FAUST
Functional Synchronous Programming for Signal Processing

Y. Orlarey

GRAME – Centre National de Création Musicale

Séminaire MaMux/Langages Synchrones

1-Introduction

Introduction

What is FAUST ?

FAUST stands for *Functional AUdio STream*:

- It is a *Domain-Specific Language* for real-time audio signal processing and synthesis.
- It can be used to develop:
  - *audio effects,*
  - *sound synthesizers*
  - real-time applications processing signals.
- Who uses FAUST ?
  - Developers of audio applications and plugins
  - Sound engineers and musical assistants
  - Researchers in Computer Music

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What is a FAUST program ?

A FAUST program describes a *signal processor* :

- A (periodically sampled) *signal* is a *time* to *samples* function:
  - $\mathbb{S} = \mathbb{N} \rightarrow \mathbb{R}$
- A *signal processor* is a *signals* to *signals* function:
  - $\mathbb{P} = \mathbb{S}^n \rightarrow \mathbb{S}^m$
- Everything in FAUST is a *signal processor* :
  - $+ : \mathbb{S}^2 \rightarrow \mathbb{S}^1 \in \mathbb{P}$,
  - $3.14 : \mathbb{S}^0 \rightarrow \mathbb{S}^1 \in \mathbb{P}, \ldots,$
- Programming in FAUST is essentially combining signal processors :
  - $\{ : \;\; , \;\; <: \;\; :> \;\; \sim \} \subset \mathbb{P} \times \mathbb{P} \rightarrow \mathbb{P}$

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Example of signal processor

- A digital signal processor, here a Lexicon 300, can be modeled as a *mathematical function* transforming *input signals* into *output signals*.
- FAUST allows to describe both the *mathematical computation* and the *user interface*.

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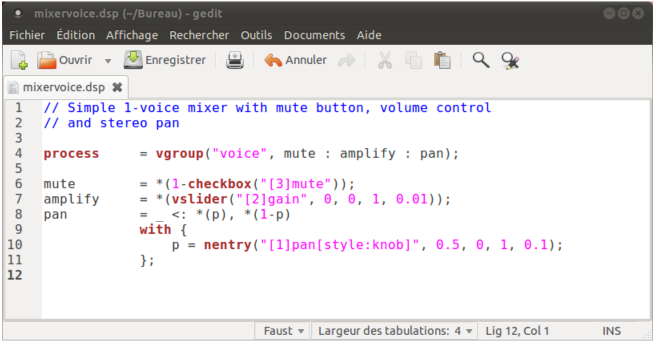
Introduction

A simple FAUST program




```
// Simple 1-voice mixer with mute button, volume control
// and stereo pan

process     = vgroup("voice", mute : amplify : pan);

mute        = *(1-checkbox("[3]mute"));
amplify     = *(vslider("[2]gain", 0, 0, 1, 0.01));
pan         = _ <: *(p), *(1-p)
            with {
                p = nentry("[1]pan[style:knob]", 0.5, 0, 1, 0.1);
            };
```

Figure: Source code of a simple 1-voice mixer

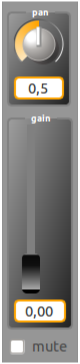


Figure: Resulting application

FAUST is based on several design principles:

- High-level Specification language
- Purely functional approach
- Textual, block-diagram oriented, syntax
- Efficient sample level processing
- Fully compiled code (sequential or parallel)
- Embeddable code (no runtime dependences, constant memory and CPU footprint)
- Easy deployment : single code multiple targets (from VST plugins to iPhone or standalone applications)

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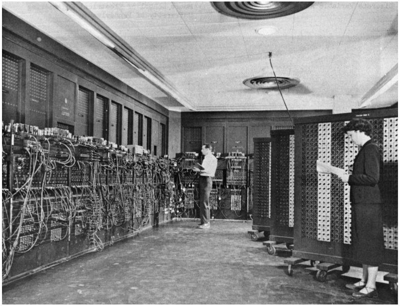
2-Block Diagram Algebra

Block-Diagram Algebra

Programming by patching is familiar to musicians :



Block-Diagram Algebra

Today programming by patching is widely used in Visual Programming Languages like Max/MSP:

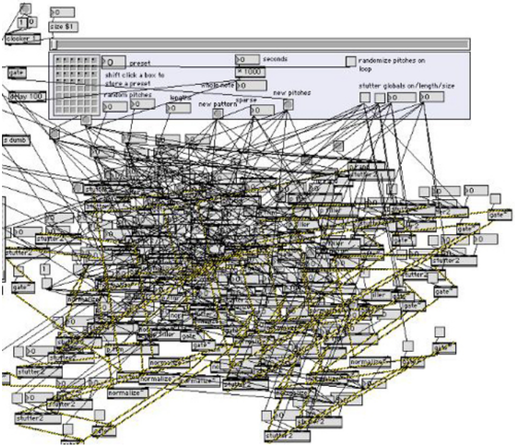


Figure: Block-diagrams can be a mess

Block-Diagram Algebra

Faust allows structured block-diagrams

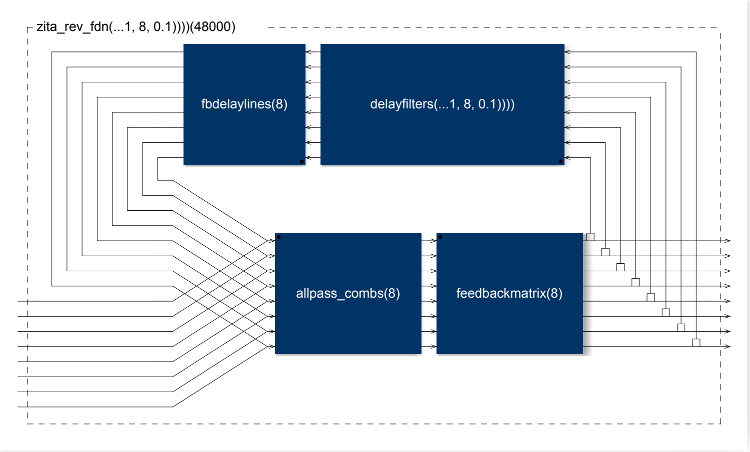


Figure: A complex but structured block-diagram

Block-Diagram Algebra

Faust syntax is based on a *block diagram algebra*

5 Composition Operators

- `(A,B)` parallel composition
- `(A:B)` sequential composition
- `(A<:B)` split composition
- `(A:>B)` merge composition
- `(A~B)` recursive composition

2 Constants

- `!` cut
- `_` wire

Block-Diagram Algebra

Parallel Composition

The *parallel composition* (A, B) is probably the simplest one. It places the two block-diagrams one on top of the other, without connections.

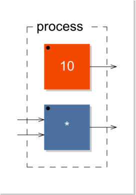


Figure: Example of parallel composition `(10,*)`

Block-Diagram Algebra
Sequential Composition

The *sequential composition* $(A : B)$ connects the outputs of A to the inputs of B. $A[0]$ is connected to $[0]B$, $A[1]$ is connected to $[1]B$, and so on.

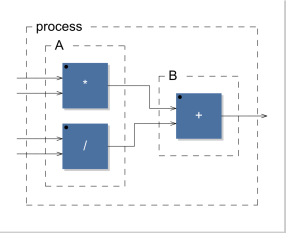


Figure: Example of sequential composition `((*,/):+)`

Block-Diagram Algebra

Split Composition

The *split composition* $(A <: B)$ operator is used to distribute A outputs to B inputs.

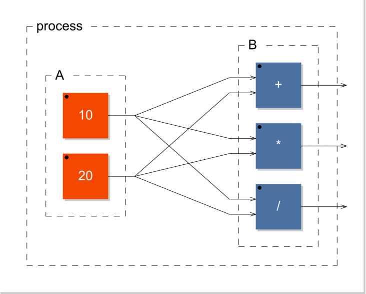


Figure: example of split composition `((10,20) <: (+,*,/))`

Block-Diagram Algebra

Merge Composition

The *merge composition* ($A :> B$) is used to connect several outputs of A to the same inputs of B.

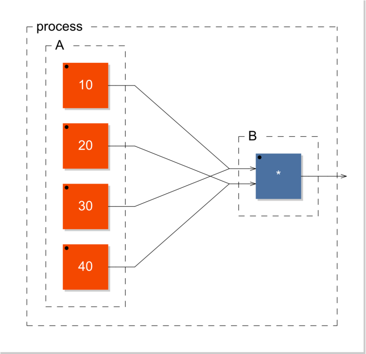


Figure: example of merge composition `((10,20,30,40) :> *)`

The *recursive composition* (A~B) is used to create cycles in the block-diagram in order to express recursive computations.

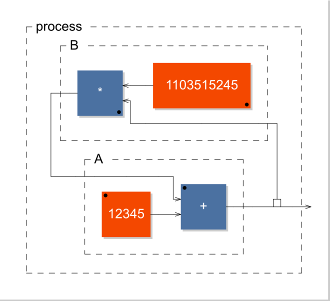


Figure: example of recursive composition +(12345) ~ *(1103515245)

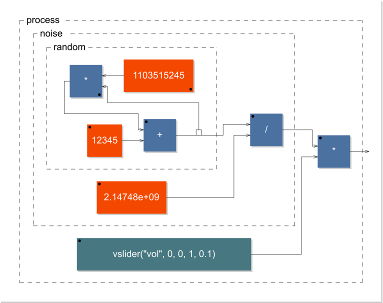
3-Some examples

Block-Diagram Algebra

Example 1

Noise Generator

```
random  = +(12345)~*(1103515245);
noise = random/2147483647.0;
process = noise * vslider("vol", 0, 0, 1, 0.1);
```

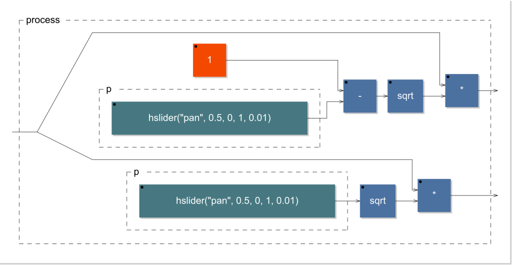


Block-Diagram Algebra

Example 2

Stereo Pan

```
p = hslider("pan", 0.5, 0, 1, 0.01);
process = _ <: *(sqrt(1 - p)), *(sqrt(p));
```



3-Primitive operations

Faust Primitives

Arithmetic operations

Syntax	**Type**	**Description**
`+`	$\mathbb{S}^2 \rightarrow \mathbb{S}^1$	addition: $y(t) = x_1(t) + x_2(t)$
`-`	$\mathbb{S}^2 \rightarrow \mathbb{S}^1$	subtraction: $y(t) = x_1(t) - x_2(t)$
`*`	$\mathbb{S}^2 \rightarrow \mathbb{S}^1$	multiplication: $y(t) = x_1(t) * x_2(t)$
$\wedge$	$\mathbb{S}^2 \rightarrow \mathbb{S}^1$	power: $y(t) = x_1(t)^{x_2(t)}$
`/`	$\mathbb{S}^2 \rightarrow \mathbb{S}^1$	division: $y(t) = x_1(t)/x_2(t)$
`%`	$\mathbb{S}^2 \rightarrow \mathbb{S}^1$	modulo: $y(t) = x_1(t)\%x_2(t)$
`int`	$\mathbb{S}^1 \rightarrow \mathbb{S}^1$	cast into an int signal: $y(t) = (int)x(t)$
`float`	$\mathbb{S}^1 \rightarrow \mathbb{S}^1$	cast into an float signal: $y(t) = (float)x(t)$

