Declarative Game Programming

PPDP 2014
Distilled Tutorial

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Declarative Game Programming?

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

- Many historical and pragmatical reasons
- More principled objection:

  With state and effects being pervasive in video games, is declarative programming a good fit?

Take-home Message # 1

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Video games can be programmed declaratively by describing ***what*** game entities are ***over*** time, not just at a point in time.

(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.)

Take-home Message # 2

You too can program games declaratively . . .

Take-home Message # 2

You too can program games declaratively . . . today!

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`

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- Idea: programming with time-varying entities.
- Originated from Functional Reactive Animation (Fran) (Elliott & Hudak).
- Has evolved in a number of directions and into different concrete implementations.
- Often realised as an ***Embedded Domain-Specific Language (EDSL)***.

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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Key FRP Features

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

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  - ***Signal Functions***: functions on signals
  - ***Switching*** between signal functions

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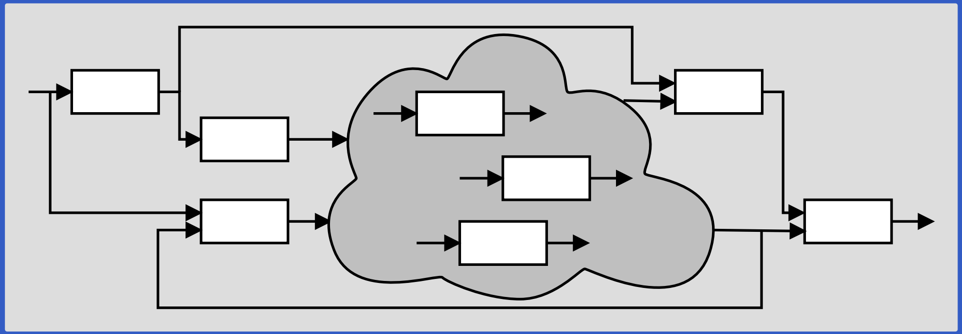
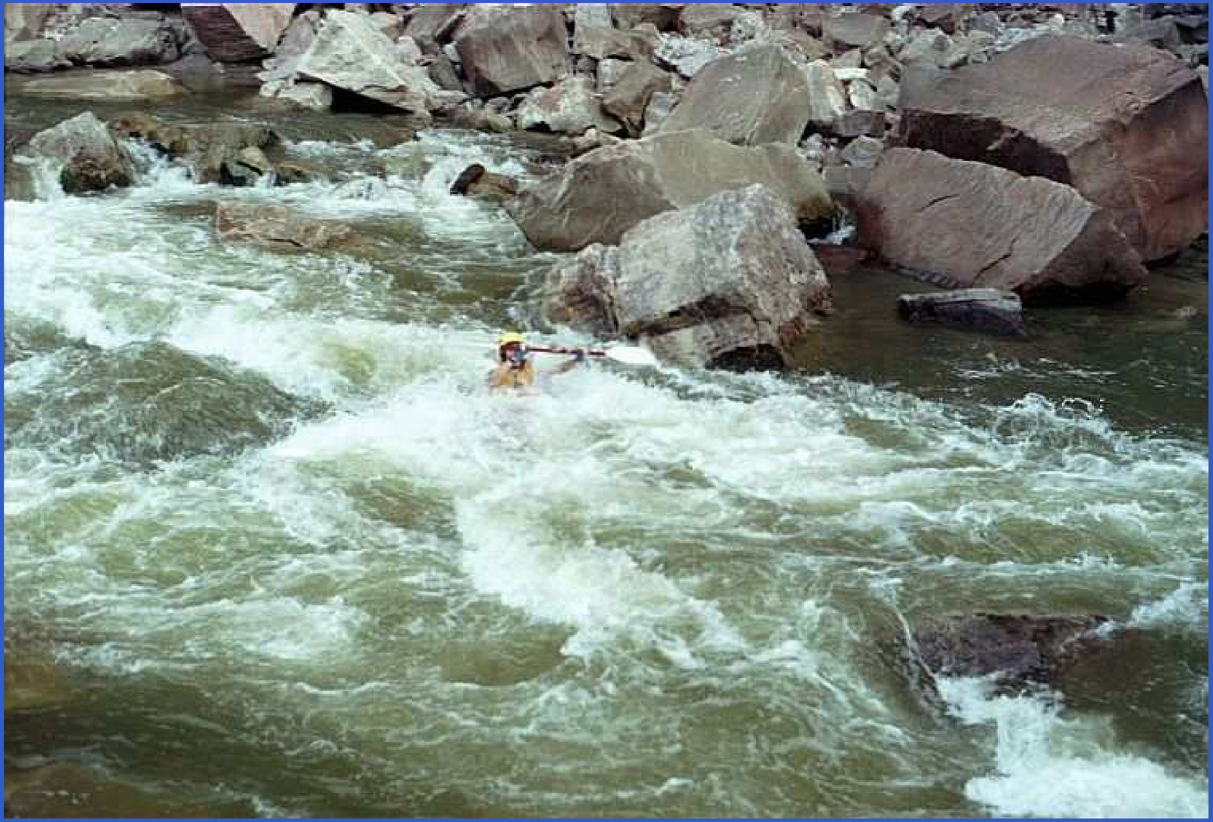
- Programming model:



Yampa?

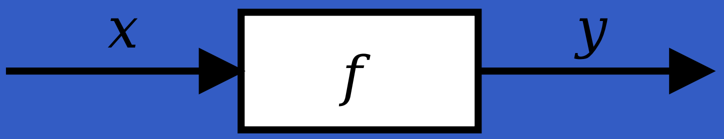
Yampa?

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

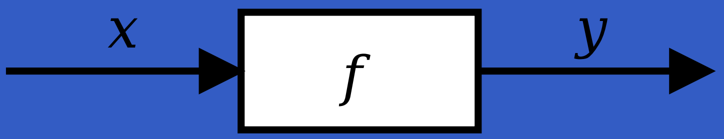


A good metaphor for hybrid systems!

Signal Functions

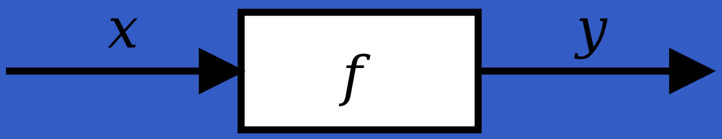


Signal Functions



Intuition:

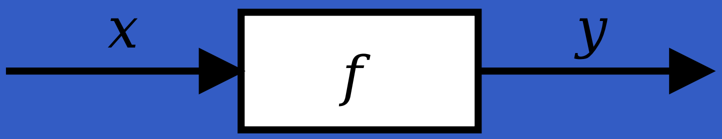
Signal Functions



Intuition:

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

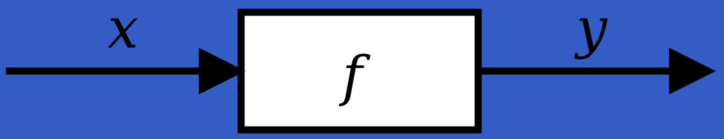
Signal Functions



Intuition:

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

Signal Functions



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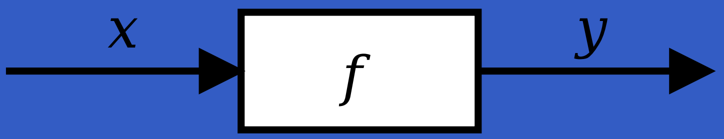
$$

Signal Functions



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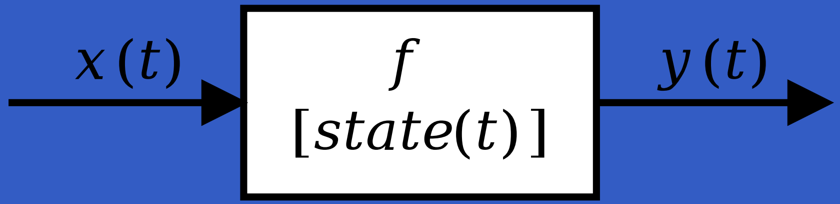
Signal functions can encapsulate ***state***.



