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, . . .
- State and effects are pervasive in video games: Is declarative programming even a conceptually good fit?

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

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- Could even be things like pictures.

“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

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- 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.

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- The totality of input from the player
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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

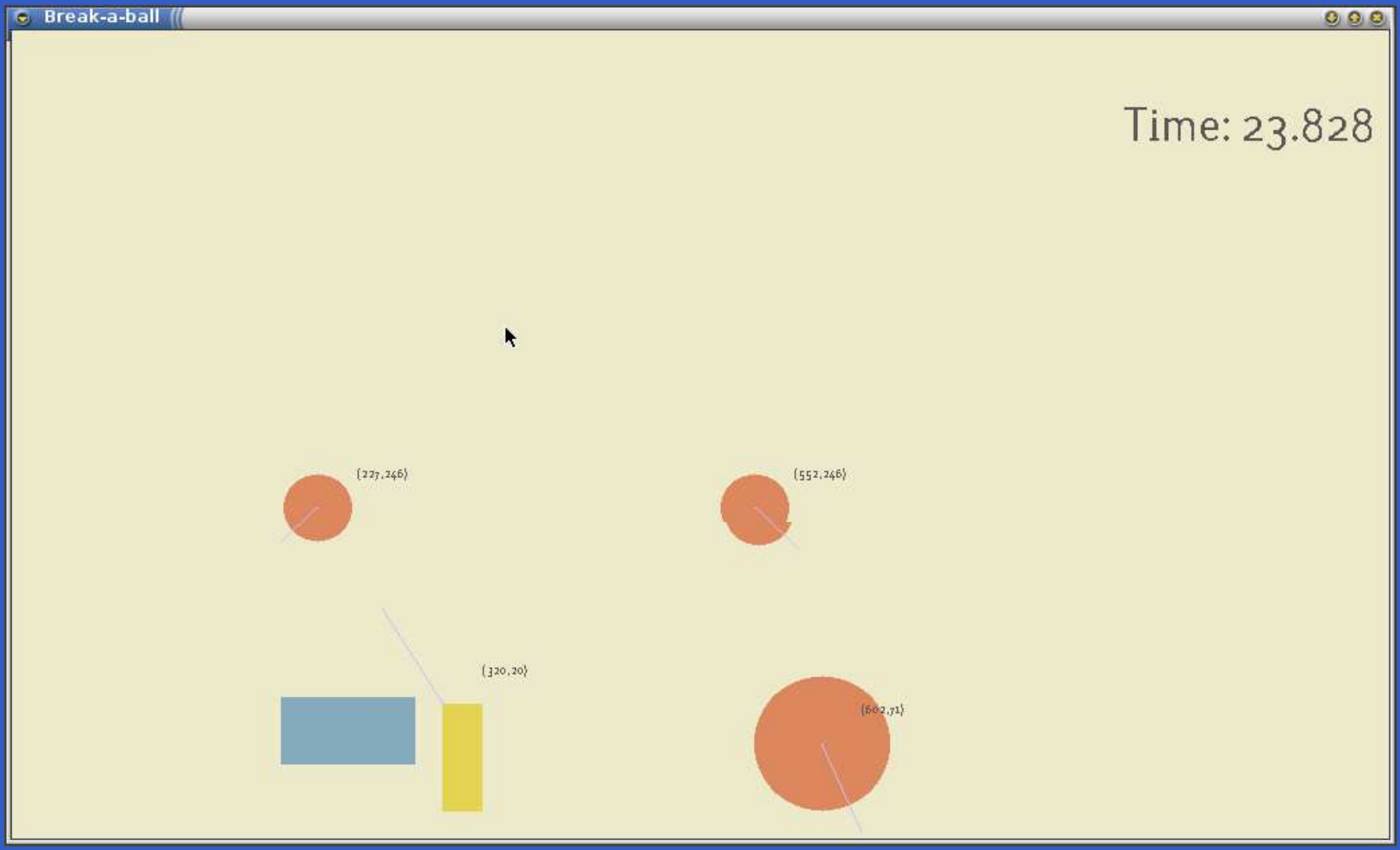
You too can program games declaratively . . .

