StreamIt Cookbook

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September, 2006

1 StreamIt Overview

Most data-flow or signal-processing algorithms can be broken down into a number of simple blocks with connections between them. In StreamIt parlance, the smallest block is a *filter*; it has a single input and a single output, and its body consists of Java-like code. Filters are then connected by placing them into one of three composite blocks: pipelines, split-joins, and feedback loops. Each of these structures also has a single input and a single output, so these blocks can be recursively composed.

A typical streaming application might be a software FM radio, as shown in Figure 1. The program receives its input from an antenna, and its output is connected to a speaker. The main program is a pipeline with a band-pass filter for the desired frequency, a demodulator, and an equalizer; the equalizer in turn is made up of a split-join, where each child adjusts the gain over a particular frequency range, followed by a filter that adds together the outputs of each of the bands.

Our goal with choosing these constructs was to create a language with most of the expressiveness of a general data-flow graph structure, but to keep the block-level abstraction that modern programming languages offer. Allowing arbitrary graphs makes scheduling and partitioning difficult for the compiler. The hierarchical graph structure allows the implementation of blocks to be "hidden" from users of the block; for example, an FFT could be implemented as a single filter or as multiple filters, but so long as there is a stream structure named "FFT" somewhere in the program the actual implementation is irrelevant to other modules that use it. Since most graphs can be readily transformed into StreamIt structures, StreamIt is suitable for working on a wide range of signal-processing applications.

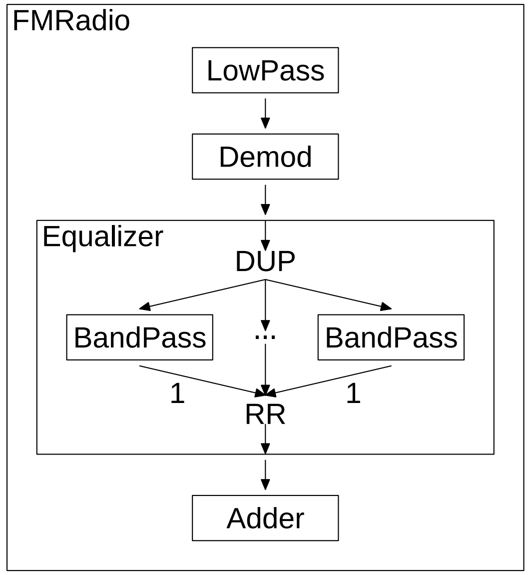
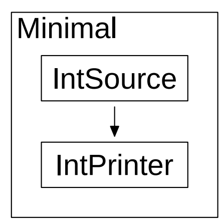


Figure 1: Stream graph for a software FM radio

2 Programming in StreamIt

2.1 A Minimal Program

```
void->void pipeline Minimal {
  add IntSource;
  add IntPrinter;
}
void->int filter IntSource {
  int x;
  init { x = 0; }
  work push 1 { push(x++); }
}
int->void filter IntPrinter {
  work pop 1 { print(pop()); }
}
```



This is the minimal interesting StreamIt program. Minimal is a StreamIt *pipeline*: the output of its first child is connected to the input of its second child, and so on. It has two children, a source and a sink. Each of these are implemented as StreamIt *filter* objects.

A filter has two special functions, an *init* function and a *work* function. Both of these are present in IntSource. The init function runs once at the start of the program; the work function runs repeatedly forever. If the init function is omitted, as it is in IntPrinter, it is assumed to be empty. Work functions declare their *data rates*, which may be static or dynamic. The source here declares that each iteration of the work function pushes a single item on to its output; the sink declares that it pops a single item from its input.

Every StreamIt structure has a single input and a single output. The filter and pipeline declarations here show the types of these inputs and outputs. C-like **int** and **float** types are available, along with **bit** for one-bit data and **complex** for complex floating-point data. **void** is used as a special type to indicate the boundary of the program: "the program" in StreamIt is defined as a stream structure with both **void** input and output types. A filter that takes no input at all should also be declared to take **void** as its input type, and similarly a **void** output can be used if a filter produces no output.

How to Compile and Run

The StreamIt compiler script **strc** can be used to compile and execute StreamIt programs. If you are using the StreamIt release, you can find all of the cookbook examples in the following directory:

```
cd $STREAMIT_HOME/apps/examples/cookbook
```

The minimal example is stored in `Minimal.str`, and the following command will compile it for the uniprocessor backend:

```
strc Minimal.str -o minimal
```

The resulting binary is stored in `minimal`, and it can be executed for 5 iterations as follows:

```
minimal -i 5
```

Doing so will print the integers from 0 to 4, in increasing order.

During the course of compilation, a number of stream graphs are ouput to `dot` files in the current directory. The `dot` format can be displayed and converted to other formats using the Graphviz software, which is available online[1]. Running the following command will draw the stream graph for the program, as pictured to the right of the source code above:

```
dotty stream-graph-simple.dot
```

There are many other `dot` files that are output by the compiler; see Section 3 of this document for more details.

The Java Library. In addition to using the StreamIt compiler, it is possible to convert StreamIt programs into equivalent Java programs that can be executed using any Java VM. This is particularly convenient for testing and debugging, as well as for cases when the compiler might encounter a bug.

To run the `Minimal` program for 5 iterations in the Java library, do as follows:

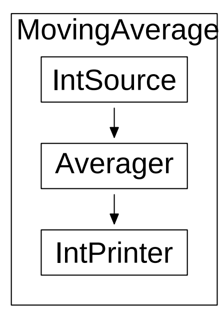
```
strc --library Minimal.str -i 5
```

This command will output a `Minimal.java` file, compile it with a Java compiler, and run it using `java`. The output should always be identical to that obtained using the compiler. In addition, the library will output a `Minimal.dot` file that can be visualized using Graphviz.

For more details on the StreamIt compiler and execution environment, please consult Section 3.