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

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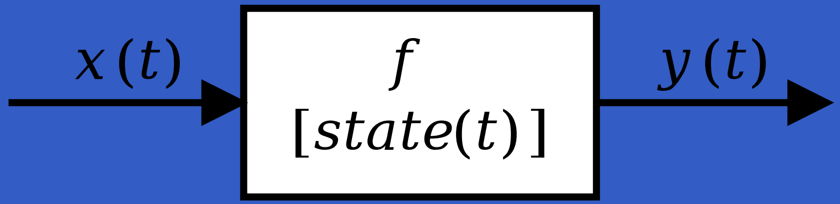

$state(t)$ summarizes input history $x(t')$, $t' \in [0, t]$.

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

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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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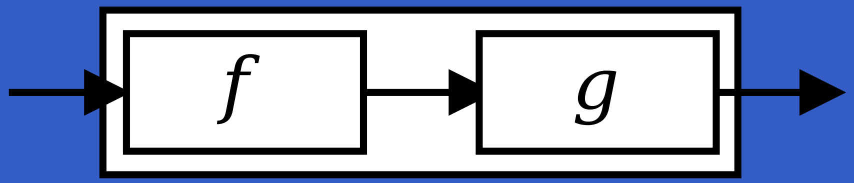
For example, serial composition:



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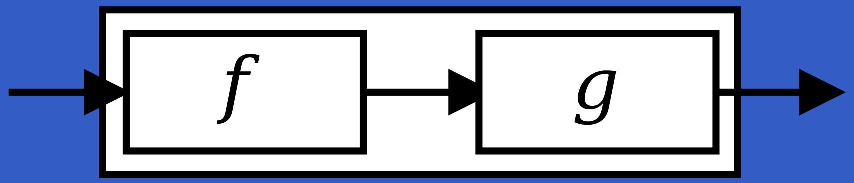

A *combinator* that captures this idea:

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

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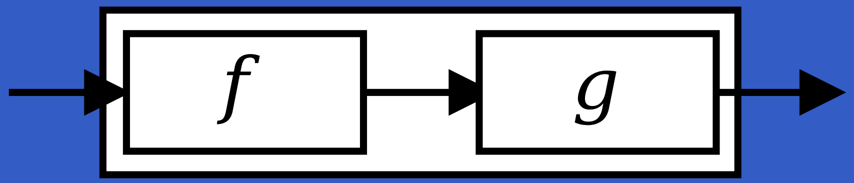

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$$(\ggg) :: SF\ a\ b \rightarrow SF\ b\ c \rightarrow SF\ a\ c$$

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

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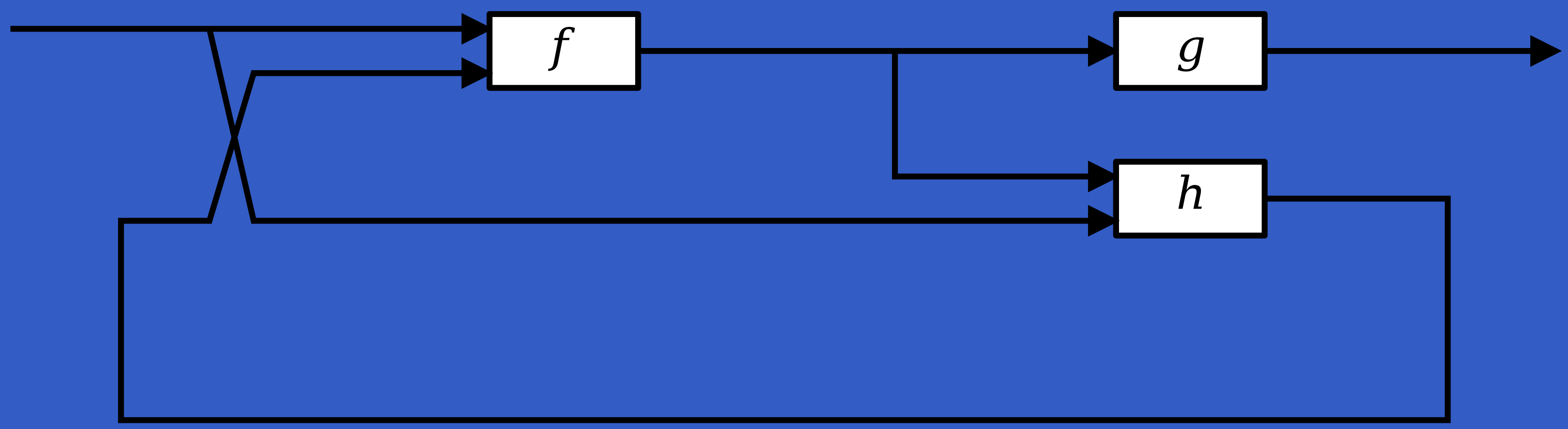
Note: there is ***no*** built-in notion of global time in Yampa: time is always ***local***, measured from when a signal function started.

Systems

What about larger networks?
How many combinators are needed?



