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FastFlow tutorial

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Abstract

FastFlow is a structured parallel programming framework targeting shared memory multicores. Its layered design and the optimized implementation of the communication mechanisms used to implement the FastFlow streaming networks provided to the application programmer as algorithmic skeletons support the development of efficient fine grain parallel applications. FastFlow is available (open source) at SourceForge[1]. This work introduces FastFlow programming techniques and points out the different ways used to parallelize existing C/C++ code using FastFlow as a software accelerator. In short: this is a kind of tutorial on FastFlow.

1 Introduction

FastFlow is an algorithmic skeleton programming environment developed at the Dept. of Computer Science of Pisa and Torino [1].

A number of different papers and technical reports discuss the different features of this programming environment [11, 6, 2], the kind of results achieved while parallelizing different applications [13, 9, 10, 3, 8, 7] and the usage of FastFlow as *software accelerator*, i.e. as a mechanisms suitable to exploit unused cores of a multicore architecture to speedup execution of sequential code [4, 5].

This paper represents instead a tutorial aimed at instructing programmers in the usage of the FastFlow skeletons and in the typical FastFlow programming techniques.

Therefore, after recalling the FastFlow design principles in Sec. 2, in Sec. 3 we describe the (trivial) installation procedure. Then, in Sections 4 to 8.3 we introduce the main features of the FastFlow programming framework. Other sections detail particular techniques related to FastFlow usage, namely: access to shared data (Sec. 7), FastFlow usage as an accelerator (Sec. 9) and the possibility to use FastFlow as a framework to experiment new (w.r.t. the ones already

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[1] `http://sourceforge.net/projects/mc-fastflow/`

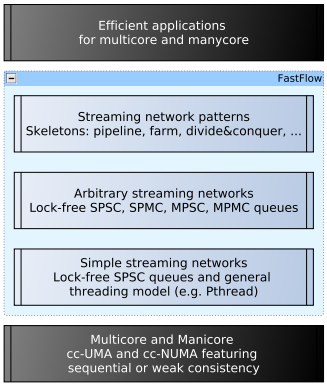


Figure 1: Layered FastFlow design

provided) skeletons (Sec. 8.3.1 and Sec. 12.1). Eventually, Sec. 13 gives a rough idea of the expected performance while running FastFlow programs and Sec. 14 outlines the main FastFlow RTS accessory routines.

2 Design principles

FastFlow[2] has been designed to provide programmers with efficient parallelism exploitation patterns suitable to implement (fine grain) stream parallel applications. In particular, FastFlow has been designed

- to promote high-level parallel programming, and in particular skeletal programming (i.e. pattern-based explicit parallel programming), and
- to promote efficient programming of applications for multi-core.

The whole programming framework has been incrementally developed according to a layered design on top of Pthread/C++ standard programming framework and targets shared memory multicore architectures (see Fig. 1).

A first layer, the **Simple streaming networks** layer, provides lock-free Single Producers Single Consumer (SPSC) queues on top of the Pthread standard threading model.

A second layer, the **Arbitrary streaming networks** layer, provides lock-free implementations for Single Producer Multiple Consumer (SPMC), Multiple Producer Single Consumer (MPSC) and Multiple Producer Multiple Consumer (MPMC) queues on top of the SPSC implemented in the first layer.

Eventually, the third layer, the **Streaming Networks Patterns** layer, provides common stream parallel patterns. The primitive patterns include pipeline

[2]see also the FastFlow home page at `http://mc-fastflow.sourceforge.net`

and farms. Simple specialization of these patterns may be used to implement more complex patterns, such as divide and conquer, map and reduce patterns.

Parallel application programmers are assumed to use FastFlow directly exploiting the parallel patterns available in the Streaming Network Patterns level. In particular:

- defining sequential concurrent activities, by sub classing a proper FastFlow class, the `ff_node` class, and
- building complex stream parallel patterns by hierarchically composing sequential concurrent activities, pipeline patterns, farm patterns and their "specialized" versions implementing more complex parallel patterns.

The `ff_node` sequential concurrent activity abstraction provide suitable ways to define a sequential activity processing data items appearing on a single input channel and delivering the related results onto a single output channel. Particular cases of `ff_nodes` may be simply implemented with no input channel or no output channel. The former is used to install a concurrent activity *generating* an output stream (e.g. from data items read from keyboard or from a disk file); the latter to install a concurrent activity *consuming* an input stream (e.g. to present results on a video or to store them on disk).

The pipeline pattern may be used to implement sequences of streaming networks $S_1 \rightarrow \ldots \rightarrow S_k$ with S_k receiving input from S_{k-1} and delivering outputs to S_{k+1}. S_i may be either a sequential activity or another parallel pattern. S_1 must be a stream generator activity and S_k a stream consuming one.

The farm pattern models different embarrassingly (stream) parallel constructs. In its simplest form, it models a master/worker pattern with workers producing no stream data items. Rather the worker consolidate results directly in memory. More complex forms including either an emitter, or a collector of both an emitter and a collector implement more sophisticated patterns:

- by adding an emitter, the user may specify policies, different from the default round robin one, to schedule input tasks to the workers;
- by adding a collector, the user may use worker actually producing some output values, which are gathered and delivered to the farm output stream. Different policies may be implemented on the collector to gather data from the worker and deliver them to the output stream.

In addition, a feedback channel may be added to a farm, moving output results back from the collector (or from the collection of workers in case no collector is specified) back to the emitter input channel. The feedback channel may only be added to the farm/pipe *at the root of the skeleton tree.*

Specialized version of the farm may be used to implement more complex patterns, such as:

- divide and conquer, using a farm with feedback loop and proper stream items tagging (input tasks, subtask results, results)

- MISD (multiple instruction single data, that is something computing

$$f_1(x_i), \ldots, f_k(x_i)$$

  out of each x_i appearing onto the input stream) pattern, using a farm with an emitter implementing a broadcast scheduling policy

- map, using an emitter partitioning an input collection and scheduling one partition per worker, and a collector gathering sub-partitions results from the workers and delivering a collection made out of all these results to the output stream.

It is worth pointing out that while using plain pipeline and farms (with or without emitters and collectors) actually can be classified as "using skeletons" in a traditional skeleton based programming framework, the usage of specialized versions of the farm streaming network can be more easily classified as "using skeleton templates", as the base features of the FastFlow framework are used to build new patterns, not provided as primitive skeletons[3].

Concerning the usage of FastFlow to support parallel application development on shared memory multicores, the framework provides two abstractions of structured parallel computation:

- a "skeleton program abstraction" which is used to implement applications completely modelled according to the algorithmic skeleton concepts. When using this abstraction, the programmer write a parallel application by providing the business logic code, wrapped into proper `ff_node` subclasses, a skeleton (composition) modelling the parallelism exploitation pattern of the application and a single command starting the skeleton computation and awaiting for its termination.

- an "accelerator abstraction" which is used to parallelize (and therefore accelerate) only some parts of an existing application. In this case, the programmer provides a skeleton (composition) which is run on the "spare" cores of the architecture and implements a parallel version of the business logic to be accelerated, that is the computing a given $f(x)$. The skeleton (composition) will have its own input and output channels. When an $f(x)$ has actually to be computed within the application, rather than writing proper code to call to the sequential f code, the programmer may insert code asynchronously "offloading" x to the accelerator skeleton. Later on, when the result of $f(x)$ is to be used, some code "reading" accelerator result may be used to retrieve the accelerator computed values.

This second abstraction fully implements the "minimal disruption" principle stated by Cole in his skeleton manifesto [12], as the programmer using the accelerator is only required to program a couple of `offload/get_result` primitives in place of the single $\ldots = f(x)$ function call statement (see Sec. 9).

[3] Although this may change in future FastFlow releases, this is the current situation as of FastFlow version 1.1

3 Installation

Before entering the details of how FastFlow may be used to implement efficient stream parallel (and not only) programs on shared memory multicore architectures, let's have a look at how FastFlow may be installed[4].

The installation process is trivial, actually:

1. first, you have to download the source code from SourceForge (`http://sourceforge.net/projects/mc-fastflow/`)
2. then you have to extract the files using a `tar xzvf fastflow-XX.tgz` command, and
3. eventually, you should use the top level directory resulting from the *tarxzvf* command as the argument of the `-I` flag of `g++`.

As an example, the currently available version (1.1) is hosted in a `fastflow-1.1.0.tar.gz` file. If you download it and extract files to your home directory, you should compile FastFlow code using the flags

`g++ -I $HOME/fastflow-1.1.0 -lpthread` in addition to any

other flags needed to compile your specific code.
Sample `makefiles` are provided both within the `fastflow-1.1.0/tests` and the `fastflow-1.1.0/examples` directories in the source distribution.