Faust Primitives

Bitwise operations

<table>
<tr><th>Syntax</th><th>Type</th><th>Description</th></tr>
<tr><td><code>&</code></td><td>$\mathbb{S}^2 \rightarrow \mathbb{S}^1$</td><td>logical AND: $y(t) = x_1(t) \& x_2(t)$</td></tr>
<tr><td><code>|</code></td><td>$\mathbb{S}^2 \rightarrow \mathbb{S}^1$</td><td>logical OR: $y(t) = x_1(t) | x_2(t)$</td></tr>
<tr><td><code>xor</code></td><td>$\mathbb{S}^2 \rightarrow \mathbb{S}^1$</td><td>logical XOR: $y(t) = x_1(t) \wedge x_2(t)$</td></tr>
<tr><td><code><<</code></td><td>$\mathbb{S}^2 \rightarrow \mathbb{S}^1$</td><td>arith. shift left: $y(t) = x_1(t) << x_2(t)$</td></tr>
<tr><td><code>>></code></td><td>$\mathbb{S}^2 \rightarrow \mathbb{S}^1$</td><td>arith. shift right: $y(t) = x_1(t) >> x_2(t)$</td></tr>
</table>

Faust Primitives

Comparison operations

Syntax	Type	Description
<	$\mathbb{S}^2 \rightarrow \mathbb{S}^1$	less than: $y(t) = x_1(t) < x_2(t)$
<=	$\mathbb{S}^2 \rightarrow \mathbb{S}^1$	less or equal: $y(t) = x_1(t) \Leftarrow x_2(t)$
>	$\mathbb{S}^2 \rightarrow \mathbb{S}^1$	greater than: $y(t) = x_1(t) > x_2(t)$
>=	$\mathbb{S}^2 \rightarrow \mathbb{S}^1$	greater or equal: $y(t) = x_1(t) >= x_2(t)$
==	$\mathbb{S}^2 \rightarrow \mathbb{S}^1$	equal: $y(t) = x_1(t) == x_2(t)$
!=	$\mathbb{S}^2 \rightarrow \mathbb{S}^1$	different: $y(t) = x_1(t)! = x_2(t)$

Faust Primitives

Trigonometric functions

Syntax	Type	Description
`acos`	$\mathbb{S}^1 \rightarrow \mathbb{S}^1$	arc cosine: $y(t) = \mathrm{acosf}(x(t))$
`asin`	$\mathbb{S}^1 \rightarrow \mathbb{S}^1$	arc sine: $y(t) = \mathrm{asinf}(x(t))$
`atan`	$\mathbb{S}^1 \rightarrow \mathbb{S}^1$	arc tangent: $y(t) = \mathrm{atanf}(x(t))$
`atan2`	$\mathbb{S}^2 \rightarrow \mathbb{S}^1$	arc tangent of 2 signals: $y(t) = \mathrm{atan2f}(x_1(t), x_2(t))$
`cos`	$\mathbb{S}^1 \rightarrow \mathbb{S}^1$	cosine: $y(t) = \mathrm{cosf}(x(t))$
`sin`	$\mathbb{S}^1 \rightarrow \mathbb{S}^1$	sine: $y(t) = \mathrm{sinf}(x(t))$
`tan`	$\mathbb{S}^1 \rightarrow \mathbb{S}^1$	tangent: $y(t) = \mathrm{tanf}(x(t))$

Faust Primitives

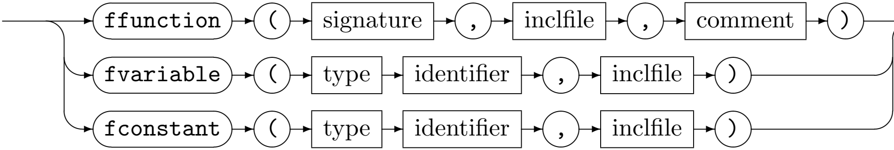
Other Math operations

Syntax	Type	Description
`exp`	$\mathbb{S}^1 \rightarrow \mathbb{S}^1$	base-e exponential: $y(t) = \mathrm{expf}(x(t))$
`log`	$\mathbb{S}^1 \rightarrow \mathbb{S}^1$	base-e logarithm: $y(t) = \mathrm{logf}(x(t))$
`log10`	$\mathbb{S}^1 \rightarrow \mathbb{S}^1$	base-10 logarithm: $y(t) = \mathrm{log10f}(x(t))$
`pow`	$\mathbb{S}^2 \rightarrow \mathbb{S}^1$	power: $y(t) = \mathrm{powf}(x_1(t), x_2(t))$
`sqrt`	$\mathbb{S}^1 \rightarrow \mathbb{S}^1$	square root: $y(t) = \mathrm{sqrtf}(x(t))$
`abs`	$\mathbb{S}^1 \rightarrow \mathbb{S}^1$	absolute value (int): $y(t) = \mathrm{abs}(x(t))$
		absolute value (float): $y(t) = \mathrm{fabsf}(x(t))$
`min`	$\mathbb{S}^2 \rightarrow \mathbb{S}^1$	minimum: $y(t) = \min(x_1(t), x_2(t))$
`max`	$\mathbb{S}^2 \rightarrow \mathbb{S}^1$	maximum: $y(t) = \max(x_1(t), x_2(t))$
`fmod`	$\mathbb{S}^2 \rightarrow \mathbb{S}^1$	float modulo: $y(t) = \mathrm{fmodf}(x_1(t), x_2(t))$
`remainder`	$\mathbb{S}^2 \rightarrow \mathbb{S}^1$	float remainder: $y(t) = \mathrm{remainderf}(x_1(t), x_2(t))$
`floor`	$\mathbb{S}^1 \rightarrow \mathbb{S}^1$	largest int $\leq$: $y(t) = \mathrm{floorf}(x(t))$
`ceil`	$\mathbb{S}^1 \rightarrow \mathbb{S}^1$	smallest int $\geq$: $y(t) = \mathrm{ceilf}(x(t))$
`rint`	$\mathbb{S}^1 \rightarrow \mathbb{S}^1$	closest int: $y(t) = \mathrm{rintf}(x(t))$