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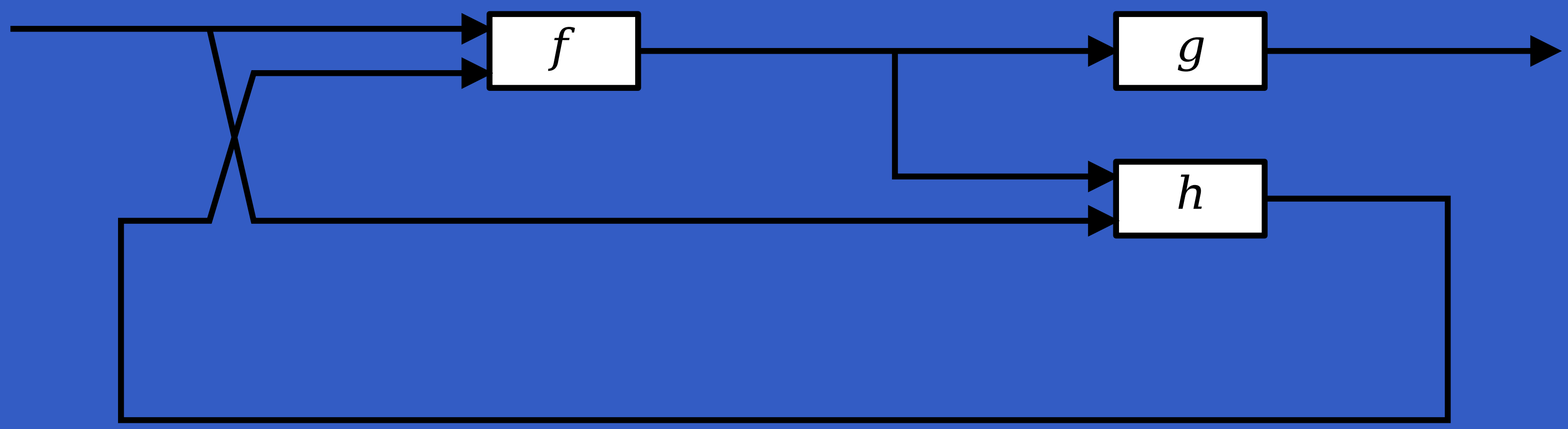
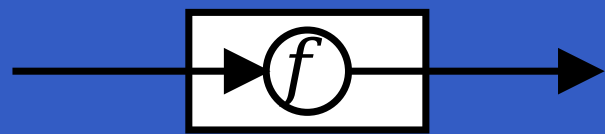
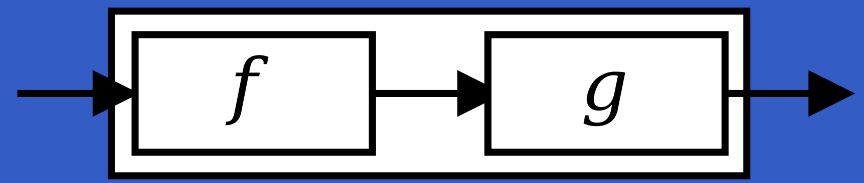


John Hughes's ***Arrow*** framework provides a good answer!

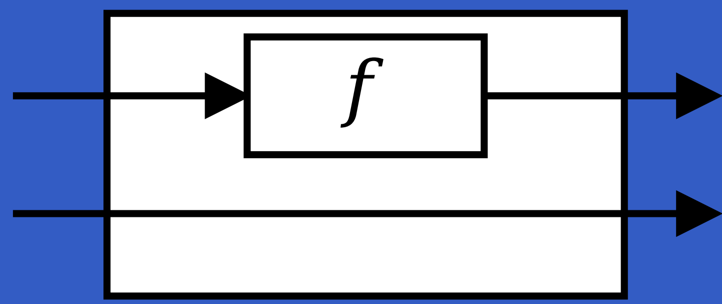
The Arrow framework (1)



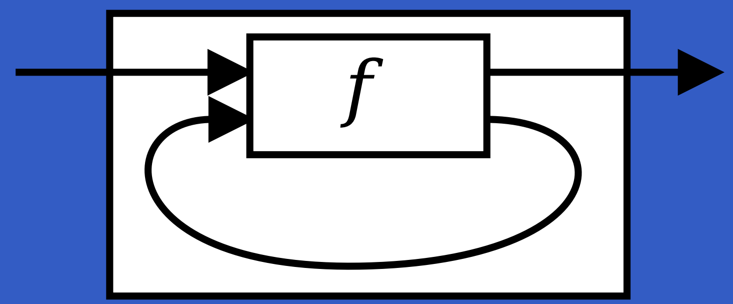
$arr\ f$



$f \ggg g$



$first\ f$



$loop\ f$

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

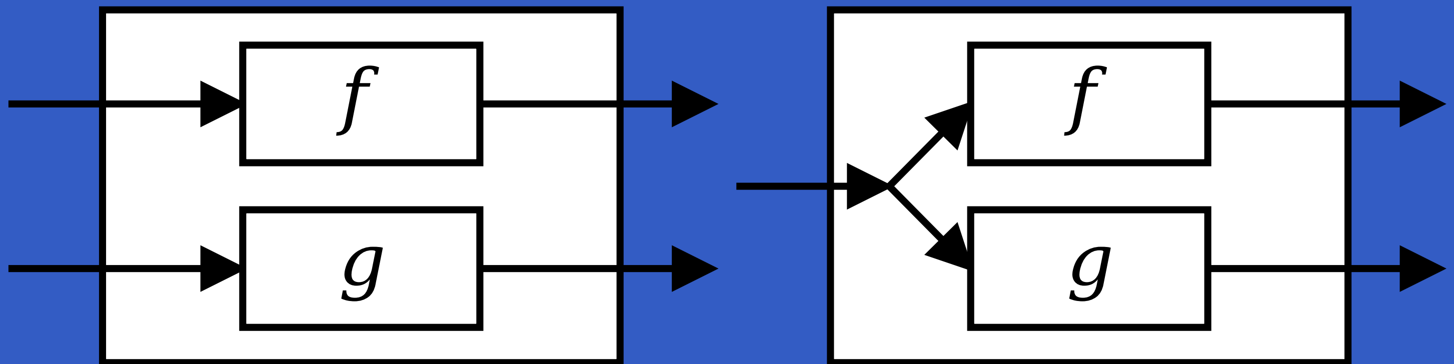
The Arrow framework (2)

Examples:

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

The Arrow framework (2)

Some derived combinators:

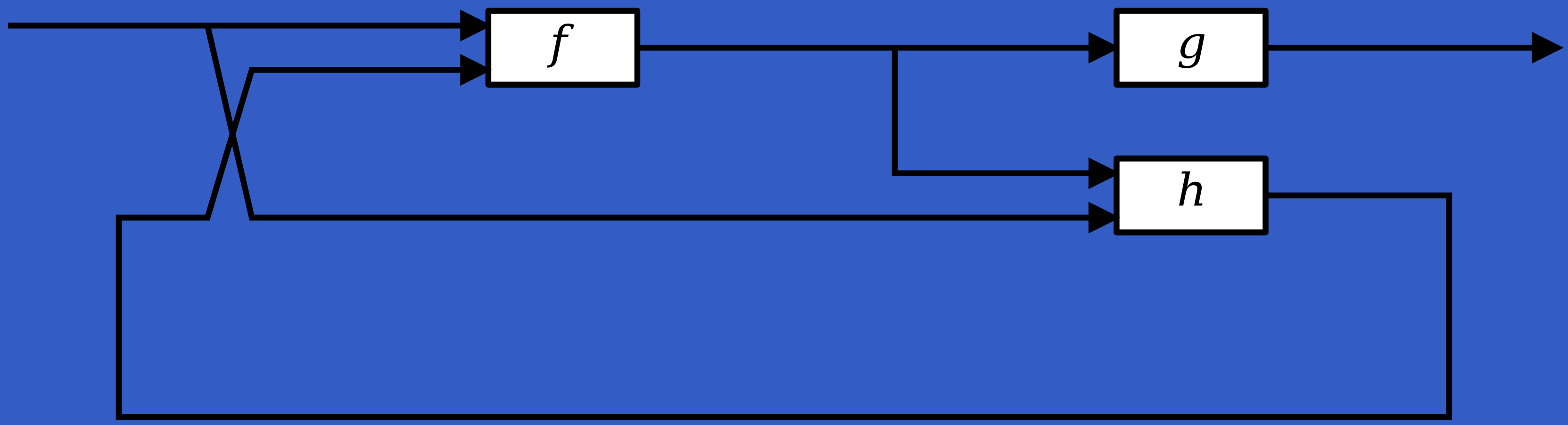


f *** g $\qquad$ f &&& g

$$(\ast\!\ast\!\ast) :: SF\ a\ b \rightarrow SF\ c\ d \rightarrow SF\ (a, c)\ (b, d)$$

