COMP4075/G54RFP: Lecture 17

Arrows, FRP, and Games

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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

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E.g. pure, declarative code:

- promotes parallelism
- eliminates many sources of errors

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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***.

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- The totality of input from the player
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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 # 1 (cont.)

- That said, we focus on the core game logic in the following: there will often be code around the “edges” (e.g., rendering, interfacing to input devices) that may not be very declarative, at least not in the sense above.
- See Perez & Nilsson (2015) for one approach.

Take-home Message # 2

You too can program games declaratively . . .

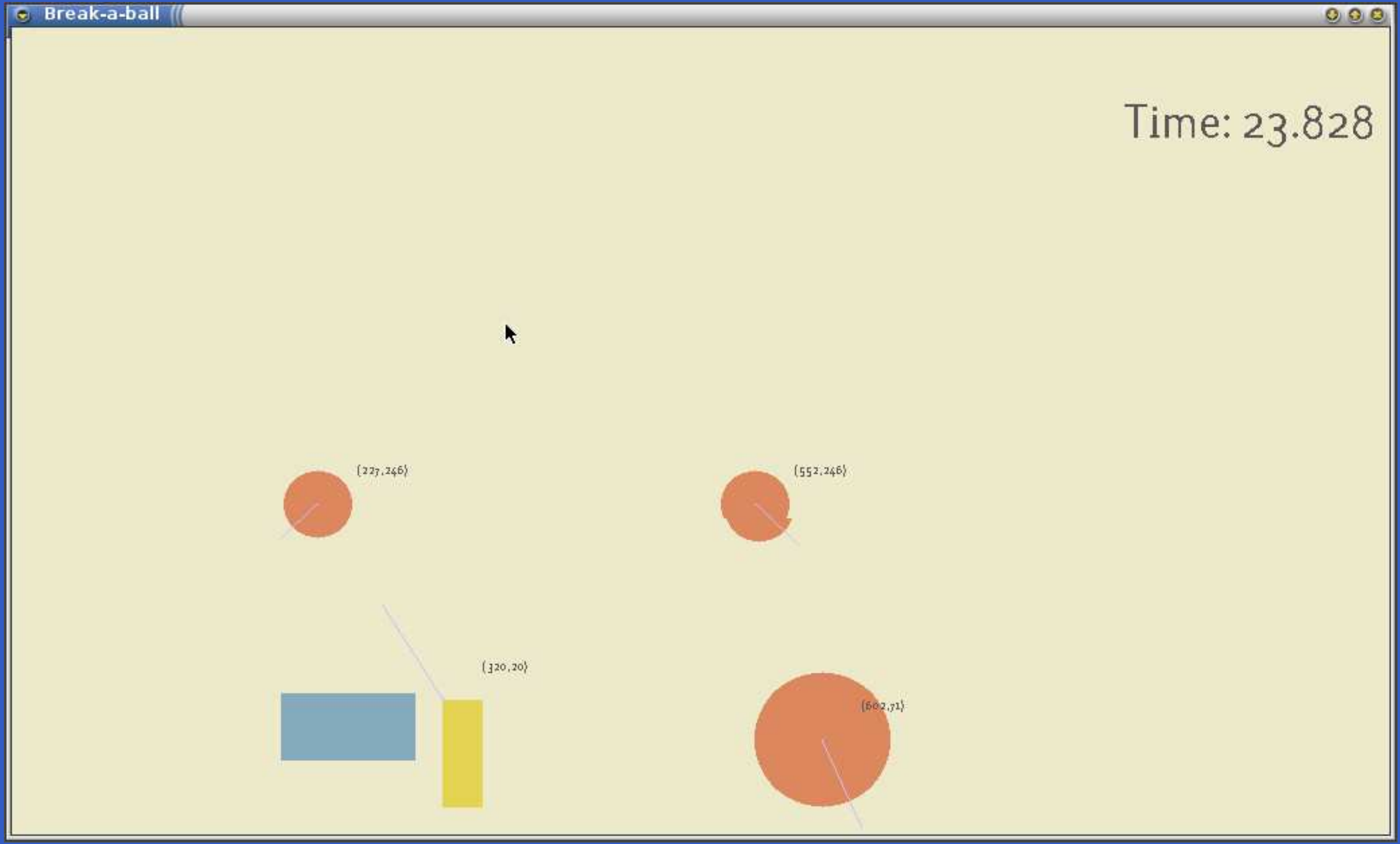
Take-home Message # 2

You too can program games declaratively . . . today!

Play Store: Keera Breakout (Keera Studios)

Take-home Game!

Or download one for free to your Android device!



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

This Tutorial

We will implement a Breakout-like game using:

- Functional Reactive Programming (FRP): a paradigm for describing time-varying entities
- Simple DirectMedia Layer (SDL) for rendering etc.

Focus on FRP as that is what we need for the game logic. We will use Yampa:

`http://hackage.haskell.org/package/Yampa-0.9.6`

Functional Reactive Programming

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- FRP has evolved in a number of directions and into different concrete implementations.
- We will use Yampa: an arrows-based FRP system embedded in Haskell.

FRP Applications

Some domains where FRP or FRP-inspired approaches have been used:

- Graphical Animation
- Robotics
- Vision
- Sound synthesis
- GUIs
- Virtual Reality Environments
- 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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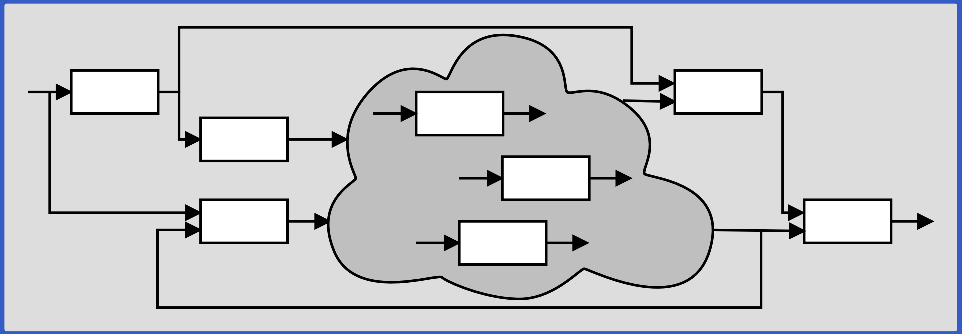
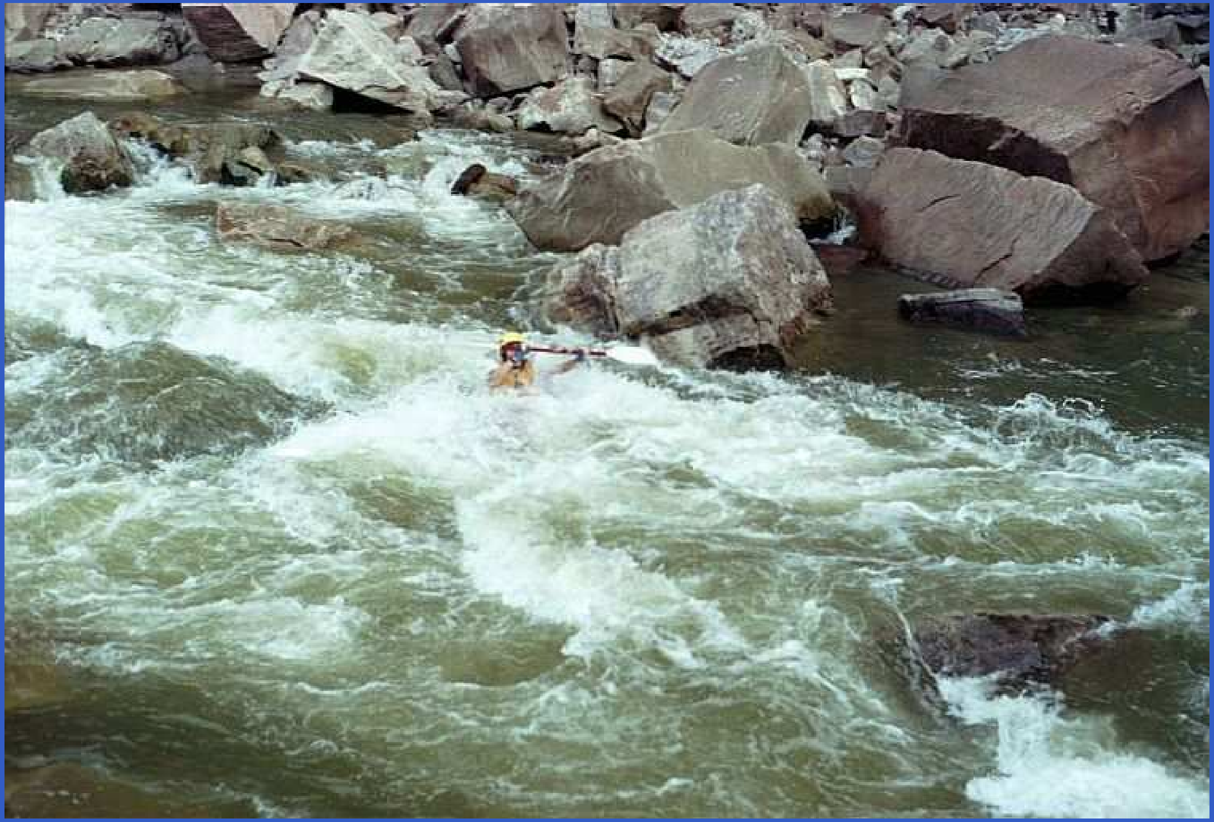
- Programming model:



Yampa?

