The Arpeggigon: A Functional Reactive Musical Automaton

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The Arpeggigon (1)

- Software realisation of the reacTogon:

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- Interactive cellular automaton:
  - Configuration
  - Performance parameters

The Arpeggigon (2)

- Implemented in Haskell using:
  - The Functional Reactive Programming (FRP) system Yampa
  - Reactive Values and Relations

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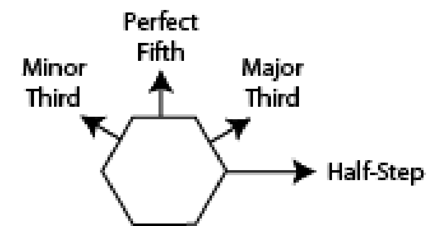
Code: https://gitlab.com/chupin/arpeggigon
Video:
https://www.youtube.com/watch?v=v0HIkFR1EN4

The Harmonic Table

	B		C		C#		D		D#		E		F
G		G#		A		A#		B		C		C#	
	E		F		F#		G		G#		A		A#
C		C#		D		D#		E		F		F#	
	A		A#		B		C		C#		D		D#
F		F#		G		G#		A		A#		B	
	D		D#		E		F		F#		G		G#
A#		B		C		C#		D		D#		E	
	G		G#		A		A#		B		C		C#
D#		E		F		F#		G		G#		A	
	C		C#		D		D#		E		F		F#
G#		A		A#		B		C		C#		D	
	F		F#		G		G#		A		A#		B
C#		D		D#		E		F		F#		G	
	A#		B		C		C#		D		D#		E



Running a Sample Configuration

Layer

Tempo

120

Layer beat

Quarter note

Volume 99

Strength 1.0

Repeat count

1

Beats per bar

4

Enable repeat count

Keep heads on restart

Acoustic Grand Piano

NoAccent

NoSlide

Quarter note

1

Add layer

Remove layer

Save configuration

Load configuration

Restart

Pause

Stop

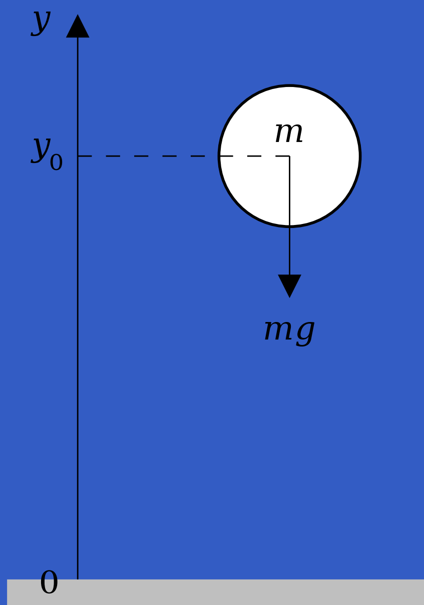
Record

This Talk

- Demonstration
- Brief introduction to FRP and Yampa
- Time in music
- The Arpeggigon core
- Brief introduction to Reactive Values and Relations
- The Arpeggigon shell

Functional Reactive Programming (1)

- Key idea: Don't program one-time-step-at-a-time, but describe an evolving entity as whole.



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

We are used to describing behaviours in totallity over time in mathematics. Why not program in the same way?

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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.

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 conceptual fit for many applications, including games and, as we will see here, interactive musical applications.

Yampa

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  - ***Signals***: time-varying values
  - ***Signal Functions***: pure functions on signals
  - ***Switching***: temporal composition of signal functions

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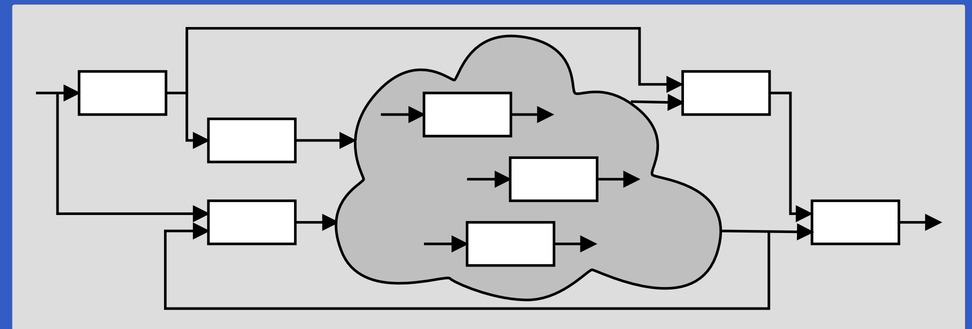
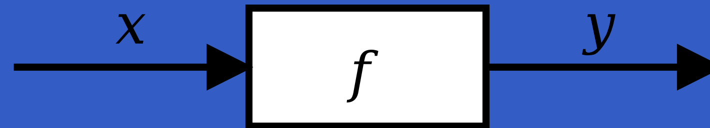
- Programming model:



Signal Functions



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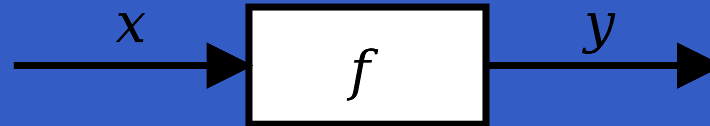
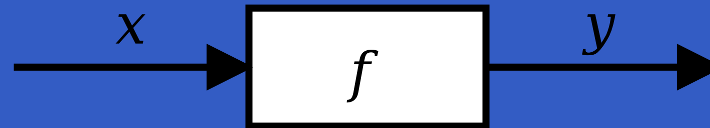


Intuition:

Signal Functions



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

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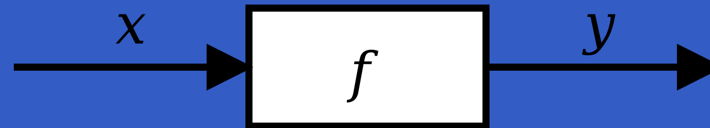

