Compiling Faust programs

GRAME – CNCM

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What is Faust ?

Faust is a *Domain-Specific Language* for real-time signal processing and synthesis. A Faust program denotes 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 mathematical function that maps a group of n input *signals* to a group of m output *signals* :
  - $\mathbb{P} = \mathbb{S}^n \rightarrow \mathbb{S}^m$
- 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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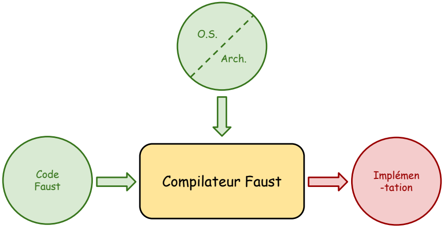
Role of the Faust Compiler

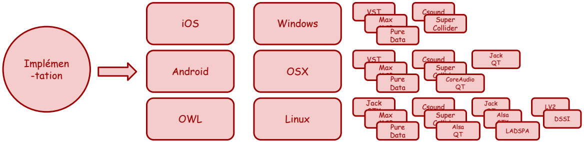
Generate efficient implementations. . .



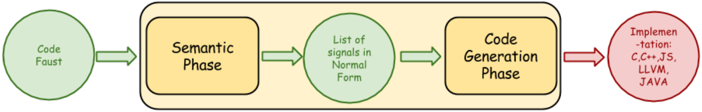
FAUST file name	STK	FAUST	Difference
blowBottle.dsp	3.23	2.49	22.91
blowHole.dsp	2.70	1.75	35.19
bowed.dsp	2.78	2.28	17.99
brass.dsp	10.15	2.01	80.20
clarinet.dsp	2.26	1.19	47.35
flutestk.dsp	2.16	1.13	47.69
saxophony.dsp	2.38	1.47	38.24
sitar.dsp	1.59	1.11	30.19
tibetanBowl.dsp	5.74	2.87	50

Table 2: *Comparison of the performance of Pure Data plug-ins using the STK C++ code with their* FAUST *generated equivalent. Values in the "STK" and "*FAUST*" columns are CPU loads in percents. The "difference" column give the gain of efficiency in percents.*

. . . for a wide range of audio architectures and plateforms



Structure of the Faust Compiler

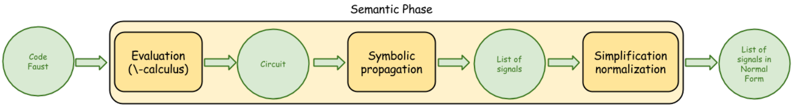


- *Semantic phase* : transforms the signal processor denoted by a Faust program into the list of signals expressions it computes.
- *Code generation* : generates the best possible implementation for this list of signal expressions

Semantic Phase

The main strategy of the Faust compiler is the idea of *semantic compilation*:

- A Faust program is not compiled as such. What is compiled is its «*mathematical meaning*».
- Therefore two different Faust programs, but with the same semantic, should result in the same implementation.



1. The Faust program is translated into a «flat» circuit.'
2. Symbolic signals are propagated into the circuit.
3. Common sub-expressions are shared by hash-consing.
4. The resulting signals are simplified, normalized and type annotated.

Semantic Phase

Moog filter example

Why not compile a Faust program as such ? To increase expressivity, modularity, reusability and clarity...

