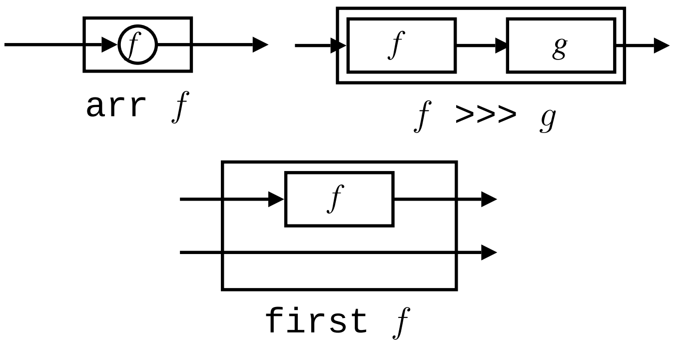
- Abstract data type interface for function-like types.
- Particularly suitable for types representing process-like computations.
- Related to ***monads***, since arrows are computations, but more general.
- Provides a minimal set of "wiring" combinators.

What is an arrow? (1)

- A ***type constructor*** a of arity two.
- Three operators:
  - ***lifting***:
    `arr :: (b->c) -> a b c`
  - ***composition***:
    `(>>>) :: a b c -> a c d -> a b d`
  - ***widening***:
    `first :: a b c -> a (b,d) (c,d)`
- A set of ***algebraic laws*** that must hold.

What is an arrow? (2)

These diagrams convey the general idea:



The `Arrow` class

In Haskell, a ***type class*** is used to capture these ideas (except for the laws):

```
class Arrow a where
    arr   :: (b -> c) -> a b c
    (>>>) :: a b c -> a c d -> a b d
    first :: a b c -> a (b,d) (c,d)
```

Functions are arrows (1)

Functions are a simple example of arrows. The arrow type constructor is just `(->)` in that case.

Exercise 1: Suggest suitable definitions of

- `arr`
- `(>>>)`
- `first`

for this case!

(We have not looked at what the laws are yet, but they are “natural”.)

Functions are arrows (2)

Solution:

- `arr = id`
  To see this, recall
  ```
  id :: t -> t
  arr :: (b->c) -> a b c
  ```
  Instantiate with

$$
\begin{aligned}
\texttt{a} &= \texttt{(->)} \\
\texttt{t} &= \texttt{b->c} = \texttt{(->) b c}
\end{aligned}
$$

Functions are arrows (3)

- `f >>> g = \a -> g (f a)` ***or***
- `f >>> g = g . f` ***or even***
- `(>>>) = flip (.)`
- `first f = \(b,d) -> (f b,d)`

Functions are arrows (4)

`Arrow` instance declaration for functions:

```
instance Arrow (->) where
    arr     = id
    (>>>)   = flip (.)
    first f = \(b,d) -> (f b,d)
```

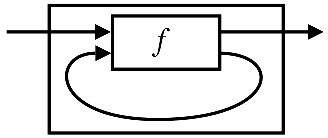
Arrow laws

```
(f >>> g) >>> h  =  f >>> (g >>> h)
  arr (f >>> g)  =  arr f >>> arr g
   arr id >>> f  =  f
              f  =  f >>> arr id
  first (arr f)  =  arr (first f)
first (f >>> g)  =  first f >>> first g
```

Exercise 2: Draw diagrams illustrating the first and last law!

The `loop` combinator (1)

Another important operator is `loop`: a fixed-point operator used to express recursive arrows or ***feedback***:



`loop` f

The `loop` combinator (2)

Not all arrow instances support `loop`. It is thus a method of a separate class:

```
class Arrow a => ArrowLoop a where
    loop :: a (b, d) (c, d) -> a b c
```

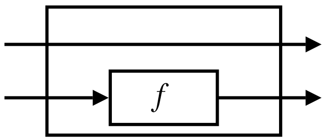
Remarkably, the four combinators `arr`, `>>>`, `first`, and `loop` are sufficient to express any conceivable wiring!

Some more arrow combinators (1)

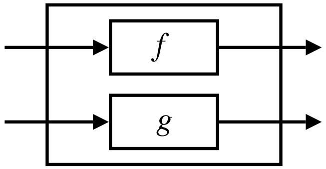
```
second :: Arrow a =>
    a b c -> a (d,b) (d,c)

(***) :: Arrow a =>
    a b c -> a d e -> a (b,d) (c,e)

(&&&) :: Arrow a =>
    a b c -> a b d -> a b (c,d)
```

Some more arrow combinators (2)

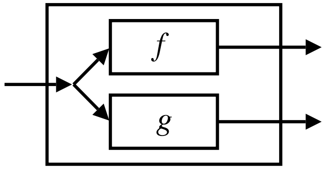
As diagrams:



`second` f



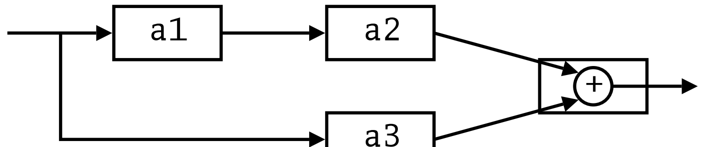
f `***` g



f &&& g

Some more arrow combinators (3)

Exercise 3: Describe the following circuit using arrow combinators:




```
a1, a2, a3 :: A Double Double
```

Exercise 4: The combinators `second`, `(***)`, and `(&&&)` are not primitive, but defined in terms of `arr`, `(>>>)`, and `first`. Suggest suitable definitions!

Reading (1)

- John Hughes. Generalising monads to arrows. *Science of Computer Programming*, 37:67–111, May 2000
- John Hughes. Programming with arrows. In *Advanced Functional Programming*, 2004. To be published by Springer Verlag.
- Henrik Nilsson, Antony Courtney, and John Peterson. Functional reactive programming, continued. In *Proceedings of the 2002 Haskell Workshop*, pp. 51–64, October 2002.

Reading (2)

- Paul Hudak, Antony Courtney, Henrik Nilsson, and John Peterson. Arrows, robots, and functional reactive programming. In *Advanced Functional Programming*, 2002. LNCS 2638, pp. 159–187.