4 Hello world in FastFlow

As all programming frameworks tutorials, we start with a *Hello world* code. In order to implement our hello world program, we use the following code:

```
#include <iostream>
#include <ff/pipeline.hpp>

using namespace ff;

class Stage1: public ff_node {
public:

    void * svc(void * task) {
        std::cout << "Hello world" << std::endl;
        return NULL;
    }
};

int main(int argc, char * argv[]) {

```

[4] We only detail instructions needed to install FastFlow on Linux/Unix/BSD machines here. A Windows port of FastFlow exist, that requires slightly different steps for the installation.

```
17      ff_pipeline pipe;
18      pipe.add_stage(new Stage1());
19
20      if (pipe.run_and_wait_end()<0) {
21          error("running pipeline\n");
22          return -1;
23      }
24
25      return 0;
26  }
```

ffsrc/helloworldSimple.cpp

Line 2 includes all what's needed to compile a FastFlow program just using a pipeline pattern and line 4 instruct compiler to resolve names looking (also) at `ff` namespace. Lines 6 to 13 host the application business logic code, wrapped into a class sub classing `ff_node`. The `void * svc(void *)` method[5] wraps the body of the concurrent activity resulting from the wrapping. It is called every time the concurrent activity is given a new input stream data item. The input stream data item pointer is passed through the input `void *` parameter. The result of the single invocation of the concurrent activity body is passed back to the FastFlow runtime returning the `void *` result. In case a `NULL` is returned, the concurrent activity actually terminates itself. The application main only hosts code needed to setup the FastFlow streaming network and to start the skeleton (composition) computation: lines 17 and 18 declare a pipeline pattern (line 17) and insert a single stage (line 18) in the pipeline. Line 20 starts the computation of the skeleton program and awaits for skeleton computation termination. In case of errors the `run_and_wait_end()` call will return a negative number (according to the Unix/Linux syscall conventions).

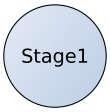
When the program is started, the FastFlow RTS accomplishes to start the pipeline. In turn the first stage is started. As the first stage `svc` returns a `NULL`, the stage is terminated immediately after by the FastFlow RTS.

If we compile and run the program, we get the following output:

```
1 ffsrc$ g++ -lpthread -I /home/marcod/Documents/Research/
      CodeProgramming/fastflow-1.1.0 helloworldSimple.cpp -o
      hello
2 ffsrc$ ./hello
3 Hello world
4 ffsrc$
```

There is nothing parallel here, however. The single pipeline stage is run just once and there is nothing else, from the programmer viewpoint, running in parallel. The graph of concurrent activities in this case is the following, trivial one:

[5] we use the term `svc` as a shortcut for "service"



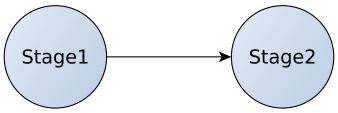
A more interesting "HelloWorld" would have been to have a two stage pipeline where the first stage prints the "Hello" and the second one, after getting the results of the computation of the first one, prints "world". In order to implement this behaviour, we have to write two sequential concurrent activities and to use them as stages in a pipeline. Additionally, we have to send something out as a result from the first stage to the second stage. Let's assume we just send the string with the word to be printed. The code may be written as follows:

```
#include <iostream>
#include <ff/pipeline.hpp>

using namespace ff;

class Stage1: public ff_node {
public:

    void * svc(void * task) {
        std::cout << "Hello " << std::endl;
        char * p = (char *) calloc(sizeof(char),10);
        strcpy(p,"World");
        sleep(1);
        return ((void *)p);
    }
};

class Stage2: public ff_node {
public:

    void * svc(void * task) {
      std::cout << ((char *)task) << std::endl;
      free(task);
      return GO_ON;
    }
};

int main(int argc, char * argv[]) {

    ff_pipeline pipe;
    pipe.add_stage(new Stage1());
    pipe.add_stage(new Stage2());

    if (pipe.run_and_wait_end()<0) {
        error("running pipeline\n");
        return -1;
```

```
37      }
38
39      return 0;
40  }
```

ffsrc/hello2stages.cpp

We define two sequential stages. The first one (lines 6–16) prints the "Hello" message, the allocates some memory buffer, store the "world" message in the buffer and send its to the output stream (return on line 14). The `sleep` on line 13 is here just for making more evident the FastFlow scheduling of concurrent activities. The second one (lines 18–26) just prints whatever he gets on the input stream (the data item stored after the `void * task` pointer of `svc` header on line 21), frees the allocated memory and then returns a `GO_ON` mark, which is intended to be a value interpreted by the FastFlow framework as: "I finished processing the current task, I give you no *result* to be delivered onto the output stream, but please keep me alive ready to receive another input task". The `main` on lines 28–40 is almost identical to the one of the previous version but for the fact we add two stages to the pipeline pattern. Implicitly, this sets up a streaming network with `Stage1` connected by a stream to `Stage2`. Items delivered on the output stream by `Stage1` will be read on the input stream by `Stage2`. The concurrent activity graph is therefore:



If we compile and run the program, however, we get a kind of unexpected result:

```
1  ffsrc$ g++ -lpthread -I /home/marcod/Documents/Research/
       CodeProgramming/fastflow-1.1.0 hello2stages.cpp -o
       hello2stages
2  ffsrc$ ./hello2stages
3  Hello
4  WorldHello
5
6  Hello World
7
8  Hello World
9
10 Hello World
11
12 ^C
13 ffsrc$
```

First of all, the program keeps running printing an "Hello world" every second. We in fact terminate the execution through a CONTROL-C. Second,

the initial sequence of strings is a little bit strange[6].

The "infinite run" is related to way FastFlow implements concurrent activities. Each `ff_node` is run as many times as the number of the input data items appearing onto the output stream, unless the `svc` method returns a `NULL`. Therefore, if the method returns either a task (pointer) to be delivered onto the concurrent activity output stream, or the `GO_ON` mark (no data output to the output stream but continue execution), it is re-executed as soon as there is some input available. The first stage, which has no associated input stream, is re-executed up to the moment it terminates the `svc` with a `NULL`. In order to have the program terminating, we therefore may use the following code for `Stage1`:

```
class Stage1: public ff_node {
public:

  Stage1() { first = (1==1); }

  void * svc(void * task) {
    if(first) {
      std::cout << "Hello " << std::endl;
      char * p = (char *) calloc(sizeof(char),10);
      strcpy(p,"World");
      sleep(1);
      first = 0;
      return ((void *)p);
    } else {
      return NULL;
    }
  }
private:
  int first;
};
```

If we compile and execute the program with this modified `Stage1` stage, we'll get an output such as:

```
ffsrc$ g++ -lpthread -I /home/marcod/Documents/Research/
    CodeProgramming/fastflow-1.1.0 hello2terminate.cpp -o
    hello2terminate
ffsrc$ ./hello2terminate
Hello
World
ffsrc$
```

that is the program terminates after a single run of the two stages. Now the question is: why the second stage terminated, although the `svc` method return

[6] and depending on the actual number of cores of your machine and on the kind of scheduler used in the operating system, the sequence may vary a little bit

value states that more work is to be done? The answer is in the stream semantics implemented by FastFlow. FastFlow streaming networks automatically manage `end-of-streams`. That is, as soon as an `ff_node` returns a `NULL`–implicitly declaring he wants to terminate its output stream, the information is propagated to the node consuming the output stream. This nodes will therefore also terminate execution–without actually executing its `svc` method–and the end of stream will be propagated onto its output stream, if any. Therefore `Stage2` terminates after the termination of `Stage1`.

The other problem, namely the appearing of the initial 2 "Hello" strings apparently related to just one "world" string is related to the fact that FastFlow does not guarantee any scheduling semantics of the `ff_node svc` executions. The first stage delivers a string to the second stage, then it is executed again and again. The `sleep` inserted in the first stage prevents to accumulate too much "hello" strings on the output stream delivered to the second stage. If we remove the `sleep` statement, in fact, the output is much more different: we will see on the input a large number of "hello" strings followed by another large number of "world" strings. This because the first stage is enabled to send as much data items on the output stream as of the capacity of the SPSC queue used to implement the stream between the two stages.

5 Generating a stream

In order to achieve a better idea of how streams are managed within FastFlow, we slightly change our `HelloWorld` code in such a way the first stage in the pipeline produces on the output stream n integer data items and then terminates. The second stage prints a "world -i-" message upon receiving each i item onto the input stream.