$$(\&\&\&) :: SF\ a\ b \rightarrow SF\ a\ c \rightarrow SF\ a\ (b, c)$$

Constructing a network



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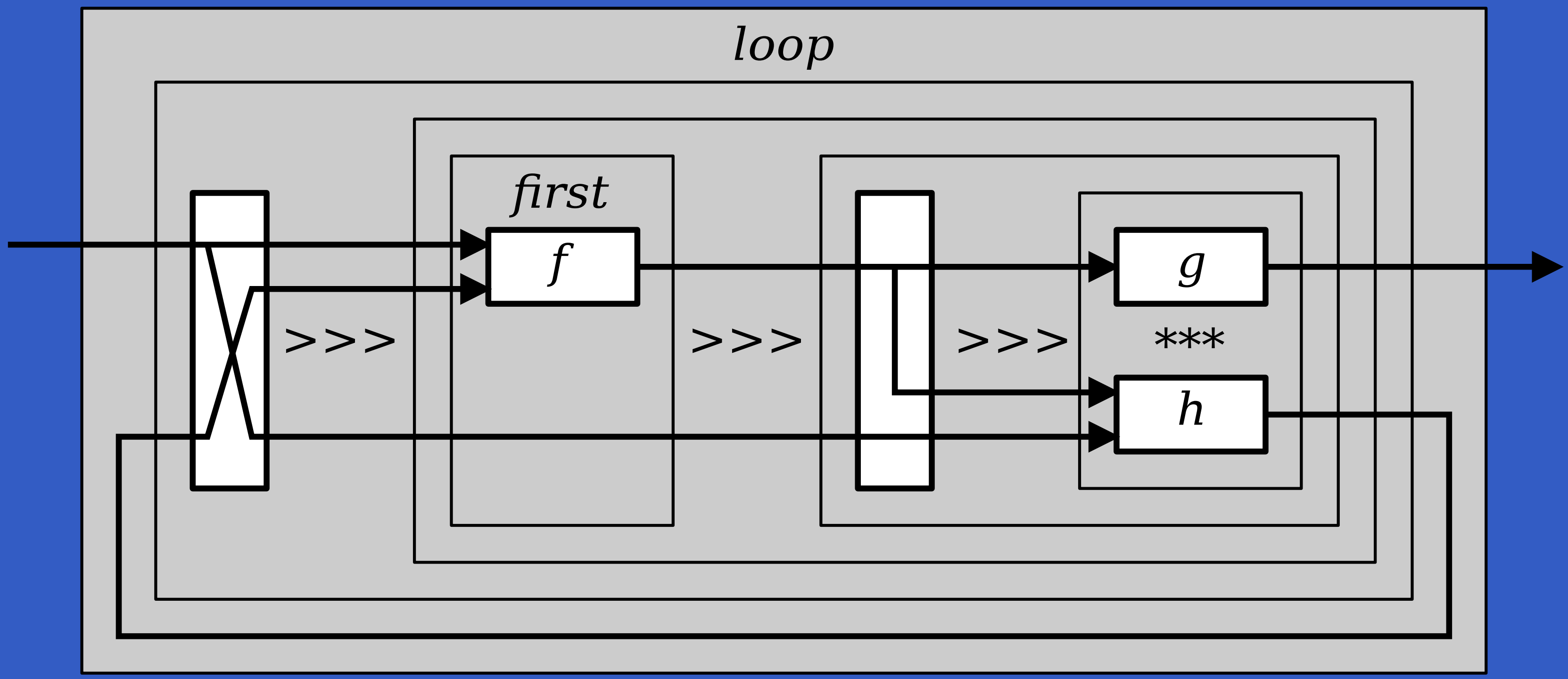