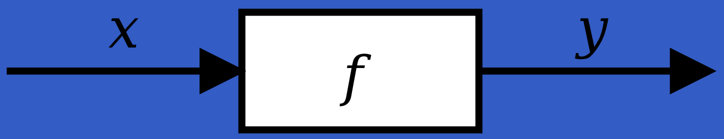
Yampa?

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

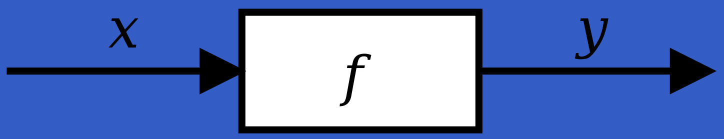


A good metaphor for hybrid systems!

Signal Functions

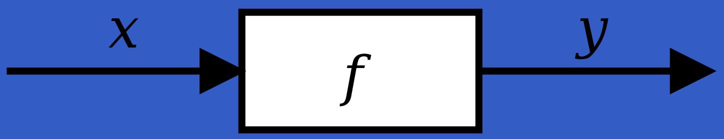


Signal Functions



Intuition:

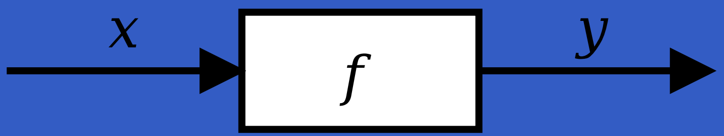
Signal Functions



Intuition:

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

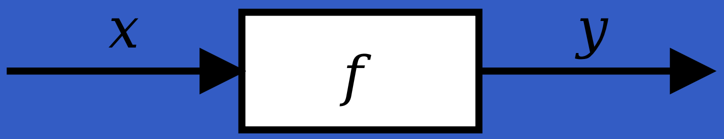
Signal Functions



Intuition:

$$Time \approx \mathbb{R}$$
$$Signal\ a \approx Time \rightarrow a$$
$$x :: Signal\ T1$$
$$y :: Signal\ T2$$

Signal Functions



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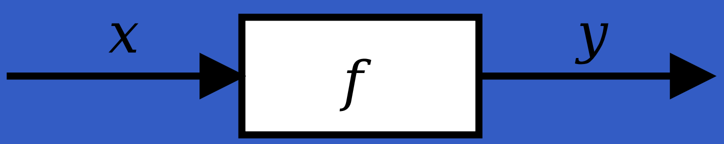

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Additionally, ***causality*** required: output at time t must be determined by input on interval $[0, t]$.

Signal Functions and State

Alternative view:

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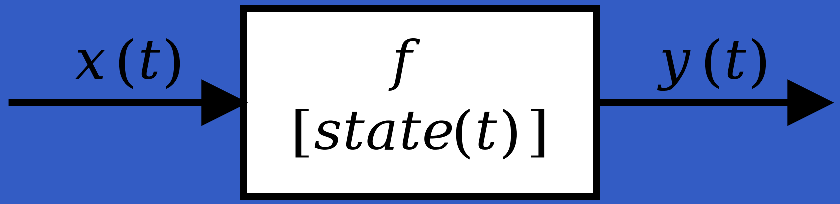
Signal functions can encapsulate ***state***.



$state(t)$ summarizes input history $x(t')$, $t' \in [0, t]$.

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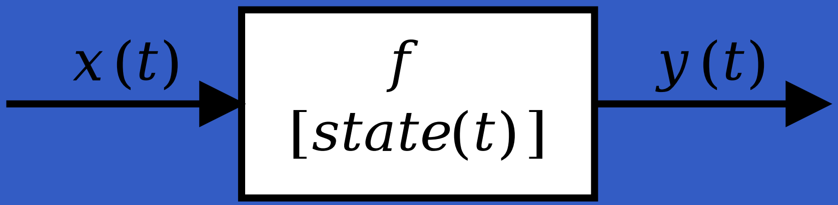

$state(t)$ summarizes input history $x(t')$, $t' \in [0, t]$.

From this perspective, signal functions are:

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

Some Basic Signal Functions

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

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

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Which are stateless and which are stateful?

Composition

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

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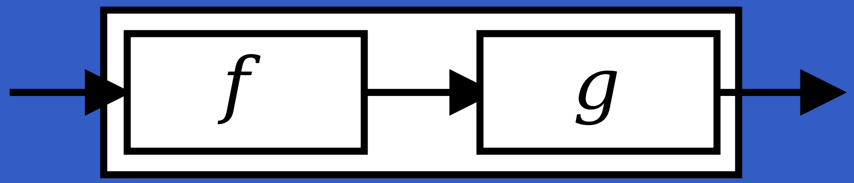
For example, serial composition:



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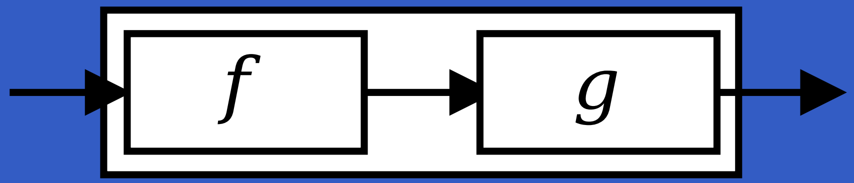

A *combinator* that captures this idea:

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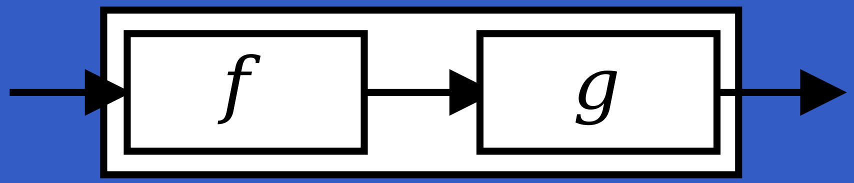

A *combinator* that captures this idea:

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

Time

Quick exercise: Define time!

$$time :: SF\ a\ Time$$

Time

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$$time :: SF\ a\ Time$$

$$time = constant\ 1.0 \ggg integral$$

Time

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$$time :: SF \;\; a \;\; Time$$

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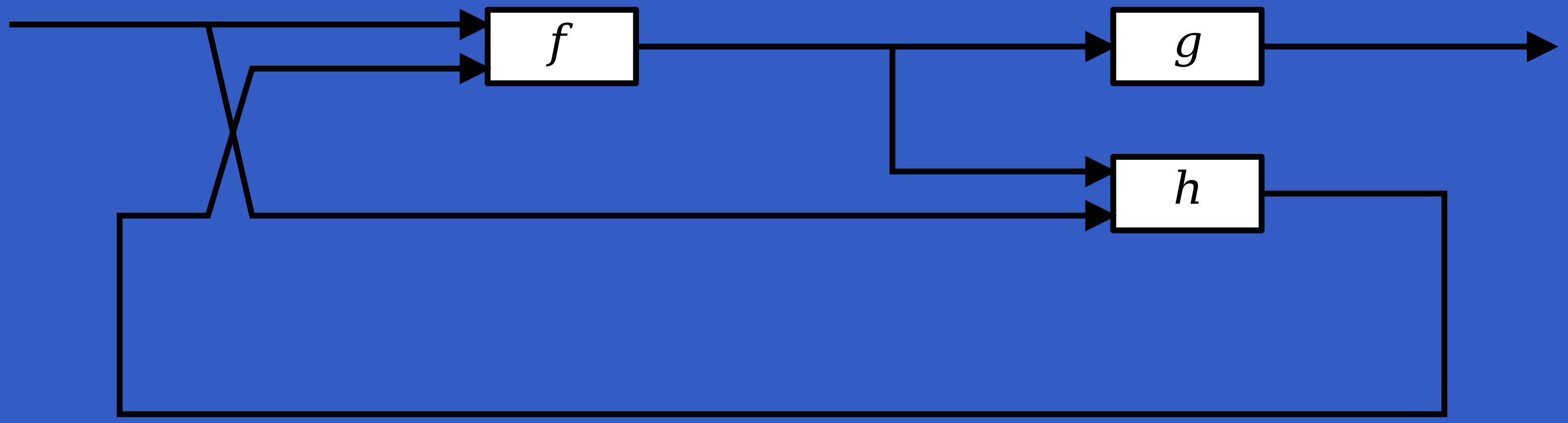
Note: there is ***no*** built-in notion of global time in Yampa: time is always ***local***, measured from when a signal function started.

