Declarative Reactive Abstractions for Games

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Why Program Games Declaratively?

Video games are not a major application area for declarative programming . . . or even a niche one.

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?

But Why NOT, Really?

Many eloquent and compelling cases for functional programming in general:

- John Backus, 1977 ACM Turing Award Lecture: Can Programming Be Liberated from the von Neumann Style?
- John Hughes, recent retrospective: Why Functional Programming Matters (on YouTube, recommended)

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)

High profile people in the games industry have pointed out potential benefits:

- John D. Carmack, id Software: Wolfenstein 3D, Doom, Quake
- Tim Sweeney, Epic Games: The Unreal Engine

E.g. pure, declarative code:

- promotes parallelism
- eliminates many sources of errors

"Whole Values" for Games?

How should we go about writing video games "declaratively"?

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

- 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.
- 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

Video games can be programmed declaratively by describing ***what*** entities are ***over*** time.

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:

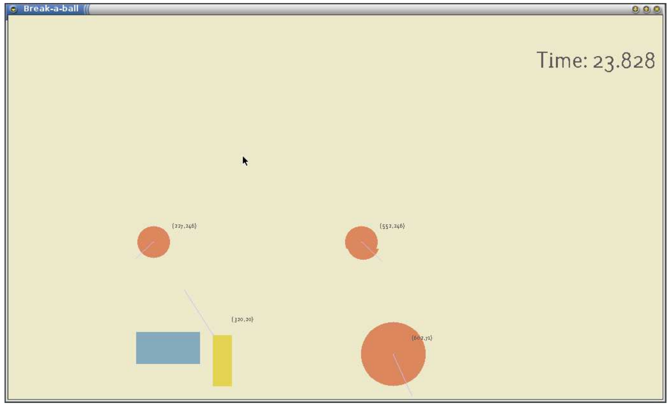
- The game: function from input to animation
- In the game: fixed point of function on collection of game objects

Take-home Message # 2

You too can program games declaratively . . . today!

Take-home Game!

Or download one for free to your Android device!



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

Key FRP Features

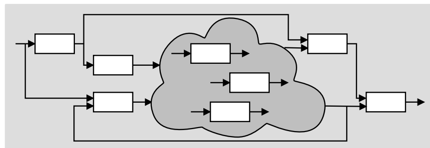
Combines conceptual simplicity of the synchronous data flow approach with the flexibility and abstraction power of higher-order functional programming:

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

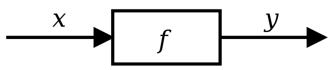
Good fit for typical video games
(but not everything labelled “FRP” supports them all).

Yampa

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



Signal Functions



Intuition:

$$\begin{array}{l} \mathit{Time} \approx \mathbb{R} \\ \mathit{Signal}\ a \approx \mathit{Time} \rightarrow a \\ x :: \mathit{Signal}\ \mathit{T1} \\ y :: \mathit{Signal}\ \mathit{T2} \\ \mathit{SF}\ a\ b \approx \mathit{Signal}\ a \rightarrow \mathit{Signal}\ b \\ f :: \mathit{SF}\ \mathit{T1}\ \mathit{T2} \end{array}$$

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

Some Basic Signal Functions

$\mathit{identity} :: \mathit{SF}\ a\ a$

$\mathit{constant} :: b \rightarrow \mathit{SF}\ a\ b$

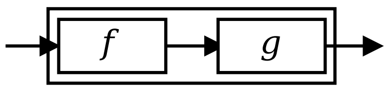
$\mathit{integral} :: \mathit{VectorSpace}\ a\ s \Rightarrow \mathit{SF}\ a\ a$

$$y(t) = \int_0^t x(\tau)\,\mathrm{d}\tau$$

Composition

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

For example, serial composition:



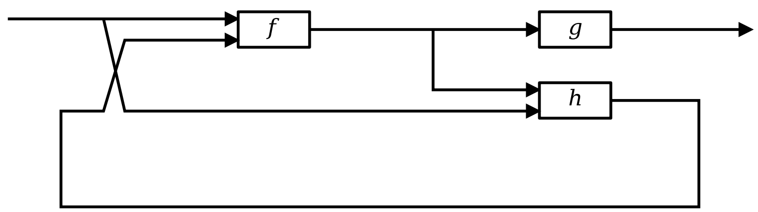
A ***combinator*** that captures this idea:

$$(\ggg) :: \mathit{SF}\ a\ b \rightarrow \mathit{SF}\ b\ c \rightarrow \mathit{SF}\ a\ c$$

Signal functions are the primary notion; signals a secondary one, only existing indirectly.