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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Good fit for typical video games

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

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

Yampa

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  - ***Signals***: time-varying values
  - ***Signal Functions***: pure functions on signals
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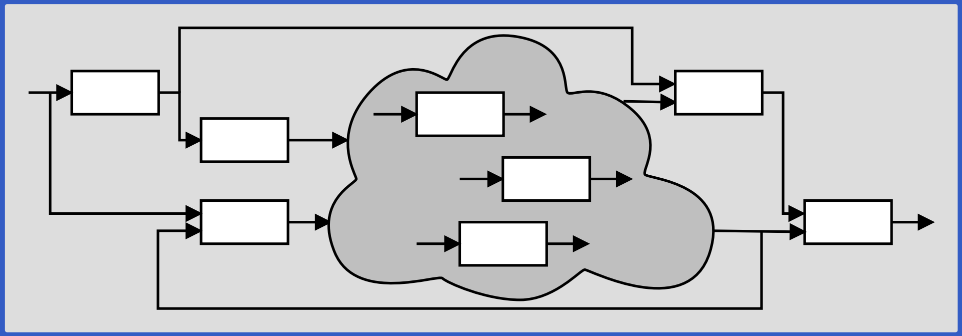
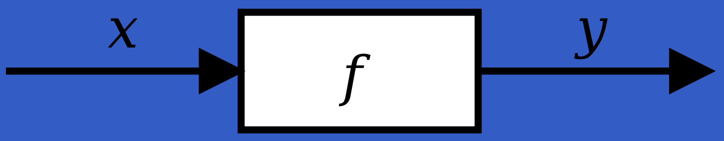
- Programming model:



Signal Functions



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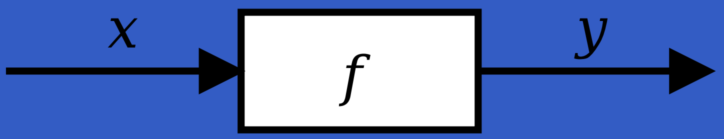
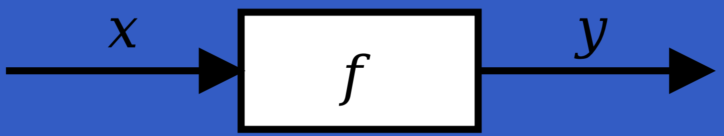


Intuition:

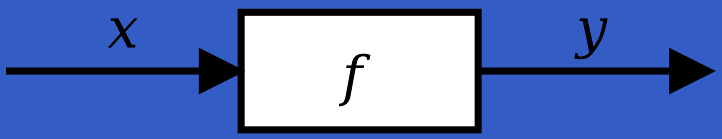
Signal Functions



Intuition:

$$Time \approx \mathbb{R}$$

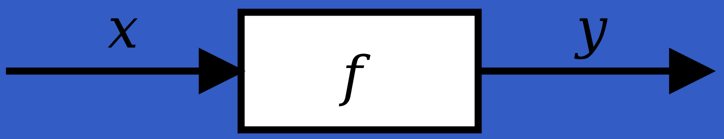
Signal Functions



Intuition:

$$
\begin{aligned}
&\mathit{Time} \approx \mathbb{R} \\
&\mathit{Signal}\ a \approx \mathit{Time} \rightarrow a \\
&x :: \mathit{Signal}\ \mathit{T1} \\
&y :: \mathit{Signal}\ \mathit{T2}
\end{aligned}
$$

Signal Functions



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$$Time \approx \mathbb{R}$$
$$Signal\ a \approx Time \rightarrow a$$
$$x :: Signal\ T1$$
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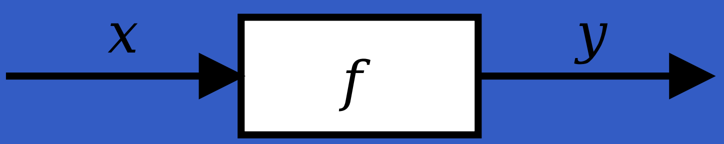
$$SF\ a\ b \approx Signal\ a \rightarrow Signal\ b$$
$$f :: SF\ T1\ T2$$