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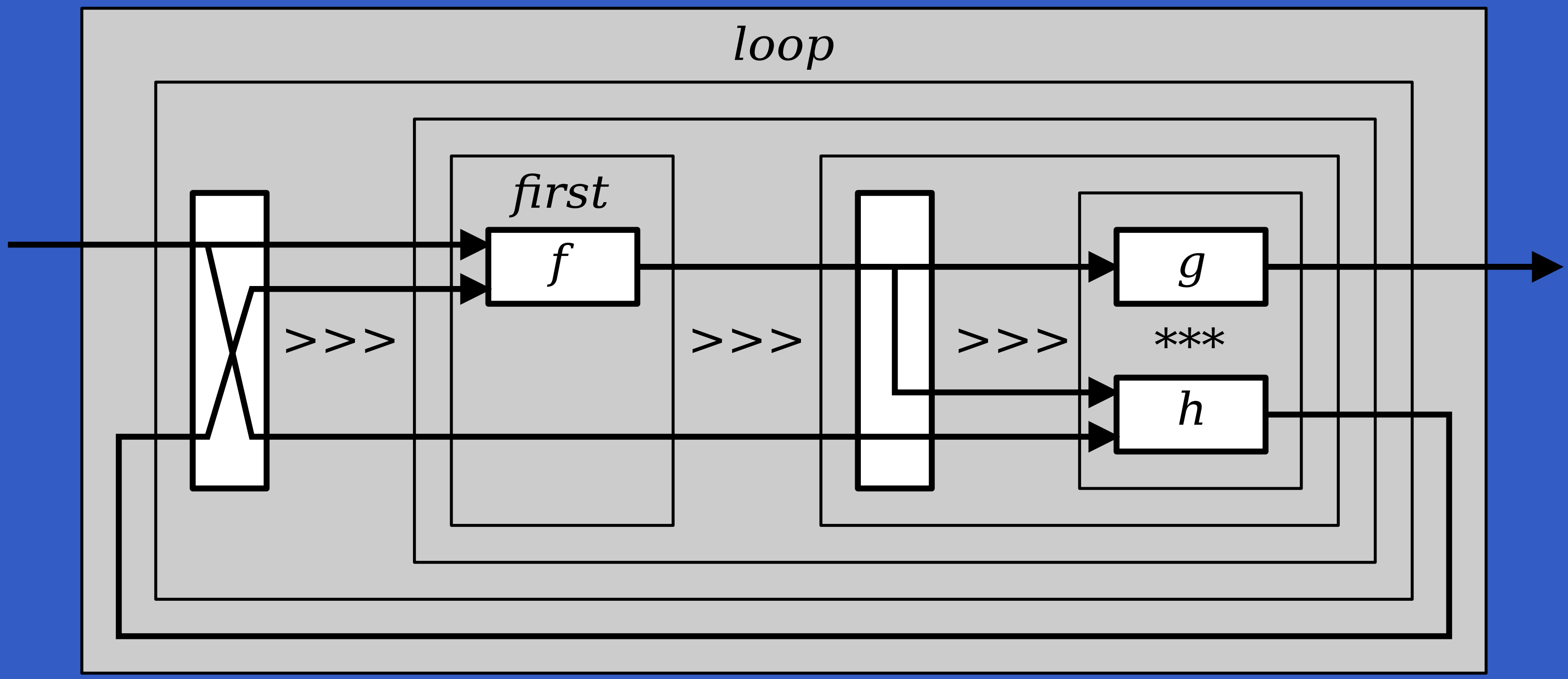
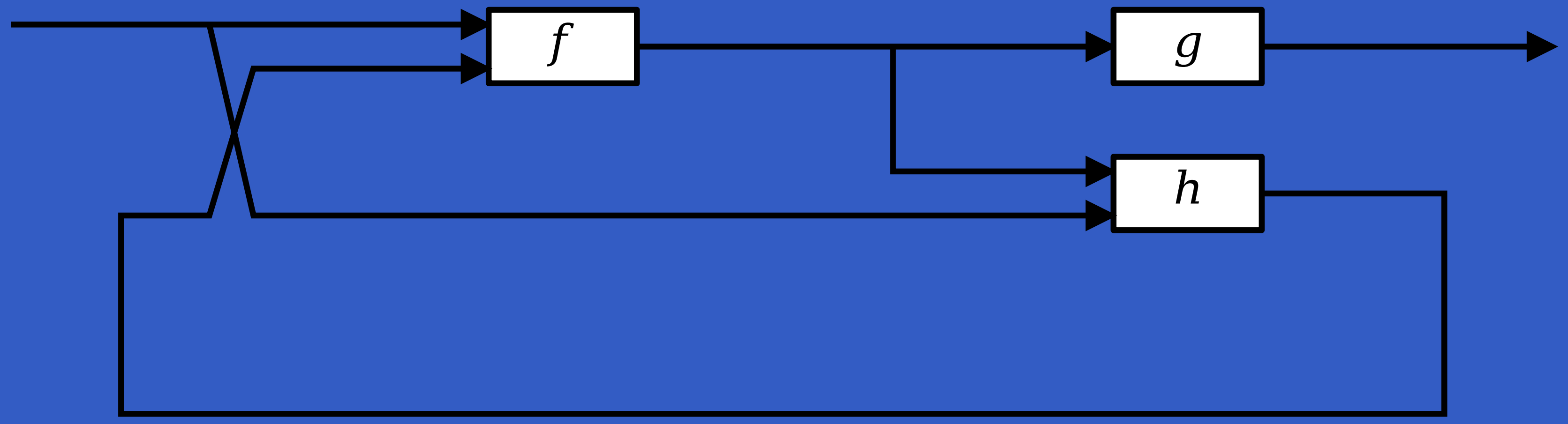


$$loop\ (arr\ (\lambda(x, y) \rightarrow ((x, y), x))$$
$$\ggg (first\ f$$
$$\ggg (arr\ (\lambda(x, y) \rightarrow (x, (x, y))) \ggg (g *** h))))$$

Arrow notation



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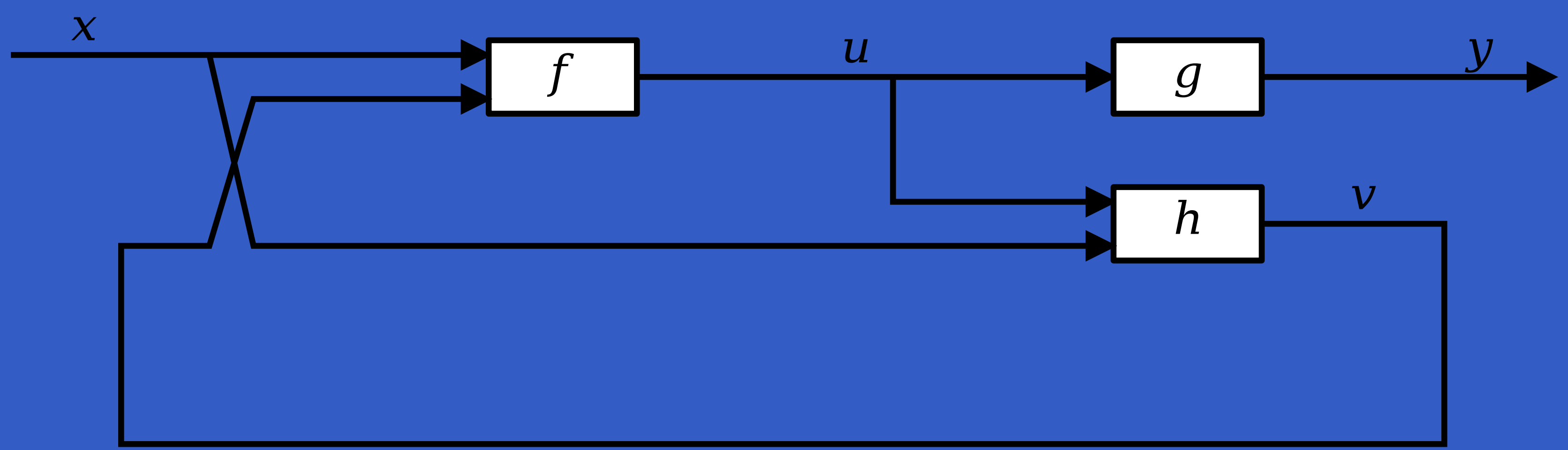

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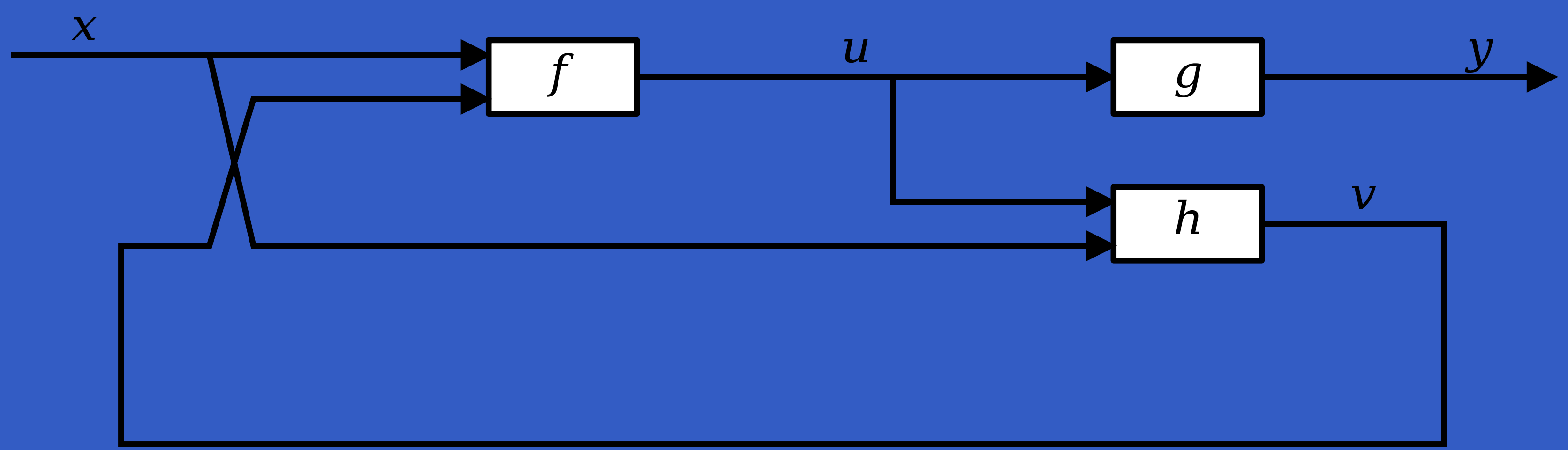