2.2 A Moving Average Filter

```
void->void pipeline MovingAverage {
  add IntSource();
  add Averager(10);
  add IntPrinter ();
}
int->int filter Averager(int n) {
  work pop 1 push 1 peek n {
    int sum = 0;
    for (int i = 0; i < n; i++)
      sum += peek(i);
    push(sum/n);
    pop();
  }
}
```



[1] `http://www.graphviz.org/`

Most of a typical StreamIt program consists of filters that produce some output from their input. The Averager filter shown here is such a filter. Like the filters shown before, Averager has a work function with statically declared input and output rates.

In addition to peeking and popping, Averager *peeks* at its input stream. The **peek**() operator returns a particular item off of the input stream, with **peek**(0) returning the next item that would normally be popped. The work function must declare a peek rate if it peeks at all, but this peek rate is a maximum, rather than an exact, rate; it would be valid for the Averager filter to **peek**(n−2) and never **peek**(n−1), but **peek**(n) is illegal. Note that mixing peeking and popping is valid, but that popping an item shifts the index of future peeks.

Averager also has a *stream parameter*. The number n is the number of items to average. This is passed like a normal function parameter from the **add** statement that creates the filter. Within the filter, the parameter is a constant: it is illegal for code to modify the parameter. This allows parameter values to be used in expressions for *e.g.* I/O rates, as in the peek rate here.

This program also provides a basic demonstration of StreamIt's filter scheduler. There is a guarantee that the Averager filter is not run until its input rates can be met, and in particular, that there are 10 inputs available so peeking can happen. For this to happen, the source needs to run nine additional times at the start of the program; there can then be steady-state exections of source, averager, printer. The StreamIt compiler handles this automatically. While all of the examples so far have had filters with matched I/O rates, the compiler also automatically schedules the execution of adjacent filters whose push and pop rates are different.

2.3 A Low-Pass Filter

```
float->float filter LowPassFilter(float rate, float cutoff,
                                  int taps, int decimation) {
  float[taps] coeff;
  init {
    int i;
    float m = taps - 1;
    float w = 2 * pi * cutoff / rate;
    for (i = 0; i < taps; i++) {
      if (i - m/2 == 0)
```

```
      coeff[i] = w/pi;
    else
      coeff[i] = sin(w*(i-m/2)) / pi / (i-m/2) *
        (0.54 - 0.46 * cos(2*pi*i/m));
  }
 }
 work pop 1+decimation push 1 peek taps {
  float sum = 0;
  for (int i = 0; i < taps; i++)
    sum += peek(i) * coeff[i];
  push(sum);
  for (int i=0; i<decimation; i++)
    pop();
  pop();
 }
}
```

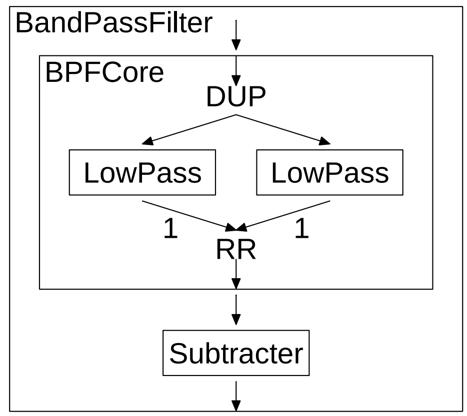
The work function for a low-pass filter looks much like the work function of the moving-average filter; however, it has extensive initialization code. From the sampling rate, cutoff frequency, and number of taps, coefficients for an FIR filter can be statically calculated. This is done once, in the init function, and saved in the `coeff` array; the work function then effectively does a convolution. StreamIt provides a number of built-in mathematical functions, such as the call to `sin()` here, along with the constant `pi`.

StreamIt's array syntax is more C-like than Java-like. Every array has a fixed length; this length can be a numeric constant or stream parameter, or other value that can be statically evaluated. In the declaration syntax, the length of the array comes between the base type and the variable name.

The coefficient array here is defined as a *field* in the filter. If the name `coeff` were used as a local variable in the init or work function, it would shadow the field, as in other languages. Otherwise, uses in both the init and work functions reference the field. If multiple low-pass filters existed, each would have its own coefficient array.

2.4 A Band-Pass Filter

```
float->float pipeline BandPassFilter
    (float rate, float low, float high, int taps) {
  add BPFCore(rate, low, high, taps);
  add Subtracter();
}
float->float splitjoin BPFCore
    (float rate, float low,
     float high, int taps) {
  split duplicate;
  add LowPass(rate, low, taps, 0);
  add LowPass(rate, high, taps, 0);
  join roundrobin;
}
float->float filter Subtracter {
  work pop 2 push 1 {
    push(peek(1) - peek(0));
    pop(); pop();
  }
}
```



We implement a band-pass filter using two low-pass filters in a StreamIt structure called a *split-join*. This structure contains a *splitter*, some number of children that run in parallel, and a *joiner*. It overall has a single input and a single output, and its children each have a single input and a single output.

This split-join has a duplicating splitter; thus, each incoming item is sent to both of the children. The joiner is a round-robin joiner, such that outputs are taken from the first child, then the second, in alternating order. There may be any number of children, in which case a round-robin joiner takes inputs from each of them in series. The order of the children is the order in which they are added.

roundrobin can be used as a splitter, as well as a joiner; the meaning is symmetric. Other syntaxes are valid: **roundrobin**(2) reads two inputs from each child in turn, and **roundrobin**(1,2,1) requires exactly three children and reads one input from the first, two from the second, and one from the third.

A typical use of a split-join is to duplicate the input, perform some computation, and then combine the results. In this case, the desired output is the difference between the two filters; the Subtracter filter is placed in a pipeline after the split-join, and finds the desired difference. In general, a child can be any StreamIt construct, not just a filter.

The implementation of **pop**() in the compiler and runtime system does not allow multiple pops to occur in the same statement. This is reflected in the implementation of Subtracter here.