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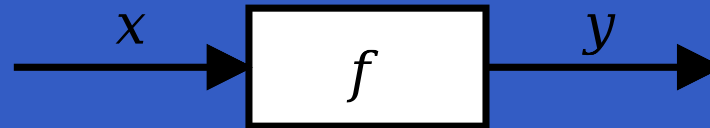
$$Time \approx \mathbb{R}$$
$$Signal\ a \approx Time \rightarrow a$$
$$x :: Signal\ T1$$
$$y :: Signal\ T2$$

Signal Functions



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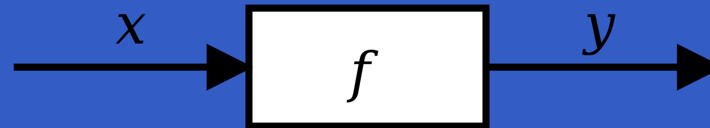
&SF\ a\ b \approx Signal\ a \rightarrow Signal\ b \\
&f :: SF\ T1\ T2
\end{aligned}
$$

Signal Functions



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$$SF\ a\ b \approx Signal\ a \rightarrow Signal\ b$$
$$f :: SF\ T1\ T2$$

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

Some Basic Signal Functions

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

Some Basic Signal Functions

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

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

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Some Basic Signal Functions

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

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

$$iPre :: a \rightarrow SF\ \ a\ \ a$$

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

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

Composition

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

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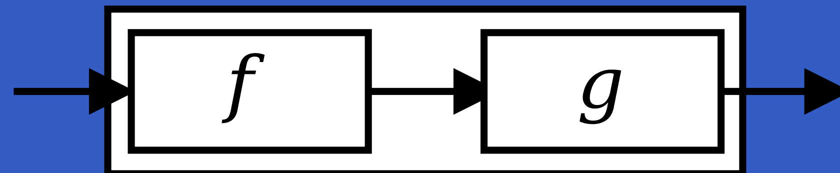
For example, serial composition:



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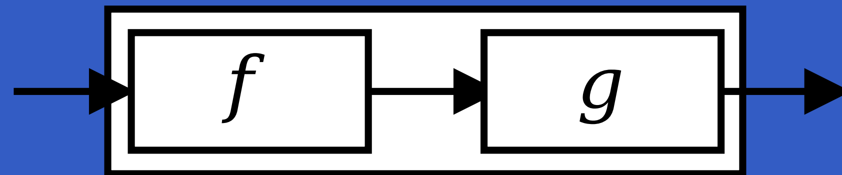

A ***combinator*** that captures this idea:

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

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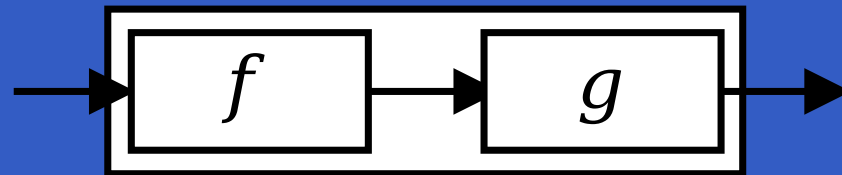
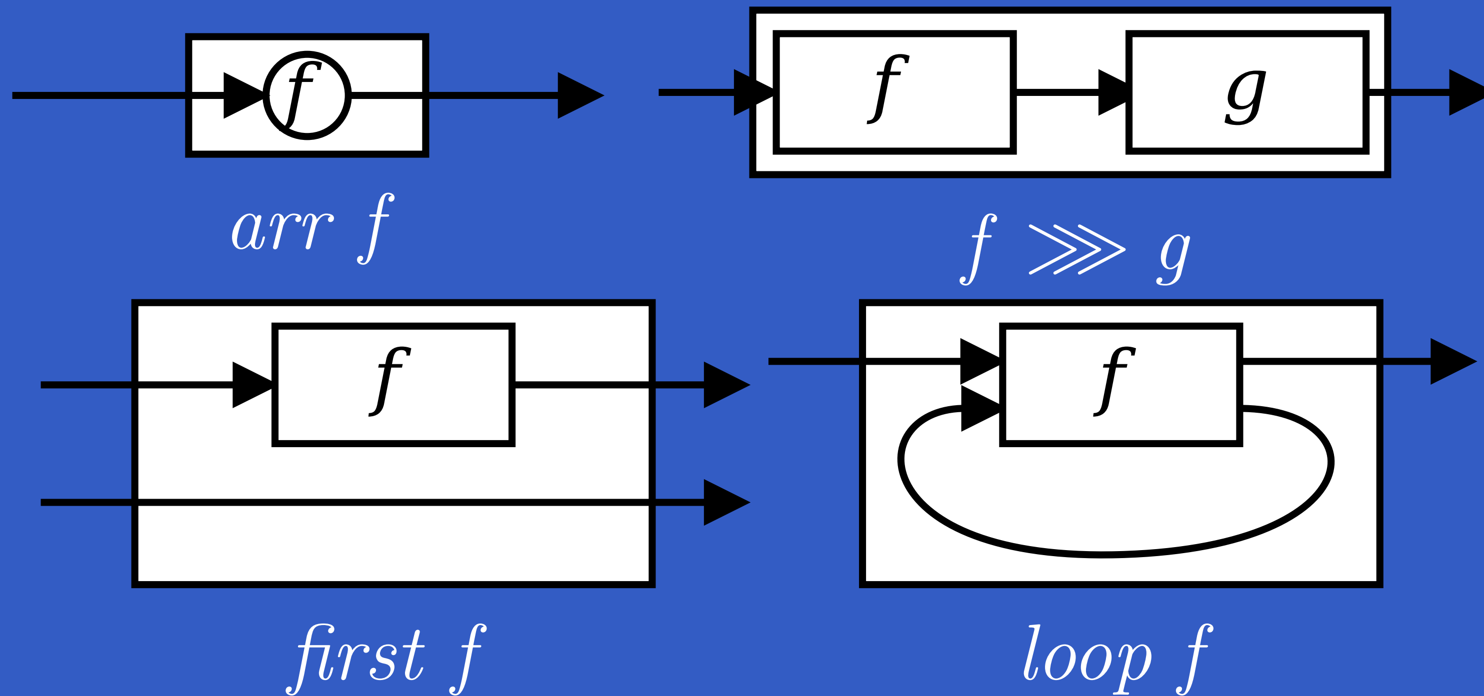