proc $x \rightarrow$ **do**

rec

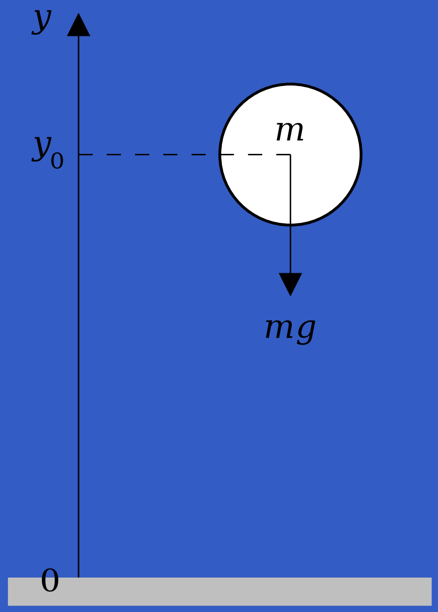
$u \leftarrow f \prec (x, v)$

$y \leftarrow g \prec u$

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

$returnA \prec y$

A Bouncing Ball



$$y = y_0 + \int v \, \mathrm{d}t$$

$$v = v_0 + \int -9.81$$

On impact:

$$v = -v(t-)$$

(fully elastic collision)

Modelling the Bouncing Ball: Part 1

Free-falling ball:

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

Discrete-time Signals or Events

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

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:

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

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.

$$switch ::$$
$$SF\ a\ (b, Event\ c)$$
$$\rightarrow\ (c \rightarrow SF\ a\ b)$$
$$\rightarrow SF\ a\ b$$

The Basic Switch

Idea:

- Allows one signal function to be replaced by another.
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Initial SF with event source

$$switch :: \boxed{SF\ a\ (b, Event\ c)} \rightarrow (c \rightarrow SF\ a\ b) \rightarrow SF\ a\ b$$

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Idea:

- Allows one signal function to be replaced by another.
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$$switch :: SF\ a\ (b, Event\ c) \rightarrow \boxed{(c \rightarrow SF\ a\ b)} \rightarrow SF\ a\ b$$

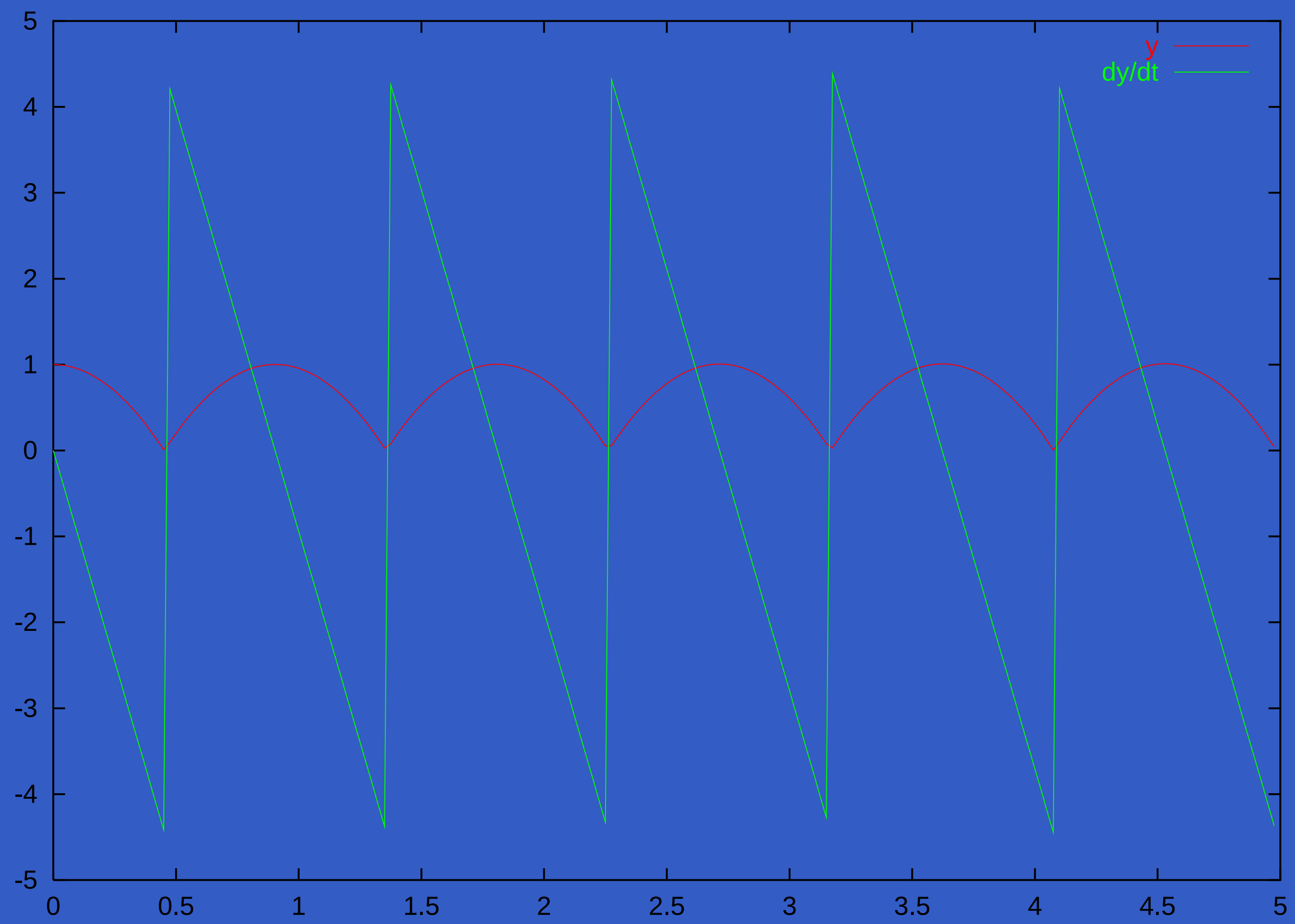
Function yielding SF to switch into

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



Modelling Using Impulses

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This can be abstracted into ***Dirac Impulses***: impulses that act instantaneously (Nilsson 2003).