2.5 An Equalizer

```
float->float pipeline Equalizer(float rate, int bands, float[bands] cutoffs,
                                float[bands] gains, int taps) {
  add EqSplit(rate, bands, cutoffs, gains, taps);
  add float->float filter {
    work pop bands-1 push 1 {
      float sum = 0;
      for (int i = 0; i < bands-1; i++)
        sum += pop();
      push(sum);
    }
  };
}
float->float splitjoin EqSplit(float rate, int bands, float[bands] cutoffs,
                               float[bands] gains, int taps) {
  split duplicate;
  for (int i = 1; i < bands; i++)
    add pipeline {
      add BandPassFilter(rate, cutoffs[i-1], cutoffs[i], taps);
      add float->float filter {
        work pop 1 push 1 { push(pop() * gains[i]); }
      };
    };
  join roundrobin;
}
```

This equalizer works by having a series of band-pass filters running in parallel, with their outputs added together. The caller provides arrays of cutoff frequency and respective gains.

In the implmentation here, the output of EqSplit is a series of bands−1 outputs from the respective low-pass filters. An *inline filter* is used to sum the results together. This is akin to an anonymous class in Java; the filter declaration does not have an explicit name, but otherwise has syntax al-

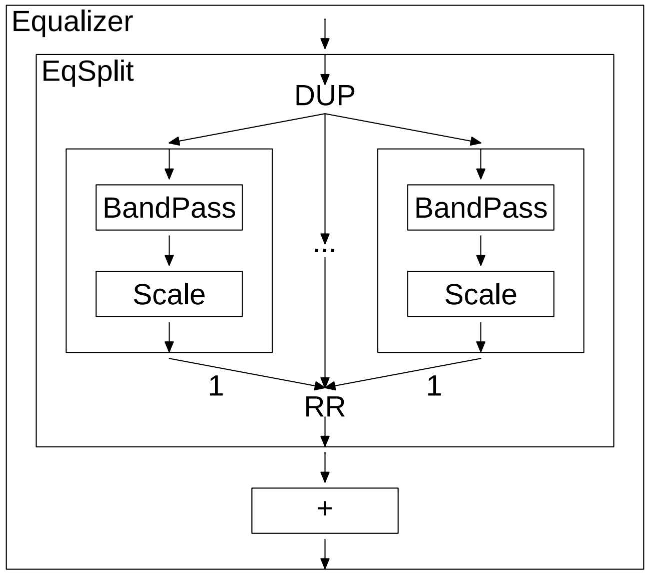


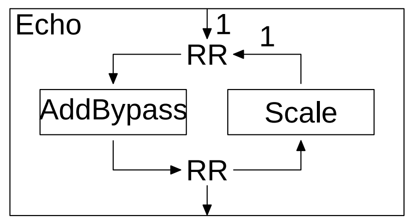
Figure 2: Stream graph for an equalizer

most identical to a top-level filter. In general, inline filters should only be used for very simple filters, such as this or the inlined amplifier in EqSplit.

EqSplit is a normal split-join, as shown previously. Its body consists of a set of near-identical inlined pipelines; for pipelines and split-joins, the input and output type declarations may be omitted on anonymous streams. Since the children are so similar, they are added within a normal **for** loop. The compiler is able to examine the loop provided that the loop bounds are expressions of constants and stream parameters.

2.6 An Echo

```
float->float feedbackloop Echo
    (int n, float f) {
  join roundrobin(1,1);
  body FloatAdderBypass();
  loop float->float filter {
    work pop 1 push 1 {
      push(pop() * f);
    }
  };
  split roundrobin;
  for (int i = 0; i < n; i++)
    enqueue(0);
}
float->float filter FloatAdderBypass {
  work pop 2 push 2 {
    push(peek(0) + peek(1));
    push(peek(0));
    pop();
    pop();
  }
}
```



This example uses a StreamIt *feedback loop* to implement an echo effect. In a sense, a feedback loop is like an inverted split-join: it has a joiner at the top and a splitter at the bottom. A feedback loop has exactly two children, which are added using the **body** and **loop** statements. Thus, this implementation takes an input from the loop input and an input from the feedback path, adds them, and outputs the result. The result is also scaled by the value f and sent back to the top of the loop.

Feedback loops have a specialized push-like statement, **enqueue**. Each enqueue statement pushes a single value on to the input to the joiner from the feedback path. There must be enough values enqueued to prevent deadlock of the loop components; values enqueued delay data from the feedback path.

2.7 Fibonacci

```
void->int feedbackloop Fib {
  join roundrobin(0,1);
  body int->int filter {
    work pop 1 push 1 peek 2 { push(peek(0) + peek(1)); pop(); }
  };
  loop Identity<int>;
  split duplicate;
  enqueue(0);
  enqueue(1);
}
```

Using a feedback loop for a Fibonacci number generator is slightly unusual but possible. The joiner reads no items from the stream input (also declared of type **void**), but reads items continuously from the feedback path. Within a feedback loop, round-robin splitters and joiners address the external path first and the feedback path second. This loop also uses the special Identity filter on the loop path; this is equivalent to an empty filter that copies its input to its output, but occurs frequently enough that a shorthand is useful to both the programmer and the compiler.

3 Using the StreamIt Compiler

This section walks through a sample session with the compiler and runtime system. We will use the `FMRadio` example from the StreamIt release as a running example. To get started, change to the following directory:

```
% cd $STREAMIT_HOME/apps/examples/cookbook
```

The example is in `FMRadio.str`. The following sections describe the compilation of `FMRadio` using the uniprocessor backend, the cluster/multicore backend, and the Java library. A summary of the compiler's command-line options can be found in Appendix B, or by typing `strc -help` at the command line.