Signal Functions



Intuition:

$$\mathit{Time} \approx \mathbb{R}$$
$$\mathit{Signal}\ a \approx \mathit{Time} \to a$$
$$x :: \mathit{Signal}\ \mathit{T1}$$
$$y :: \mathit{Signal}\ \mathit{T2}$$
$$\mathit{SF}\ a\ b \approx \mathit{Signal}\ a \to \mathit{Signal}\ b$$
$$f :: \mathit{SF}\ \mathit{T1}\ \mathit{T2}$$

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

Some Basic Signal Functions

$$identity :: SF\ a\ a$$

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$$identity :: SF\ a\ a$$

$$constant :: b \rightarrow SF\ a\ b$$

Some Basic Signal Functions

$$identity :: SF\ a\ a$$

$$constant :: b \rightarrow SF\ a\ b$$

$$integral :: VectorSpace\ a\ s \Rightarrow SF\ a\ a$$

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

Composition

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

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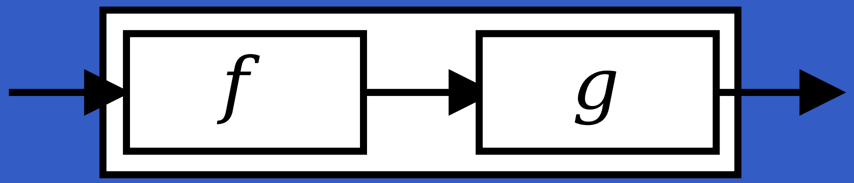
For example, serial composition:



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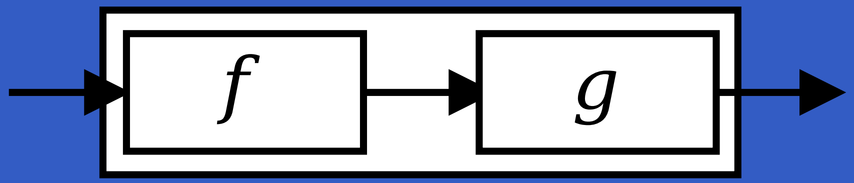

A ***combinator*** that captures this idea:

$$(\ggg) :: SF\ a\ b \rightarrow SF\ b\ c \rightarrow SF\ a\ c$$

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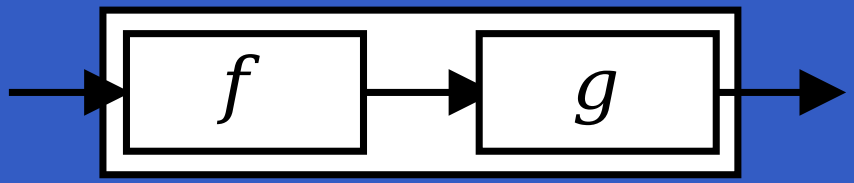