A ***combinator*** that captures this idea:

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

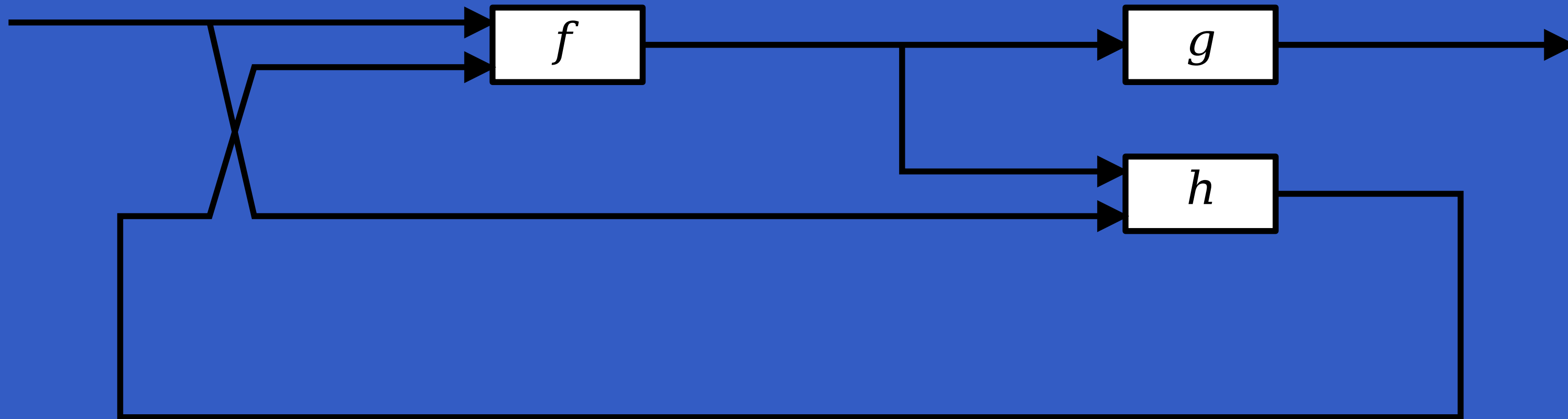
Signal functions are the primary notion; signals a secondary one, only existing indirectly.

The Arrow Combinators



$$arr :: (a \to b) \to SF\ a\ b$$
$$(\ggg) :: SF\ a\ b \to SF\ b\ c \to SF\ a\ c$$
$$first :: SF\ a\ b \to SF\ (a, c)\ (b, c)$$
$$loop :: SF\ (a, c)\ (b, c) \to SF\ a\ b$$

Paterson's Arrow Notation



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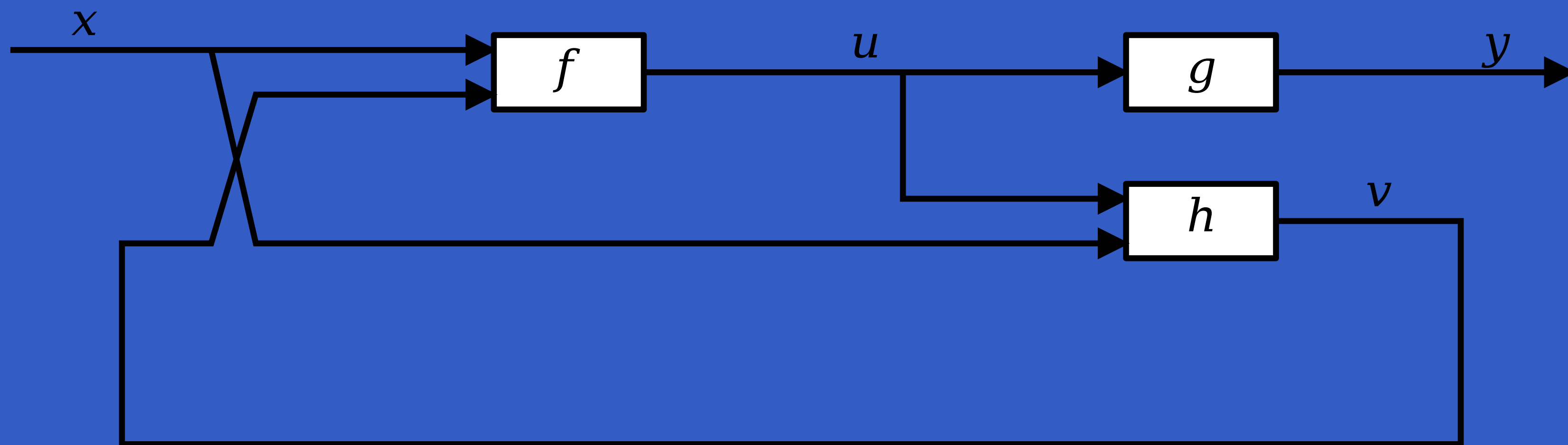

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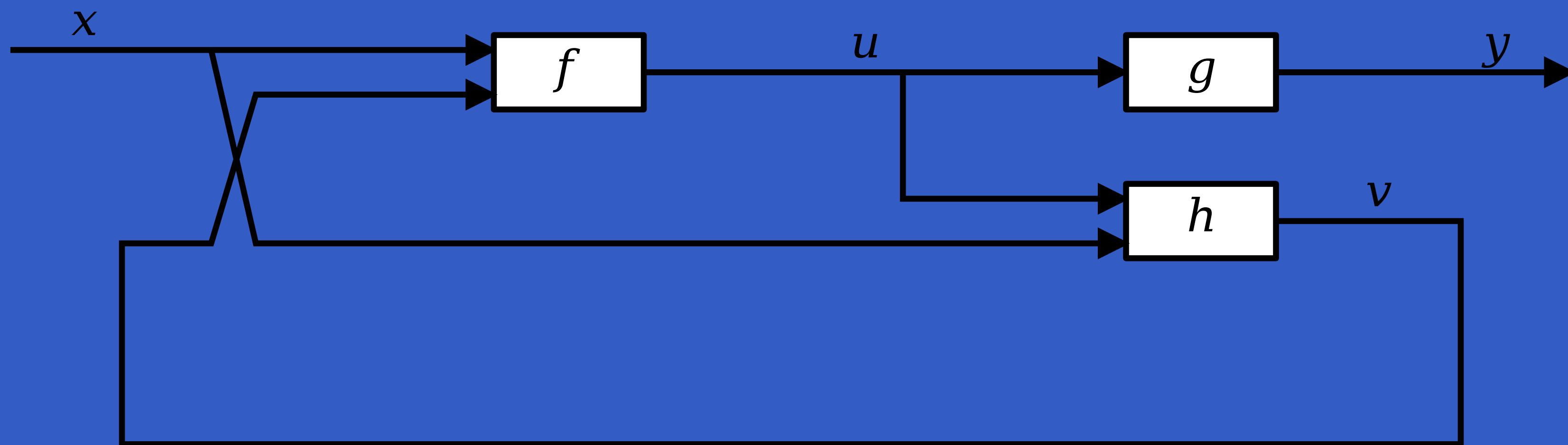