3.1 Compiling for a Uniprocessor

There are two ways to compile a StreamIt program for execution on a general-purpose processor. The first method (the default) compiles to a set of C++ files, which are linked against a StreamIt runtime library. It uses the same infrastructure as our cluster backend and supports the full suite of StreamIt features and optimizations. The second method (invoked with the `-simpleC` option) emits a standalone C file in which the entire program is inlined into a single function. The simpleC backend is not fully featured[2] but the output is readable and the C interface may be useful for some compiler projects. As we recommend using the default backend, we focus on it for the remainder of this section.

To compile `FMRadio` using the uniprocessor backend, issue the following command (the compiler output is shown):

```
% strc FMRadio.str -o fm
Starting Kopi2SIR... done.
Entry to Cluster Backend (uniprocessor)
Running Constant Prop and Unroll... done.
Running Constant Field Propagation... done.
Estimating Code size of Filters... done.
Estimating Code size of Filters... done.
Running Partitioning... target number of threads: 1
Done Partitioning...
Generating cluster code...
Done generating cluster code.
gcc34 -O3 -I/u/thies/research/streams/streams/library/cluster
      -c -o combined_threads.o combined_threads.cpp
gcc34 -O3 -o fm combined_threads.o
      -L/u/thies/research/streams/streams/library/cluster
      -lpthread -lcluster -lstdc++
```

This will create a number of threadXX.cpp files, one for each filter, splitter, and joiner in the original program. The files are concatenated into a single file (combined_threads.cpp) and compiled to create a binary named `fm`. The binary can be executed for 5 steady-state iterations as follows:

```
% ./fm -i 5
278073.968750
278074.750000
278075.406250
278075.968750
278076.437500
```

During the compilation process, several `dot` graphs are generated. The `dot` format can be displayed and converted to other formats using the Graphviz software, which is available online[3]. For example, we can examine a stream graph for the FM application as follows:

[2]As of this release, simpleC lacks support for dynamic rates, teleport messaging, prework functions, general helper functions, domain-specific optimizations, cache optimizations, and other features.

[3]`http://www.graphviz.org/`

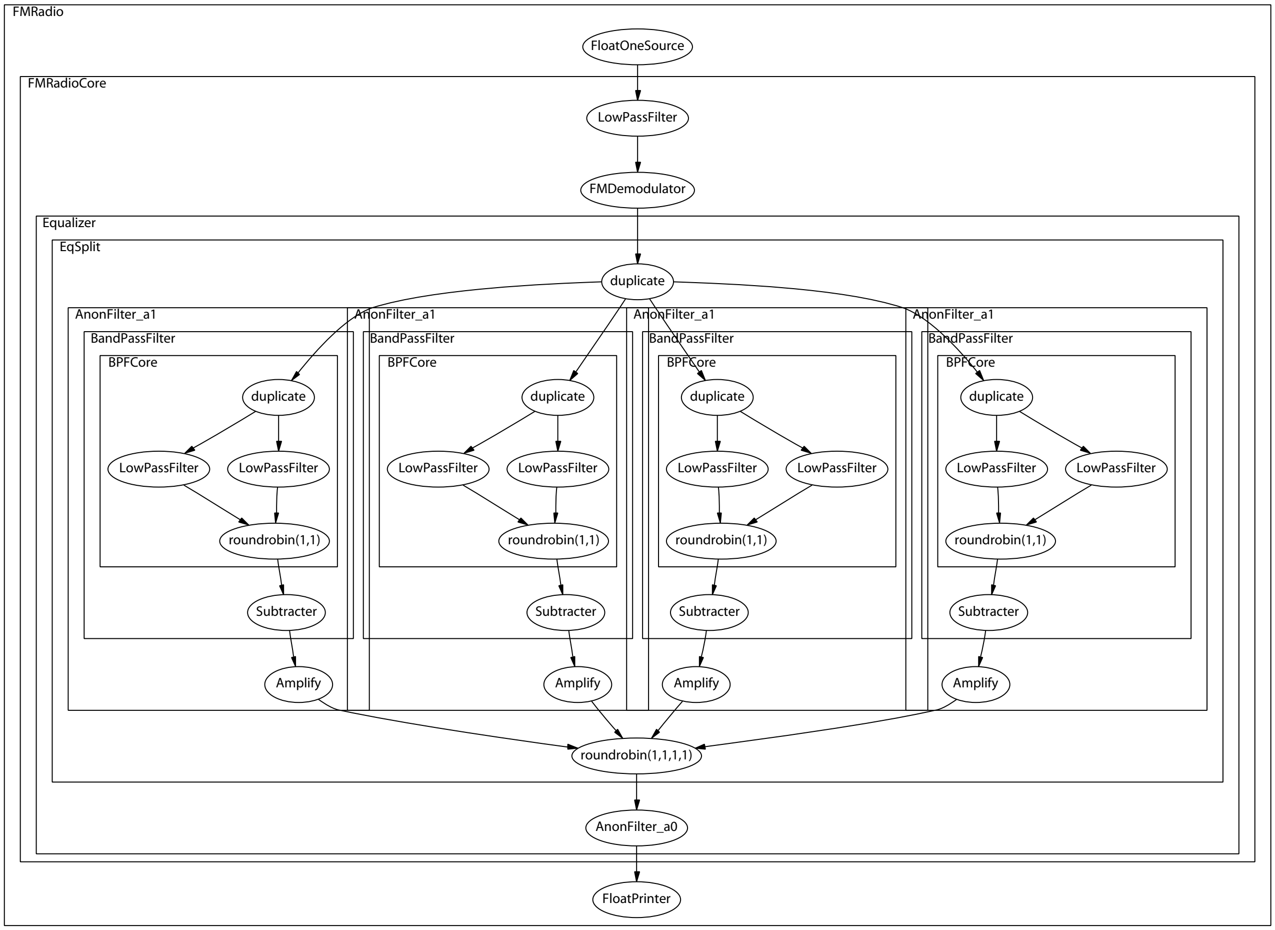


Figure 3: `stream-graph-simple.dot` for the FMRadio example.

```
% dotty stream-graph-simple.dot
```

The result appears in Figure 3. A complete list of the `dot` graphs that are produced on the normal uniprocessor path are shown in Figure 4.