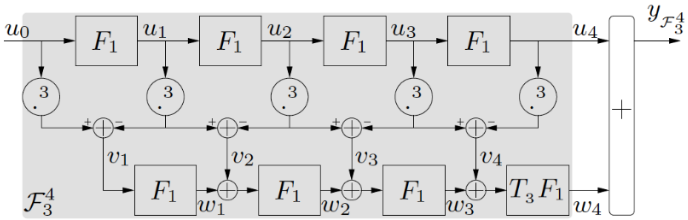
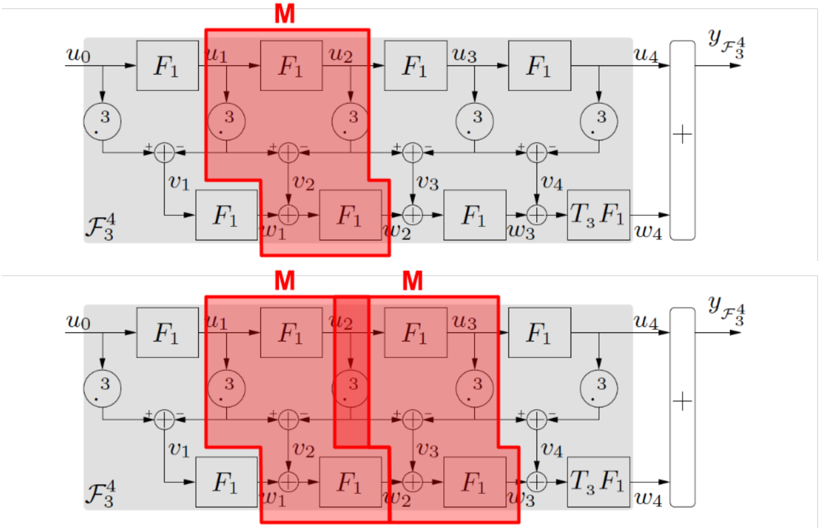


Figure: Digital model of a Moog analog filter (T. Helie/IRCAM)

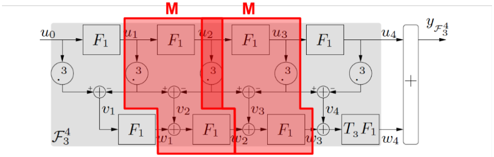
Semantic Phase

Moog filter example



Semantic Phase

Moog filter example




```
M = (_ <: _, (_^3, F1^3 : -)),_ : _,+ : F1,F1;
process = _,0 : M : M : M : S;
```

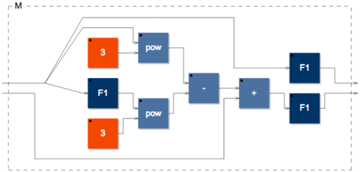


Figure: Module M

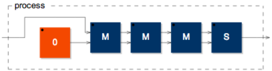
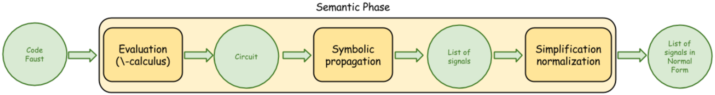


Figure: Moog filter

Semantic Phase

Evaluation to circuits



$$\text{Circuit } C \;::=\; P \mid C1 : C2 \mid C1 , C2 \mid C1 <: C2 \mid C1 :> C2 \mid C1 \,\tilde{}\, C2$$

Where $P \in \{*, +, -, \ldots, sin, cos, e^x, \ldots\}$ is a *primitive* operation on signals; $C1 : C2$ the *sequential* composition of two circuits; $C1 , C2$ the *parallel* composition; $C1 <: C2$ and $C1 :> C2$ the *split* and *merge* compositions; and $C1 \,\tilde{}\, C2$ the *recursive* composition.

Semantic Phase

Evaluation to circuits

Set $\mathbb{W}$ of well formed circuits:

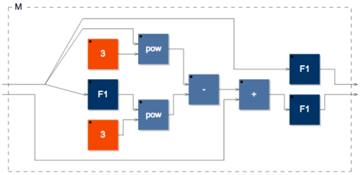
$$
\begin{array}{rcl}
P \in \mathbb{W} & & \\
(C1 : C2) \in \mathbb{W} & \Leftrightarrow & C1 \in \mathbb{W},\ C2 \in \mathbb{W},\ O(C1) = I(C2) \\
(C1 , C2) \in \mathbb{W} & \Leftrightarrow & C1 \in \mathbb{W},\ C2 \in \mathbb{W} \\
(C1 <: C2) \in \mathbb{W} & \Leftrightarrow & C1 \in \mathbb{W},\ C2 \in \mathbb{W},\ O(C1).k = I(C2) \\
(C1 :> C2) \in \mathbb{W} & \Leftrightarrow & C1 \in \mathbb{W},\ C2 \in \mathbb{W},\ O(C1) = I(C2).k \\
(C1 \sim C2) \in \mathbb{W} & \Leftrightarrow & C1 \in \mathbb{W},\ C2 \in \mathbb{W},\ O(C1) \geq I(C2),\ I(C1) \geq O(C2)
\end{array}
$$