proc $x \rightarrow$ **do**

rec

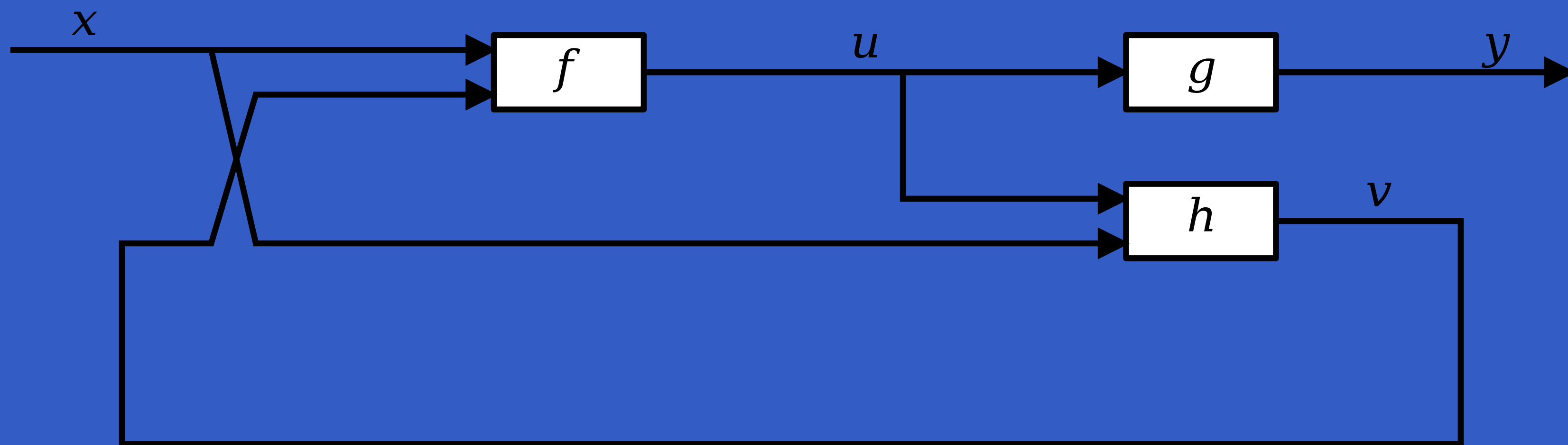
$u \leftarrow f \prec (x, v)$

$y \leftarrow g \prec u$

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

$returnA \prec y$

Paterson's Arrow Notation



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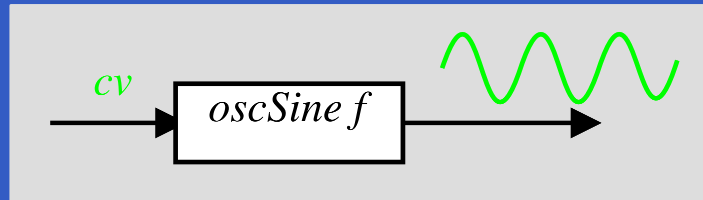
Only syntactic sugar: everything translated into a combinator expression.

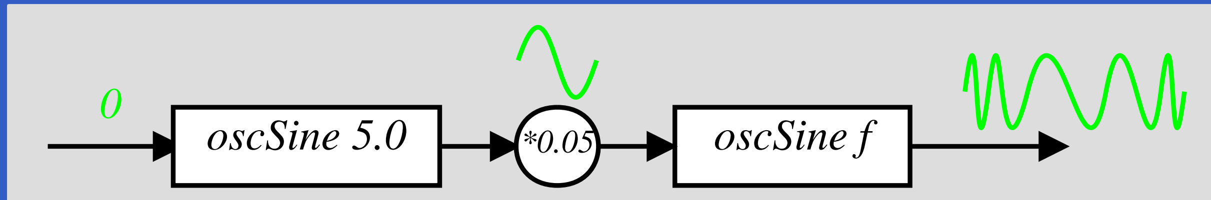
Example 1: Sine oscillator



$$oscSine :: Frequency \to SF\ \ CV\ \ Sample$$
$$oscSine\ f0 = \mathbf{proc}\ cv \to \mathbf{do}$$
$$\quad \mathbf{let}\ f = f0 * (2 ** cv)$$
$$\quad phi \leftarrow integral \prec 2 * pi * f$$
$$\quad returnA \prec sin\ phi$$