We already discussed the role of the return value of the `svc` method. Therefore a first version of this program may be implemented using as the `Stage1` class the following code:

```
#include <iostream>
#include <ff/pipeline.hpp>

using namespace ff;

class Stage1: public ff_node {
public:

  Stage1(int n) {
    streamlen = n;
    current = 0;
  }

  void * svc(void * task) {
    if(current < streamlen) {
      current++;
```

```
      std::cout << "Hello number " << current << " " << std::endl;
      int * p = (int *) calloc(sizeof(int),1);
      *p = current;
      sleep(1);
      return ((void *)p);
    } else {
      return NULL;
    }
  }
private:
  int streamlen, current;
};

class Stage2: public ff_node {
public:

    void * svc(void * task) {
      int * i = (int *) task;
      std::cout << "World -" << *i << "- " << std::endl;
      free(task);
      return GO_ON;
    }
};

int main(int argc, char * argv[]) {

    ff_pipeline pipe;
    pipe.add_stage(new Stage1(atoi(argv[1])));
    pipe.add_stage(new Stage2());

    if (pipe.run_and_wait_end()<0) {
        error("running pipeline\n");
        return -1;
    }

    return 0;
}
```

ffsrc/helloStream.cpp

The output we get is the following one:

```
ffsrc$ g++ -lpthread -I /home/marcod/Documents/Research/CodeProgramming/fastflow-1.1.0 helloStream.cpp -o helloStream
ffsrc$ ./helloStream 5
Hello number 1
Hello number 2World - 1-

Hello number World -32 -
```

```

World -3- Hello number
4
Hello number 5World - 4-

World -5-
ffsrc$
```

However, there is another way we can use to generate the stream, which is a little bit more "programmatic". FastFlow makes available an `ff_send_out` method in the `ff_node` class, which can be used to direct a data item onto the concurrent activity output stream, without actually using the `svc return` way.

In this case, we could have written the `Stage` as follows:

```
class Stage1: public ff_node {
public:

  Stage1(int n) {
    streamlen = n;
    current = 0;
  }

  void * svc(void * task) {
    while(current < streamlen) {
      current++;
      std::cout << "Hello number " << current << " " << std::
          endl;
      int * p = (int *) calloc(sizeof(int),1);
      *p = current;
      sleep(1);
      ff_send_out(p);
    }
    return NULL;
  }
private:
  int streamlen, current;
};
```

In this case, the `Stage1` is run just once (as it immediately returns a `NULL`. However, during the single run the `svc while` loop delivers the intended data items on the output stream through the `ff_send_out` method. In case the sends fill up the SPSC queue used to implement the stream, the `ff_send_out` will block up to the moment `Stage2` consumes some items and consequently frees space in the SPSC buffers.

6 More on ff_node

The ff_node class actually defines three distinct virtual methods:

```
public:
    virtual void* svc(void * task) = 0;
    virtual int   svc_init() { return 0; };
    virtual void  svc_end()  {}
```

The first one is the one defining the behaviour of the node while processing the input stream data items. The other two methods are automatically invoked once and for all by the FastFlow RTS when the concurrent activity represented by the node is started (svc_init) and right before it is terminated (svc_end).

These virtual methods may be overwritten in the user supplied ff_node subclasses to implement initialization code and finalization code, respectively. Actually, the svc method *must* be overwritten as it is defined as a pure virtual method.

We illustrate the usage of the two methods with another program, computing the Sieve of Eratosthenes. The sieve uses a number of stages in a pipeline. Each stage stores the first integer it got on the input stream. Then is cycles passing onto the output stream only the input stream items which are not multiple of the stored integer. An initial stage injects in the pipeline the sequence of integers starting at 2, up to n. Upon completion, each stage has stored a prime number.

We can implement the Eratostheness sieve with the following FastFlow program.

```
#include <iostream>
#include <ff/pipeline.hpp>

using namespace ff;

class Sieve: public ff_node {
public:

  Sieve() { filter = 0; }

  void * svc(void * task) {
    unsigned int * t = (unsigned int *)task;

    if (filter == 0) {
      filter = *t;
      return GO_ON;
    } else {
      if(*t % filter == 0)
        return GO_ON;
      else
        return task;
```

```
    }
  }

  void svc_end() {
    std::cout << "Prime(" << filter << ")\n";
    return;
  }


private:
  int filter;
};

class Generate: public ff_node {
public:

  Generate(int n) {
    streamlen = n;
    task = 2;
    std::cout << "Generate object created" << std::endl;
    return;
  }


  int svc_init() {
    std::cout << "Sieve started. Generating a stream of " << streamlen <<
      " elements, starting with " << task << std::endl;
    return 0;
  }

  void * svc(void * tt) {
    unsigned int * t = (unsigned int *)tt;

    if(task < streamlen) {
      int * xi = (int *) calloc(1, sizeof(int));
      *xi = task++;
      return xi;
    } else {
      return NULL;
    }
  }
private:
  int streamlen;
  int task;
};

class Printer: public ff_node {

  int svc_init() {
```

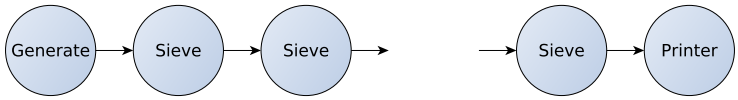
```
    std::cout << "Printer started " << std::endl;
    first = 0;
  }

  void * svc(void *t) {
    int * xi = (int *) t;
    if (first == 0) {
      first = *xi;
    }
    return GO_ON;
  }

  void svc_end() {
    std::cout << "Sieve terminating, prime numbers found up to " << first
        << std::endl;
  }

private:
  int first;
};

int main(int argc, char * argv[]) {
  if (argc!=3) {
    std::cerr << "use: "  << argv[0] << " nstages streamlen\n";
    return -1;
  }

  ff_pipeline pipe;
  int nstages = atoi(argv[1]);
  pipe.add_stage(new Generate(atoi(argv[2])));
  for(int j=0; j<nstages; j++)
    pipe.add_stage(new Sieve());
  pipe.add_stage(new Printer());

  ffTime(START_TIME);
  if (pipe.run_and_wait_end()<0) {
    error("running pipeline\n");
    return -1;
  }
  ffTime(STOP_TIME);

  std::cerr << "DONE, pipe  time= " << pipe.ffTime() << " (ms)\n";
  std::cerr << "DONE, total time= " << ffTime(GET_TIME) << " (ms)\n";
  pipe.ffStats(std::cerr);
  return 0;
}
```

ffsrc/sieve.cpp

The `Generate` stage at line 35–66 generates the integer stream, from 2 up to a value taken from the command line parameters. It uses an `svc_init` just to point out when the concurrent activity is started. The creation of the object used to represent the concurrent activity is instead evidenced by the message printed in the constructor.

The `Sieve` stage (lines 6–28) defines the generic pipeline stage. This stores the initial value got from the input stream on lines 14–16 and then goes on passing the inputs not multiple of the stored values on lines 18–21. The `svc_end` method is executed right before terminating the concurrent activity and prints out the stored value, which happen to be the prime number found in that node.

The `Printer` stage is used as the last stage in the pipeline (the pipeline build on lines 98–103 in the program `main`) and just discards all the received values but the first one, which is kept to remember the point where we arrived storing prime numbers. It defines both an `svc_init` method (to print a message when the concurrent activity is started) and an `svc_end` method, which is used to print the first integer received, representing the upper bound (non included in) of the sequence of prime numbers discovered with the pipeline stages. The concurrent activity graph of the program is the following one:



The program output, when run with 7 `Sieve` stages on a stream from 2 to 30, is the following one:

```
ffsrc$ ./sieve 7 30
Generate object created
Printer started
Sieve started. Generating a stream of 30 elements, starting
    with 2
Prime(2)
Prime(3)
Prime(5)
Prime(7)
Prime(Prime(Sieve terminating, prime numbers found up to 1317)
)
19
Prime(11)
DONE, pipe  time= 0.275 (ms)
DONE, total time= 25.568 (ms)
FastFlow trace not enabled
ffsrc$
```

showing that the prime numbers up to 19 (excluded) has been found.

7 Managing access to shared objects

Shared objects may be accessed within FastFlow programs using the classical `pthread` concurrency control mechanisms. The FastFlow program is actually a multithreaded code using the `pthread` library, in fact.

We demonstrate how access to shared objects may be ensured within a FastFlow program forcing mutual exclusion in the access to the `std::cout` file descriptor. This will be used to have much nicer strings output on the screen when running the Sieve program illustrated in the previous section.

