Declarative Reactive Abstractions for Games

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Why Program Games Declaratively?

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Perhaps not so surprising:

- Many pragmatical reasons: performance, legacy issues, . . .
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Perhaps not so surprising:

- Many pragmatical reasons: performance, legacy issues, . . .
- State and effects are pervasive in video games: Is declarative programming even a conceptually good fit?
Many eloquent and compelling cases for functional programming in general:
But Why **NOT**, Really?

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One key point: Program with whole values, not a word-at-a-time. (Will come back to this.)
Possible Gains (1)

With his Keera Studios hat on, Ivan’s top three reasons:

- Reliability.
- Lower long-term maintenance cost.
- Lower production cost and fast time-to-prototype.
Possible Gains (2)

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E.g. pure, declarative code:

- promotes parallelism
- eliminates many sources of errors
“Whole Values” for Games?

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In particular, what should those “whole values” be?
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- Could even be things like pictures.
“Whole Values” for Games?

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In particular, what should those “whole values” be?

- Could be conventional entities like vectors, arrays, lists and aggregates of such.
- Could even be things like pictures.

But we are going to go one step further and consider programming with **time-varying entities**.
Functional Reactive Programming
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- Key idea: Don’t program one-time-step-at-a-time, but describe an evolving entity as whole.
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FRP originated in Conal Elliott and Paul Hudak’s work on Functional Reactive Animation (Fran).
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Functional Reactive Programming

- Key idea: Don’t program one-time-step-at-a-time, but describe an evolving entity as whole.
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FRP has evolved in a number of directions and into different concrete implementations.

We will use Yampa: an FRP system embedded in Haskell.
Take-home Message # 1
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Video games can be programmed declaratively by describing *what* entities are *over* time.
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Our whole values are things like:

- The totality of input from the player
- The animated graphics output
- The entire life of a game object
Take-home Message # 1

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Our whole values are things like:

- The totality of input from the player
- The animated graphics output
- The entire life of a game object

We construct and work with *pure* functions on these:

- The game: function from input to animation
- In the game: fixed point of function on collection of game objects
Take-home Message # 2

You too can program games declaratively . . .
Take-home Message # 2

You too can program games declaratively . . . today!
Take-home Game!

Or download one for free to your Android device!

Play Store: Pang-a-lambda (Keera Studios)
Key FRP Features

Combines conceptual simplicity of the synchronous data flow approach with the flexibility and abstraction power of higher-order functional programming:
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- Synchronous
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Good fit for typical video games
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- First class temporal abstractions
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Good fit for typical video games (but not everything labelled “FRP” supports them all).
Yampa

- FRP implementation embedded in Haskell
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- Key notions:
  - *Signals*: time-varying values
  - *Signal Functions*: pure functions on signals
  - *Switching*: temporal composition of signal functions
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- Key notions:
  - **Signals**: time-varying values
  - **Signal Functions**: pure functions on signals
  - **Switching**: temporal composition of signal functions
- Programming model:
Signal Functions
Signal Functions

Intuition:
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\[ Time \approx \mathbb{R} \]
Signal Functions

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

**Intuition:**

\[ Time \approx \mathbb{R} \]

\[ Signal \ a \approx Time \rightarrow a \]

\[ x :: Signal \ T1 \]

\[ y :: Signal \ T2 \]

\[ SF \ a \ b \approx Signal \ a \rightarrow Signal \ b \]

\[ f :: SF \ T1 \ T2 \]
Signal Functions

Intuition:

\[
\begin{align*}
\text{Time} & \approx \mathbb{R} \\
\text{Signal } a & \approx \text{Time } \to a \\
x & :: \text{Signal } T1 \\
y & :: \text{Signal } T2 \\
\text{SF } a \ b & \approx \text{Signal } a \to \text{Signal } b \\
f & :: \text{SF } T1 \ T2
\end{align*}
\]

Additionally, *causality* required: output at time \( t \) must be determined by input on interval \([0, t]\).
Some Basic Signal Functions

\[ \text{identity} :: SF ~ a ~ a \]
Some Basic Signal Functions

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

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

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

\[ \text{constant} :: b \rightarrow SF \ a \ b \]

\[ \text{integral} :: \text{VectorSpace} \ a \ s \Rightarrow SF \ a \ a \]

\[ y(t) = \int_{0}^{t} x(\tau) \, d\tau \]
Composition

In Yampa, systems are described by combining signal functions (forming new signal functions).
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For example, serial composition:
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A *combinator* that captures this idea:

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

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A *combinator* that captures this idea:

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Signal functions are the primary notion; signals a secondary one, only existing indirectly.
What about larger, more complicated networks? How many combinators are needed?
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John Hughes’s *Arrow* framework provides a good answer!
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The Arrow framework (1)

\[ arr \ f \quad \text{(arr)} \quad f \gg g \quad \text{(arr)} \]

\[ \text{first } f \quad \text{(first)} \quad \text{loop } f \quad \text{(loop)} \]

\[
\begin{align*}
arr &:: (a \to b) \to SF\ a\ b \\
(\gg\gg) &:: SF\ a\ b \to SF\ b\ c \to SF\ a\ c \\
\text{first} &:: SF\ a\ b \to SF\ (a, c)\ (b, c) \\
\text{loop} &:: SF\ (a, c)\ (b, c) \to SF\ a\ b
\end{align*}
\]
The Arrow framework (2)

Examples:

\[
\text{identity :: } SF \ a \ a \\
\text{identity} = \text{arr id}
\]

\[
\text{constant :: } b \rightarrow SF \ a \ b \\
\text{constant } b = \text{arr } (\text{const } b)
\]

\[
\langle \langle : (b \rightarrow c) \rightarrow SF \ a \ b \rightarrow SF \ a \ c \\
f \langle \langle sf = sf \rangle \rangle = \text{arr } f
\]
proc $x \rightarrow do$

rec

$u \leftarrow f \prec (x, v)$

$y \leftarrow g \prec u$

$v \leftarrow h \prec (u, x)$

$return A \leftarrow y$
Arrow notation

\[
\text{proc } x \rightarrow \text{ do}
\]

\[
\text{rec}
\]

\[
u \leftarrow f \prec (x, v)
\]

\[
y \leftarrow g \prec u
\]

\[
v \leftarrow h \prec (u, x)
\]

\[
\text{return } A \prec y
\]

Only syntactic sugar: everything translated into a combinator expression.
Oscillator from Pang-a-lambda

This oscillator determines the movement of blocks:

\[
osi \; ampl \; period = proc _ \rightarrow do
\]
\[
rec
\]
\[
let \; a = -(2.0 \times pi \div period) \uparrow 2 \times p
\]
\[
v \leftarrow \text{integral} \leftarrow a
\]
\[
p \leftarrow (ampl+) \leftrightsquigarrow \text{integral} \leftrightsquigarrow v
\]
\[
returnA \leftarrow p
\]

Direct transliteration of standard equations.
A Bouncing Ball

Lots of bouncing balls in Pang-a-lambda!

\[ y = y_0 + \int v \, dt \]

\[ v = v_0 + \int -9.81 \]

On impact:

\[ v = -v(t^-) \]

(fully elastic collision)
Modelling the Bouncing Ball: Part 1

Free-falling ball:

```plaintext
type Pos = Double
type Vel = Double

fallingBall :: Pos → Vel → SF () (Pos, Vel)
fallingBall y0 v0 = proc () → do
  v ← (v0+) ⪆ integral ← 9.81
  y ← (y0+) ⪆ integral ← v
  returnA ← (y, v)
```

Declarative Reactive Abstractions for Games – p.22/30
Yampa models discrete-time signals by lifting the \textit{co-domain} of signals using an option-type:

\[
data \ Event \ a = \text{NoEvent} \mid \ Event \ a
\]

\textit{Discrete-time signal} $=$ \text{Signal} (\text{Event} $\alpha$).
Yampa models discrete-time signals by lifting the co-domain of signals using an option-type:

\[
\text{data } \text{Event } a = \text{NoEvent} \mid \text{Event } a
\]