Systems

What about larger networks?
How many combinators are needed?



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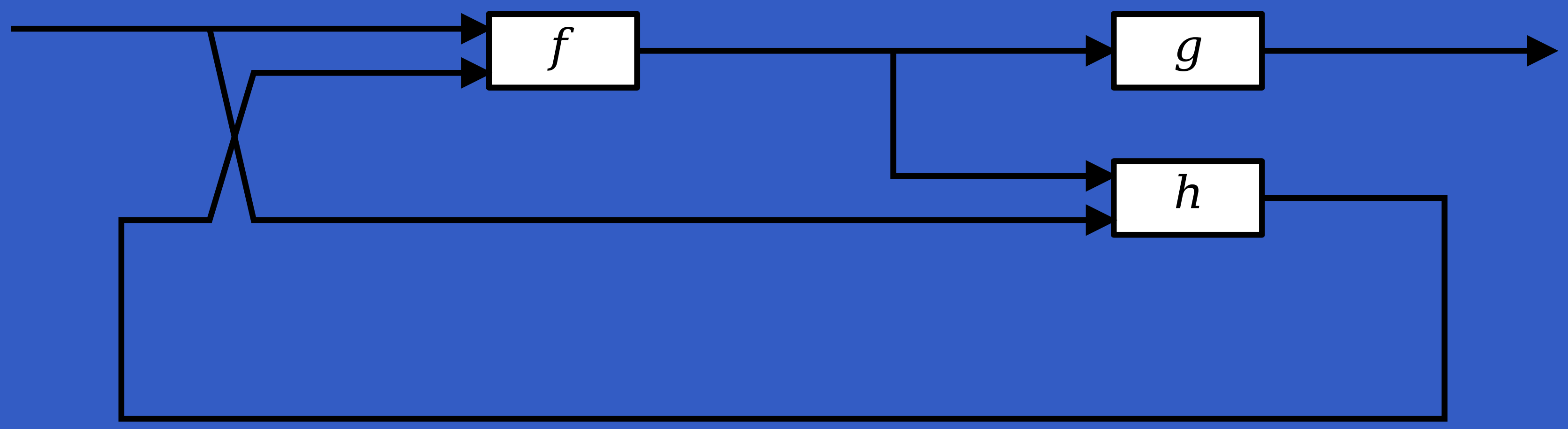

John Hughes's ***Arrow*** framework provides a good answer!

The Arrow framework (1)

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- Abstract data type interface for ***function-like objects*** (or "blocks") with ***effects***.

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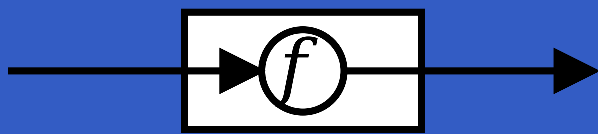
The Arrow framework (1)

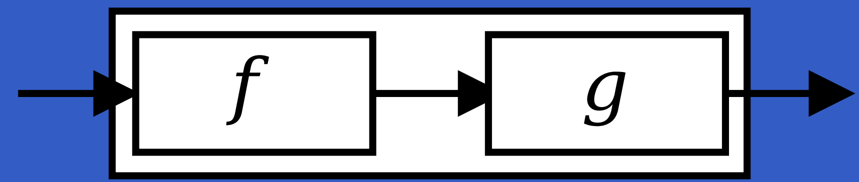
John Hughes' ***arrow*** framework:

- Abstract data type interface for ***function-like objects*** (or "blocks") with ***effects***.
- 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.

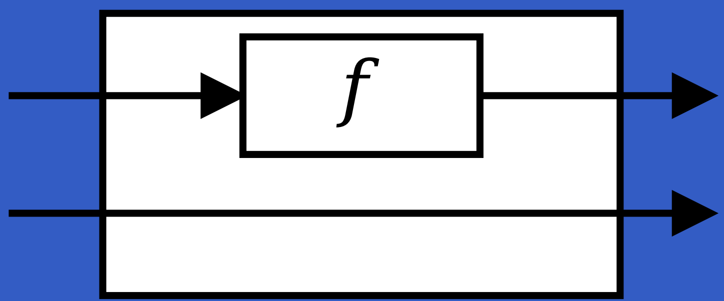
The Arrow framework (2)



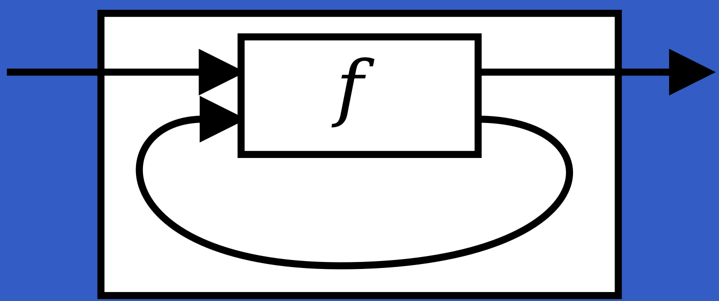
$arr\ f$



$f \ggg g$



$first\ f$



$loop\ f$

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

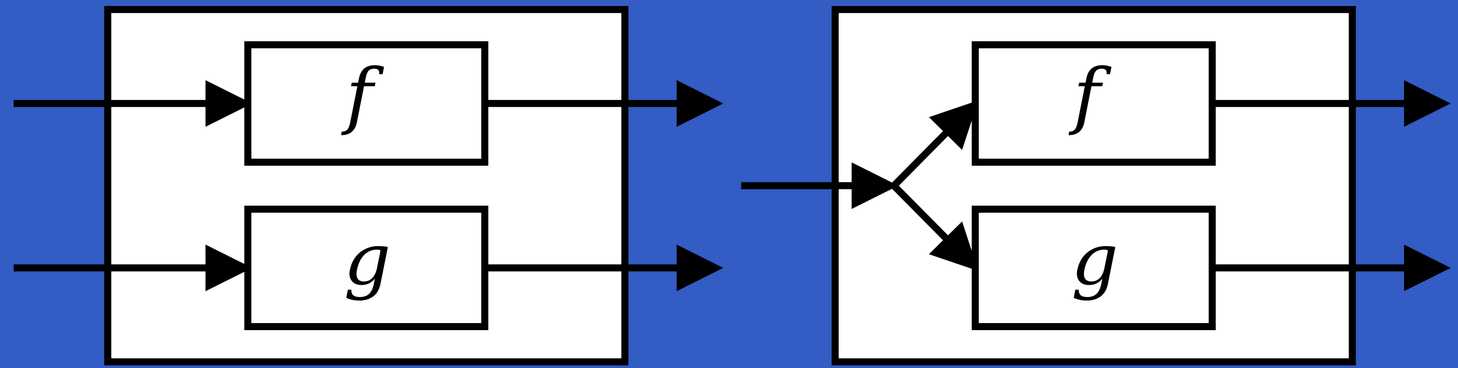
The Arrow framework (3)

Examples:

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

The Arrow framework (4)

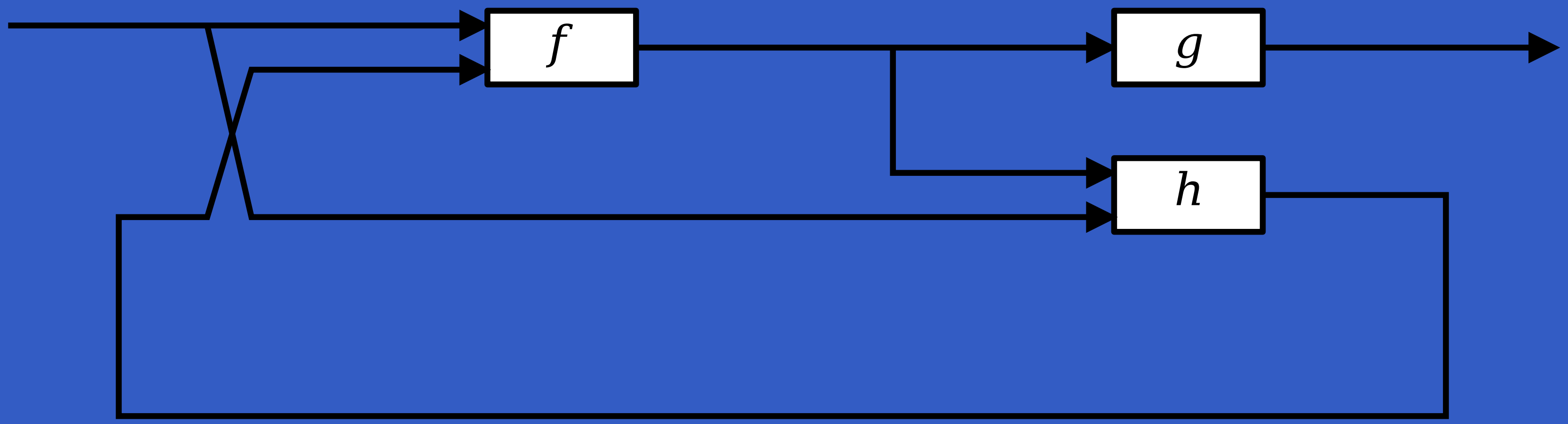
Some derived combinators:



$f \ggg g$ $f \,\&\&\&\, g$

$$(***) \;::\; SF\ a\ b \to SF\ c\ d \to SF\ (a, c)\ (b, d)$$
$$(\&\&\&) \;::\; SF\ a\ b \to SF\ a\ c \to SF\ a\ (b, c)$$

Constructing a network



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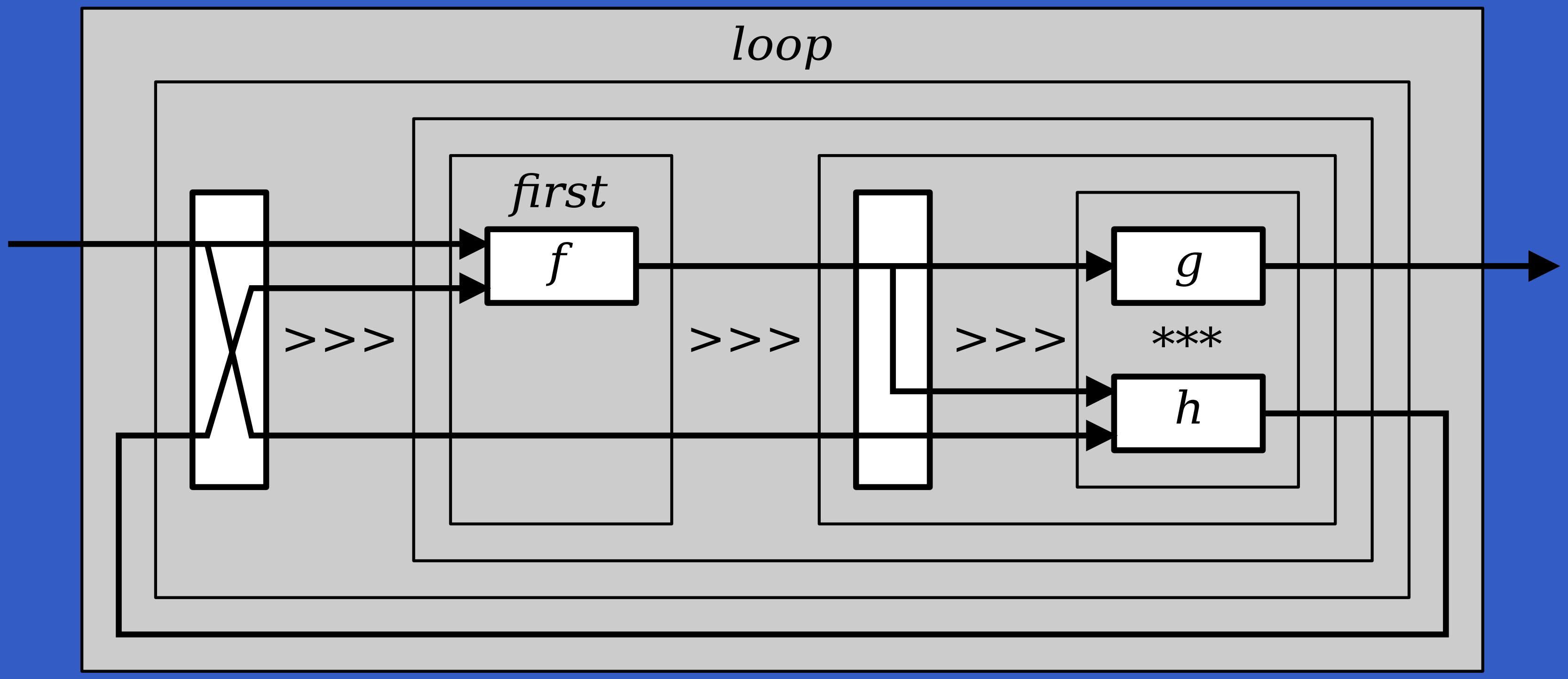

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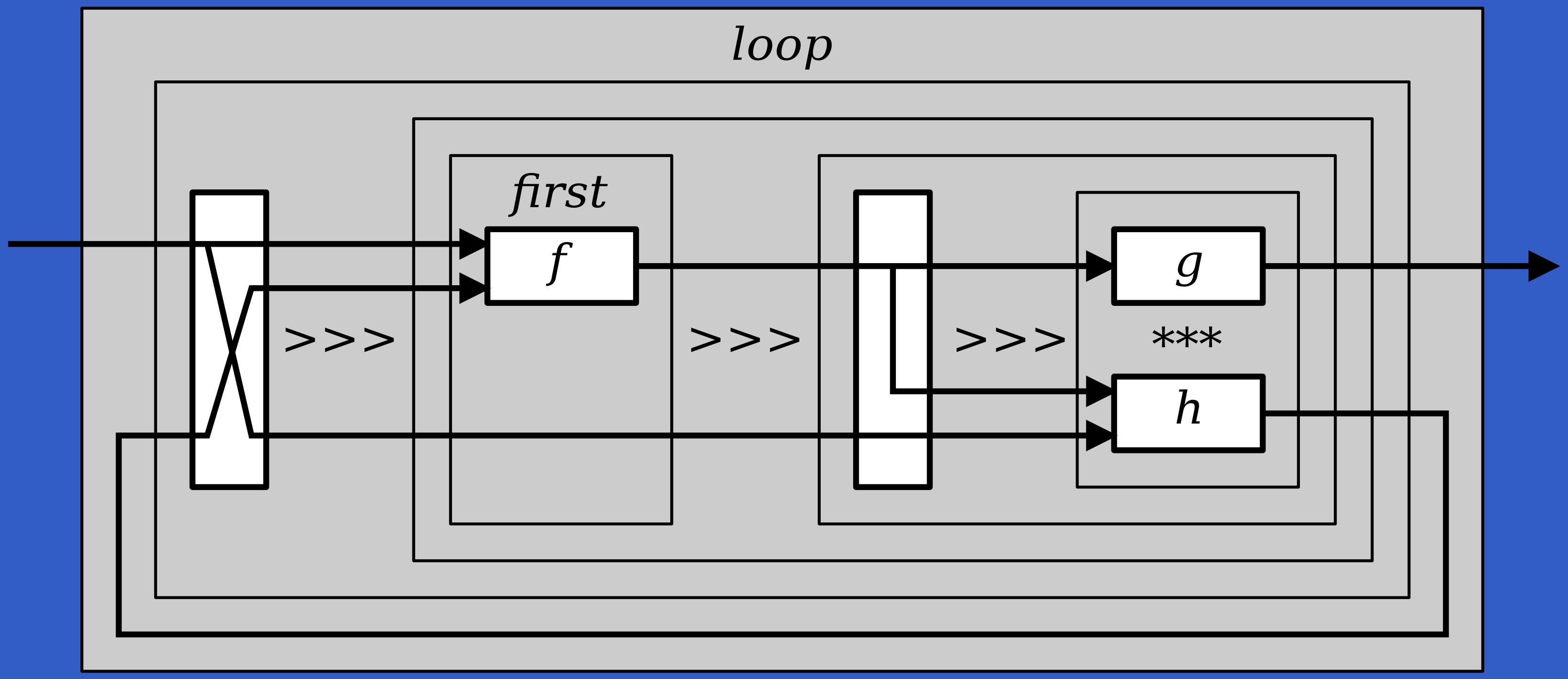
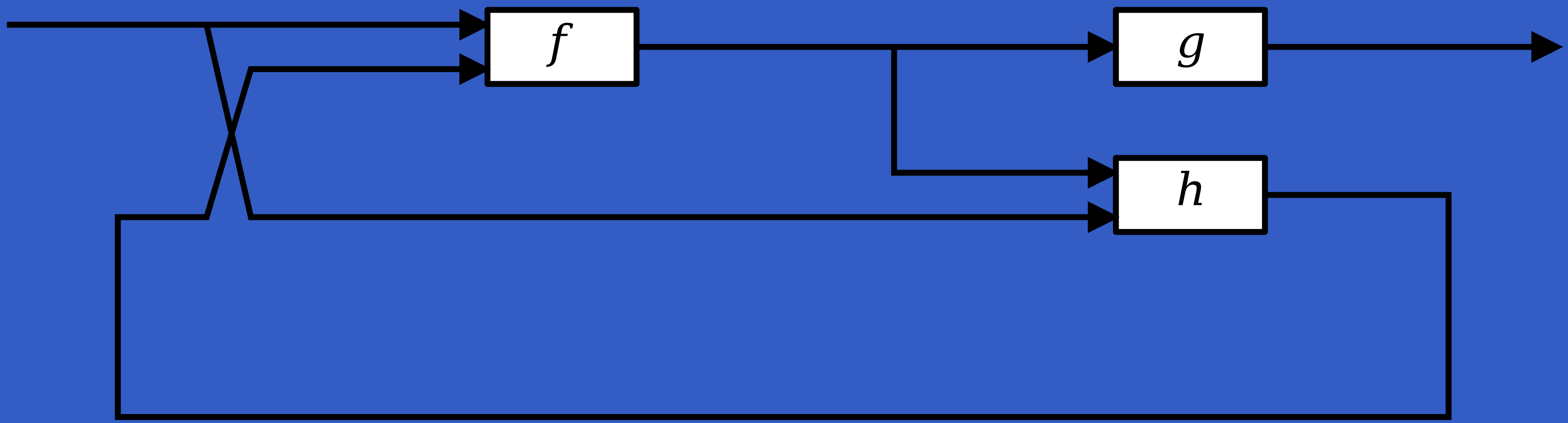


$$loop\ (arr\ (\lambda(x,y) \rightarrow ((x,y),x))$$
$$\ggg (first\ f$$
$$\ggg (arr\ (\lambda(x,y) \rightarrow (x,(x,y))) \ggg (g *** h))))$$