Faust Primitives

Add new ones using Foreign Functions

foreignexp



- Reference to external C *functions*, *variables* and *constants* can be introduced using the *foreign function* mechanism.
- example :

```
asinh = ffunction(float asinhf (float), <math.h>, "");
```

Faust Primitives

Delays and Tables

Syntax	Type	Description
`mem`	$\mathbb{S}^1 \rightarrow \mathbb{S}^1$	1-sample delay: $y(t+1) = x(t), y(0) = 0$
`prefix`	$\mathbb{S}^2 \rightarrow \mathbb{S}^1$	1-sample delay: $y(t+1) = x_2(t), y(0) = x_1(0)$
`@`	$\mathbb{S}^2 \rightarrow \mathbb{S}^1$	fixed delay: $y(t + x_2(t)) = x_1(t), y(t < x_2(t)) = 0$
`rdtable`	$\mathbb{S}^3 \rightarrow \mathbb{S}^1$	read-only table: $y(t) = T[r(t)]$
`rwtable`	$\mathbb{S}^5 \rightarrow \mathbb{S}^1$	read-write table: $T[w(t)] = c(t); y(t) = T[r(t)]$
`select2`	$\mathbb{S}^3 \rightarrow \mathbb{S}^1$	select between 2 signals: $T[] = \{x_0(t), x_1(t)\}; y(t) = T[s(t)]$
`select3`	$\mathbb{S}^4 \rightarrow \mathbb{S}^1$	select between 3 signals: $T[] = \{x_0(t), x_1(t), x_2(t)\}; y(t) = T$

Faust Primitives

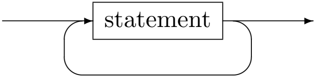
User Interface Primitives

Syntax	Example
button(*str*)	button("play")
checkbox(*str*)	checkbox("mute")
vslider(*str*, *cur*, *min*, *max*, *inc*)	vslider("vol",50,0,100,1)
hslider(*str*, *cur*, *min*, *max*, *inc*)	hslider("vol",0.5,0,1,0.01)
nentry(*str*, *cur*, *min*, *max*, *inc*)	nentry("freq",440,0,8000,1)
vgroup(*str*, *block-diagram*)	vgroup("reverb", ...)
hgroup(*str*, *block-diagram*)	hgroup("mixer", ...)
tgroup(*str*, *block-diagram*)	vgroup("parametric", ...)
vbargraph(*str*, *min*, *max*)	vbargraph("input",0,100)
hbargraph(*str*, *min*, *max*)	hbargraph("signal",0,1.0)

4-Expressions

Faust Program

program



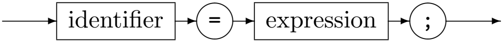
- A Faust program is essentially a list of *statements*. These statements can be :
  - metadata *declarations*,
  - file *imports*
  - *definitions*
- Example :

```
declare name        "noise";
declare copyright   "(c)GRAME␣2006";
import("music.lib");
process = noise * vslider("volume", 0, 0, 1, 0.1);
```

Definitions

Simple Definitions

definition



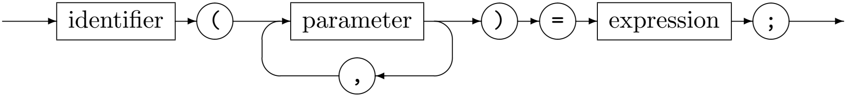
- A *definition* associates an identifier with an expression it stands for. Example :

```
random = +(12345) ~ *(1103515245);
```

Definitions

Functions' definitions

definition



- Definitions with formal parameters correspond to functions' definitions. Example :

```
linear2db(x) = 20*log10(x);
```

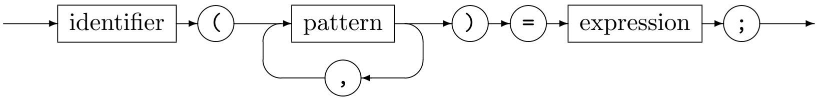
- Alternative notation using a *lambda-abstraction*:

```
linear2db = \(x).(20*log10(x));
```

Definitions

Pattern Matching Definitions

definition



- Formal parameters can also be full expressions representing patterns. Example :

```
duplicate(1,exp) = exp;
duplicate(n,exp) = exp, duplicate(n-1,exp);
```

- Alternative notation :

```
duplicate = case {
              (1,exp) => exp;
              (n,exp) => duplicate(n-1,exp);
            };
```