A circuit $C \in \mathbb{W}$ has $I(C)$ *input signals* and $O(C)$ *output signals*:

$$
\begin{array}{rcl}
I(P) & \in & \mathbb{N} \\
I(C1 : C2) & = & I(C1) \\
I(C1 , C2) & = & I(C1) + I(C2) \\
I(C1 <: C2) & = & I(C1) \\
I(C1 :> C2) & = & I(C1) \\
I(C1 \sim C2) & = & I(C1) - O(C2)
\end{array}
\qquad
\begin{array}{rcl}
O(P) & \in & \mathbb{N} \\
O(C1 : C2) & = & O(C2) \\
O(C1 , C2) & = & O(C1) + O(C2) \\
O(C1 <: C2) & = & O(C2) \\
O(C1 :> C2) & = & O(C2) \\
O(C1 \sim C2) & = & O(C1)
\end{array}
$$

Semantic Phase

Evaluation to circuits



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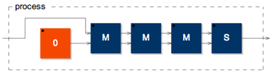


Figure: Moog filter

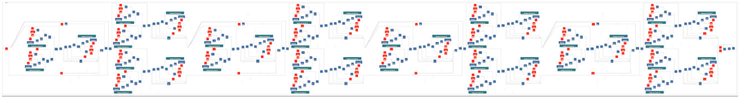
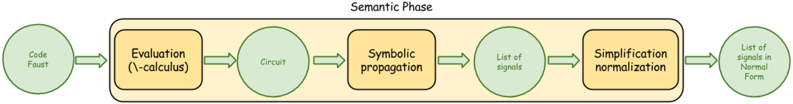


Figure: Flat Moog circuit after evaluation

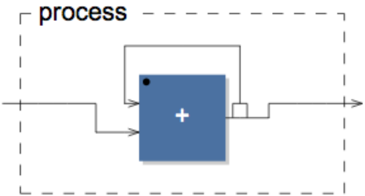
The Semantic Phase

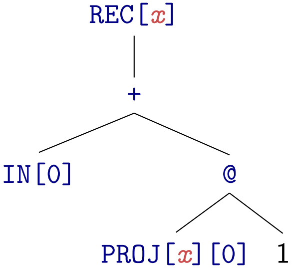
Symbolic propagation



Signal S ::= $P(S1..Sn)$ | IN[i] | n
| REC[x]($S1..Sn$) | PROJ[x][i]

```
process = +~_;
```





The Faust compiler heavily relies on *hash-consing* to discover common sub-expressions, and on *memoization* to speedup compilation.

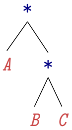
$$\begin{aligned} T_1 = T_2 &\Rightarrow \mathrm{Addr}(T_1) = \mathrm{Addr}(T_2) \\ \mathrm{Addr}(T_1) \neq \mathrm{Addr}(T_2) &\Rightarrow T_1 \neq T_2 \end{aligned}$$

Problem : Hash-consing can miss potential sharings. Simplification and normalization are used to improve sharing and common subexpression elimination.