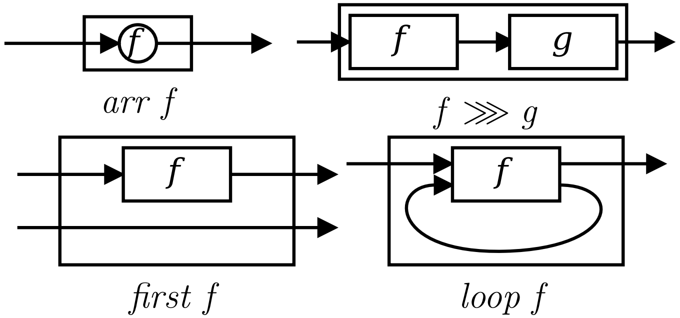
Systems

What about larger, more complicated networks? How many combinators are needed?



John Hughes's ***Arrow*** framework provides a good answer!

The Arrow framework (1)



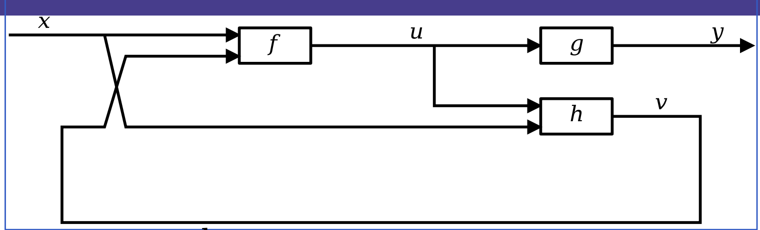
$$
\begin{aligned}
&arr \;\; :: (a \to b) \to SF\ a\ b \\
&(\ggg) :: SF\ a\ b \to SF\ b\ c \to SF\ a\ c \\
&first \;\; :: SF\ a\ b \to SF\ (a, c)\ (b, c) \\
&loop \;\; :: SF\ (a, c)\ (b, c) \to SF\ a\ b
\end{aligned}
$$

The Arrow framework (2)

Examples:

$$
\begin{aligned}
&identity :: SF\ a\ a \\
&identity = arr\ id \\
&constant :: b \to SF\ a\ b \\
&constant\ b = arr\ (const\ b) \\
&\hat{}\!\ll :: (b \to c) \to SF\ a\ b \to SF\ a\ c \\
&f\ \hat{}\!\ll\ sf = sf \ggg arr\ f
\end{aligned}
$$

Arrow notation



$$
\begin{aligned}
&\mathbf{proc}\ x \to \mathbf{do} \\
&\quad \mathbf{rec} \\
&\qquad u \leftarrow f \prec (x, v) \\
&\qquad y \leftarrow g \prec u \\
&\qquad v \leftarrow h \prec (u, x) \\
&\quad returnA \prec y
\end{aligned}
$$

Only syntactic sugar: everything translated into a combinator expression.

Oscillator from Pang-a-lambda

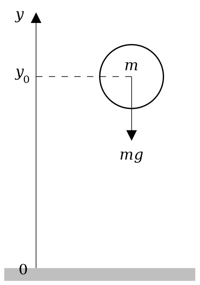
This oscillator determines the movement of blocks:

$$
\begin{aligned}
&osci\ ampl\ period = \mathbf{proc}\ \_ \to \mathbf{do} \\
&\quad \mathbf{rec} \\
&\qquad \mathbf{let}\ a = -(2.0 * pi\ /\ period) \uparrow 2 * p \\
&\qquad v \leftarrow \qquad\qquad\qquad integral \prec a \\
&\qquad p \leftarrow (ampl+)\ \hat{}\!\ll\ integral \prec v \\
&\quad returnA \prec p
\end{aligned}
$$

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:

$$\begin{array}{l}
\textbf{type } Pos = Double \\
\textbf{type } Vel = Double \\
fallingBall :: Pos \rightarrow Vel \rightarrow SF\ ()\ (Pos, Vel) \\
fallingBall\ y0\ v0 = \textbf{proc}\ () \rightarrow \textbf{do} \\
\quad v \leftarrow (v0+)\ \hat{}\!\!\ll integral \prec\ -9.81 \\
\quad y \leftarrow (y0+)\ \hat{}\!\!\ll integral \prec v \\
\quad returnA \prec (y, v)
\end{array}$$

Events

Yampa models discrete-time signals by lifting the ***co-domain*** of signals using an option-type:

$$\textbf{data } Event\ a = NoEvent \mid Event\ a$$

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

Some functions and event sources:

$$\begin{array}{l}
tag :: Event\ a \rightarrow b \rightarrow Event\ b \\
after :: Time \rightarrow b \rightarrow SF\ a\ (Event\ b) \\
edge :: SF\ Bool\ (Event\ ())
\end{array}$$