Statement

Import file

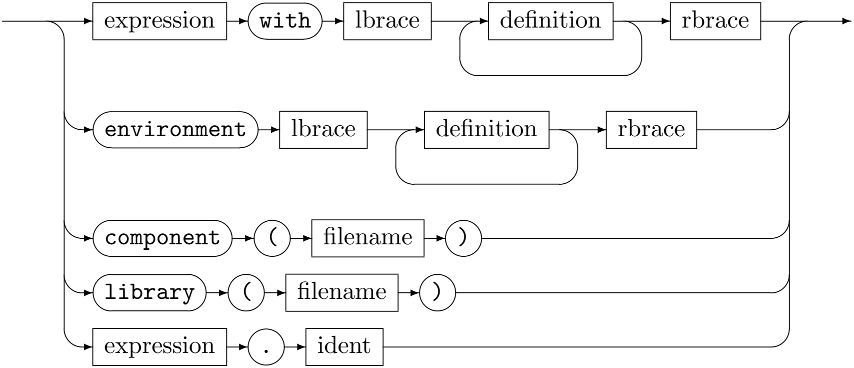
fileimport

- allows to import definitions from other source files.
- for example `import("math.lib");` imports the definitions from `"math.lib"` file, a set of additional mathematical functions provided as foreign functions.

Expressions

Environments

envexp

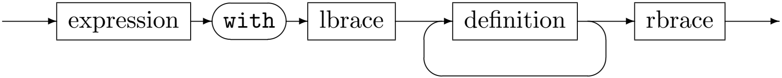


- Each Faust expression has an associated *lexical environment*

Environments

With Expression

withexpression



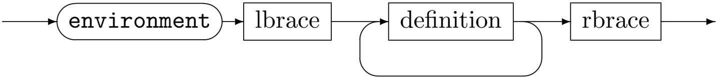
- With expression allows to specify a *local environment*, a private list of definitions that will be used to evaluate the left hand expression
- example pink noise filter :

```
pink = f : + ~ g with {
     f(x) = 0.04957526213389*x
          - 0.06305581334498*x@1
          + 0.01483220320740*x@2;
     g(x) = 1.80116083982126*x
          - 0.80257737639225*x@1;
    };
```

Environments

Environment

environment



- an `environment` is used to group together related definitions :

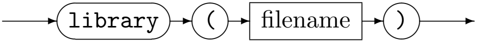
```
constant = environment {
    pi = 3.14159;
     e = 2,718 ;
     ....
   };
```

- definitions of an environment can be easily accessed : `constant.pi`

Environments

Library

library

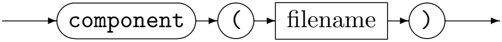


- allows to create an environment by reading the definitions from a file.
- example : `library("filter.lib")`
- definitions are accesed like this : `library("filter.lib").smooth`

Environments

Component

component



- allows to reuse a full Faust program as a simple expression.
- example :

```
component("osc.dsp")<:component("freeverb.dsp")
```

- equivalence between :

```
component("freeverb.dsp")
```

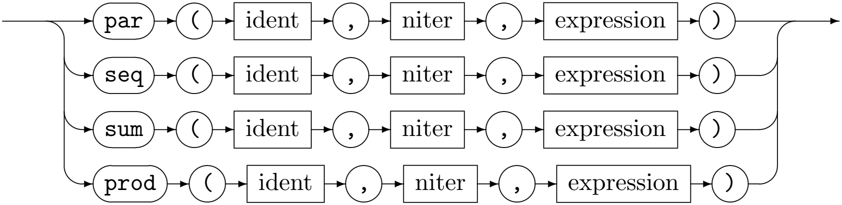
and

```
library("freeverb.dsp").process
```

Expressions

Iterations

diagiteration



- Iterations are analog to `for(...)` loops
- provide a convenient way to automate some complex block-diagram constructions.

Expressions

Iterations

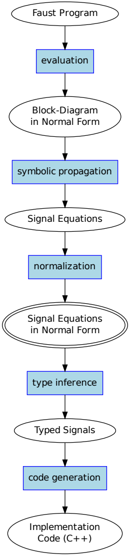
The following example shows the use of seq to create a 10-bands filter:

```
process   = seq(i, 10,
                 vgroup("band␣%i",
                     bandfilter( 1000*(1+i) )
                 )
             );
```

5-Compiler/Code Generation

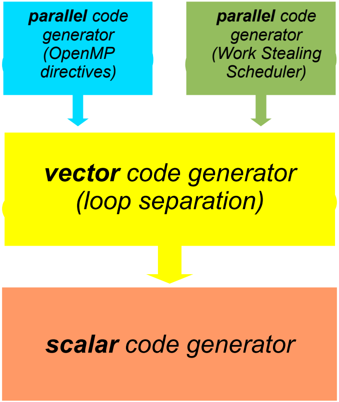
FAUST Compiler

Main Phases of the compiler



FAUST Compiler

Four Code generation modes



5-Performances

Performance of the generated code

How the C++ code generated by FAUST compares with hand written C++ code ?

STK vs FAUST (CPU load)

File name	STK	FAUST	Difference
blowBottle.dsp	3,23	2,49	-22%
blowHole.dsp	2,70	1,75	-35%
bowed.dsp	2,78	2,28	-17%
brass.dsp	10,15	2,01	-80%
clarinet.dsp	2,26	1,19	-47%
flutestk.dsp	2,16	1,13	-47%
saxophony.dsp	2,38	1,47	-38%
sitar.dsp	1,59	1,11	-30%
tibetanBowl.dsp	5,74	2,87	-50%

Overall improvement of about 41 % in favor of FAUST.