Domain-specific optimizations. It turns out that our version of the FMRadio has a lot of redundant computation the way in which it is written. For example, each `BandPassFilter` could be implemented as a single FIR filter rather than a composition of `LowPassFilter`'s; in fact, the entire equalizer could be collapsed to a single FIR filter. Further, some of these operations are more efficient if executed in the frequency domain, with an FFT/IFFT being used to translate to and from the time domain.

Filename	Description
`stream-graph-simple.dot`	Original stream graph, as written by programmer.
`stream-graph.dot`	Original stream graph, including I/O rates.
`after-collapse-sjs.dot`	Partial canonicalization of stream graph, after collapsing data parallelism in the application. (The parallelism can be restored if needed.)
`canonical-graph.dot`	Canonical version of stream graph, after further eliminating unneeded synchronization.

Figure 4: Notable `dot` graphs produced on the uniprocessor path.

The StreamIt compiler includes a set of domain-specific optimizations that will automatically perform the transformations described above. The analysis considers all filters that are "linear"—that is, each of their outputs is an affine combination of their inputs. The compiler automatically detects linear filters by analyzing the code in their work functions. Then, it performs algebraic simplification of adjacent linear filters, as well as automatic translation to the frequency domain. Since these transformations can sometimes hamper performance, the compiler also does a global cost/benefit analysis to determine the best set of transformations for a given stream graph.

The `linearpartition` option to strc will enable linear analysis and optimizations[4]:

```
% strc -linearpartition FMRadio.str -o fm
Starting Kopi2SIR... done.
Entry to Cluster Backend (uniprocessor)
Running Constant Prop and Unroll... done.
Running Constant Field Propagation... done.
Estimating Code size of Filters... done.
Running linear analysis...
WARNING: Assuming method call expression non linear(atan).
```

[4]In contrast, the `linearreplacement` and `frequencyreplacement` options will perform maximal algebraic simplification and frequency translation, respectively, even in cases where it is not beneficial.

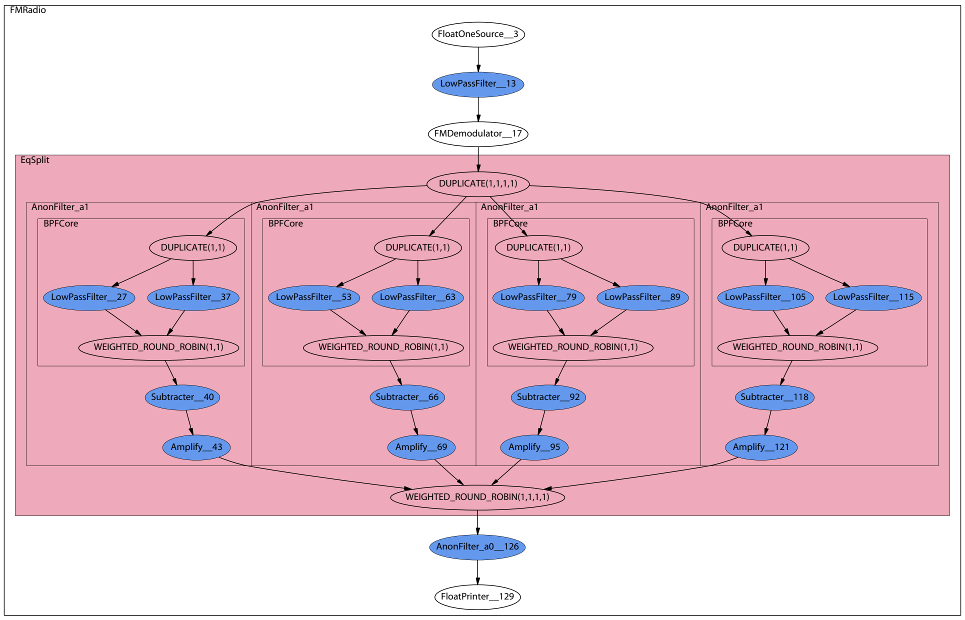


Figure 5: `linear-simple.dot`, which illustrates the linear sections of FMRadio. Linear filters are shaded blue, while linear containers are shaded pink.

```
         Also removing all field mappings.
done with linear analysis.
Running linear partitioner...
Linear partitioner took 0 secs to calculate partitions.
Estimating Code size of Filters... done.
Running Partitioning... target number of threads: 1
Done Partitioning...
Generating cluster code...
Done generating cluster code.
gcc34 -O3 -I/u/thies/research/streams/streams/library/cluster
      -c -o combined_threads.o combined_threads.cpp
gcc34 -O3 -o fm combined_threads.o
      -L/u/thies/research/streams/streams/library/cluster
      -lpthread -lcluster -lstdc++ -lsrfftw -lsfftw
```

The linear analysis produces its own set of `dot` files that we can use to inspect the results of the optimizations. For example, the following command will display the stream graph with the linear sections highlighted:

```
% dotty linear-simple.dot
```

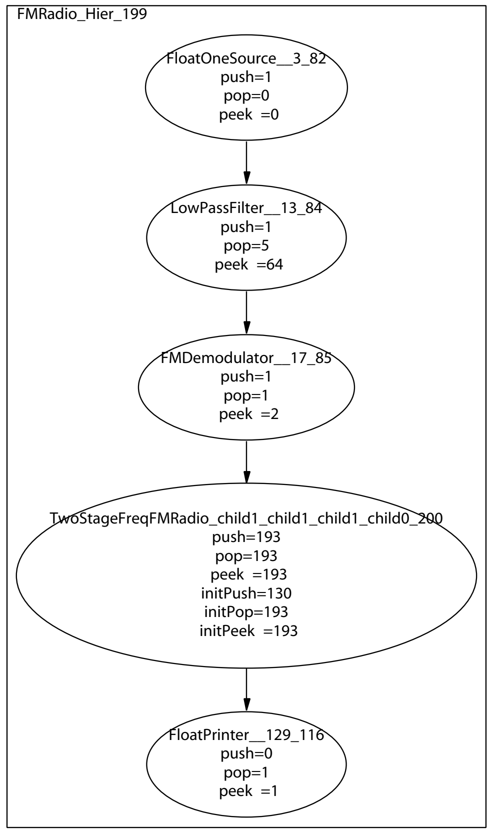


Figure 6: Final stream graph (`after-linear.dot`) for the FMRadio, compiling with the `-linearpartition` option.