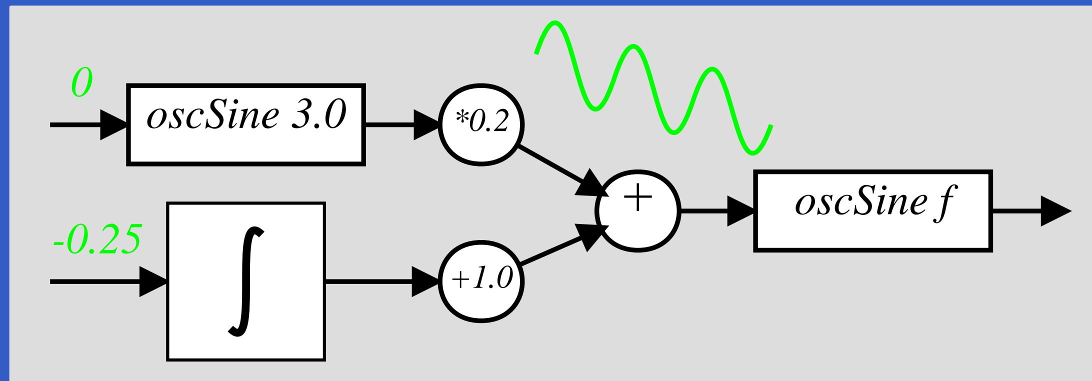
$$constant\ 0 \ggg oscSine\ 440$$

Example 2: Vibrato



$$constant\ 0$$
$$\ggg\ oscSine\ 5.0$$
$$\ggg\ arr\ (*0.05)$$
$$\ggg\ oscSine\ 440$$

Example 3: 50's Sci Fi



$$
\begin{array}{l}
sciFi :: SF\ ()\ Sample \\
sciFi = \textbf{proc}\ () \rightarrow \textbf{do} \\
\quad und \leftarrow arr\ (*0.2) \lll oscSine\ 3.0 \prec 0 \\
\quad swp \leftarrow arr\ (+1.0) \lll integral \prec -0.25 \\
\quad audio \leftarrow oscSine\ 440 \prec und + swp \\
\quad returnA \prec audio
\end{array}
$$

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 $=$ `Signal` $($`Event` $\alpha)$.

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

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

Some functions and event sources:

$$tag :: Event\ a \to b \to Event\ b$$

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

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

Switching

Q: How and when do signal functions "start"?

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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.

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

The Basic Switch

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Initial SF with event source

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

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$$switch ::$$
$$SF\ a\ (b, Event\ c)$$
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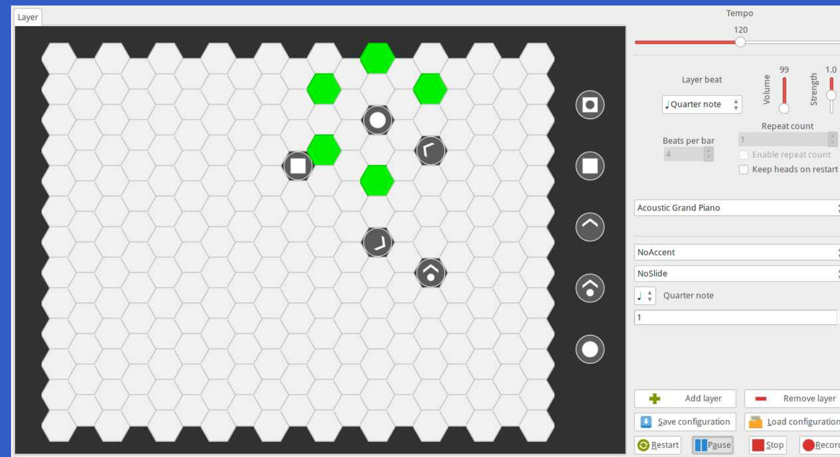
Function yielding SF to switch into

Time in Music

Time inherent to music. Both continuous-time and discrete-time aspects:

- Discrete or ***striated*** time:
  - Time signatures
  - Notes in a musical score
- Continuous or ***smooth*** time:
  - Crescendo
  - Ritardando
  - Portamento
  - Filter sweeps (cf. 50’s SciFi)

Aspects of the Arpeggigon (1)



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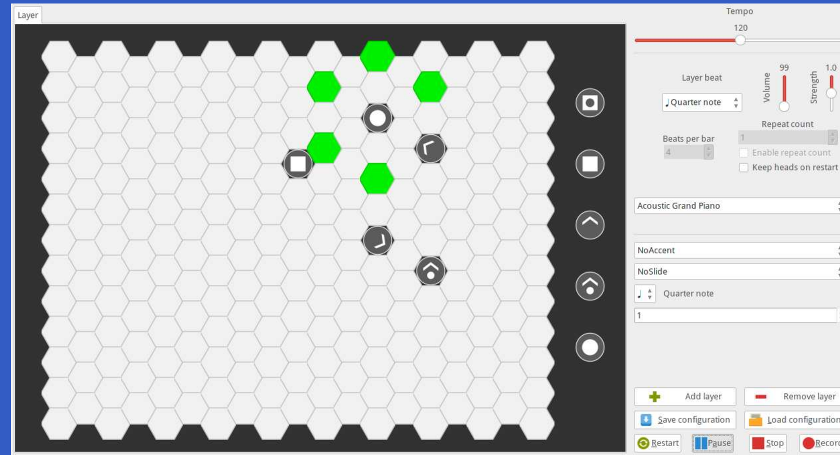

- ***Interactive***

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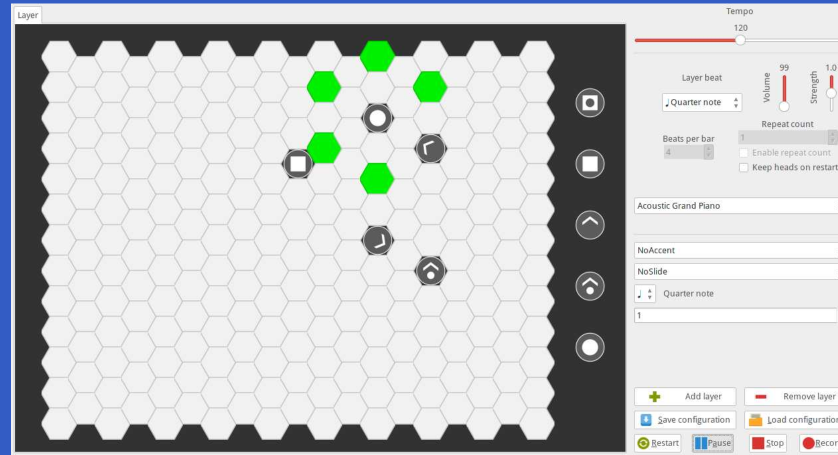