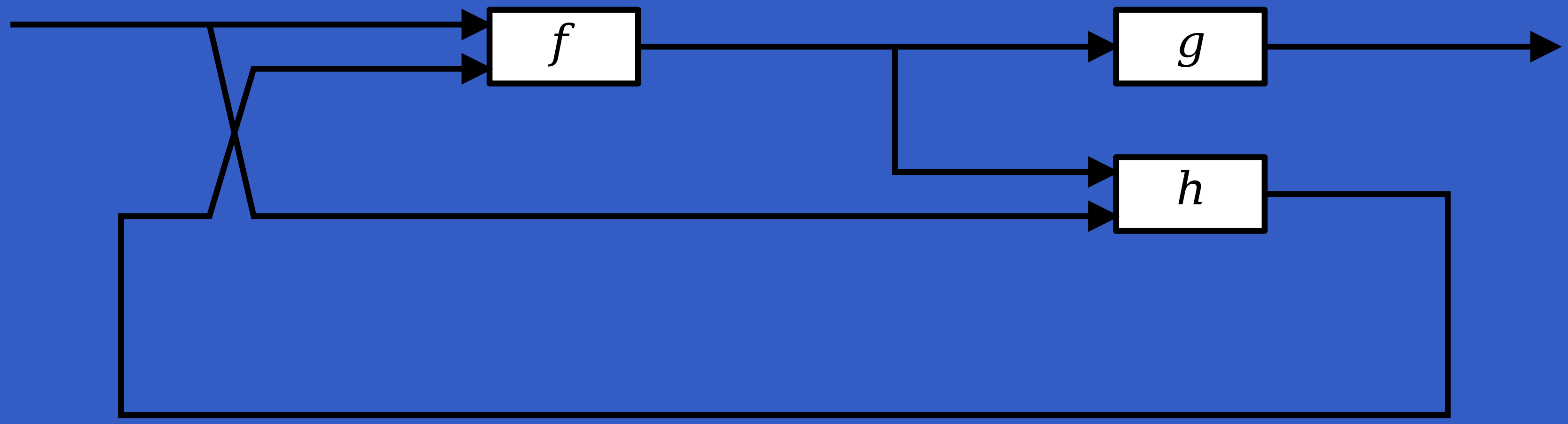
A ***combinator*** that captures this idea:

$$(\ggg) :: SF\ a\ b \rightarrow SF\ b\ c \rightarrow SF\ a\ c$$

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?



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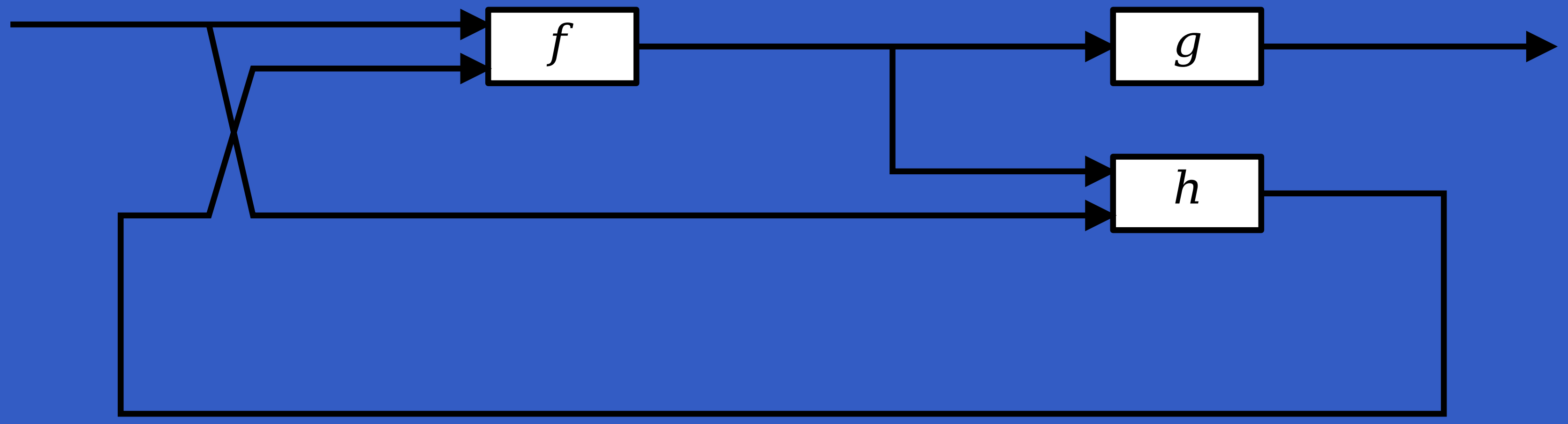
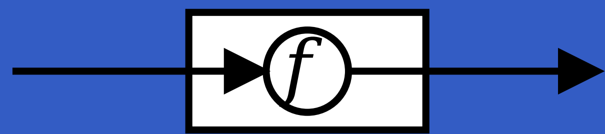
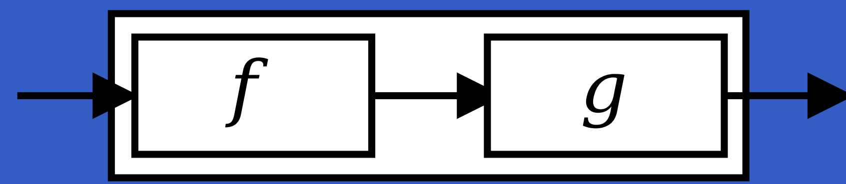


John Hughes's ***Arrow*** framework provides a good answer!