Arrow notation



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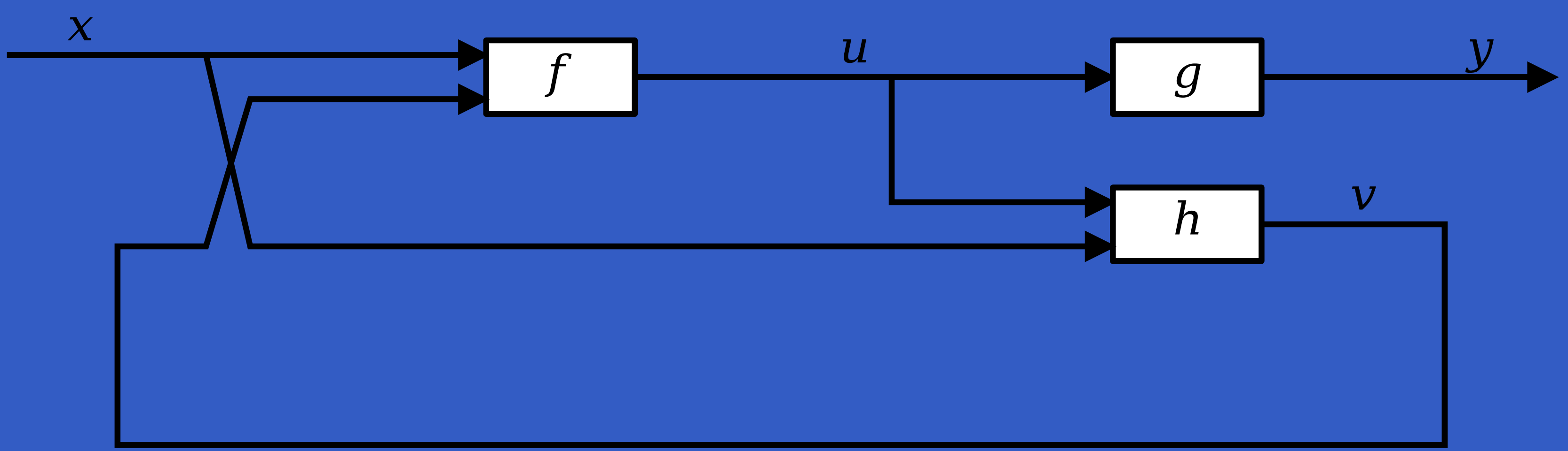

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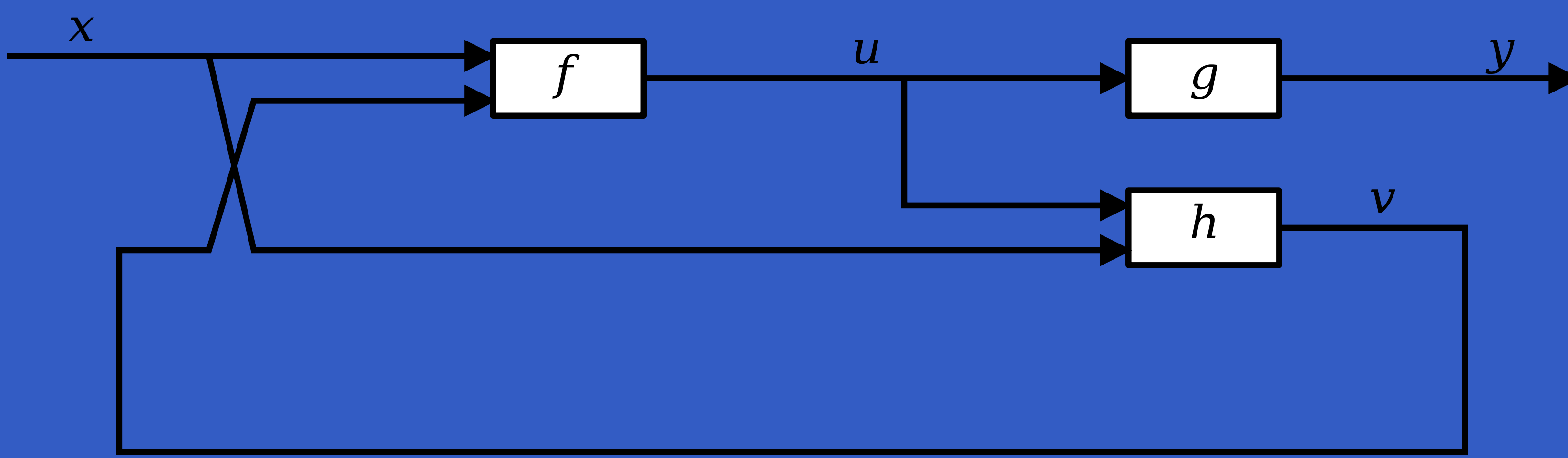
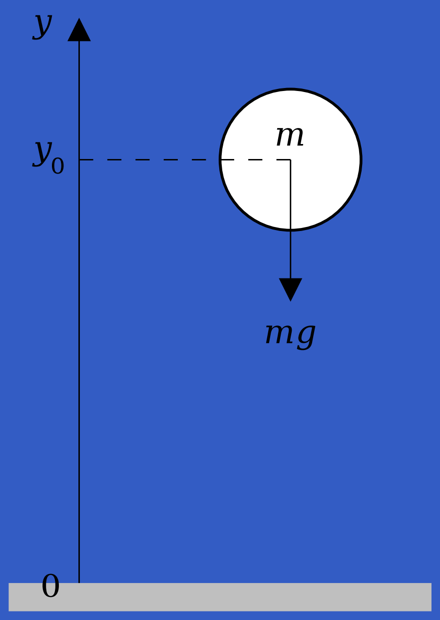


$$
\begin{array}{l}
\textbf{proc } x \rightarrow \textbf{do} \\
\quad \textbf{rec} \\
\qquad u \leftarrow f \prec (x, v) \\
\qquad y \leftarrow g \prec u \\
\qquad v \leftarrow h \prec (u, x) \\
\quad returnA \prec y
\end{array}
$$

A Bouncing Ball



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

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

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

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

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

Some Event Functions and Sources

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

$$never :: SF\ a\ (Event\ b)$$

$$now :: b \rightarrow SF\ a\ (Event\ b)$$

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

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

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

$$notYet :: SF\ (Event\ a)\ (Event\ a)$$

$$once :: SF\ (Event\ a)\ (Event\ a)$$

Modelling the Bouncing Ball: Part 2

Detecting when the ball goes through the floor:

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

Switching

Q: How and when do signal functions “start”?

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- ***Switchers*** “apply” a signal functions to its input signal at some point in time.
- This creates a “running” signal function ***instance***.
- The new signal function instance 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 takes place on the first occurrence of the switching event source.

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

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.

Initial SF with event source

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

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.