As shown in Figure 5, FMRadio contains many linear components, including the first LowPassFilter and the equalizer. To see the stream graph after linear optimizations have been applied, we can issue the following command:

```
% dotty after-linear.dot
```

As illustrated in Figure 6, this stream graph shows that the equalizer was collapsed into a single filter and then was translated to the frequency domain (by virtue of the “Freq” prefix in the filter’s name.) However, the LowPassFilter at the top was left unmodified; this is because it has a large pop rate that degrades the performance of the frequency transformation. In this case, the linear optimizations lead to a 6.7X improvement in throughput.

The linear optimizations produce additional `dot` graphs; see Figure 7

Filename	Description
`linear-simple.dot`	Stream graph with linear filters highlighted.
`linear.dot`	Same as linear-simple, but including I/O rates of each node.
`linear-partitions.dot`	Illustration of which nodes are combined by linear optimizations.
`after-linear.dot`	The stream graph after linear transformations are complete.

Figure 7: `dot` graphs produced by linear optimizations.

for details. For more information on the linear analysis and optimization, please refer to `http://cag.lcs.mit.edu/linear`.

3.2 Compiling for a Cluster or Multicore

The `-cluster N` option selects a backend that compiles to N parallel threads that communicate using sockets. When targeting a cluster of workstations, the sockets communicate over the network using TCP/IP. When targeting a multicore architecture, the sockets provide an interface to shared memory. A hybrid setup is also possible, in which there are multiple machines and multiple threads per machine; some threads communicate via memory, while others communicate over the network.

3.2.1 Multicores

By default, the StreamIt compiler will map all of the threads to the current host (i.e., the one that issued the compile command). This is suitable for multicores, as running the resulting executable will spawn the threads on a single machine.

For example, consider compiling the FMRadio to eight parallel threads:

```
% strc -cluster 8 FMRadio.str -o fm
Starting Kopi2SIR... done.
Entry to Cluster Backend
Running Constant Prop and Unroll... done.
```

```
Running Constant Field Propagation... done.
Estimating Code size of Filters... done.
Estimating Code size of Filters... done.
Running Partitioning... target number of threads: 8
Running Partitioning... target number of threads: 8
  Found 0 tiles.
  Building stream config...
Trying 8 tiles.
  Calculating partition info...
  Tracing back...
  Work Estimates:
    Fused_SplitJoin0_EqSplit_81...      1545    (21%)
    Fused_SplitJoin0_EqSplit_81...      1545    (21%)
    Fused_SplitJoin0_EqSplit_81...      1545    (21%)
    Fused_SplitJoin0_EqSplit_81...      1545    (21%)
    LowPassFilter__13                   730     (10%)
    FMDemodulator__17                   221     (3%)
    Fused_Spl_Ano_Flo                   89      (1%)
    FloatOneSource__3                   35      (0%)
  Building stream config...
Trying 8 tiles.
  Calculating partition info...
  Tracing back...
Done Partitioning...
Generating cluster code...
NOTE: Missing or empty $STREAMIT_HOME/cluster-machines.txt file,
  so all threads assigned to cagfarm-49 in cluster-config.txt.
Done generating cluster code.
gcc34 -O3 -I/u/thies/research/streams/streams/library/cluster
      -c -o combined_threads.o combined_threads.cpp
gcc34 -O3 -o fm combined_threads.o
      -L/u/thies/research/streams/streams/library/cluster
      -lpthread -lcluster -lstdc++
```

The compiler used a partitioning algorithm to fuse filters in the graph down to eight load-balanced units. The stream graph following this partitioning can be found in `after-partition.dot`:

```
% dotty after-partition.dot
```

The result appears in Figure 9. The array of eight low-pass filters was collapsed to a width of four, and the bottom half of the application (Subtracter, Amplify, Printer filters) was fused into a single filter. The other auto-generated files provide more information about the distribution of work amongst these filters; see Figure 8 for details.

Running the `fm` binary will spawn all eight threads on the current host.

Filename	Description
`before-partition.dot`	Stream graph before partitioning into requested number of threads.
`after-partition.dot`	Stream graph after partitioning into requested number of threads.
`work-before-partition.dot`	The stream graph before partitioning, annotated with estimates of the steady-state work within each node. Nodes with the same amount of work are given the same color (although the colors themselves are meaningless.)
`work-before-partition.txt`	Text listing of the work estimates for filters in the graph, before load balancing.
`work-after-partition.dot`	The stream graph after partitioning, annotated with work estimates as above.
`work-after-partition.txt`	Text listing of the work estimates for filters in the graph, after load balancing.
`work-estimate.txt`	Same as above, but indexed by the thread numbers in cluster-config.txt.
`cluster-config.txt`	Mapping from threads to machines.

Figure 8: Files produced by the cluster/multicore backend, above and beyond those produced by the uniprocessor backend.