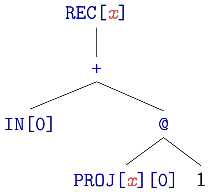
The Semantic Phase

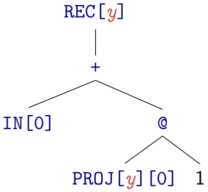
Hash-consing

Miss due to associativity or commutativity :



Miss due to $\alpha-$equivalence :





The Semantic Phase

Simplification and normalization

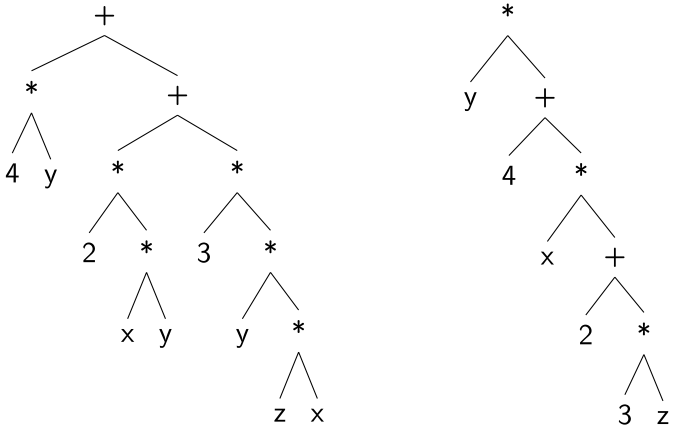
Polynomial expressions are rewritten as sum of products : $k_1 A^m B^n \ldots + k_2 C^i D^j \ldots$ and then factorized.

$$
\begin{aligned}
0 * A &\rightarrow 0 \\
1 * A &\rightarrow A \\
A * k &\rightarrow k * A \\
(k * A) * (k' * B) &\rightarrow (k * k') * (A * B) \\
B * A &\rightarrow A * B \\
A^n * A^m &\rightarrow A^{n+m} \\
0 + A &\rightarrow A \\
B + A &\rightarrow A + B \\
A * B + A * C &\rightarrow A * (B + C)
\end{aligned}
$$

The Semantic Phase

Simplification and normalization

Example : $4y + 2xy + 3xyz \rightarrow y(4 + x(2 + 3z))$



Reorganization of delay lines moved towards inputs :

$$
\begin{aligned}
0z^{-n} &\rightarrow 0 \\
Az^{0} &\rightarrow A \\
(k * A)z^{-n} &\rightarrow k * Az^{-n} \\
Az^{-n}z^{-m} &\rightarrow Az^{-(n+m)}
\end{aligned}
$$

The Semantic Phase

Sharing of recursive terms

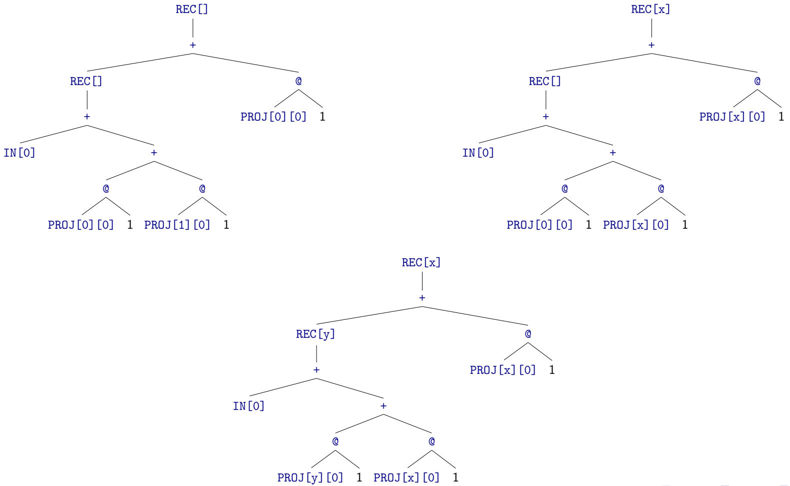
Problem with hash-consing : $\alpha-$equivalent recursive terms in standard notation are not shared:

Open terms in de Bruijn notation are incorrectly shared:

The Semantic Phase

Sharing of recursive terms

Solution : start in de Bruijn notation and progressively transform de Bruijn terms into standard terms.