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Using a `switch` to capture the interaction between the ball and the floor may seem unnatural.

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This can be abstracted into ***Dirac Impulses***: impulses that act instantaneously (Nilsson 2003).

Yampa does provide a derived version of `integral` capturing the basic idea:

$$
\begin{aligned}
&\mathit{impulseIntegral} :: \\
&\quad \mathit{VectorSpace}\ a\ k \Rightarrow \\
&\qquad \mathit{SF}\ (a, \mathit{Event}\ a)\ a
\end{aligned}
$$

The Decoupled Switch

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

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

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&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.

Lots of Switches . . .

$$rSwitch, drSwitch ::$$
$$SF\ a\ b \rightarrow SF\ (a, Event\ (SF\ a\ b))\ b$$

Lots of Switches . . .

$$rSwitch, drSwitch ::$$
$$SF\ a\ b \rightarrow SF\ (a, Event\ (SF\ a\ b))\ b$$

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$$SF\ a\ b \rightarrow SF\ (a, b)\ (Event\ c)$$
$$\rightarrow (SF\ a\ b \rightarrow c \rightarrow SF\ a\ b) \rightarrow SF\ a\ b$$

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$$pSwitch, dpSwitch, rpSwitch, drpSwitch :: \ldots$$

Lots of Switches . . .

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$$pSwitch, dpSwitch, rpSwitch, drpSwitch :: \ldots$$

However, they can ***all*** be defined in terms of $switch$ or $dSwitch$ and a notion of ***ageing*** signal functions:

$$age :: SF\ a\ b \rightarrow SF\ a\ (b, SF\ a\ b)$$

Game Objects (1)

Observable aspects of game entities:

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

Game Objects (2)

$$\begin{aligned}\textbf{data}\ \mathit{ObjectKind} = {} & \mathit{Ball}\ \ \mathit{Double} \\ \mid {} & \mathit{Paddle}\ \mathit{Size2D} \\ \mid {} & \mathit{Block}\ \ \mathit{Energy}\ \mathit{Size2D} \\ \mid {} & \mathit{Side}\ \ \mathit{Side}\end{aligned}$$

Game Objects (3)

$$
\begin{array}{l}
\textbf{type}\ \mathit{ObjectSF} = \mathit{SF}\ \mathit{ObjectInput}\ \mathit{ObjectOutput} \\
\textbf{data}\ \mathit{ObjectInput} = \mathit{ObjectInput}\ \{ \\
\quad \mathit{userInput} \quad\quad\ :: \mathit{Controller}, \\
\quad \mathit{collisions} \quad\quad :: [\mathit{Collision}], \\
\quad \mathit{knownObjects} :: [\mathit{Object}] \\
\} \\
\textbf{data}\ \mathit{ObjectOutput} = \mathit{ObjectOutput}\ \{ \\
\quad \mathit{outputObject} \ :: \mathit{Object}, \\
\quad \mathit{harakiri} \quad\quad\ \ :: \mathit{Event}\ () \\
\}
\end{array}
$$

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:

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

Paddle, Take 1

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

Paddle, Take 2

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

Ball, Take 1

$$objBall :: ObjectSF$$
$$objBall =$$
$$\quad switch\ followPaddleDetectLaunch\ \$\ \lambda p \rightarrow$$
$$\quad objBall$$

$$followPaddleDetectLaunch = \textbf{proc}\ oi \rightarrow \textbf{do}$$
$$\quad o \leftarrow followPaddle \prec oi$$
$$\quad click \leftarrow edge \prec controllerClick\ (userInput\ oi)$$
$$\quad returnA \prec (o, click\ `tag`\ (objectPos\ (outputObject\ o)))$$

Ball, Take 2

$$objBall :: ObjectSF$$
$$objBall =$$
$$\quad switch\ followPaddleDetectLaunch\ \$\ \lambda p \rightarrow$$
$$\quad switch\ (freeBall\ p\ initBallVel \&\&\& never)\ \$\ \lambda\_ \rightarrow$$
$$\quad objBall$$

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

Ball, Take 3

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

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

Making the Ball Bounce

$bouncingBall\ p0\ v0 =$
$\quad switch\ (moveFreelyDetBounce\ p0\ v0)\ \$\ \lambda(p', v') \rightarrow$
$\quad bouncingBall\ p'\ v'$

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

Highly dynamic system structure?

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

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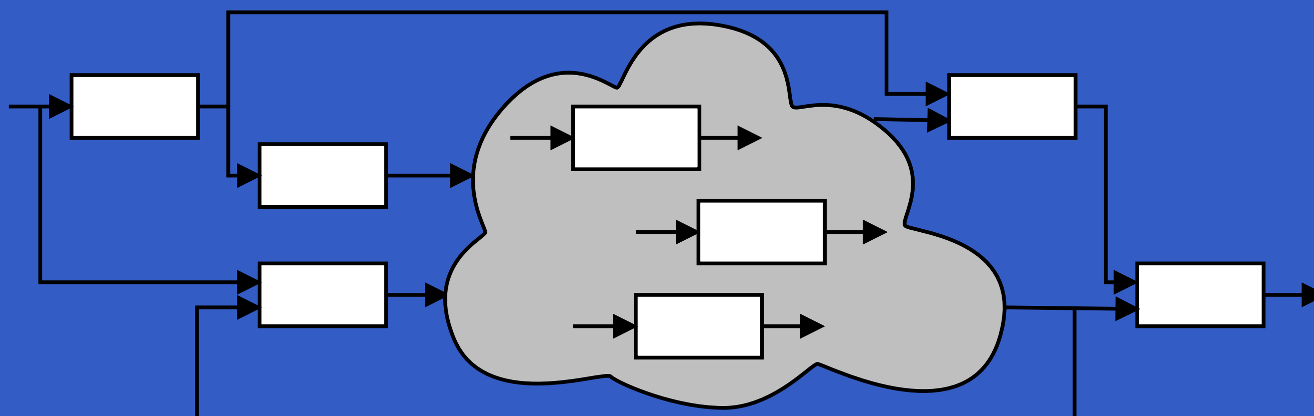
- What about more general structural changes?



We want blocks to disappear!