- ***Interactive***
- Layers can be added/removed: ***dynamic structure***

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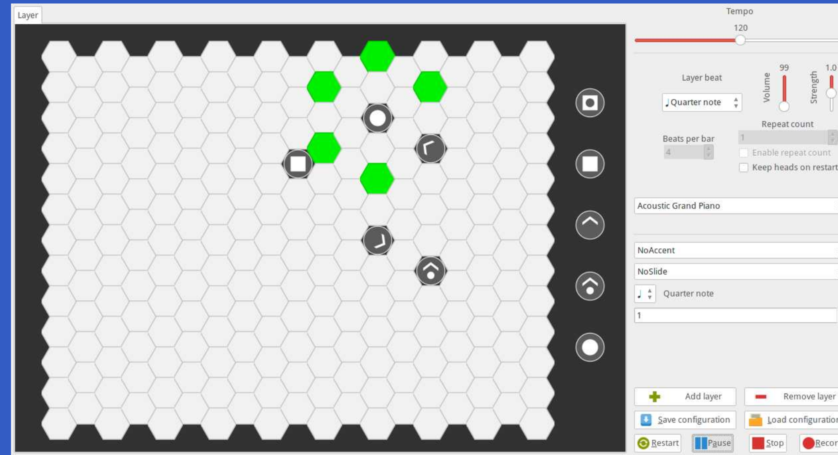

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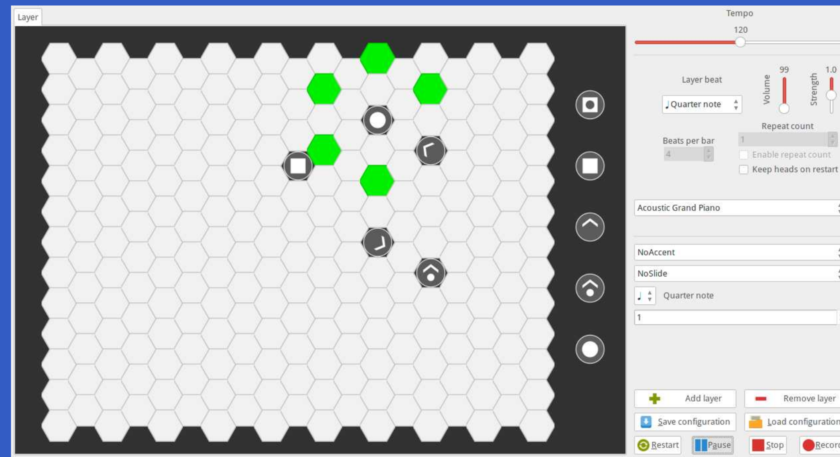

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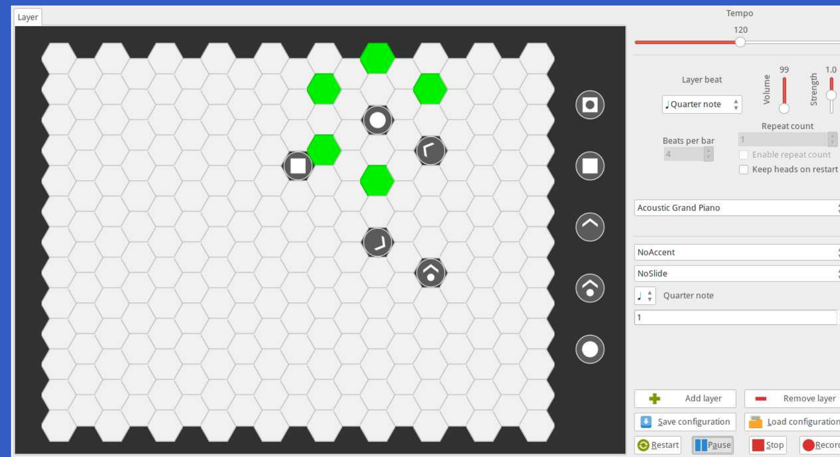

- ***Interactive***
- Layers can be added/removed: ***dynamic structure***
- Notes generated at ***discrete*** points in time
- Notes played ***slightly shorter*** than nominal length
- Configuration and performance parameters can be changed at ***any*** time

Aspects of the Arpeggigon (2)

Potential further enhancements, e.g.:

- Swing: alternately lengthening and shortening pulse divisions
- Staccato and legato playing
- Sliding notes
- Automated, smooth, performance parameter changes

Aspects of the Arpeggigon (2)

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- Swing: alternately lengthening and shortening pulse divisions
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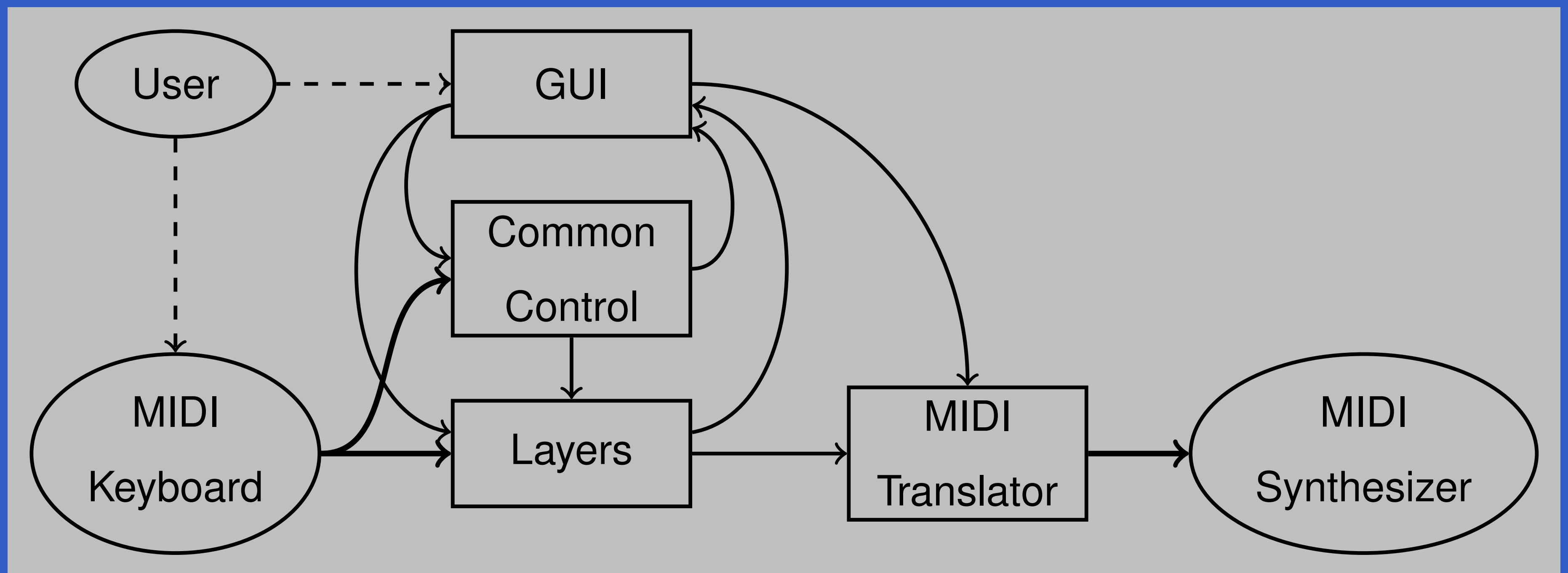
Natural fit for an interactive framework supporting both discrete and continuous time. Like ***Yampa***.