The Semantic Phase

Type Annotation and interval computation

Signals are annotated with various information used to guide the code generation :

- *nature*: integer or floating point values
- *boolean*: when a signal stands for a boolean value
- *variability*: how fast values change (constant, at each block or at each sample)
- *computability*: when values are available (at compile time, at initialization time, at execution time)
- *vectorability*: when a signal computation can be vectorized
- *interval*: minimal and maximal values a signal can take
- *occurrence context*: maximal delay, number of occurrences

The Semantic Phase

Resulting signals for the Moog example

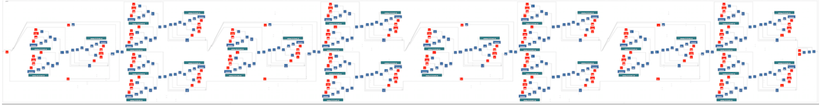


Figure: Flat circuit after evaluation of the Faust program

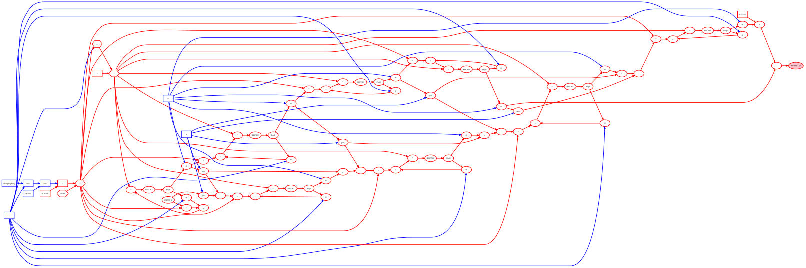
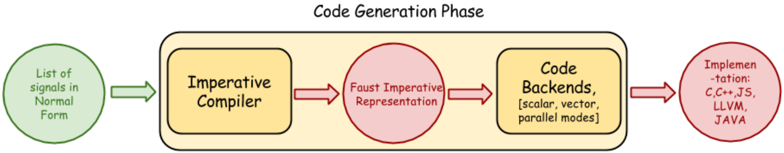


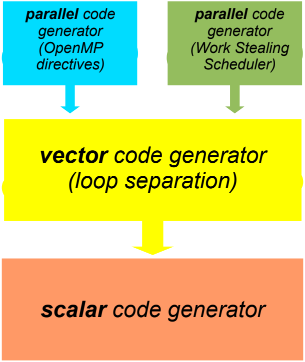
Figure: Resulting signal after symbolic propagation in the circuit and normalization

Code Generation Phase



Code Generation Phase

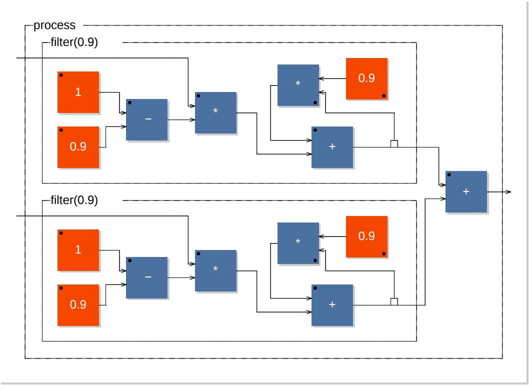
Four Code generation modes



Code Generation Phase

two 1-pole filters in parallel connected to an adder

```
filter(c) = *(1-c) : + ~ *(c);
process = filter(0.9), filter(0.9) : +;
```



Code Generation Phase

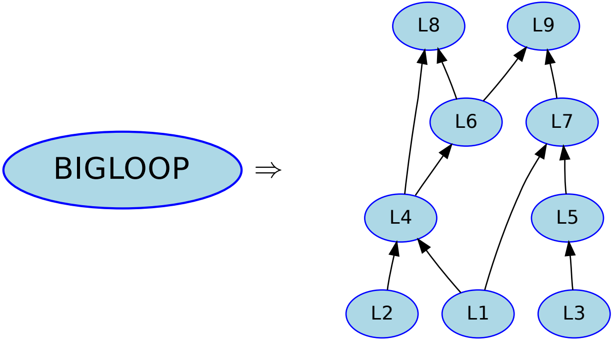
Scalar Code

```
virtual void compute (int count, float** input, float** output) {
  float* input0 = input[0];
  float* input1 = input[1];
  float* output0 = output[0];
  for (int i=0; i<count; i++) {
    fRec0[0] = (0.1f * input1[i]) + (0.9f * fRec0[1]);
    fRec1[0] = (0.1f * input0[i]) + (0.9f * fRec1[1]);
    output0[i] = (fRec1[0] + fRec0[0]);
    // post processing
    fRec1[1] = fRec1[0];
    fRec0[1] = fRec0[0];
  }
}
```

Code Generation Phase

Loop Separation

The *Vector* Compilation Backend simplifies the autovectorization work of the C++ compiler by splitting the sample processing loop into several simpler loops.