In order to guarantee mutual exclusion on the shared `std::cout` descriptor we use a `pthread_mutex_lock`. The lock is declared and properly initialized as a static, global variable in the program (see code below, line 7). Then each one of the writes to the `std::cout` descriptor in the concurrent activities relative to the different stages of the pipeline are protected through a `pthread_mutex_lock` / `pthread_mutex_unlock` "brackets" (see line 29–31 in the code below, as an example).

```
1  #include <iostream>
2  #include <ff/pipeline.hpp>
3  #include <pthread.h>
4
5  using namespace ff;
6
7  static pthread_mutex_t lock = PTHREAD_MUTEX_INITIALIZER;
8
9  class Sieve: public ff_node {
10 public:
11
12   Sieve() { filter = 0; }
13
14   void * svc(void * task) {
15     unsigned int * t = (unsigned int *)task;
16
17     if (filter == 0) {
18       filter = *t;
19       return GO_ON;
20     } else {
21       if(*t % filter == 0)
22   return GO_ON;
23       else
24   return task;
25     }
26   }
27
28   void svc_end() {
29     pthread_mutex_lock(&lock);
30     std::cout << "Prime(" << filter << ")\n";
31     pthread_mutex_unlock(&lock);
32     return;
```

```
  }


private:
  int filter;
};

class Generate: public ff_node {
public:

  Generate(int n) {
    streamlen = n;
    task = 2;
    pthread_mutex_lock(&lock);
    std::cout << "Generate object created" << std::endl;
    pthread_mutex_unlock(&lock);
    return;
  }


  int svc_init() {
    pthread_mutex_lock(&lock);
    std::cout << "Sieve started. Generating a stream of " << streamlen <<
      " elements, starting with " << task << std::endl;
    pthread_mutex_unlock(&lock);
    return 0;
  }

  void * svc(void * tt) {
    unsigned int * t = (unsigned int *)tt;

    if(task < streamlen) {
      int * xi = (int *) calloc(1, sizeof(int));
      *xi = task++;
      return xi;
    } else {
      return NULL;
    }
  }
private:
  int streamlen;
  int task;
};

class Printer: public ff_node {

  int svc_init() {
    pthread_mutex_lock(&lock);
    std::cout << "Printer started " << std::endl;
```

```
    pthread_mutex_unlock(&lock);
    first = 0;
  }

  void * svc(void *t) {
    int * xi = (int *) t;
    if (first == 0) {
      first = *xi;
    }
    return GO_ON;
  }

  void svc_end() {
    pthread_mutex_lock(&lock);
    std::cout << "Sieve terminating, prime numbers found up to " << first
        << std::endl;
    pthread_mutex_unlock(&lock);
  }

private:
  int first;
};

int main(int argc, char * argv[]) {
  if (argc!=3) {
    std::cerr << "use: " << argv[0] << " nstages streamlen\n";
    return -1;
  }

  ff_pipeline pipe;
  int nstages = atoi(argv[1]);
  pipe.add_stage(new Generate(atoi(argv[2])));
  for(int j=0; j<nstages; j++)
    pipe.add_stage(new Sieve());
  pipe.add_stage(new Printer());

  ffTime(START_TIME);
  if (pipe.run_and_wait_end()<0) {
    error("running pipeline\n");
    return -1;
  }
  ffTime(STOP_TIME);

  std::cerr << "DONE, pipe  time= " << pipe.ffTime() << " (ms)\n";
  std::cerr << "DONE, total time= " << ffTime(GET_TIME) << " (ms)\n";
  pipe.ffStats(std::cerr);
```

```
  return 0;
}
```

ffsrc/sievelock.cpp

When running the program, we get a slightly different output than the one we obtained when the usage of `std::cout` was not properly regulated:

```
ffsrc$ ./a.out 7 30
Generate object created
Printer started
Sieve started. Generating a stream of 30 elements, starting
    with 2
Prime(2)
Prime(5)
Prime(13)
Prime(11)
Prime(7)
Sieve terminating, prime numbers found up to 19
Prime(3)
Prime(17)
DONE, pipe  time= 58.439 (ms)
DONE, total time= 64.473 (ms)
FastFlow trace not enabled
ffsrc$
```

The strings are printed in clearly separated lines, although some apparently unordered string sequence appears, which is due to the FastFlow scheduling of the concurrent activities *and* to the way locks are implemented and managed in the `pthread` library.

It is worth pointing out that

- FastFlow ensures correct access sequences to the shared object used to implement the streaming networks (the graph of concurrent activities), such as the SPSC queues used to implement the streams, as an example.
- FastFlow stream semantics guarantee correct sequencing of activation of the concurrent activities modelled through `ff_node`s and connected through streams. The stream implementation actually ensures *pure data flow* semantics.
- any access to any user defined shared data structure must be protected with either the primitive mechanisms provided by FastFlow (see Sec. 7) or the primitives provided within the `pthread` library.

8 More skeletons: the FastFlow farm

In the previous sections, we used only pipeline skeletons in the sample code. Here we introduce the other primitive skeleton provided in FastFlow, namely

the `farm` skeleton.

The simplest way to define a farm skeleton in FastFlow is by declaring a `farm` object and adding a vector of *worker* concurrent activities to the `farm`. An excerpt of the needed code is the following one

```
#include <ff/farm.hpp>

using namespace ff;

int main(int argc, char * argv[]) {

  ...
  ff_farm<> myFarm;
  std::vector<ff_node *> w;
  for(int i=0;i<nworkers;++i)
    w.push_back(new Worker);
  myFarm.add_workers(w);
  ...
```

This code basically defines a farm with `nworkers` workers processing the data items appearing onto the farm input stream and delivering results onto the farm output stream. The scheduling policy used to send input tasks to workers is the default one, that is round robin one. Workers are implemented by the `ff_node` `Worker` objects. These objects may represent sequential concurrent activities as well as further skeletons, that is either pipeline or farm instances.

However, this farm may not be used alone. There is no way to provide an input stream to a FastFlow streaming network but having the first component in the network generating the stream. To this purpose, FastFlow supports two options:

- we can use the farm defined with a code similar to the one described above as the second stage of a pipeline whose first stage generates the input stream according to one of the techniques discussed in Sec. 5. This means we will use the farm writing a code such as:

```
  ...
  ff_pipeline myPipe;

  myPipe.add_stage(new GeneratorStage());
  myPipe.add_stage(myFarm);
```

- or we can provide an `emitter` and a `collector` to the farm, specialized in such a way they can be used to produce the input stream and consume the output stream of the farm, respectively, while inheriting the default scheduling and gathering policies.

The former case is simple. We only have to understand why adding the farm to the pipeline as a pipeline stage works. This will discussed in detail in Sec. 10. The latter case is simple as well, but we discuss it through some more code.

8.1 Farm with emitter and collector

First, let us see what kind of objects we have to build to provide the farm an `emitter` and a `collector`. Both `emitter` and `collector` must be supplied as `ff_node` subclass objects. If we implement the `emitter` just providing the `svc` method, the tasks delivered by the `svc` on the output stream either using a `ff_send_out` or returning the proper pointer with the `svc` `return` statement, those elements will be dispatched to the available workers according to the default round robin scheduling. An example of `emitter` node, generating the stream of tasks actually eventually processed by the farm `worker` nodes is the following one:

```
1  class Emitter: public ff_node {
2  public:
3      Emitter(int n) {
4          streamlen = n;
5          task = 0;
6      };
7
8      void * svc(void *) {
9          sleep(1);
10         task++;
11         int * t = new int(task);
12         if (task<streamlen)
13             return t;
14         else
15             return NULL;
16     }
17
18 private:
19     int streamlen;
20     int task;
21 };
```

In this case, the node `svc` actually does not take into account any input stream item (the input parameter name is omitted on line 5). Rather, each time the node is activated, it returns a task to be computed using the internal `ntasks` value. The task is directed to the "next" worker by the FastFlow farm run time support.

Concerning the `collector`, we can also use a `ff_node`: in case the results need further processing, they can be directed to the next node in the streaming network using the mechanisms detailed in Sec. 5. Otherwise, they can be processed within the `svc` method of the `ff_node` subclass.

As an example, a `collector` just printing the tasks/results he gets from the workers may be programmed as follows:

```
class Collector: public ff_node {
public:
    void * svc(void * task) {
        int * t = (int *)task;
        std::cout << "Collector got " << *t << std::endl;
        return GO_ON;
    }
};
```

With these classes defined and assuming to have a worker defined by the class:

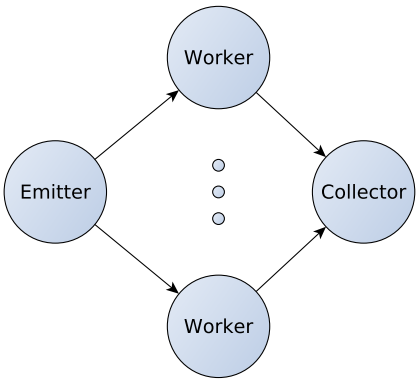
```
class Worker: public ff_node {
public:
    void * svc(void * task) {
        int * t = (int *)task;
        (*t)++;
        return task;
    }
};
```

we can define a program processing a stream of integers by increasing each one of them with a farm as follows:

```
int main(int argc, char * argv[]) {
    int nworkers=atoi(argv[1]);
    int streamlen=atoi(argv[2]);

    ff_farm<> farm;

    Emitter E(streamlen);
    farm.add_emitter(&E);

    std::vector<ff_node *> w;
    for(int i=0;i<nworkers;++i)
      w.push_back(new Worker);
    farm.add_workers(w);

    Collector C;
    farm.add_collector(&C);

    if (farm.run_and_wait_end()<0) {
        error("running farm\n");
        return -1;
    }
    return 0;
```

```
}
```

The concurrent activity graph in this case is the following one:



When run with the first argument specifying the number of workers to be used and the second one specifying the length of the input stream generated in the collector node, we get the expected output:

```
ffsrc$ ./a.out 2 10
Collector got 2
Collector got 3
Collector got 4
Collector got 5
Collector got 6
Collector got 7
Collector got 8
Collector got 9
Collector got 10
ffsrc$
```

8.2 Farm with no collector

We move on considering a further case: a farm with emitter but no collector. Having no collector the workers may not deliver results: all the results computed by the workers must be consolidated in memory. The following code implements a farm where a stream of tasks of type `TASK` with an integer tag `i` and an integer value `t` are processed by the worker of the farm by:

- computing `t++` and
- storing the result in a global array at the position given by the tag `i`.