Arpeggigon Architecture



Some Basic Types

$$\begin{aligned}
&\textbf{data}\ \mathit{PlayHead} = \\
&\quad \mathit{PlayHead}\ \{ \\
&\qquad \mathit{phPos} \quad :: \mathit{Pos}, \\
&\qquad \mathit{phBTM} :: \mathit{Int}, \\
&\qquad \mathit{phDir} \quad :: \mathit{Dir} \\
&\quad \}
\end{aligned}$$

$$\begin{aligned}
&\textbf{data}\ \mathit{Note} = \mathit{Note}\ \{ \\
&\quad \mathit{notePch} :: \mathit{Pitch}, \\
&\quad \mathit{noteStr} \ :: \mathit{Strength}, \\
&\quad \mathit{noteDur} :: \mathit{Duration}, \\
&\quad \mathit{noteOrn} :: \mathit{Ornaments} \\
&\}
\end{aligned}$$

Cellular Automaton

State transition function for the cellular automaton:

$$advanceHeads :: Board \to BeatNo \to RelPitch \to Strength \to [PlayHead] \to ([PlayHead], [Note])$$

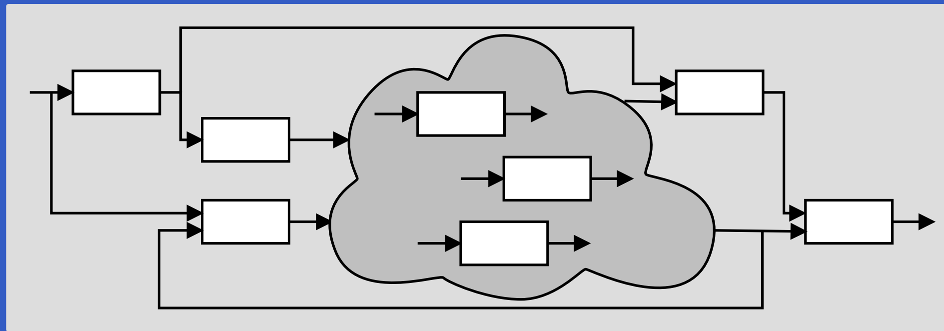
Lifted into a signal function primarily using $accumBy$:

$$accumBy :: (b \to a \to b) \to b \to SF\ (Event\ a)\ (Event\ b)$$

$$automaton :: [PlayHead] \to SF\ (Board, DynamicLayerCtrl, Event\ BeatNo)\ (Event\ [Note], [PlayHead])$$

Layers (1)

- A layer has two states: running and stopped
- Swithing allows for:
  - Moving between states
  - Adding and removing layers dynamically



Layers (2)

A running layer is an instance of $automaton$ along with a meteronome:

$$
\begin{aligned}
&layerRunning :: StaticLayerCtrl \rightarrow [PlayHead] \\
&\quad \rightarrow SF\ (Event\ AbsBeat, Board, LayerCtrl, Event\ RunStatus) \\
&\qquad\qquad (Event\ [Note], [PlayHead]) \\
&layerRunning\ islc\ iphs = \\
&\quad switch\ (lrAux\ islc\ iphs)\ \$\ \lambda(rs', islc', iphs') \rightarrow \\
&\qquad \mathbf{case}\ rs'\ \mathbf{of} \\
&\qquad\quad Stopped\ \ \rightarrow layerStopped \\
&\qquad\quad Running \rightarrow layerRunning\ islc'\ iphs'
\end{aligned}
$$

Layers (3)

$$
\begin{aligned}
& \mathit{lrAux}\ \mathit{islc}\ \mathit{iphs} = \mathbf{proc}\ (\mathit{clk}, b, (\mathit{slc}, \mathit{dlc}, _), \mathit{ers}) \rightarrow \mathbf{do} \\
& \quad \mathit{lbc} \quad\ \ \leftarrow \mathit{layerMetronome}\ \mathit{islc} \prec (\mathit{clk}, \mathit{dlc}) \\
& \quad \mathit{enphs} \leftarrow \mathit{automaton}\ \mathit{iphs} \prec (b, \mathit{dlc}, \mathit{lbc}) \\
& \quad e \qquad\ \leftarrow \mathit{notYet} \prec \mathit{fmap}\ (\lambda \mathit{rs} \rightarrow (\mathit{rs}, \mathit{slc}, \mathit{startHeads}\ b))\ \mathit{ers} \\
& \quad \mathit{returnA} \prec (\mathit{enphs}, e)
\end{aligned}
$$

The static part of $\mathit{LayerControl}$ are parameters can't usefully be changed while the automaton is running. slc is ***sampled*** at the point of switching, and becomes the new islc. The board b is sampled as well and used to compute the new iphs.

Automatic Restarting of a Layer

A useful feature is to allow optional automatic restart of a layer every n bars.