3.2.2 Cluster of Workstations

In order to compile for a cluster of workstations, one should create a list of available machines and store it in the following location:

```
$STREAMIT_HOME/cluster-machines.txt
```

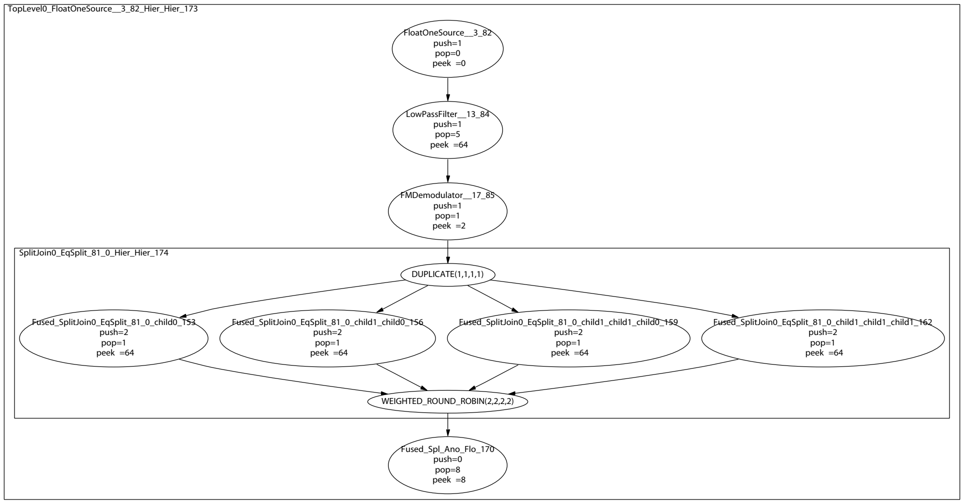


Figure 9: The FMRadio example partitioned to eight threads (`after-partition.dot`).

This file should contain one machine name (or IP address) per line. When the compiler generates N threads, it will assign one thread per machine (for the first N machines in the file). If there are fewer than N machines available, it will distribute the threads across the machines.

For example, consider that our `cluster-machines.txt` file contains the following:

```
machine-1
machine-2
machine-3
machine-4
```

Let's say that each machine is a dual-processor, so we again compile FMRadio for eight threads as shown previously. The resulting mapping from threads to machines can be found in `cluster-config.txt`:

```
% strc -cluster 8 FMRadio.str -o fm
...
% cat cluster-config.txt
0 machine-1
1 machine-1
2 machine-1
3 machine-2
4 machine-2
5 machine-2
```

```
6 machine-3
7 machine-3
8 machine-4
9 machine-4
```

This file indicates that threads 0, 1, and 2 are mapped to machine-1; threads 3, 4, and 5 are mapped to machine-2, and so on. The cluster-config file contains 10 threads (rather than eight) because a thread is also generated for each splitter and joiner in the stream graph. However, as these threads rarely do as much work as the filters, it is not detrimental for a processor to acquire them.

To execute the program on the cluster, one should run the `fm` executable from each machine that is assigned one or more threads. Each instance of the program will wait until all of its network connections are established before starting to process data. To measure performance, a built-in timer keeps track of the elapsed time after the connections are made.

As the cluster-config file is read at application load time, one can freely modify it to experiment with various layouts or to move the program from one cluster to another. Mapping all the threads to a single machine will have the same effect as compiling to a multicore (as described previously).

3.3 Using the Java Library

A convenient aspect of the StreamIt compilation toolchain is that all StreamIt programs are first translated to Java files that can be executed against a Java runtime library using a normal Java Virtual Machine. This is especially useful for testing and debugging applications, as well as validating the output of the compiler.

The library can be invoked with the `-library` flag. Since `strc` will both compile and execute the file in the library, you can specify the number of iterations to execute with the `-i` flag. For example, to compile FMRadio and run for 5 iterations in the library, do as follows[5]:

```
% strc -library -i 5 FMRadio.str
278073.94
278074.75
278075.38
278075.94
278076.4
```

[5]In this case, the library's output is marginally different from the compiler's due to numerical precision issues.

You can also inspect the FMRadio.java file, which was generated for execution in the library. It can be compiled and run with a standard Java compiler and JVM. The library also produces a dot graph of the program; it is given the same name as the StreamIt file, but with a dot extension (*i.e.,* it is FMRadio.dot in this case.)

There are a few additional options available in the library. For instance, you can direct the library not to execute the program, but to instead just print the schedule of filter firings:

```
% strc -library -norun -printsched FMRadio.str
init = [
$0 = FloatOneSource@1.work
$1 = LowPassFilter@4.work
$2 = FMDemodulator@5.work
$3 = EqSplit@8.streamit.misc.Pair@1386000
$4 = BPFCore@16.streamit.misc.Pair@a470b8
$5 = BPFCore@24.streamit.misc.Pair@cdedfd
$6 = BPFCore@32.streamit.misc.Pair@116471f
$7 = BPFCore@40.streamit.misc.Pair@12558d6
$8 = { {379 $0} {64 $1} {63 $2} {63 $3} {63 $4} {63 $5}
       {63 $6} {63 $7} }
]
steady = [
$9 = LowPassFilter@18.work
$10 = LowPassFilter@19.work
$11 = BPFCore@16.streamit.misc.Pair@18e2b22
$12 = Subtracter@17.work
$13 = Amplify@15.work
$14 = LowPassFilter@26.work
$15 = LowPassFilter@27.work
$16 = BPFCore@24.streamit.misc.Pair@bf2d5e
$17 = Subtracter@25.work
$18 = Amplify@23.work
$19 = LowPassFilter@34.work
$20 = LowPassFilter@35.work
$21 = BPFCore@32.streamit.misc.Pair@1ee3914
$22 = Subtracter@33.work
$23 = Amplify@31.work
$24 = LowPassFilter@42.work
$25 = LowPassFilter@43.work
$26 = BPFCore@40.streamit.misc.Pair@12a54f9
$27 = Subtracter@41.work
$28 = Amplify@39.work
$29 = EqSplit@8.streamit.misc.Pair@1662dc8
$30 = AnonFilter_a0@9.work
$31 = FloatPrinter@3.work
```

```
$32 = { {5 $0} $1 $2 $3 $4 $9 $10 $11 $12 $13 $5 $14
        $15 $16 $17 $18 $6 $19 $20 $21 $22 $23 $7
        $24 $25 $26 $27 $28 $29 $30 $31 }
]
!ml sched size = 39
!ml buff size = 1299
```