**Discrete-time signal** = \( \text{Signal (Event } \alpha) \).

Some functions and event sources:

\[
\text{tag} :: \text{Event } a \to b \to \text{Event } b
\]

\[
\text{after} :: \text{Time} \to b \to \text{SF } a (\text{Event } b)
\]

\[
\text{edge} :: \text{SF } \text{Bool} (\text{Event } ())
\]
Detecting when the ball goes through the floor:

\[
\text{fallingBall'} ::
\]
\[
\text{Pos} \rightarrow \text{Vel} \rightarrow \text{SF} () \ ((\text{Pos}, \text{Vel}), \text{Event} (\text{Pos}, \text{Vel}))
\]
\[
\text{fallingBall'} y0 v0 = \text{proc} () \rightarrow \text{do}
\]
\[
yv@ (y, \_ ) \leftarrow \text{fallingBall} y0 v0 \leftarrow ()
\]
\[
\text{hit} \leftarrow \text{edge} \quad \rightarrow y \leq 0
\]
\[
\text{returnA} \leftarrow (yv, \text{hit} \text{ ‘tag’ } yv)
\]
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.
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  • This is *temporal composition* of signal functions.
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Switchers thus allow systems with *varying structure* to be described.
Q: How and when do signal functions “start”?  
A: • **Switchers** apply a signal function to its input signal at some point in time.  
  • This is *temporal composition* of signal functions.  

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

Generalised switches allow composition of *collections* of signal functions. Can be used to model e.g. varying number of objects in a game.
The Basic Switch

Idea:

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

\[
\text{switch:: }
\]

\[
\begin{align*}
\text{SF} & \ a \ (b, \ Event \ c) \\
\rightarrow & \ (c \rightarrow \ \text{SF} \ a \ b) \\
\rightarrow & \ \text{SF} \ a \ b
\end{align*}
\]
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\rightarrow SF \ a \ b
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The Basic Switch

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

\[
\text{switch} ::
\]

\[
SF \ a \ (b, \ Event \ c)
\]

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

\[
\rightarrow SF \ a \ b
\]

Function yielding SF to switch into
Making the ball bounce:

\[
\text{bouncingBall} :: \text{Pos} \rightarrow \text{SF} () (\text{Pos}, \text{Vel})
\]

\[
bouncingBall \ y0 = \text{bbAux} \ y0 \ 0.0
\]

where

\[
\text{bbAux} \ y0 \ v0 = \ \\
\text{switch} (\text{fallingBall}' \ y0 \ v0) \ # \ \lambda (y, v) \rightarrow \\
\text{bbAux} \ y (-v)
\]
Game Objects

```haskell
data Object = Object {
  objectName :: ObjectName,
  objectKind :: ObjectKind,
  objectPos :: Pos2D,
  objectVel :: Vel2D,
  ...
}
```

```haskell
data ObjectKind = Ball . . . | Player . . . | . . .
```

```haskell
data ObjectInput = ObjectInput
  { userInput :: Controller,
    collisions :: Collisions
  }
```
Overall Game Structure

\[
gamePlay :: [\text{ListSF} \ \text{ObjectInput} \ \text{Object}] \\
\rightarrow \text{SF Controller} ([\text{Object}], \text{Time})
\]

\[
gamePlay \ \text{objs} = \text{loopPre} \ [\ ] \$
\]

\[
\text{proc} \ (\text{input}, \ cs) \rightarrow \text{do}
\]

\[
\text{let} \ \text{oi} = \text{ObjectInput} \ \text{input} \ \text{cs}
\]

\[
\text{ol} \leftarrow \text{dlSwitch} \ \text{objs} \leftarrow \text{oi}
\]

\[
\text{let} \ \text{cs}' = \text{detectCollisions} \ \text{ol}
\]

\[
\text{tLeft} \leftarrow \text{time} \leftarrow ()
\]

\[
\text{returnA} \leftarrow (((\text{ol}, \text{tLeft}), \text{cs}'))
\]

*ListSF* and *dlSwitch* are related abstractions that allow objects to die or spawn new ones.
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  - Not everything fit easily into the FRP paradigm: e.g., interfacing to existing GUI toolkits, other imperative APIs.
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- It allows systems to be described in terms of whole values varying over time.

- Not covered in this talk:
  - Not everything fit easily into the FRP paradigm: e.g., interfacing to existing GUI toolkits, other imperative APIs.
  - But also such APIs can be given a “whole-value treatment” to improve the fit within a declarative setting. E.g. Reactive Values and Relations.