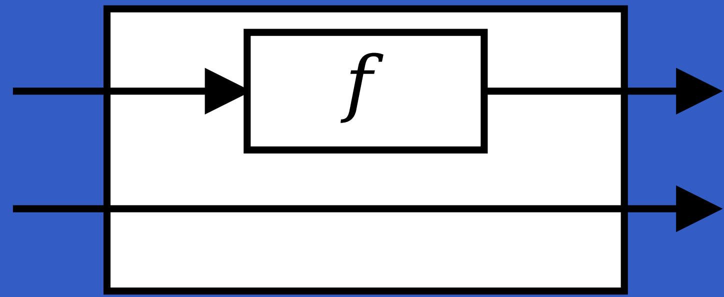
The Arrow framework (1)



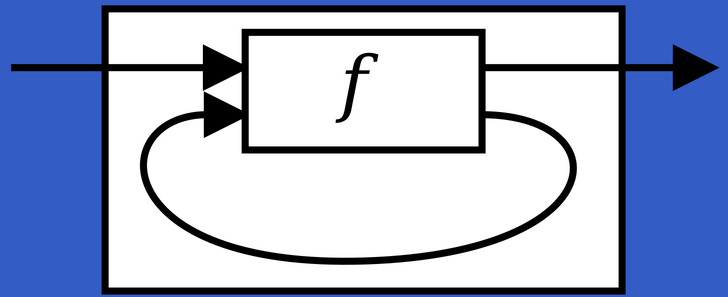
$arr\ f$



$f \ggg g$



$first\ f$



$loop\ f$

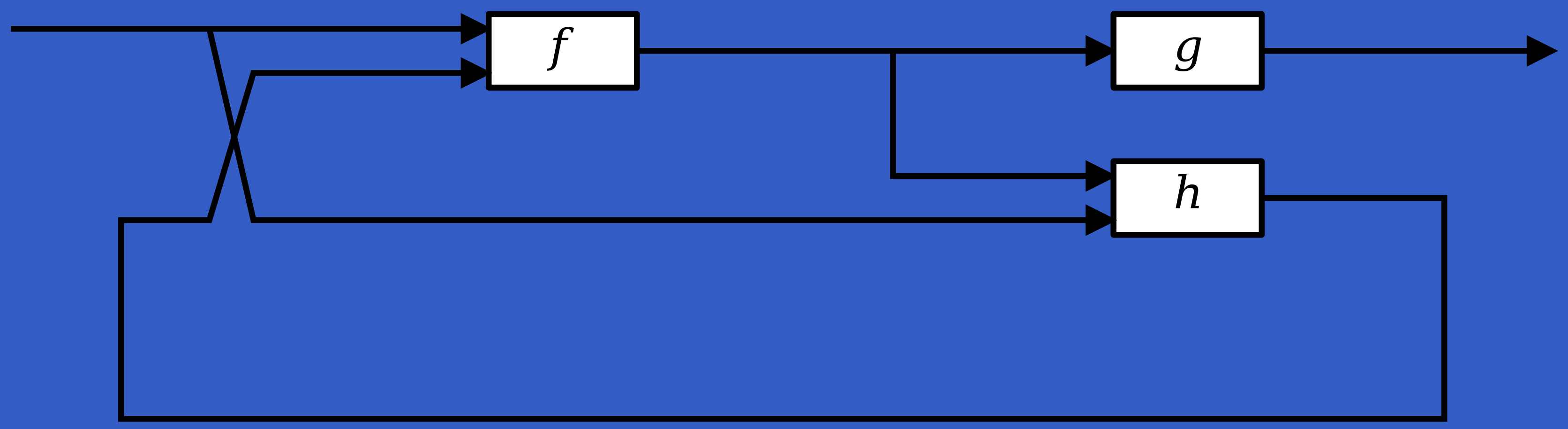
$$
\begin{aligned}
arr &:: (a \rightarrow b) \rightarrow SF\ a\ b \\
(\ggg) &:: SF\ a\ b \rightarrow SF\ b\ c \rightarrow SF\ a\ c \\
first &:: SF\ a\ b \rightarrow SF\ (a, c)\ (b, c) \\
loop &:: SF\ (a, c)\ (b, c) \rightarrow SF\ a\ b
\end{aligned}
$$