Code Generation Phase

Vector Code

```
...
// SECTION : 1
for (int i=0; i<count; i++) {
  fRec0[i] = (0.1f * input1[i]) + (0.9f * fRec0[i-1]);
}
for (int i=0; i<count; i++) {
  fRec1[i] = (0.1f * input0[i]) + (0.9f * fRec1[i-1]);
}
// SECTION : 2
for (int i=0; i<count; i++) {
  output0[i] = fRec1[i] + fRec0[i];
}
...
```

Code Generation Phase

Parallel Code – OpenMP

```
...
// SECTION : 1
#pragma omp sections
{
  #pragma omp section
  for (int i=0; i<count; i++) {
    fRec0[i] = (0.1f * input1[i]) + (0.9f * fRec0[i-1]);
  }
  #pragma omp section
  for (int i=0; i<count; i++) {
    fRec1[i] = (0.1f * input0[i]) + (0.9f * fRec1[i-1]);
  }
}
// SECTION : 2
#pragma omp for
for (int i=0; i<count; i++) {
  output0[i] = (fRec1[i] + fRec0[i]);
}
...
```

Code Generation Phase

Parallel Code – Work Stealing

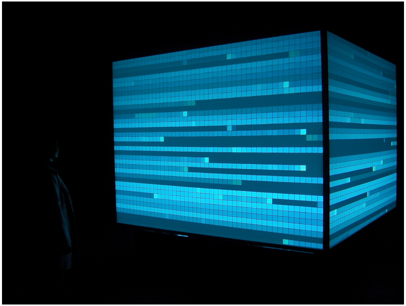
```
taskqueue.InitTaskList(task_list_size, task_list, fDynamicNumThreads,
                                                  cur_thread, tasknum);
while (!fIsFinished) {
  switch (tasknum) {
    case WORK_STEALING_INDEX: {
      tasknum = TaskQueue::GetNextTask(cur_thread, fDynamicNumThreads);
      break;
    }case LAST_TASK_INDEX: {
      fIsFinished = true;
      break;
    }case 2: {
      // LOOP 0x7fd873509e00
      ....
      fGraph.ActivateOneOutputTask(taskqueue,4,tasknum);
      break;
    }case 3: {
      // LOOP 0x7fd873703d70
      ....
      fGraph.ActivateOneOutputTask(taskqueue,4,tasknum);
      break;
    }case 4: {
      // LOOP 0x7fd873509d20
      ....
      tasknum = LAST_TASK_INDEX;
      break;
    }
  }
};
```

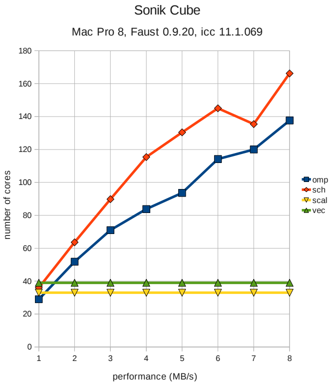
Code Generation Phase

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).





Available Faust Compilers

- Faust standalone compiler
- Faust online compiler (http://faust.grame.fr)
- LibFaust embedded compiler (FaustLive, MaxMSP, Csound, Antescofo, Open Music, iScore, Webaudio API) [ANR-INEDIT]
- Remote compiler service (http://faustservice.grame.fr) [ANR-FEEVER]
- Faustine (Faust Multirate interpreter) [ANR-FEEVER]
- Faust Multirate/Multidimension compiler [ANR-FEEVER]