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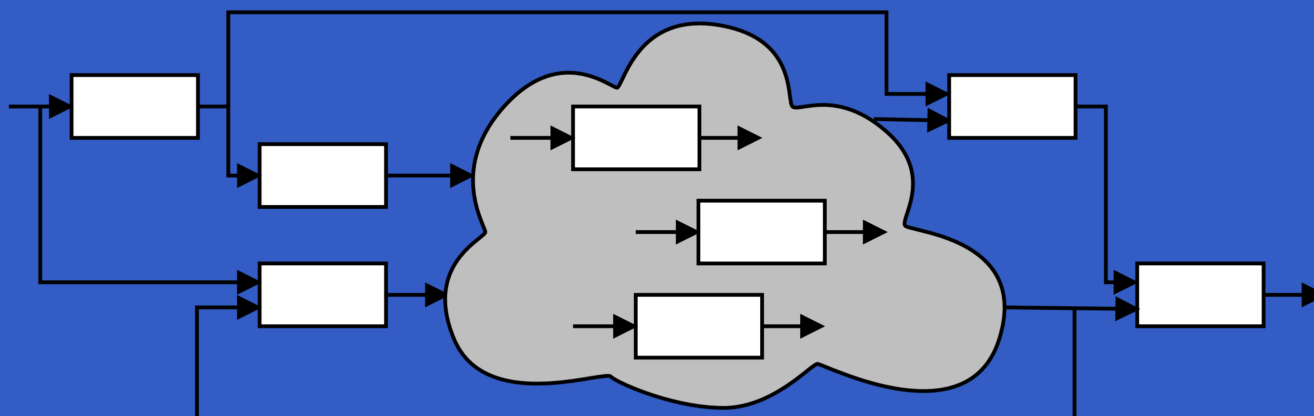
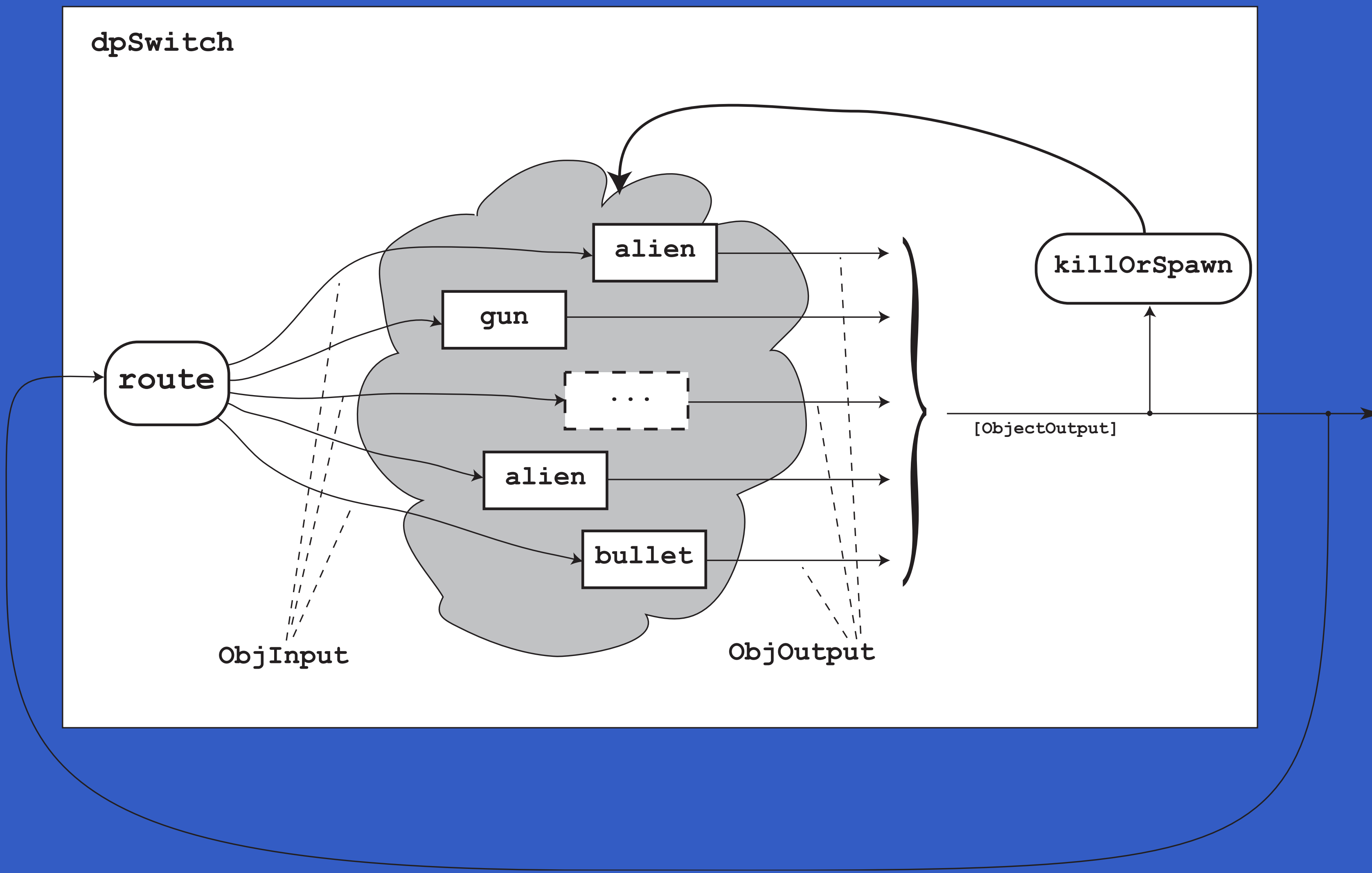


We want blocks to disappear!

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

Routing function

dpSwitch

Need ability to express:

- How input routed to each signal function.
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- 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)
```

Initial collection

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

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)
```

Function yielding SF to switch into

Routing

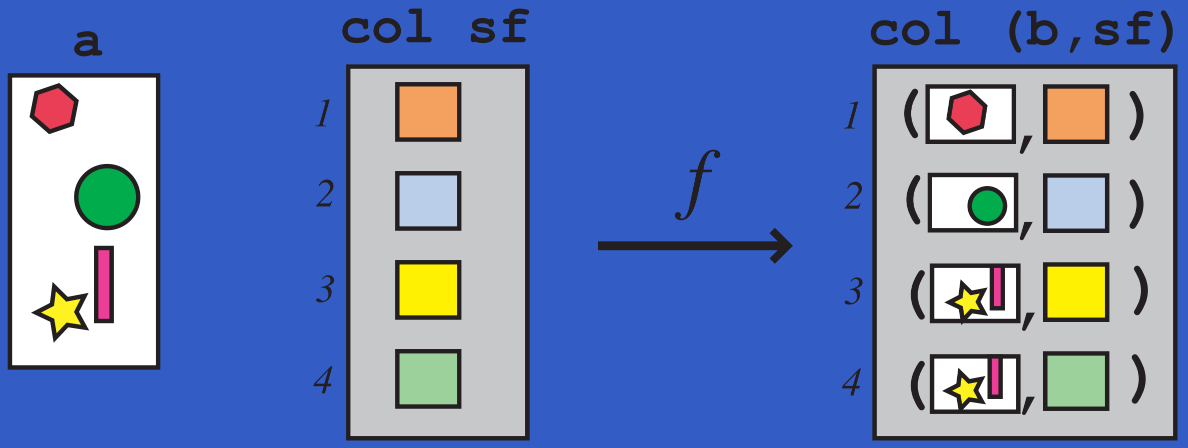
Idea:

- 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:

$$\mathit{Functor}\ \mathit{col} \Rightarrow$$
$$(\mathit{forall}\ \mathit{sf} \circ (a \rightarrow \mathit{col}\ \mathit{sf} \rightarrow \mathit{col}\ (b, \mathit{sf})))$$

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

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

The Game Core

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

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

Recovering Blocks

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