Modelling the Bouncing Ball: Part 2

Detecting when the ball goes through the floor:

$$\begin{array}{l}
fallingBall' :: \\
\quad Pos \rightarrow Vel \rightarrow SF\ ()\ ((Pos, Vel), Event\ (Pos, Vel)) \\
fallingBall'\ y0\ v0 = \textbf{proc}\ () \rightarrow \textbf{do} \\
\quad yv@(y, _) \leftarrow fallingBall\ y0\ v0 \prec () \\
\quad hit \qquad\quad\ \leftarrow edge \qquad\qquad\qquad \prec y \leqslant 0 \\
\quad returnA \prec (yv, hit\ `tag`\ yv)
\end{array}$$

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 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.

$$\begin{aligned}&\mathit{switch} ::\\ &\quad \mathit{SF}\ a\ (b, \mathit{Event}\ c)\\ &\quad \rightarrow (c \rightarrow \mathit{SF}\ a\ b)\\ &\quad \rightarrow \mathit{SF}\ a\ b\end{aligned}$$

Modelling the Bouncing Ball: Part 3

Making the ball bounce:

$$\begin{aligned}&\mathit{bouncingBall} :: \mathit{Pos} \rightarrow \mathit{SF}\ ()\ (\mathit{Pos}, \mathit{Vel})\\ &\mathit{bouncingBall}\ \mathit{y0} = \mathit{bbAux}\ \mathit{y0}\ 0.0\\ &\quad \mathbf{where}\\ &\qquad \mathit{bbAux}\ \mathit{y0}\ \mathit{v0} =\\ &\qquad\quad \mathit{switch}\ (\mathit{fallingBall}'\ \mathit{y0}\ \mathit{v0})\ \$\ \lambda(y, v) \rightarrow\\ &\qquad\quad \mathit{bbAux}\ y\ (-v)\end{aligned}$$

Game Objects

$$\begin{aligned}&\mathbf{data}\ \mathit{Object} = \mathit{Object}\ \{\ \mathit{objectName} :: \mathit{ObjectName}\\ &\qquad\qquad\qquad\qquad\quad ,\mathit{objectKind} :: \mathit{ObjectKind}\\ &\qquad\qquad\qquad\qquad\quad ,\mathit{objectPos} :: \mathit{Pos2D}\\ &\qquad\qquad\qquad\qquad\quad ,\mathit{objectVel} :: \mathit{Vel2D}\\ &\qquad\qquad\qquad\qquad\quad \ldots\\ &\qquad\qquad\qquad\qquad\quad \}\\ &\mathbf{data}\ \mathit{ObjectKind} = \mathit{Ball} \ldots \mid \mathit{Player} \ldots \mid \ldots\\ &\mathbf{data}\ \mathit{ObjectInput} = \mathit{ObjectInput}\\ &\quad \{\ \mathit{userInput} :: \mathit{Controller}\\ &\quad ,\mathit{collisions} :: \mathit{Collisions}\\ &\quad \}\end{aligned}$$

Overall Game Structure

$$
\begin{aligned}
&\mathit{gamePlay} :: [\mathit{ListSF}\ \mathit{ObjectInput}\ \mathit{Object}] \\
&\qquad\qquad \to \mathit{SF}\ \mathit{Controller}\ ([\mathit{Object}], \mathit{Time}) \\
&\mathit{gamePlay}\ \mathit{objs} = \mathit{loopPre}\ [\,]\ \$ \\
&\quad \mathbf{proc}\ (\mathit{input}, \mathit{cs}) \to \mathbf{do} \\
&\qquad \mathbf{let}\ \mathit{oi} = \mathit{ObjectInput}\ \mathit{input}\ \mathit{cs} \\
&\qquad \mathit{ol} \leftarrow \mathit{dlSwitch}\ \mathit{objs} \prec \mathit{oi} \\
&\qquad \mathbf{let}\ \mathit{cs}' = \mathit{detectCollisions}\ \mathit{ol} \\
&\qquad \mathit{tLeft} \leftarrow \mathit{time} \prec () \\
&\qquad \mathit{returnA} \prec ((\mathit{ol}, \mathit{tLeft}), \mathit{cs}')
\end{aligned}
$$

ListSF and $\mathit{dlSwitch}$ are related abstractions that allow objects to die or spawn new ones.

Conclusions

- FRP offers one way to write interactive games and similar software in a declarative way.
- 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***.