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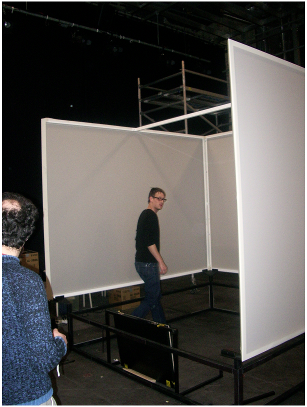
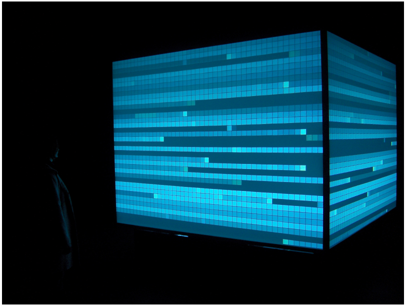
Performance of the generated code

What improvements to expect from parallelized code ?

Sonik Cube

Audio-visual installation involving a cube of light, reacting to sounds, immersed in an audio feedback room (Trafik/Orlarey 2006).



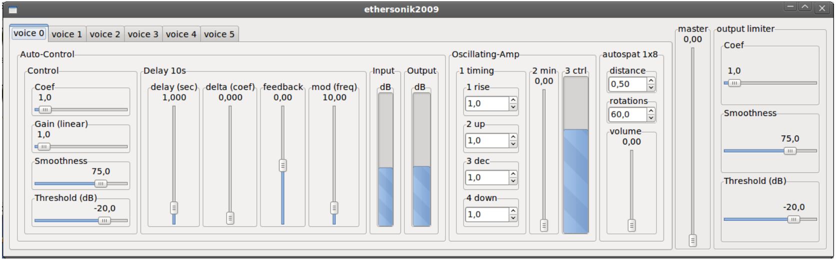


Performance of the generated code

What improvements to expect from parallelized code ?

Sonik Cube

- 8 loudspeakers
- 6 microphones
- audio software, written in FAUST, controlling the audio feedbacks and the sound spatialization.

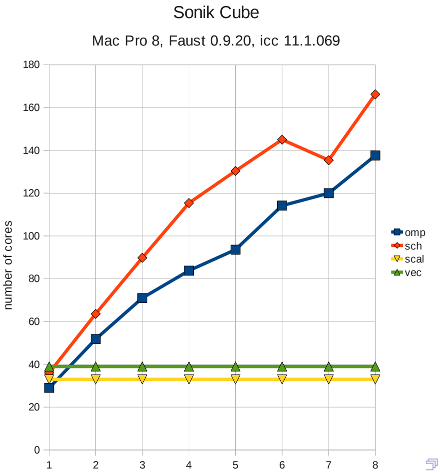


Performance of the generated code

What improvements to expect from parallelized code ?

Sonik Cube

Compared performances of the various C++ code generation strategies according to the number of cores :



6-Automatic documentation

- Binary and source code preservation of programs is not enough : quick obsolescence of languages, systems and hardware.
- We need to preserve the mathematical meaning of these programs independetly of any programming language.
- The solution is to generate automatically the mathematical description of any FAUST program

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Automatic Mathematical Documentation

Motivations et Principles

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Automatic Mathematical Documentation

Tools provided

- The easiest way to generate the complete mathematical documentation is to call the `faust2mathdoc` script on a FAUST file.
- This script relies on a new option of the FAUST compile : `-mdoc`
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Automatic Mathematical Documentation

Files generated by `Faust2mathdoc noise.dsp`

- ▼ `noise-mdoc/`
  - ▼ `cpp/`
    - ◇ `noise.cpp`
  - ▼ `pdf/`
    - ◇ `noise.pdf`
  - ▼ `src/`
    - ◇ `math.lib`
    - ◇ `music.lib`
    - ◇ `noise.dsp`
  - ▼ `svg/`
    - ◇ `process.pdf`
    - ◇ `process.svg`
  - ▼ `tex/`
    - ◇ `noise.pdf`
    - ◇ `noise.tex`

7-Architectures

Faust Architecture System

Motivations

- Easy deployment (one Faust code, multiple audio targets) is an essential feature of the Faust project
- This is why Faust programs say nothing about audio drivers or GUI toolkits to be used.
- There is a *separation of concerns* between the audio computation itself, and its usage.

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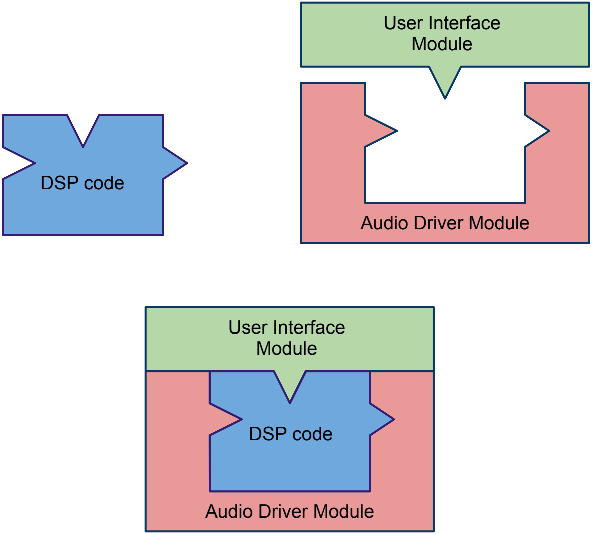
Faust Architecture System

The *architecture file* describes how to connect the audio computation to the external world.



Faust Architecture System

Examples of supported architectures

- Audio plugins :
  - LADSPA
  - DSSI
  - Max/MSP
  - VST
  - PD
  - CSound
  - Supercollider
  - Pure
  - Chuck
  - Octave
  - Flash
- Standalone audio applications :
  - Jack
  - Alsa
  - CoreAudio
  - iPhone

8-Multirate extension

Extensions

What is currently missing in FAUST

- Applications that we can't address :
  - oversampling, upsampling, downsampling
  - spectral processing
  - video processing
- What we need :
  - multirate signals
  - multidimension signals

Extensions

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Extensions

What we propose

- Minimal extension with 4 new primitives
  - Vectorize
  - Serialize
  - Concat
  - Access
- Only Vectorize and Serialize change rates (but keep the flow constant).
- All other operations assume arguments at the same rate
- All numerical operations extended to vectors, vectors of vectors, etc.