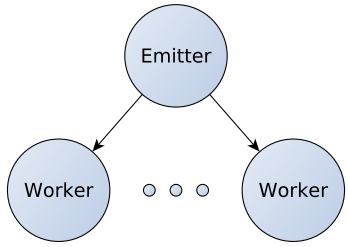
Writes to the global result array need not to be synchronized as each worker writes different positions in the array (the `TASK` tags are unique).

```
#include <vector>
#include <iostream>
#include <ff/farm.hpp>

static int * results;

typedef struct task_t {
    int i;
    int t;
} TASK;

using namespace ff;

class Worker: public ff_node {
public:
    void * svc(void * task) {
        TASK * t = (TASK *) task;
        results[t->i] = ++(t->t);
        return GO_ON;
    }
};


class Emitter: public ff_node {
public:
    Emitter(int n) {
        streamlen = n;
        task = 0;
    };

    void * svc(void *) {
        task++;
        TASK * t = (TASK *) calloc(1,sizeof(TASK));
        t->i = task;
        t->t = task*task;
        if (task<streamlen)
            return t;
        else
            return NULL;
    }

private:
    int streamlen;
    int task;
};


int main(int argc, char * argv[]) {

```

```
50      int nworkers=atoi(argv[1]);
51      int streamlen=atoi(argv[2]);
52      results = (int *) calloc(streamlen,sizeof(int));
53
54      ff_farm<> farm;
55
56      Emitter E(streamlen);
57      farm.add_emitter(&E);
58
59      std::vector<ff_node *> w;
60      for(int i=0;i<nworkers;++i)
61          w.push_back(new Worker);
62      farm.add_workers(w);
63
64      std::cout << "Before starting computation" << std::endl;
65      for(int i=0; i<streamlen; i++)
66          std::cout << i << " : " << results[i] << std::endl;
67      if (farm.run_and_wait_end()<0) {
68          error("running farm\n");
69          return -1;
70      }
71      std::cout << "After computation" << std::endl;
72      for(int i=0; i<streamlen; i++)
73          std::cout << i << " : " << results[i] << std::endl;
74      return 0;
75  }
```

ffsrc/farmNoC.cpp

The `Worker` code at lines 14–21 defines an `svc` method that returns a `GO_ON`. Therefore no results are directed to the collector (non existing, see lines 55-74: they define the farm but they do not contain any `add_collector` in the program `main`). Rather, the results computed by the worker code at line 18 are directly stored in the global array. In this case the concurrent activity graph is the following:



The main program prints the results vector before calling the FastFlow `start_and_wait_end()` and after the call, and you can easily verify the results are actually computed and stored in the correct place in the vector:

```
ffsrc$ farmNoC 2 10
Before starting computation
```

```
0 : 0
1 : 0
2 : 0
3 : 0
4 : 0
5 : 0
6 : 0
7 : 0
8 : 0
9 : 0
After computation
0 : 0
1 : 2
2 : 5
3 : 10
4 : 17
5 : 26
6 : 37
7 : 50
8 : 65
9 : 82
ffsrc$
```

Besides demonstrating how a farm without collector may compute useful results, the program of the last listing also demonstrates how complex task data structures can be delivered and retrieved to and from the FastFlow streaming network streams.

8.3 Specializing the scheduling strategy in a farm

In order to select the worker where an incoming input task has to be directed, the FastFlow farm uses an internal `ff_loadbalancer` that provides a method `int selectworker()` returning the index in the worker array corresponding to the worker where the next task has to be directed. This method cannot be overwritten, actually. But the programmer may subclass the `ff_loadbalancer` and provide his own `selectworker()` method and pass the new load balancer to the farm emitter, therefore implementing a farm with a user defined scheduling policy.

The steps to performed in this case are exemplified with the following, relevant portions of code.

First, we subclass the `ff_loadmanager` and provide our own `setworker()` method:

```
class my_loadbalancer: public ff_loadbalancer {
protected:
    // implement your policy...
    inline int selectworker() { return victim; }

```

```
public:
    // this is necessary because ff_loadbalancer has non default parameters....
    my_loadbalancer(int max_num_workers):ff_loadbalancer(max_num_workers) {}

    void set_victim(int v) { victim=v;}

private:
    int victim;
};
```

Then we create a farm with specifying the new load balancer class as a type parameter:

```
ff_farm<my_loadbalancer> myFarm(...);
```

Eventually, we create an emitter that within its `svc` method invokes the `set_victim` method right before outputting a task towards the worker string, either with a `ff_send_out(task)` or with a `return(task)`. The emitter is declared as:

```
class myEmitter: public ff_node {

  myEmitter(ff_loadbalancer * ldb) {
    lb = ldb;
  }

  ...

  void * svc(void * task) {
    ...
    workerToBeUsed = somePolicy(...);
    lb->set_victim(workerToBeUsed);
    ...
    ff_send_out(task);
    return GO_ON;
  }

  ...
private:
  ff_loadbancer * lb;
}
```

and inserted in the farm with the code

```
myEmitter emitter(myFarm.getlb());
myFarm.add_emitter(emitter);
```

What we get is a farm where the worker to be used to execute the task appearing onto the input stream is decided by the programmer through the proper implementation of `my_loadbancer` rather than being decided by the current FastFlow implementation.

Two particular cases specializing the scheduling policy in different way by using FastFlow predefined code are illustrated in the following two subsections.

8.3.1 Broadcasting a task to all workers

FastFlow supports the possibility to direct a task to all the workers in a farm. It is particularly useful if we want to process the task by workers implementing different functions. The broadcasting is achieved through the declaration of a specialized load balancer, in a way very similar to what we illustrated in Sec. 8.3.

The following code implements a farm whose input tasks are broadcasted to all the workers, and whose workers compute different functions on the input tasks, and therefore deliver different results on the output stream.

```
#include <iostream>
#include <ff/farm.hpp>
#include <ff/node.hpp>
#include <math.h>

using namespace std;
using namespace ff;


// should be global to be accessible from workers
#define MAX 4
int x[MAX];

class WorkerPlus: public ff_node {
  int svc_init() {
    cout << "Worker initialized" << endl;
    return 0;
  }

  void * svc(void * in) {
    int *i = ((int *) in);
    int ii = *i;
    *i++;
    cout << "WorkerPLus got " << ii << " and computed " << *i
        << endl ;
    return in;
  }
};

```

```
class WorkerMinus: public ff_node {
  int svc_init() {
    cout << "Worker initialized" << endl;
    return 0;
  }

  void * svc(void * in) {
    int *i = ((int *) in);
    int ii = *i;
    *i--;
    cout << "WorkerMinus got " << ii << " and computed " << *i << endl ;
    return in;
  }
};

class my_loadbalancer: public ff_loadbalancer {
public:
    // this is necessary because ff_loadbalancer has non default parameters....
    my_loadbalancer(int max_num_workers):ff_loadbalancer(max_num_workers) {}

    void broadcast(void * task) {
        ff_loadbalancer::broadcast_task(task);
    }
};

class Emitter: public ff_node {
public:
    Emitter(my_loadbalancer * const lb):lb(lb) {}
    void * svc(void * task) {
        lb->broadcast(task);
        return GO_ON;
    }
private:
    my_loadbalancer * lb;
};

class Collector: public ff_node {
public:
    Collector(int i) {}
    void * svc(void * task) {
        cout << "Got result " << * ((int *) task) << endl;
        return GO_ON;
    }


};

```

```


#define NW 2

int main(int argc, char * argv[])
{
  ffTime(START_TIME);

  cout << "init " << argc  << endl;
  int nw = (argc==1 ? NW : atoi(argv[1]));

  cout << "using " << nw << " workers " << endl;

  // init input (fake)
  for(int i=0; i<MAX; i++) {
    x[i] = (i*10);
  }
  cout << "Setting up farm" << endl;
    // create the farm object
    ff_farm<my_loadbalancer> farm(true,nw);
    // create and add emitter object to the farm
    Emitter E(farm.getlb());
    farm.add_emitter(&E);
  cout << "emitter ok "<< endl;


  std::vector<ff_node *> w;   // prepare workers
  w.push_back(new WorkerPlus);
  w.push_back(new WorkerMinus);
  farm.add_workers(w);        // add them to the farm
  cout << "workers ok "<< endl;

    Collector C(1);
    farm.add_collector(&C);
  cout << "collector ok "<< endl;

  farm.run_then_freeze();     // run farm asynchronously

  cout << "Sending tasks ..." << endl;
  int tasks[MAX];
  for(int i=0; i<MAX; i++) {
     tasks[i]=i;
     farm.offload((void *) &tasks[i]);
  }
  farm.offload((void *) FF_EOS);

  cout << "Waiting termination" << endl;
  farm.wait();

  cout << "Farm terminated after computing for " << farm.
```

```
        ffTime() << endl;

    ffTime(STOP_TIME);
    cout << "Spent overall " << ffTime(GET_TIME) << endl;

}
```

ffsrc/ff_misd.cpp

At lines 44-52 a `ff_loadbalancer` is defined providing a `broadcast` method. The method is implemented in terms of an `ff_loadbalancer` internal method. This new loadbalancer class is used as in the case of other user defined schedulers (see Sec. 8.3) and the emitter eventually uses the load balancer `broadcast` method *instead* of delivering the task to the output stream (i.e. directly to the string of the workers). This is done through the `svc` code at lines 57–60.