The Arrow framework (2)

Examples:

$$identity :: SF\ a\ a$$
$$identity = arr\ id$$
$$constant :: b \rightarrow SF\ a\ b$$
$$constant\ b = arr\ (const\ b)$$
$$\hat{}\!\ll :: (b \rightarrow c) \rightarrow SF\ a\ b \rightarrow SF\ a\ c$$
$$f\ \hat{}\!\ll sf = sf \ggg arr\ f$$

Arrow notation



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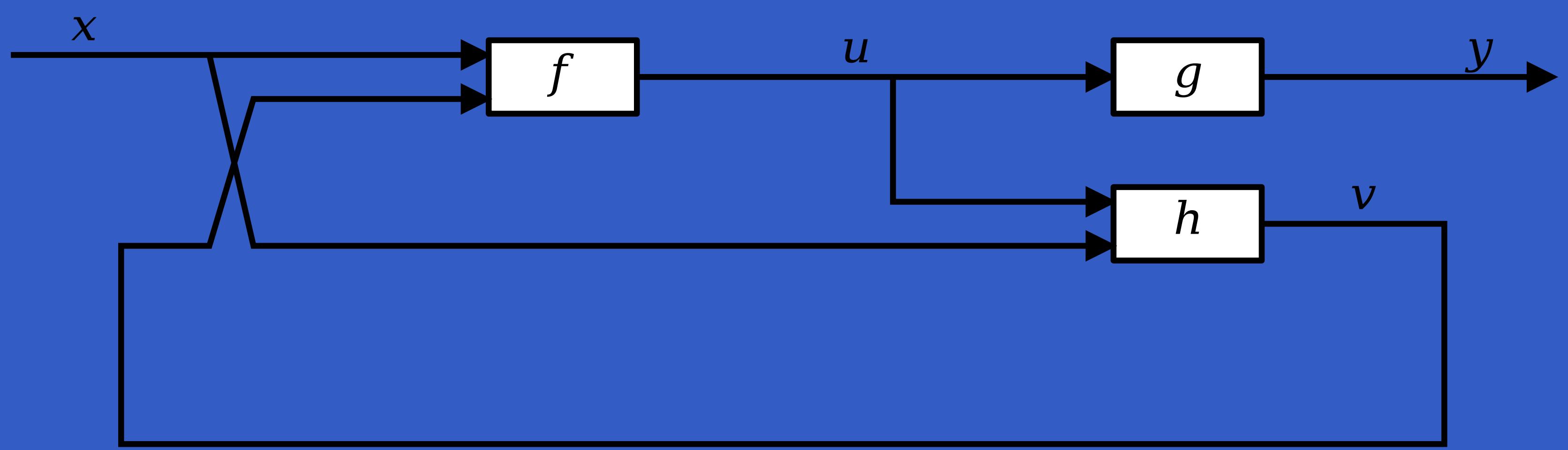