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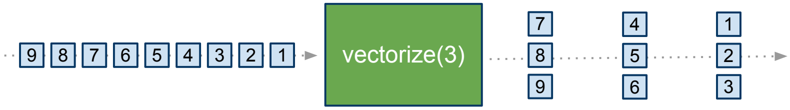
Extensions

Vectorize



$$\text{vectorize} : T^r \times n \rightarrow [n]T^{r/n}$$

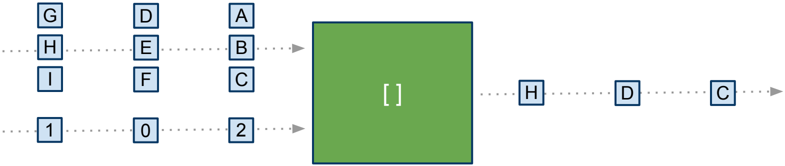
Extensions

Serialize

$$\text{serialize} : [n]\,T^{r/n} \rightarrow T^{r}$$

Extensions

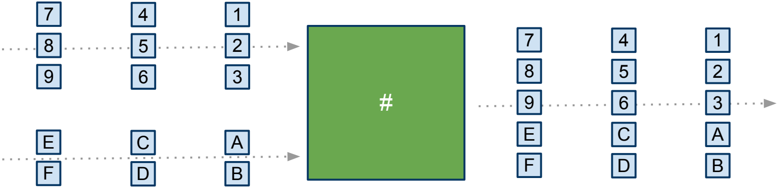
Access



$$\text{access} : [n]\,T^r \times \mathbb{N}[0..n]^r \rightarrow T^r$$

Extensions

Concat



$$\# : [n]T^r \times [m]T^r \rightarrow [n+m]T^r$$

Some very simple examples involving the multirate extension.

- upsampling : `up2 = vectorize(1) <: # : serialize;`
- downsampling : `down2 = vectorize(2) : [0];`
- sliding window :
  `slide(n) = vectorize(n) <: @(1),_ : #;`

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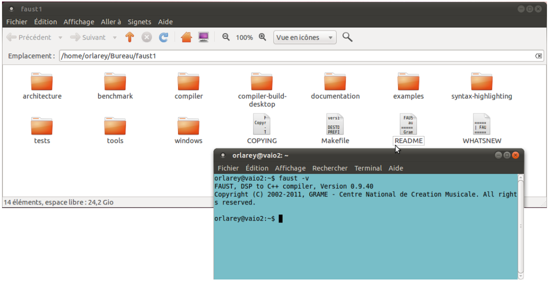
9-Resources

Resources

FAUST Distribution on Sourceforge



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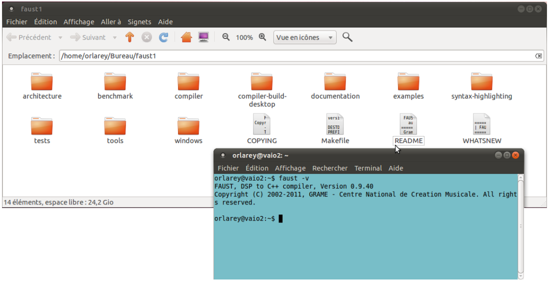

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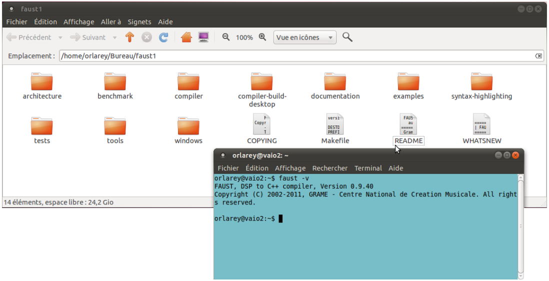

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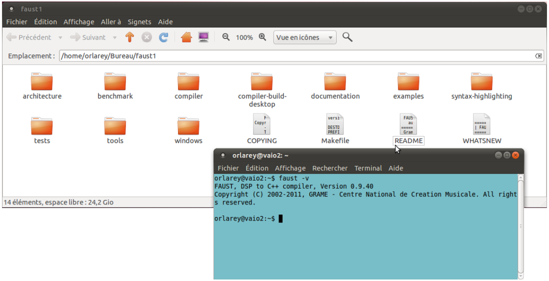

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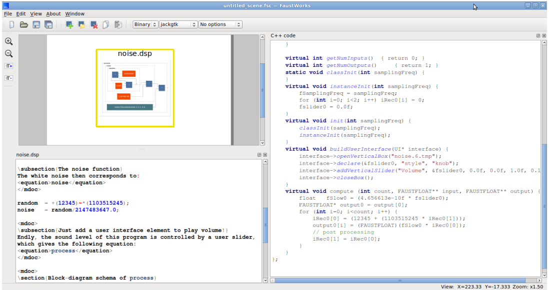
FaustWorks IDE on Sourceforge



- http://sourceforge.net/projects/faudiostream/files/FaustWorks-0.3.2.tgz/download
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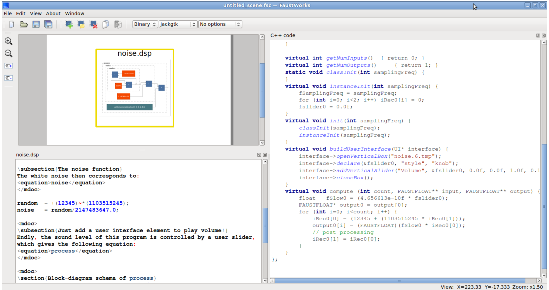