Lines 103 and 104 are used to add two different workers to the farm.

The rest of the program is standard, but for the fact the resulting farm is used as an accelerator (lines 112–123, see Sec. 9).

8.3.2 Using autoscheduling

FastFlow provides suitable tools to implement farms with "auto scheduling", that is farms where the workers "ask" for something to be computed rather than accepting tasks sent by the emitter (explicit or implicit) according to some scheduling policy. This scheduling behaviour may be simply implemented by using the `ff_farm` method `set_scheduling_ondemand()`, as follows:

```
ff_farm myFarm(...);
myFarm.set_scheduling_ondemand();
...
farm.add_emitter(...);
...
```

The scheduling policy implemented in this case is an approximation of the auto scheduling, indeed. The emitter simply checks the length of the SPSC queues connecting the emitter to the workers, and delivers the task to the first worker whose queue length is less or equal to 1. To be more precise, FastFlow should have implemented a request queue where the workers may write tasks requests tagged with the worker id and the emitter may read such request to choose the worker where the incoming tasks is to be directed. This is not possible as of FastFlow 1.1 because it still doesn't allow to read from multiple SPSC queues preserving the FIFO order.

9 FastFlow as a software accelerator

Up to know we just showed how to use FastFlow to write a "complete skeleton application", that is an application whose complete flow of control is defined

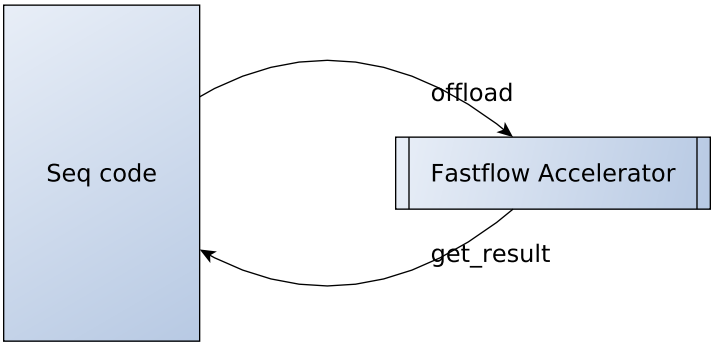


Figure 2: FastFlow accelerator

through skeletons. In this case the `main` of the C/C++ program written by the user is basically providing the structure of the parallel application by defining a proper FastFlow skeleton nesting and the commands to start the computation of the skeleton program and to wait its termination. All the business logic of the application is embedded in the skeleton parameters.

Now we want to discuss the second kind of usage which is supported by FastFlow, namely FastFlow accelerator mode. The term "accelerator" is used the way it used when dealing with hardware accelerators. An hardware accelerator–a GPU or an FPGA or even a more "general purpose" accelerator such as Tilera 64 core chips, Intel Many Core or IBM WireSpeed/PowerEN–is a device that can be used to compute particular kind of code faster that the CPU. FastFlow accelerator is a software device that can be used to speedup skeleton structured portions of code using the cores left unused by the main application. In other words, it's a way FastFlow supports to accelerate particular computation by using a skeleton program and offloading to the skeleton program tasks to be computed.

The FastFlow accelerator will use $n-1$ cores of the n core machine, assuming that the calling code is not parallel and will try to ensure a $n-1$ fold speedup is achieved in the computation of the tasks offloaded to the accelerator, provide a sufficient number of tasks are given to be computed.

Using FastFlow accelerator mode is not too much different from using FastFlow to write an application only using skeletons (see Fig. 2). In particular, the following steps must be followed:

- A skeleton program has to be written, using the FastFlow skeletons (or their customized versions), computing the tasks that will be given to the accelerator. The skeleton program used to program the accelerator is supposed to have an input stream, used to offload the tasks to the accelerator.

- Then, the skeleton program must be run using a particular method, different from the `run_and_wait_end` we have already seen, that is a `run_then_freeze()` method. This method will start the accelerator

skeleton program, consuming the input stream items to produce either output stream items or to consolidate (partial) results in memory. When we want to stop the accelerator, we will deliver and end-of-stream mark to the input stream.

- Eventually, we must wait the computation of the accelerator is terminated.

A simple program using FastFlow accelerator mode is shown below:

```
#include <vector>
#include <iostream>
#include <ff/farm.hpp>
#include <time.h>

using namespace ff;

int * x;
int nworkers = 0;

class Worker: public ff_node {
public:

  Worker(int i) {
    my_id = i;
  }

  void * svc(void * task) {
    int * t = (int *)task;
    x[my_id] = *t;
    return GO_ON;
  }
private:
  int my_id;
};

int main(int argc, char * argv[]) {

  if (argc<3) {
    std::cerr << "use: "
        << argv[0]
        << " nworkers streamlen\n";
    return -1;
  }

  nworkers=atoi(argv[1]);
  int streamlen=atoi(argv[2]);

  x = (int *) calloc(nworkers,sizeof(int));
  for(int i=0; i<nworkers; i++)
    x[i] = 0;

```

```
43    ff_farm<> accelerator(true);
44
45    std::vector<ff_node *> w;
46    for(int i=0;i<nworkers;++i)
47      w.push_back(new Worker(i));
48    accelerator.add_workers(w);
49
50    if (accelerator.run_then_freeze()<0) {
51      error("running farm\n");
52      return -1;
53    }
54
55    for(int i=0; i<=streamlen; i++) {
56      int * task = new int(i);
57      accelerator.offload(task);
58    }
59    accelerator.offload((void *) FF_EOS);
60    accelerator.wait();
61
62    for(int i=0; i<nworkers; i++)
63      std::cout << i << ":" << x[i] << std::endl;
64
65    return 0;
66  }
```

ffsrc/acc.cpp

We use a farm accelerator. The accelerator is declared at line 43. The "true" parameter is the one telling FastFlow this has to be used as an accelerator. Workers are added at lines 45–48. Each worker is given its id as a constructor parameters. This is the same as the code in plain FastFlow applications. Line 50 starts the skeleton code in accelerator mode. Lines 55 to 58 offload tasks to be computed to the accelerator. These lines could be part of any larger C++ program, indeed. The idea is that whenever we have a task ready to be submitted to the accelerator, we simply "offload" it to the accelerator. When we have no more tasks to offload, we send and end-of-stream (line 59) and eventually we wait for the completion of the computation of tasks in the accelerator (line 60).

This kind of interaction with an accelerator not having an output stream is intended to model those computations than consolidate results directly in memory. In fact, the `Worker` code actually writes results into specific position of the vector `x`. Each worker writes the task it receives in the i-th position of the vector, being i the index of the worker in the farm worker string. As each worker writes a distinct position in the vector, no specific synchronization is needed to access vector positions. Eventually the last task received by worker i will be stored at position i in the vector.

We can also assume that results are awaited from the accelerator through its output stream. In this case, we first have to write the skeleton code of the accelerator in such a way an output stream is supported. In the new version the

accelerator sample program below, we add a collector to the accelerator farm (line 45). The collector is defined as just collecting results from workers and delivering the results to the output stream (lines 18–24). Once the tasks have been offloaded to the accelerator, rather waiting for accelerator completion, we can ask computed results as delivered to the accelerator output stream through the `bool load_result(void **)` method (see lines 59–61).

```
1  #include <vector>
2  #include <iostream>
3  #include <ff/farm.hpp>
4  #include <time.h>
5
6  using namespace ff;
7
8  class Worker: public ff_node {
9  public:
10
11   void * svc(void * task) {
12     int * t = (int *)task;
13     (*t)++;
14     return task;
15   }
16 };
17
18 class Collector: public ff_node {
19 public:
20     void * svc(void * task) {
21         int * t = (int *)task;
22         return task;
23     }
24 };
25
26
27 int main(int argc, char * argv[]) {
28
29   if (argc<3) {
30     std::cerr << "use: "
31         << argv[0]
32         << " nworkers streamlen\n";
33     return -1;
34   }
35
36   int nworkers=atoi(argv[1]);
37   int streamlen=atoi(argv[2]);
38
39   ff_farm<> accelerator(true);
40
41   std::vector<ff_node *> w;
42   for(int i=0;i<nworkers;++i)
43     w.push_back(new Worker());
```

```
  accelerator.add_workers(w);
  accelerator.add_collector(new Collector());

  if (accelerator.run_then_freeze()<0) {
    error("running farm\n");
    return -1;
  }

  for(int i=0; i<=streamlen; i++) {
    int * task = new int(i);
    accelerator.offload(task);
  }
  accelerator.offload((void *) FF_EOS);

  void * result;
  while(accelerator.load_result(&result)) {
    std::cout << "Got result :: "<<  (*((int *)result)) << std
        ::endl;
  }
  accelerator.wait();

  return 0;
}
```

ffsrc/accColl.cpp

The `bool load_result(void **)` methods synchronously await for one item being delivered on the accelerator output stream. If such item is available, the method returns "true" and stores the item pointer in the parameter. If no other items will be available, the method returns "false".