Function yielding SF to switch into

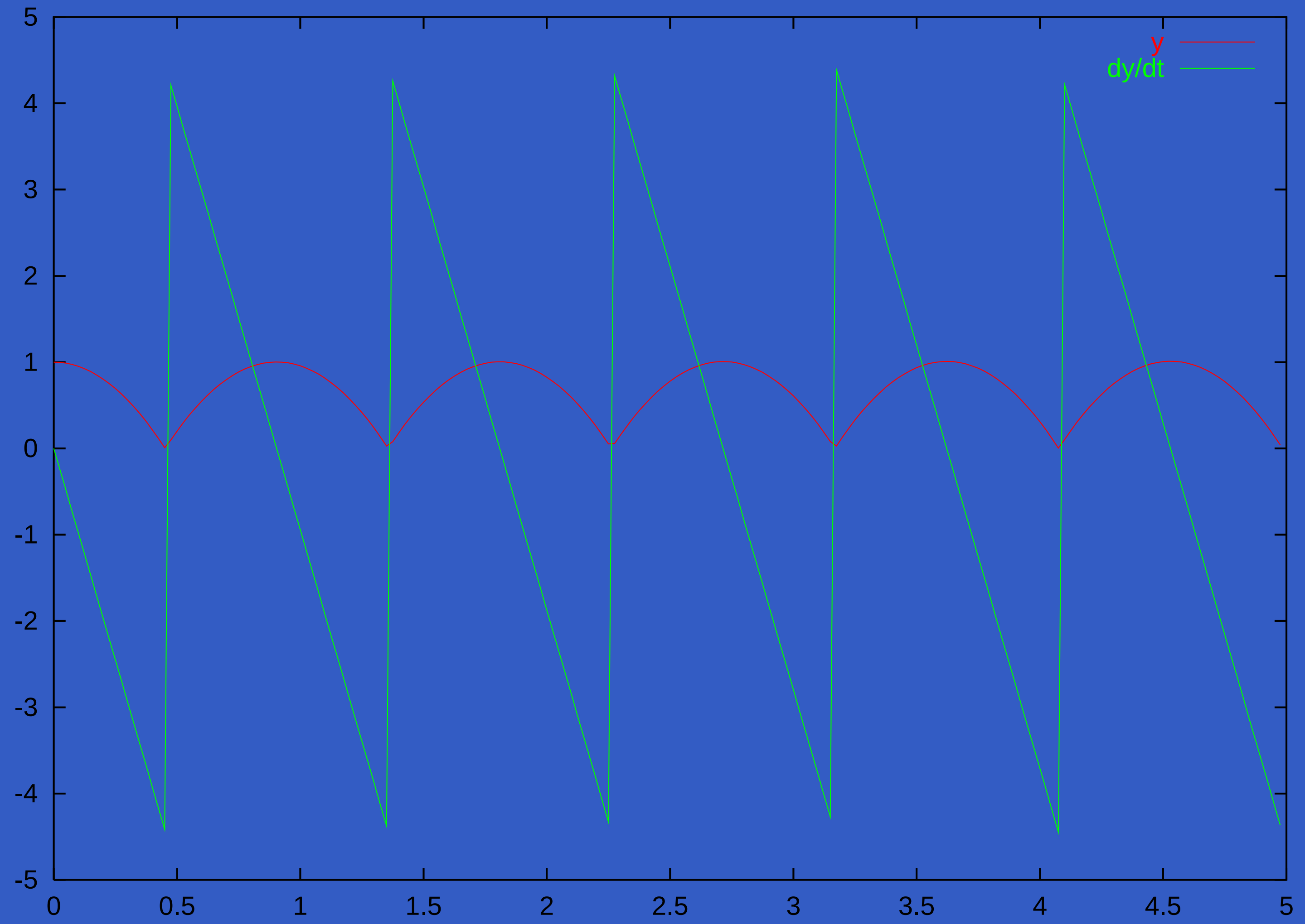
$$
\begin{aligned}
&switch :: \\
&\quad SF\ a\ (b, Event\ c) \\
&\quad \rightarrow \boxed{(c \rightarrow SF\ a\ b)} \\
&\quad \rightarrow SF\ a\ b
\end{aligned}
$$

Modelling the Bouncing Ball: Part 3

Making the ball bounce:

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

Simulation of the Bouncing Ball



The Decoupled Switch

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

The Decoupled Switch

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

- Output at the point of switch is taken from the old subordinate signal function, ***not*** the new residual signal function.

The Decoupled Switch

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

- Output at the point of switch is taken from the old subordinate signal function, ***not*** the new residual signal function.
- ***Output*** at the current point in time thus ***independent*** of whether or not the ***switching event*** occurs at that point. Hence decoupled. Useful e.g. in some feedback scenarios.

Game Objects (1)

Observable aspects of game entities:

$$
\begin{array}{l}
\textbf{data}\ \mathit{Object} = \mathit{Object}\ \{ \\
\quad \mathit{objectName} :: \mathit{ObjectName}, \\
\quad \mathit{objectKind} \ \ :: \mathit{ObjectKind}, \\
\quad \mathit{objectPos} \ \ \ :: \mathit{Pos2D}, \\
\quad \mathit{objectVel} \ \ \ :: \mathit{Vel2D}, \\
\quad \mathit{objectAcc} \ \ \ :: \mathit{Acc2D}, \\
\quad \mathit{objectDead} \ :: \mathit{Bool}, \\
\quad \mathit{objectHit} \ \ \ :: \mathit{Bool}, \\
\qquad \ldots \\
\}
\end{array}
$$

Game Objects (2)

$$
\begin{array}{llll}
\mathbf{data}\ \mathit{ObjectKind} = & \mathit{Ball} & \mathit{Double} & \\
\mid & \mathit{Paddle} & \mathit{Size2D} & \\
\mid & \mathit{Block} & \mathit{Energy} & \mathit{Size2D} \\
\mid & \mathit{Side} & \mathit{Side} &
\end{array}
$$

Game Objects (3)

$$\textbf{type}\ \mathit{ObjectSF} = \mathit{SF}\ \mathit{ObjectInput}\ \mathit{ObjectOutput}$$

$$\begin{array}{l}
\textbf{data}\ \mathit{ObjectInput} = \mathit{ObjectInput}\ \{\\
\quad \begin{array}{ll}
\mathit{userInput} & :: \mathit{Controller},\\
\mathit{collisions} & :: [\mathit{Collision}],\\
\mathit{knownObjects} & :: [\mathit{Object}]
\end{array}\\
\}
\end{array}$$

$$\begin{array}{l}
\textbf{data}\ \mathit{ObjectOutput} = \mathit{ObjectOutput}\ \{\\
\quad \begin{array}{ll}
\mathit{outputObject} & :: \mathit{Object},\\
\mathit{harakiri} & :: \mathit{Event}\ ()
\end{array}\\
\}
\end{array}$$

Observing the Game World

- Note that $[Object]$ appears in the input type.

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Observing the Game World

- Note that $[\,Object\,]$ appears in the input type.
- This allows each game object to observe ***all*** live game objects.
- Similarly, $[\,Collision\,]$ allows interactions ***between*** game objects to be observed.
- Typically achieved through delayed feedback to ensure the feedback is well-defined:

$$
\begin{array}{l}
loopPre :: c \to SF\ (a, c)\ (b, c) \to SF\ a\ b \\
loopPre\ c\_init\ sf = \\
\quad loop\ (second\ (iPre\ c\_init) \ggg sf)
\end{array}
$$

Paddle, Take 1

$$
\begin{array}{l}
objPaddle :: ObjectSF \\
objPaddle = \mathbf{proc}\ (ObjectInput\ ci\ cs\ os) \rightarrow \mathbf{do} \\
\quad \mathbf{let}\ name = \texttt{"paddle"} \\
\quad \mathbf{let}\ isHit\ = inCollision\ name\ cs \\
\quad \mathbf{let}\ p \qquad = refPosPaddle\ ci \\
\quad v \leftarrow derivative \prec p \\
\quad returnA \prec livingObject\ \$\ Object\ \{ \\
\qquad\qquad\qquad\qquad\qquad\qquad objectName = name, \\
\qquad\qquad\qquad\qquad\qquad\qquad objectPos = p, \\
\qquad\qquad\qquad\qquad\qquad\qquad objectVel\ = v, \\
\qquad\qquad\qquad\qquad\qquad\qquad \ldots\}
\end{array}
$$

Paddle, Take 2

$$
\begin{array}{l}
\mathit{objPaddle} :: \mathit{ObjectSF} \\
\mathit{objPaddle} = \mathbf{proc}\ (\mathit{ObjectInput}\ \mathit{ci}\ \mathit{cs}\ \mathit{os}) \rightarrow \mathbf{do} \\
\quad \mathbf{let}\ \mathit{name} = \texttt{"paddle"} \\
\quad \mathbf{let}\ \mathit{isHit}\ = \mathit{inCollision}\ \mathit{name}\ \mathit{cs} \\
\quad \mathbf{rec} \\
\qquad \mathbf{let}\ v = \mathit{limitNorm}\ (20.0 \mathbin{*\hat{}}\ (\mathit{refPosPaddle}\ \mathit{ci} \\
\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad \hat{-}\hat{}\ p)) \\
\qquad\qquad\qquad\qquad\qquad\qquad \mathit{maxVNorm} \\
\qquad p \leftarrow (\mathit{initPosPaddle}\ \hat{+}\hat{}\ )\hat{\ll}\ \mathit{integral} \prec v \\
\quad \mathit{returnA} \prec \mathit{livingObject}\ \$\ \mathit{Object}\ \{\ldots\}
\end{array}
$$

Ball, Take 1

$$
\begin{aligned}
&\mathit{objBall} :: \mathit{ObjectSF}\\
&\mathit{objBall} =\\
&\quad \mathit{switch}\ \mathit{followPaddleDetectLaunch}\ \$\ \lambda p \rightarrow\\
&\quad \mathit{objBall}\\
&\mathit{followPaddleDetectLaunch} = \mathbf{proc}\ \mathit{oi} \rightarrow \mathbf{do}\\
&\quad o \quad\quad \leftarrow \mathit{followPaddle} \prec \mathit{oi}\\
&\quad \mathit{click} \leftarrow \mathit{edge} \quad\quad\quad \prec \mathit{controllerClick}\\
&\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad (\mathit{userInput}\ \mathit{oi})\\
&\quad \mathit{returnA} \prec (o, \mathit{click}\ \text{`}\mathit{tag}\text{`}\ (\mathit{objectPos}\\
&\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad (\mathit{outputObject}\ o)))
\end{aligned}
$$