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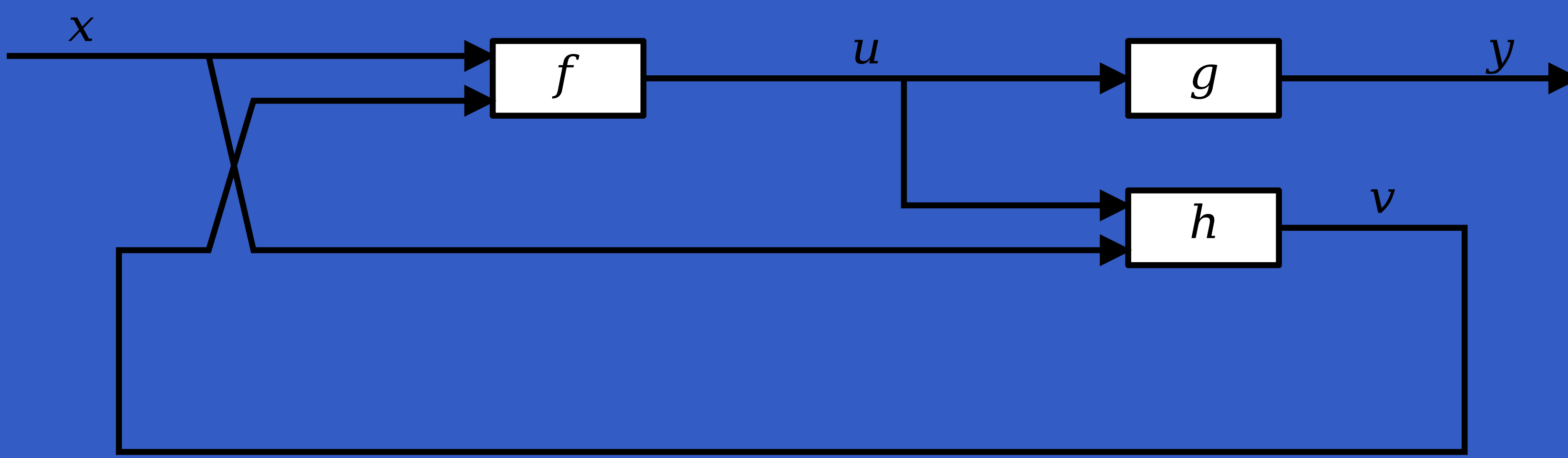