An asynchronoud method is also available `bool load_results_nb(void **)`. In this case, if no result is available at the moment, the method returns a "false" value, and you should retry later on to see whether a result may be retrieved.

10 Skeleton nesting

In FastFlow skeletons may be arbitrarily nested. As the current version only supports farm and pipeline skeletons, this means that:

- farms may be used as pipeline stages, and
- pipelines may be used as farm workers.

There are no limitations to nesting, but the following one :

- skeletons using the `wrap_around` facility (see also Sec. 11) cannot be used as parameters of other skeletons.

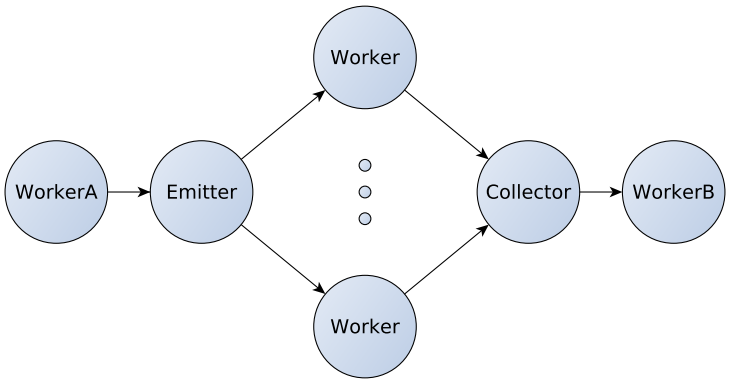
  As an example, you can define a farm with pipeline workers as follows:

```
ff_farm<> myFarm;

std::vector<ff_node *> w;
for(int i=0; i<NW; i++)
  ff_pipeline * p = new ff_pipeline;
  p->add_stage(new S1());
  p->add_stage(new S2());
  w.push_back(p);
}
myFarm.addWorkers(w);
```

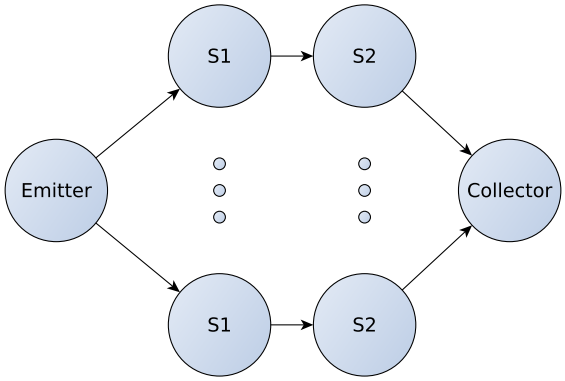
or we can use a farm as a pipeline stage by using a code such as:

```
ff_pipeline * p = new ff_pipeline;
ff_farm <>     f = new ff_farm;

...

f.addWorkers(w);

...

p->add_stage(new SeqWorkerA());
p->add_stage(f);
p->add_stage(new SeqWorkerB());
```

The concurrent activity graph in this case will be the following one:



while in the former case it will be such as



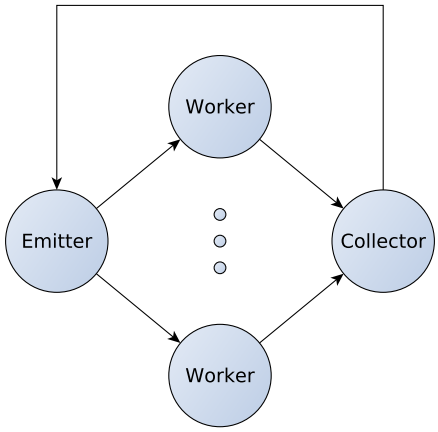
11 Feedback channels

In some cases, it will be useful to have the possibility to route back some results to the streaming network input stream. As an example, this allows to implement divide and conquer using farms. Task injected in the farm are split by the workers and the resulting splitted tasks are routed back to the input stream for further processing. Tasks that can be computed using the base case code, are computed instead and their results are used for the conquer phase, usually performed in memory.

All what's needed to implement the feedback channel is to invoke the `wrap_around` method on the interested skeleton. In case our applications uses a farm pattern as the outermost skeleton, we may therefore add the method call after instantiating the farm object:

```
ff_farm<> myFarm;
...
myFarm.add_emitter(&e);
myFarm.add_collector(&c);
myFarm.add_workers(w);

myFarm.wrap_aroud();
...
```

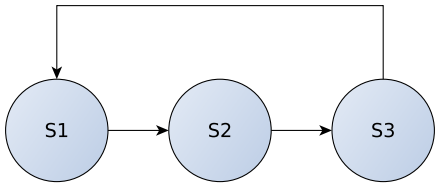
and this will lead to the concurrent activity graph



The same if parallelism is expressed by using a pipeline as the outermost skeleton:

```
ff_pipeline myPipe;

myPipe.add_stage(s1);
myPipe.add_stage(s2);
myPipe.add_stage(s3);
...
myPipe.wrap_around();
...
```

leading to the concurrent activity graph:



As of FastFlow 1.1, the only possibility to use the feedback channel provided by the `wrap_around` method is relative to the outermost skeleton, that is the one with no input stream. This because at the moment FastFlow does not support merging of input streams. In future versions this constrain will be possibly eliminated.

12 Introducing new skeletons

Current version of FastFlow (1.1) only supports stream parallel pipeline and farm skeletons. However, the skeletons themselves may be used/customized to serve as "implementation templates"[7] for different kinds of skeletons. The

[7] according to the terminology used in the algorithmic skeleton community

FastFlow distribution already includes sample applications where the farm with feedback is used to support divide&conquer applications. Here we want to discuss how a data parallel *map* skeleton may be used in FastFlow, exploiting the programmability of farm skeleton emitter and collector.

12.1 Implementing a Map skeleton with a Farm "template"

In a pure map pattern all the items in a collection are processed by means of a function f. If the collection was

$$x = \langle x_1, \ldots, x_m \rangle$$

then the computation

$$map\ f\ x$$

will produce as a result

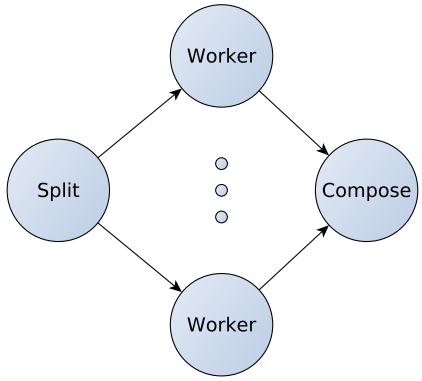
$$\langle f(x_1), \ldots, f(x_m) \rangle$$

In more elaborated map skeletons, the user is allowed to define a set of (possibly overlapping) partitions of the input collection, a function to be applied on each one of the partitions, and a strategy to rebuild–from the partial results computed on the partitions–the result of the map.

As an example, a matrix multiplication may be programmed as a map such that:

- the input matrixes A and B are considered as collections of rows and columns, respectively
- a set of items $\langle A_{i,*}, B_{*,j} \rangle$–the $i-th$ row of A and the $j-th$ column of B–are used to build the set of partitions
- an inner product is computed on each $\langle A_{i,*}, B_{*,j} \rangle$: this is $c_{i,j}$ actually
- the C matrix ($C = A \times B$) is computed out of the different $c_{i,j}$.

If we adopt this second, more general approach, a map may be build implementing a set of concurrent activities such as:



where the `Split` node create the partitions and delivers them to the workers, the workers compute each $c_{i,j}$ and deliver the results to the `Compose`. The `Compose` eventually rebuilds the full C out of the n^2 $c_{i,j}$.