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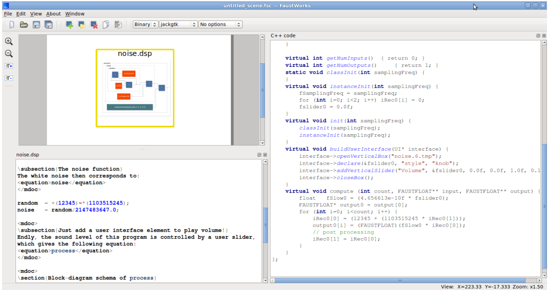

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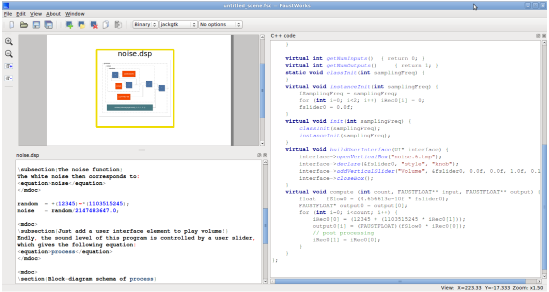

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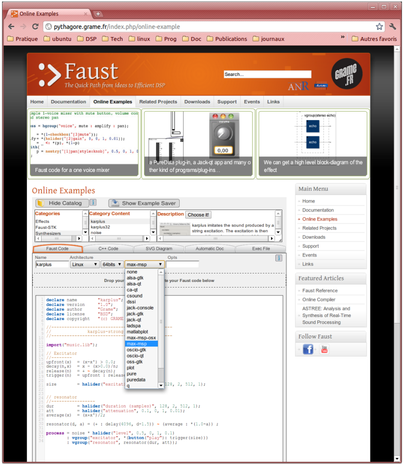
Using FAUST Online Compiler



- http://faust.grame.fr
- No installation required
- Compile to C++ as well as binary (Linux, MacOSX and Windows)

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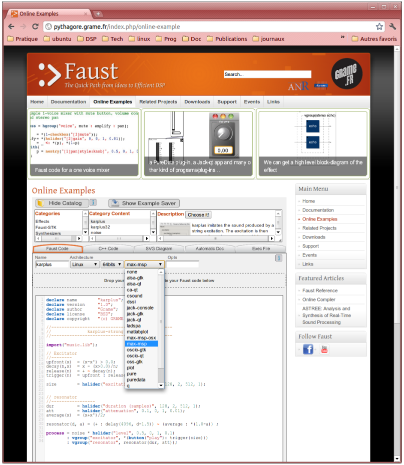

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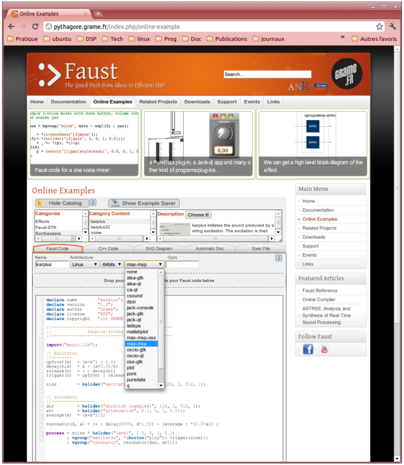

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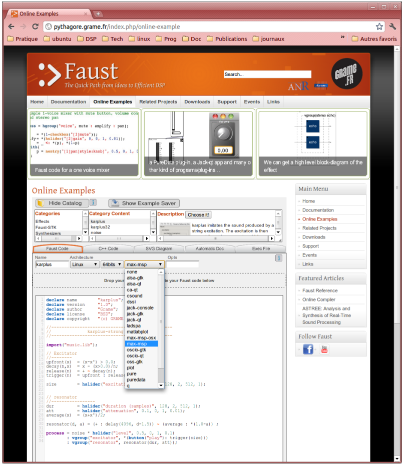

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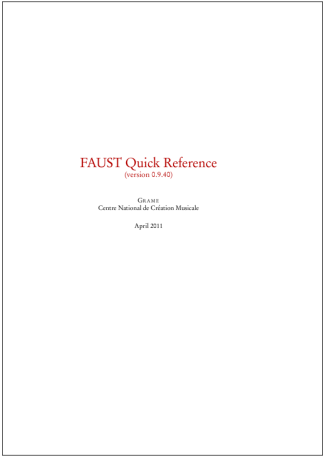
FAUST Quick Reference


FAUST Quick Reference
(version 0.9.40)

GRAME
Centre National de Création Musicale

April 2011

Figure: *Faust Quick Reference*, Grame

Resources

Some research papers

- 2004 : **Syntactical and semantical aspects of Faust**, Orlarey, Y. and Fober, D. and Letz, S., in *Soft Computing*, vol 8(9), p623-632, Springer.
- 2009 : **Parallelization of Audio Applications with Faust**, Orlarey, Y. and Fober, D. and Letz, S., in *Proceedings of the SMC 2009-6th Sound and Music Computing Conference*,
- 2011 : **Dependent vector types for data structuring in multirate Faust**, Jouvelot, P. and Orlarey, Y., in *Computer Languages, Systems & Structures*, Elsevier

10-Acknowledgments

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Former Students

Tiziano Bole, Damien Cramet, Étienne Gaudrin, Matthieu Leberre, Mathieu Leroi, Nicolas Scaringella