proc $x \rightarrow$ **do**

rec

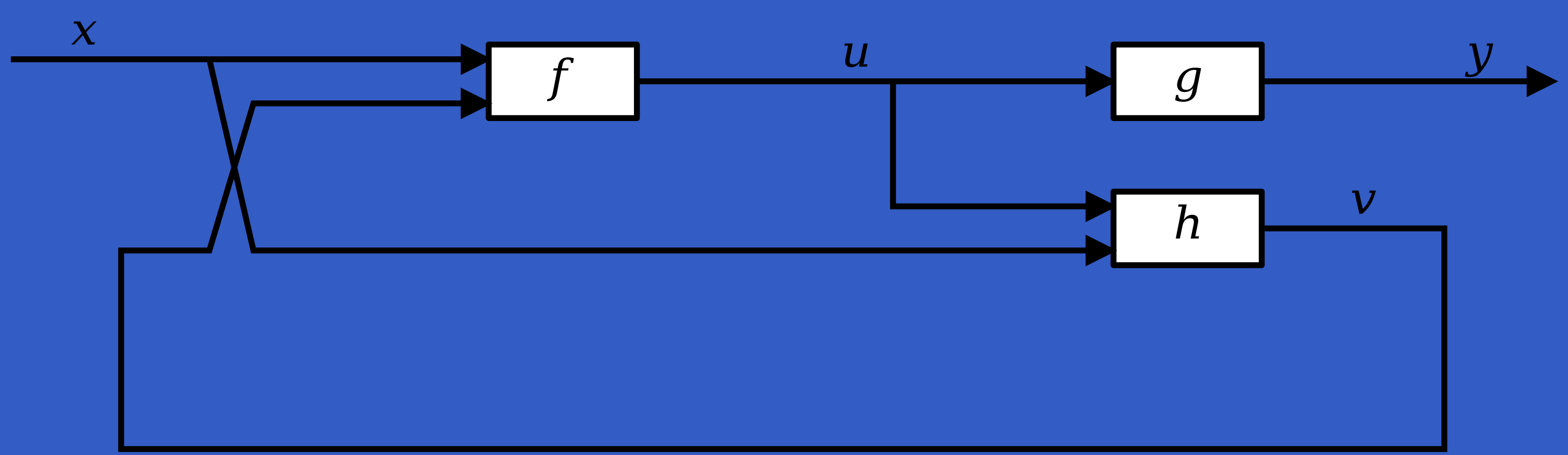
$u \leftarrow f \prec (x, v)$

$y \leftarrow g \prec u$

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

$returnA \prec y$

Arrow notation



proc $x \rightarrow$ **do**

rec

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

$y \leftarrow g \prec u$

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

$returnA \prec y$

Only syntactic sugar: everything translated into a combinator expression.

Oscillator from Pang-a-lambda

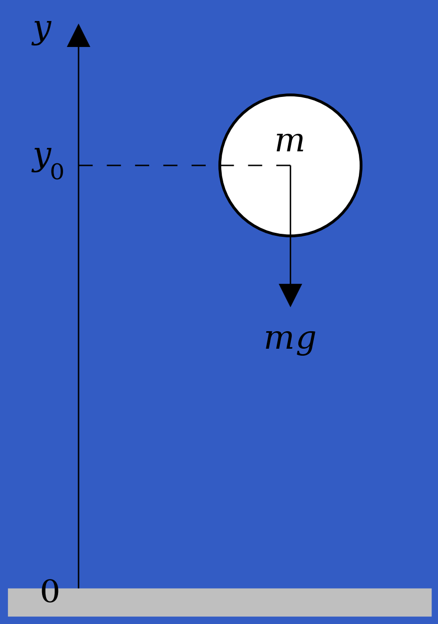
This oscillator determines the movement of blocks:

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

Direct transliteration of standard equations.

A Bouncing Ball

Lots of bouncing balls in Pang-a-lambda!



$$
\begin{aligned}
y &= y_0 + \int v \,\mathrm{d}t \\
v &= v_0 + \int -9.81
\end{aligned}
$$

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:

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

Discrete-time signal $= \mathtt{Signal}\ (\mathtt{Event}\ \alpha)$.

Events

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

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

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

Some functions and event sources:

$$tag :: Event\ a \rightarrow b \rightarrow Event\ b$$

$$after :: Time \rightarrow b \rightarrow SF\ a\ (Event\ b)$$

$$edge :: SF\ Bool\ (Event\ ())$$

Modelling the Bouncing Ball: Part 2

Detecting when the ball goes through the floor:

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

Switching

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

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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.

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

The Basic Switch

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Initial SF with event source

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

The Basic Switch

Idea:

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Function yielding SF to switch into

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

Modelling the Bouncing Ball: Part 3

Making the ball bounce:

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

Game Objects

$$
\begin{aligned}
&\textbf{data}\ \mathit{Object} = \mathit{Object}\ \{\ \mathit{objectName} :: \mathit{ObjectName}\\
&\qquad\qquad\qquad\qquad\quad ,\ \mathit{objectKind}\ \ :: \mathit{ObjectKind}\\
&\qquad\qquad\qquad\qquad\quad ,\ \mathit{objectPos}\ \ \ :: \mathit{Pos2D}\\
&\qquad\qquad\qquad\qquad\quad ,\ \mathit{objectVel}\ \ \ :: \mathit{Vel2D}\\
&\qquad\qquad\qquad\qquad\quad \ldots\\
&\qquad\qquad\qquad\qquad\quad \}
\end{aligned}
$$

$$\textbf{data}\ \mathit{ObjectKind} = \mathit{Ball}\ \ldots \mid \mathit{Player}\ \ldots \mid \ldots$$

$$
\begin{aligned}
&\textbf{data}\ \mathit{ObjectInput} = \mathit{ObjectInput}\\
&\quad \{\ \mathit{userInput} \quad :: \mathit{Controller}\\
&\quad ,\ \mathit{collisions} \quad :: \mathit{Collisions}\\
&\quad \}
\end{aligned}
$$

Overall Game Structure

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

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

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- Not covered in this talk:

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- 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.
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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***.