Ball, Take 2

$$
\begin{array}{l}
objBall :: ObjectSF \\
objBall = \\
\quad switch\ followPaddleDetectLaunch \,\$\, \lambda p \rightarrow \\
\quad switch\ (freeBall\ p\ initBallVel \,\&\&\&\, never) \,\$\, \lambda\_ \rightarrow \\
\quad objBall
\end{array}
$$

$$
\begin{array}{l}
freeBall\ p0\ v0 = \mathbf{proc}\ (ObjectInput\ ci\ cs\ os) \rightarrow \mathbf{do} \\
\quad p \leftarrow (p0\ \hat{}{+}\hat{}\ )\hat{}{\ll}\ integral \prec v0' \\
\quad returnA \prec livingObject \,\$\, \{\ldots\} \\
\quad \mathbf{where} \\
\quad\quad v0' = limitNorm\ v0\ maxVNorm
\end{array}
$$

Ball, Take 3

$$
\begin{aligned}
&objBall :: ObjectSF \\
&objBall = \\
&\quad switch\ followPaddleDetectLaunch \quad \$\ \lambda p \rightarrow \\
&\quad switch\ (bounceAroundDetectMiss\ p)\ \$\ \lambda\_ \rightarrow \\
&\quad objBall
\end{aligned}
$$

$$
\begin{aligned}
&bounceAroundDetectMiss\ p = \mathbf{proc}\ oi \rightarrow \mathbf{do} \\
&\quad o \quad \leftarrow bouncingBall\ p\ initBallVel \prec oi \\
&\quad miss \leftarrow collisionWithBottom \qquad \prec collisions\ oi \\
&\quad returnA \prec (o, miss)
\end{aligned}
$$

Making the Ball Bounce

$$
\begin{array}{l}
\mathit{bouncingBall}\ \mathit{p0}\ \mathit{v0} = \\
\quad \mathit{switch}\ (\mathit{moveFreelyDetBounce}\ \mathit{p0}\ \mathit{v0})\ \$\ \lambda(p', v') \rightarrow \\
\quad \mathit{bouncingBall}\ p'\ v'
\end{array}
$$

$$
\begin{array}{l}
\mathit{moveFreelyDetBounce}\ \mathit{p0}\ \mathit{v0} = \\
\quad \mathbf{proc}\ \mathit{oi}@(\mathit{ObjectInput}\ \_\ \mathit{cs}\ \_) \rightarrow \mathbf{do} \\
\qquad o \leftarrow \mathit{freeBall}\ \mathit{p0}\ \mathit{v0} \prec \mathit{oi} \\
\qquad \mathit{ev} \leftarrow \mathit{edgeJust} \lll \mathit{initially}\ \mathit{Nothing} \\
\qquad\qquad\quad \prec \mathit{changedVelocity}\ \texttt{"ball"}\ \mathit{cs} \\
\quad \mathit{returnA} \prec (o, \mathit{fmap}\ (\lambda v \rightarrow (\mathit{objectPos}\ (\ldots o), v)) \\
\qquad\qquad\qquad\qquad \mathit{ev})
\end{array}
$$

Highly dynamic system structure?

The basic switch allows one signal function to be replaced by another.

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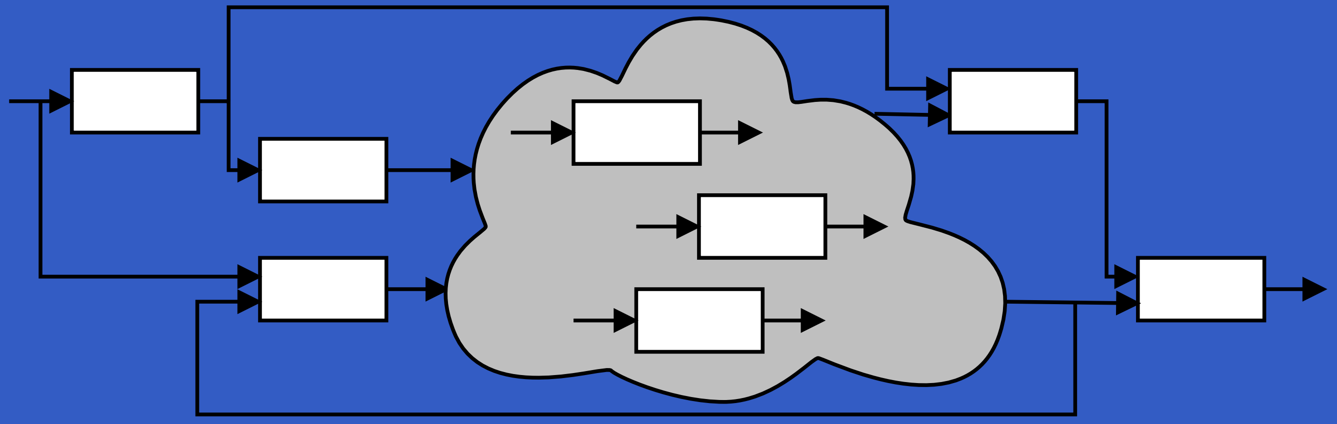
- What about more general structural changes?



We want blocks to disappear!

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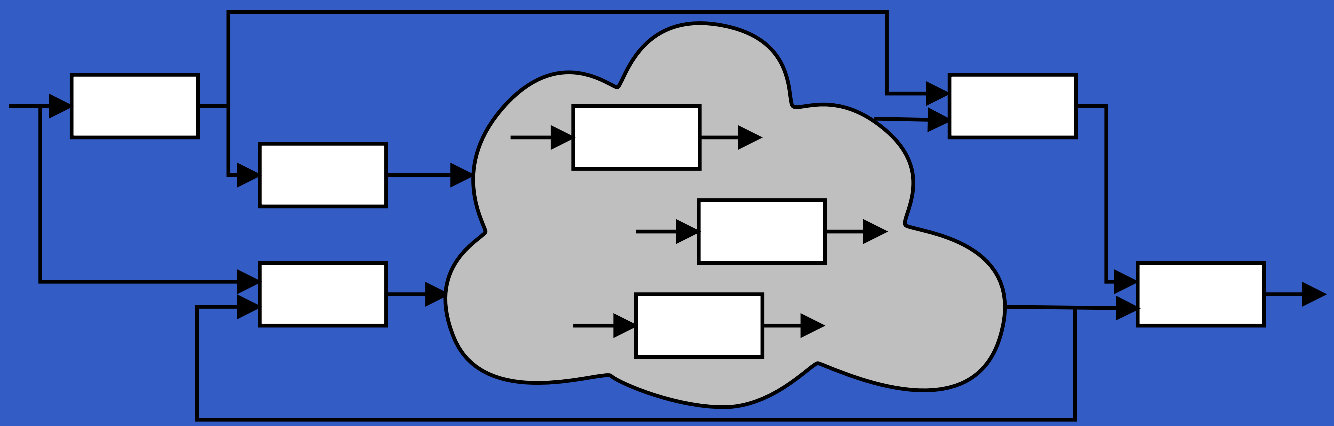
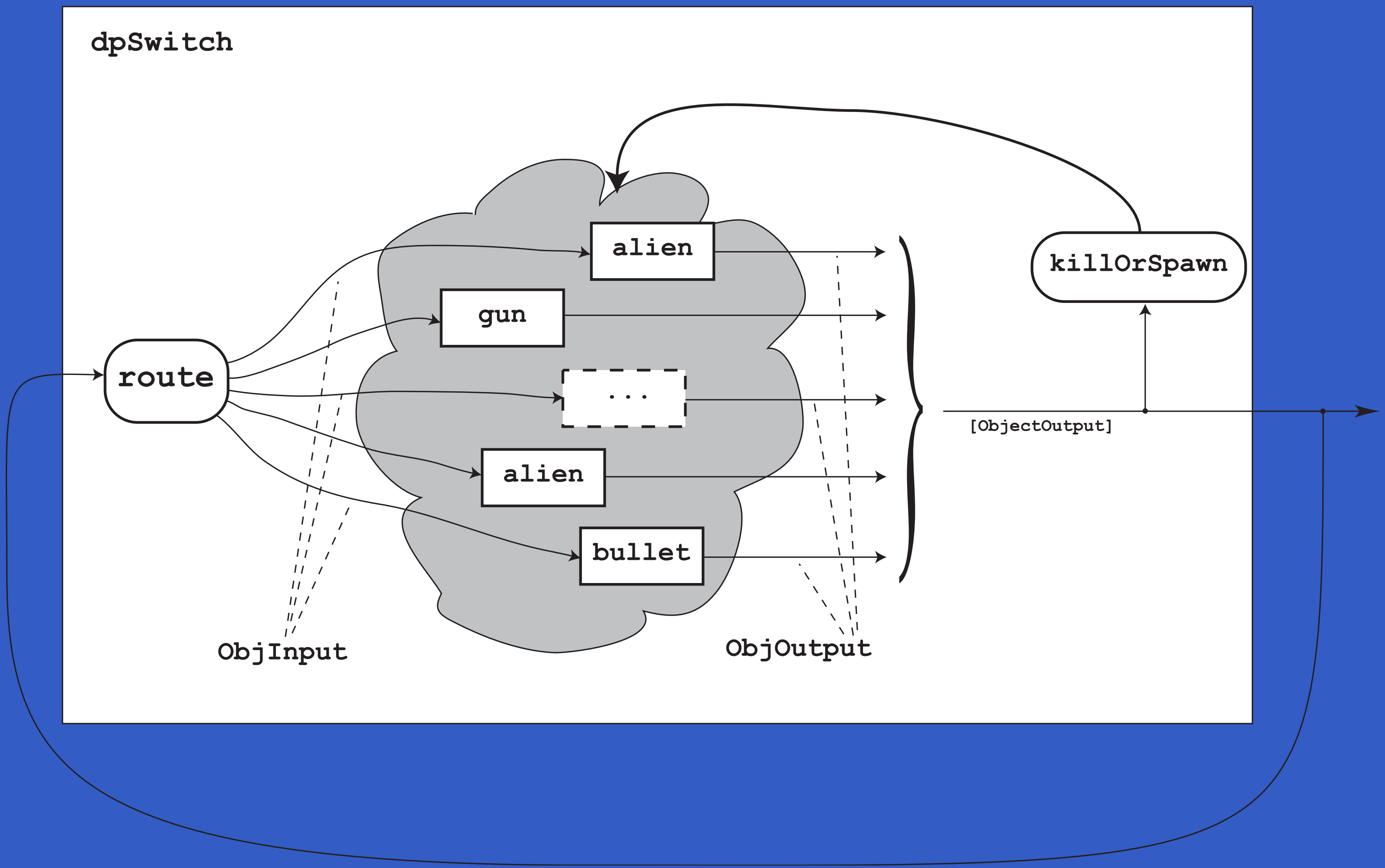