We can therefore program the whole map as a FastFlow farm. After defining proper task, subtask and partial result data structures:

```
// a task requires to compute the matrix multiply C = A x B
// we assume square matrixes, for the sake of simplicity
typedef struct {
  int n;
  float **a;
  float **b;
  float **c;
  int tag;    // used to gather partial results from the same task
} TASK;

// a subtask is the computation of the inner product or A, row i, by B, col j
typedef struct {
  int i,j;
  TASK * t;
} SUBTASK;

// a partial result is the i,j item in the result matrix
typedef struct {
  int i,j;
  float x;
  TASK * t;
} PART_RESULT;
```

we define the emitter to be used in the farm as follows:

```
// this node is used to generate the task list out of the initial data
// kind of user defined iterator over tasks
class Split: public  ff_node {
   void * svc(void * t) {
     TASK * task = (TASK *) t;     // tasks come in already allocated
     for(int i=0; i<task->n; i++)
       for(int j=0; j< task->n; j++)  {
         // SUBTASKe are allocated in the splitter and destroyed in the worker
         SUBTASK * st = (SUBTASK *) calloc(1,sizeof(SUBTASK));
         st->i = i;
         st->j = j;
         st->t = task;
         ff_send_out((void *)st);
```

```
        }
      return GO_ON;
    }
};
```

Basically, the first time the emitter is called, we generate all the tasks relative to the different $\langle A_{i,*}, B_{*,j} \rangle$. These tasks are directed to the workers, that will compute the different $c_{i,j}$ and direct the `PART_RESULT` to the collector. The worker `ff_node` will therefore be programmed as:

```
class Worker: public ff_node {
public:

    void * svc(void * task) {
        SUBTASK * t = (SUBTASK *) task;
        float * x = new float(0.0);
        for(int k=0; k<(t->t)->n; k++) {
          *x = *x + (t->t->a)[t->i][k] * (t->t->b)[k][t->j];
        }
        // prepare the partial result to be delivered
        PART_RESULT * pr = (PART_RESULT *) calloc(1,sizeof(
            PART_RESULT));
        pr->i = t->i;
        pr->j = t->j;
        pr->t = t->t;
        pr->x = *x;
        // the subtask is no more useful, deallocate it
        free(task);
        // return the partial result
        return pr;
    }
};
```

The collector will be defined in such a way the different partial results computed by the workers are eventually consolidated in memory. Therefore each $c_{i,j}$ received is stored at the correct entry of the C matrix. The pointer of the result matrix is in fact a field in the `TASK` data strcuture and $c_{i,j}$, i and j are fields of teh `PART_RESULT` data structure. The code for the collector is therefore:

```
class Compose: public ff_node {
public:
   Compose() {
     n = 0;
     for(int i=0; i<MAXDIFF; i++)
       tags[i] = 0;
   }

   void * svc(void * t) {
```

```
    PART_RESULT * r = (PART_RESULT *) t;
    TASK * tt = r->t;
    // consolidate result in memory
    ((r->t)->c)[r->i][r->j] = r->x;
    tags[((r->t)->tag)%MAXDIFF]++;
    if(tags[((r->t)->tag)%MAXDIFF] == ((r->t)->n)*((r->t)->n)) {
      tags[((r->t)->tag)%MAXDIFF]  = 0;
      free(t);
      return(tt);
    } else {
      free(t);
      return GO_ON;
    }
  }
private:
  int n;
  int tags[MAXDIFF];
};
```

The tags here are used to deliver a result on the farm output stream (i.e. the output stream of the collector) when exactly n^2 results relative to the same input task have been received by the collector. A `MAXDIFF` value is used assuming that no more than `MAXDIFF` different matrix multiplication tasks may be circulating at the same time in the farm, due to variable time spent in the computation of the single $c_{i,j}$.

With these classes, our map may be programmed as follows:

```
    ff_farm<> farm(true);

    farm.add_emitter(new Split());        // add the splitter emitter
    farm.add_collector(new Compose());    // add the composer collector
    std::vector<ff_node *> w;             // add the convenient # of workers
    for(int i=0;i<nworkers;++i)
        w.push_back(new Worker);
    farm.add_workers(w);
```

It is worth pointing out that:

- the kind of knowledge required to write the `Split` and `Compose` nodes to the application programmer is very application specific and not too much related to the implementation of the map
- this implementation of the map transforms a data parallel pattern into a stream parallel one. Some overhead is paid to move the data parallel

sub-tasks along the streams used to implement the farm. This overhead may be not completely negligible

- a much coarser grain implementation could have been designed assuming that the `Split` node outputs tasks representing the computation of a whole $C_{i,*}$ row and modifying accordingly the `Worker`.
- usually, the implementation of a map data parallel pattern generates as many subtasks as the amount of available workers. In our implementation, we could have left to the `Split` node this task, using the FastFlow primitive mechanisms to retrieve the number of workers actually allocated to the farm[8] and modifying accordingly both the `Worker` and the `Compose` code.

Also, the proposed implementation for the map may be easily encapsulated in a proper `ff_map` class:

```
class ff_map {
public:

  // map constructor
  // takes as parameters: the splitter,
  // the string of workers and the result rebuilder

  ff_map(ff_node * splt, std::vector<ff_node *> wrks, ff_node
      * cmps) {

      exec.add_emitter(splt);      // add the splitter emitter
      exec.add_collector(cmps);    // add the composer
          collector
      exec.add_workers(wrks);      // add workers
  }

    operator ff_node*() {          // (re)define what's
        returned when
    return (ff_node*)&exec;        // asking a pointer to the
        class object
    }

private:
  ff_farm<> exec;                  // this is the farm actually
      used to compute
};
```

With this definition, the user could have defined the map (and added the map stage to a pipeline) using the following code:

[8] this is the `getnworkers` method of the farm loadbalancer.

```
std::vector<ff_node *> w;
for(int i=0;i<nworkers;++i)
  w.push_back(new Worker);
ff_map myMap(new Split(), w, new Compose());

...

myPipe.add_stage(myMap);
```

13 Performance

Up to now we only discussed how to use FastFlow to build parallel programs, either applications completely coded with skeletons, or FastFlow software accelerators. We want to shortly discuss here the typical performances improvements got through FastFlow.

In skeleton application or in software accelerator, using a FastFlow farm would in general lead to a performance increase proportional to the number of workers used (that is to the parallelism degree of the farm). This unless:

- we introduce serial code fragments–in this case the speedup will be limited according to the Amdahl law–or
- we use more workers than the available tasks
- or eventually the time spent to deliver a task to be computed to the worker and retrieving a result from the worker are higher than the computation time of the task.

This means that if the time spent to compute m tasks serially is T_{seq}, we can expect the time spent computing the same m tasks with an nw worker farm will be more or less $\frac{T_{seq}}{nw}$. It is worth pointing out here that the *latency* relative to the computation of the single task does not decrease w.r.t. the sequential case.

In case a k stage FastFlow pipeline is used to implement a parallel computation, we may expect the overall service time of the pipeline is

$$T_S = max\{T_{S_1}, \ldots, T_{S_k}\}$$

As a consequence, the time spent computing m tasks is approximately $m \times T_S$ and the relative speedup may be quantified as

$$\frac{m \times \sum_{i=1}^{k} T_{S_i}}{m \times max\{T_{S_1}, \ldots, T_{S_k}\}} = \frac{\sum_{i=1}^{k} T_{S_i}}{max\{T_{S_1}, \ldots, T_{S_k}\}}$$

In case of balanced stages, that is pipeline stages all taking the same time to compute a task, this speedup may be approximated as k, being

$$\sum_{i=1}^{k} T_{S_i} = k \times T_{S_1}$$

and

$$max\{T_{S_1}, \ldots, T_{S_k}\} = T_{S_1}$$

14 Run time routines

Several utility routines are defined in FastFlow. We recall here the main ones.

- `virtual int  get_my_id()`
  returns a virtual id of the node where the concurrent activity (its `svc` method) is being computed
- `const int ff_numCores()`
  returns the number of cores in the target architecture
- `int ff_mapThreadToCpu(int cpu_id, int priority_level=0)`
  pins the current thread to `cpu_id`. A priority may be set as well, but you need root rights in general, and therefore this should non be specified by normal users
- `void error(const char * str, ...)`
  is used to print error messages
- `virtual bool ff_send_out(void * task,`
  `unsigned intretry=((unsigned int)-1),`
  `unsigned int ticks=(TICKS2WAIT))`
  delivers an item onto the output stream, possibly retrying upon failre a given number of times, after waiting a given number of clock ticks.
- `double ffTime()`
  returns the time spent in the computation of a farm or of pipeline, including the `svc_init` and `svc_end` time. This is method of both classes pipeline and farm.
- `double ffwTime()`
  returns the time spent in the computation of a farm or of pipeline, in the `svc` method only.
- `double ffTime(int tag)`
  is used to measure time in portions of code. The `tag` may be: `START_TIME`, `STOP_TIME` or `GET_TIME`
- `void ffStats(std::ostream & out)`
  prints the statistics collected while using FastFlow. The program must be compiled with `TRACE_FASTFLOW` defined, however.

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