An additional static layer parameter $restart :: Maybe\ int$ along with the following modificatio to $lrAux$ achieves this:

$$
\begin{aligned}
& r \leftarrow \textbf{case}\ restart\ islc\ \textbf{of} \\
& \qquad Nothing \rightarrow never \\
& \qquad Just\ n \quad \rightarrow countTo\ (n * barLength + 1) \\
& \quad \prec lbc \\
& \textbf{let}\ ers' = ers\ `lMerge`\ (r\ `tag`\ Running) \\
& e \leftarrow notYet \prec fmap\ (\lambda rs \rightarrow (rs, slc, startHeads\ b))\ ers'
\end{aligned}
$$

Automated Smooth Tempo Change

Smooth transition between two preset tempos:

$$\begin{array}{l}
\mathit{smoothTempo} :: \mathit{Tempo} \to \mathit{SF}\ (\mathit{Bool}, \mathit{Tempo}, \mathit{Tempo}, \mathit{Rate})\ \mathit{Temp} \\
\mathit{smoothTempo}\ \mathit{tpo0} = \mathbf{proc}\ (\mathit{sel1}, \mathit{tpo1}, \mathit{tpo2}, \mathit{rate}) \to \mathbf{do} \\
\quad \mathbf{rec} \\
\qquad \mathbf{let}\ \mathit{desTpo} = \mathbf{if}\ \mathit{sel1}\ \mathbf{then}\ \mathit{tpo1}\ \mathbf{else}\ \mathit{tpo2} \\
\qquad\quad \mathit{diff} \quad = \mathit{desTpo} - \mathit{curTpo} \\
\qquad\quad \mathit{rate}' \quad = \mathbf{if}\ \ \mathit{diff} > 0.1\ \ \mathbf{then}\ \mathit{rate} \\
\qquad\qquad\qquad \mathbf{else\ if}\ \mathit{diff} < -0.1\ \mathbf{then}\ -\mathit{rate} \\
\qquad\qquad\qquad \mathbf{else}\ \ 0 \\
\qquad \mathit{curTpo} \leftarrow \mathit{arr}\ (+\mathit{tpo0}) \lll \mathit{integral} \prec \mathit{rate}' \\
\quad \mathit{returnA} \prec \mathit{curTpo}
\end{array}$$

Reactive Values and Relations (1)

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  - GUI: GTK+
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- The Arpeggigon interacts with the outside world using two imperative toolkits:
  - GUI: GTK+
  - MIDI I/O: Jack
- Very imperative APIs: Hard or impossible to provide FRP wrappers.
- Instead, we use ***Reactive Values and Relations*** (RVR) to wrap the FRP core in a "shell" that acts as a bridge between the outside world and the pure FRP core.

Reactive Values and Relations (2)

- A Reactive Value (RV) is a typed mutable value with access rights and subscribable change notification.

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- RVs provide a uniform interface to GUI widgets, files, network devices, . . .

  For example, the text field of a text input widget becomes an RV.
- Reactive Relations (RR) allow RVs to automatically be kept in synch by specifying the relations that should hold between them.

Reactive Values and Relations (3)

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- Of course, RVR bindings need to be written for libraries that we wish to use unless available. Inevitably imperative code.
- RVR bindings for GTK+ are available; Jack bindings were written from scratch.

System Tempo Slider

```
globalSettings :: IO (VBox, ReactiveFieldReadWrite IO Int)
globalSettings = do
  globalSettingsBox ← vBoxNew False 10
  tempoAdj          ← adjustmentNew 120 40 200 1 1 1
  tempoLabel        ← labelNew (Just "Tempo")
  boxPackStart globalSettingsBox tempoLabel PackNatural 0
  tempoScale        ← hScaleNew tempoAdj
  boxPackStart globalSettingsBox tempoScale PackNatural 0
  scaleSetDigits tempoScale 0
  let tempoRV =
    bijection (floor, fromIntegral)
    `liftRW` scaleValueReactive tempoScale
  return (globalSettingsBox, tempoRV)
```

Pause

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- Easy to implement by combining two RVs:

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\begin{aligned}
& \mathit{tempoRV'} = \\
& \quad \mathit{liftR2}\ (\lambda \mathit{tempo}\ \mathit{paused} \rightarrow \textbf{if}\ \mathit{paused}\ \textbf{then}\ 0\ \textbf{else}\ \mathit{tempo}) \\
& \qquad\quad \mathit{tempoRV} \\
& \qquad\quad \mathit{pauseButtonRV}
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$$

- This is an equation defining $tempoRV'$ once and for all.

Connecting the Core to the Shell

The following function makes a signal function available as RVs:

$$
\begin{aligned}
&\mathit{yampaReactiveDual} :: \\
&\quad a \\
&\quad \rightarrow \mathit{SF}\ a\ b \\
&\quad \rightarrow \mathit{IO}\ (\mathit{ReactiveFieldWrite}\ \mathit{IO}\ a, \mathit{ReactiveFieldRead}\ \mathit{IO}\ b)
\end{aligned}
$$

This creates two reactive values: one for the input and one for the output of the signal function. After writing a value to the input, the corresponding output at that point in time can be read.

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- Yampa (FRP) good fit for writing interactive musical applications in a declarative way.
- Reactive Values and Relations proved very helpful for bridging the gap between the outside world and the FRP core in a fairly declarative way.
- Performance in terms of overall execution time and space perfectly fine.
- ***Timing*** is not as tight as it should be due to naive MIDI generation.

Reading (1)

- Henrik Nilsson and Guerric Chupin. Funky Grooves: Declarative Programming of Full-Fledged Musical Applications. In *9th International Symposium on Practical Aspects of Declarative Languages (PADL 2017)*, pp. 163–172, January 2017.
- 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)*, pp. 47–58, September 2015.

Reading (2)

- Henrik Nilsson, Antony Courtney, and John Peterson. Functional reactive programming, continued. In *Proceedings of the 2002 Haskell Workshop*, pp. 51–64, October 2002.
- Antony Courtney and Henrik Nilsson and John Peterson. The Yampa Arcade. In *Proceedings of the 2003 Haskell Workshop*, pp. 7–18, August 2003.