We want blocks to disappear!

- What about state?

Typical Overall Game Structure



Dynamic Signal Function Collections

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- Switch over ***collections*** of signal functions.

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- On event, “freeze” running signal functions into collection of signal function ***continuations***, preserving encapsulated ***state***.

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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    -> SF (a, col c) (Event d)
    -> (col (SF b c) -> d -> SF a (col c))
    -> SF a (col c)
```

Routing function

dpSwitch

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- 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)                              Initial collection
   ->  SF (a, col c) (Event d)
   ->  (col (SF b c) -> d -> SF a (col c))
   -> SF a (col c)
```

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   -> SF (a, col c) (Event d)
   -> (col (SF b c) -> d -> SF a (col c))
   -> SF a (col c)
```

Event source

dpSwitch

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   -> col (SF b c)
   -> SF (a, col c) (Event d)
   -> (col (SF b c) -> d -> SF a (col c))
   -> SF a (col c)
```

Function yielding SF to switch into

Routing

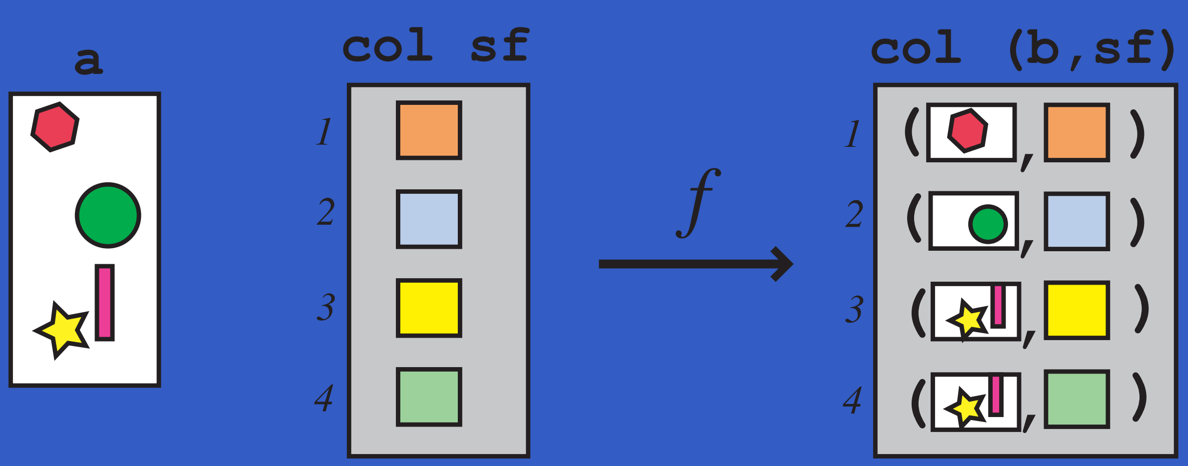
Idea:

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

Routing

Idea:

- 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 Routing Function Type

Universal quantification over the collection members:

$$
\begin{aligned}
&\mathit{Functor}\ \mathit{col} \Rightarrow \\
&\quad (\mathit{forall}\ \mathit{sf} \circ (a \rightarrow \mathit{col}\ \mathit{sf} \rightarrow \mathit{col}\ (b, \mathit{sf})))
\end{aligned}
$$

Collection members thus ***opaque***:

- Ensures only signal function instances from argument can be returned.
- Unfortunately, does not prevent duplication or discarding of signal function instances.

Blocks

$$
\begin{array}{l}
objBlockAt\ (x, y)\ (w, h) = \\
\quad \mathbf{proc}\ (ObjectInput\ ci\ cs\ os) \rightarrow \mathbf{do} \\
\qquad \mathbf{let}\ name = \texttt{"blockat"} +\!\!+\ show\ (x, y) \\
\qquad\quad isHit \quad = inCollision\ name\ cs \\
\qquad hit \leftarrow edge \qquad\qquad\qquad\qquad\qquad \prec isHit \\
\qquad lives \leftarrow accumHoldBy\ (+)\ 3 \prec (hit\ `tag`\ (-1)) \\
\qquad \mathbf{let}\ isDead = lives \leqslant 0 \\
\qquad dead \leftarrow edge \prec isDead \\
\qquad returnA \prec ObjectOutput \\
\qquad\quad (Object\ \{\ldots\}) \\
\qquad\quad dead
\end{array}
$$

The Game Core

$$
\begin{array}{l}
\mathit{processMovement} :: \\
\quad [\,\mathit{ObjectSF}\,] \rightarrow \mathit{SF}\ \mathit{ObjectInput}\ (\mathit{IL}\ \mathit{ObjectOutput}) \\
\mathit{processMovement}\ \mathit{objs} = \\
\quad \mathit{dpSwitchB}\ \mathit{objs} \\
\qquad\qquad\qquad (\mathit{noEvent} \longrightarrow \mathit{arr}\ \mathit{suicidalSect}) \\
\qquad\qquad\qquad (\lambda \mathit{sfs}'\ f \rightarrow \mathit{processMovement}'\ (f\ \mathit{sfs}'))
\end{array}
$$

$$
\begin{array}{l}
\mathit{loopPre}\ ([\,], [\,], 0)\ \$ \\
\quad \mathit{adaptInput} \\
\quad \ggg \mathit{processMovement}\ \mathit{objs} \\
\quad \ggg (\mathit{arr}\ \mathit{elemsIL} \&\&\& \mathit{detectCollisions})
\end{array}
$$

Recovering Blocks

$$
\begin{array}{l}
objBlockAt\ (x, y)\ (w, h) = \\
\quad \mathbf{proc}\ (ObjectInput\ ci\ cs\ os) \rightarrow \mathbf{do} \\
\qquad \mathbf{let}\ name = \texttt{"blockat"} +\!\!+\ show\ (x, y) \\
\qquad\quad isHit \quad = inCollision\ name\ cs \\
\qquad hit \qquad\ \leftarrow edge \qquad\qquad\quad \prec isHit \\
\qquad recover \leftarrow delayEvent\ 5.0 \prec hit \\
\qquad lives \quad\ \leftarrow accumHoldBy\ (+)\ 3 \\
\qquad\qquad\qquad \prec (hit\ `tag`\ (-1) \\
\qquad\qquad\qquad\qquad `lMerge`\ recover\ `tag`\ 1) \\
\qquad \ldots
\end{array}
$$

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)

- Antony Courtney and Henrik Nilsson and John Peterson. The Yampa Arcade. In *Proceedings of the 2003 Haskell Workshop*, pp. 7–18, August 2003.
- Ivan Perez and Henrik Nilsson. Bridging the GUI gap with reactive values and relations. In *Proceedings of the 8th ACM SIGPLAN Symposium on Haskell (Haskell'15)*, pages 47–58, 2015.