Currently, the default scheduler is a minimal latency scheduler that uses phases to compress the code size. The schedule listed above has two components: an initialization schedule (to initialize buffers for filters that peek) and a steady-state schedule (that can loop infinitely). Each filter and splitter in the graph is given a number for easy reference, and then the schedule is printed at the bottom. A loop nest in the schedule is denoted by `(N F)`, where the filter `F` executes `N` times. The schedule size and buffer size required are printed at the end of the listing.

Additional options for the library can be found in Appendix B.

A Keyword Review

Stream object types:

filter Declares a filter with a work function

pipeline Declares a series of stream objects, with the output of the first connected to the input of the second, etc.

splitjoin Declares a parallel set of stream objects, with a splitter and a joiner distributing and collecting data

feedbackloop Declares a feedback loop with two children, with a joiner combining input data and the output of the loop and a splitter distributing the output of the body to the output and the input of the loop

Filter work or helper functions:

push Pushes an item on to the output of the filter. Must be called the exact number of times as in the rate declaration.

pop Retrieves and removes the first item from the input of the filter. Must be called the exact number of times as in the rate declaration.

peek(k) Retrieves the $k + 1$-th item from the input of the filter, without removing it. If n items have been popped, $k + n$ must be less than the declared peek rate.

Composite stream declarations:

add Adds a child after the existing children. (pipeline, splitjoin)

body Adds a child as the body part of a feedback loop.

loop Adds a child as the loop part of a feedback loop.

enqueue Pushes an item on to the input of the joiner coming from the loop part of a feedback loop.

split Declares the type and weights of the splitter. (splitjoin, feedbackloop)

join Declares the type and weights of the joiner. (splitjoin, feedbackloop)

duplicate Splitter type that takes each input item and copies it to the input of each child.

roundrobin Splitter or joiner type that takes a specified number of items from the input (or output) and copies it to the input (or output) of each child.

B Options

--help Displays a summary of common options.

--more-help Displays a summary of advanced options (which are not described below).

--cluster ⟨*n*⟩ Compile for a cluter or multicore with ⟨*n*⟩ nodes.

--library Produce a Java file compatible with the StreamIt Java library, and compile and run it.

--simpleC Generate a simple C file that inlines the entire application into a single function. This is sometimes more readable than the default uniprocessor output, but the backend is not fully-featured.

--raw ⟨*n*⟩, -r ⟨*n*⟩ Compile for an ⟨*n*⟩-by-⟨*n*⟩ Raw processor.

--rstream, -R Generate a C-like file to be compiled by the RStream compiler from Reservoir Labs.

--output ⟨*filename*⟩, -o ⟨*filename*⟩ Places the resulting binary in ⟨*filename*⟩.

--verbose Show intermediate commands as they are executed.

Options available for all backends

-O0 Do not optimize (default).

-O1 Perform basic optimizations that should improve performance in most cases. Adds `--unroll 16 --destroyfieldarray --partition --wbs`.

-O2 Perform extended optimizations that should improve performance in most cases, but may also cause the compiler to become unstable. Adds `--unroll 256 --destroyfieldarray --partition --wbs --macros`.

--iterations $\langle n \rangle$**, -i**$\langle n \rangle$ Run the program for $\langle n \rangle$ steady-state iterations. Defaults to infinity. For the uniprocessor, cluster, and simpleC backends, the number of iterations can also be passed at the command line of the final executable (`a.out -i 100`).

--linearreplacement Domain-specific optimization: combine adjacent "linear" filters in the program into a single matrix multiplication operation wherever possible. Corresponds to the "linear" option in the PLDI'03 paper.

--statespace In combination with `--linearreplacement`, performs combination and optimization of linear statespace filters as described in the CASES'05 paper.

--unroll $\langle n \rangle$**, -u**$\langle n \rangle$ Specify loop unrolling limit. The default value is 0.

Options specific to Uniprocessor and Cluster backends

--cacheopt Performs cache optimizations as described in the LCTES'05 paper.

--l1d $\langle n \rangle$ Sets the L1 data cache size (in KB) for cache optimizations. The default is 8 KB.

--l1i $\langle n \rangle$ Sets the L1 instruction cache size (in KB) for cache optimizations. The default is 8 KB.

--l2 $\langle n \rangle$ Sets the L2 cache size (in KB) for cache optimizations (we assume a unified L2 cache). The default is 256 KB.

--linearpartition, -L Domain-specific optimization: perform linear replacement and frequency replacement selectively, based on an estimate of where it is most beneficial. Corresponds to the "autosel" option in the PLDI'03 paper. (Relies on FFTW installation.)

Options specific to Raw backend

--asciifileio Specifies that FileReader's and FileWriter's should use ASCII format rather than binary. Also works under the `--simpleC` backend.

--numbers $\langle n \rangle$**, -N**$\langle n \rangle$ Instrument code to gather performance statistics on simulated code over $\langle n \rangle$ steady-state cycles. The results are placed in results.out in the current directory.

--ssoutputs $\langle n \rangle$ For applications containing a dynamic I/O rate, this option indicates how many outputs should count as a steady-state when gathering numbers (with `--numbers`).

--rawcol $\langle m \rangle$**, -c**$\langle m \rangle$ Specify number of columns in Raw processor; –raw specifies number of rows.

--wbs When laying out communication instructions, use the work-based simulator to estimate exactly when items will be produced and consumed. This improves the scheduling of routing instructions.