StarPU Handbook

for StarPU 1.0.0rc4

Table of Contents

Preface

This manual documents the usage of StarPU version 1.0.0rc4. It was last updated on 21 March 2012.

1 Introduction to StarPU

1.1 Motivation

The use of specialized hardware such as accelerators or coprocessors offers an interesting approach to overcome the physical limits encountered by processor architects. As a result, many machines are now equipped with one or several accelerators (e.g. a GPU), in addition to the usual processor(s). While a lot of efforts have been devoted to offload computation onto such accelerators, very little attention as been paid to portability concerns on the one hand, and to the possibility of having heterogeneous accelerators and processors to interact on the other hand.

StarPU is a runtime system that offers support for heterogeneous multicore architectures, it not only offers a unified view of the computational resources (i.e. CPUs and accelerators at the same time), but it also takes care of efficiently mapping and executing tasks onto an heterogeneous machine while transparently handling low-level issues such as data transfers in a portable fashion.

1.2 StarPU in a Nutshell

StarPU is a software tool aiming to allow programmers to exploit the computing power of the available CPUs and GPUs, while relieving them from the need to specially adapt their programs to the target machine and processing units.

At the core of StarPU is its run-time support library, which is responsible for scheduling application-provided tasks on heterogeneous CPU/GPU machines. In addition, StarPU comes with programming language support, in the form of extensions to languages of the C family (see Chapter 11 [C Extensions], page 69), as well as an OpenCL front-end (see Chapter 12 [SOCL OpenCL Extensions], page 75).

StarPU's run-time and programming language extensions support a *task-based programming model*. Applications submit computational tasks, with CPU and/or GPU implementations, and StarPU schedules these tasks and associated data transfers on available CPUs and GPUs. The data that a task manipulates are automatically transferred among accelerators and the main memory, so that programmers are freed from the scheduling issues and technical details associated with these transfers.

StarPU takes particular care of scheduling tasks efficiently, using well-known algorithms from the literature (see Section 6.5 [Task scheduling policy], page 44). In addition, it allows scheduling experts, such as compiler or computational library developers, to implement custom scheduling policies in a portable fashion (see Section 14.6.1 [Scheduling Policy API], page 124).

The remainder of this section describes the main concepts used in StarPU.

1.2.1 Codelet and Tasks

One of the StarPU primary data structures is the **codelet**. A codelet describes a computational kernel that can possibly be implemented on multiple architectures such as a CPU, a CUDA device or a Cell's SPU.

Another important data structure is the **task**. Executing a StarPU task consists in applying a codelet on a data set, on one of the architectures on which the codelet is implemented. A task thus describes the codelet that it uses, but also which data are accessed, and how they are accessed during the computation (read and/or write). StarPU tasks are asynchronous: submitting a task to StarPU is a non-blocking operation. The task structure can also specify a **callback** function that is called once StarPU has properly executed the task. It also contains optional fields that the application may use to give hints to the scheduler (such as priority levels).

By default, task dependencies are inferred from data dependency (sequential coherence) by StarPU. The application can however disable sequential coherency for some data, and dependencies be expressed by hand. A task may be identified by a unique 64-bit number chosen by the application which we refer as a **tag**. Task dependencies can be enforced by hand either by the means of callback functions, by submitting other tasks, or by expressing dependencies between tags (which can thus correspond to tasks that have not been submitted yet).

1.2.2 StarPU Data Management Library

Because StarPU schedules tasks at runtime, data transfers have to be done automatically and "just-in-time" between processing units, relieving the application programmer from explicit data transfers. Moreover, to avoid unnecessary transfers, StarPU keeps data where it was last needed, even if was modified there, and it allows multiple copies of the same data to reside at the same time on several processing units as long as it is not modified.

1.2.3 Glossary

A **codelet** records pointers to various implementations of the same theoretical function.

A **memory node** can be either the main RAM or GPU-embedded memory.

A **bus** is a link between memory nodes.

A **data handle** keeps track of replicates of the same data (**registered** by the application) over various memory nodes. The data management library manages keeping them coherent.

The **home** memory node of a data handle is the memory node from which the data was registered (usually the main memory node).

A **task** represents a scheduled execution of a codelet on some data handles.

A **tag** is a rendez-vous point. Tasks typically have their own tag, and can depend on other tags. The value is chosen by the application.

A **worker** execute tasks. There is typically one per CPU computation core and one per accelerator (for which a whole CPU core is dedicated).

A **driver** drives a given kind of workers. There are currently CPU, CUDA, OpenCL and Gordon drivers. They usually start several workers to actually drive them.

A **performance model** is a (dynamic or static) model of the performance of a given codelet. Codelets can have execution time performance model as well as power consumption performance models.

A data **interface** describes the layout of the data: for a vector, a pointer for the start, the number of elements and the size of elements ; for a matrix, a pointer for the start, the number of elements per row, the offset between rows, and the size of each element ; etc. To

access their data, codelet functions are given interfaces for the local memory node replicates of the data handles of the scheduled task.

Partitioning data means dividing the data of a given data handle (called **father**) into a series of **children** data handles which designate various portions of the former.

A **filter** is the function which computes children data handles from a father data handle, and thus describes how the partitioning should be done (horizontal, vertical, etc.)

Acquiring a data handle can be done from the main application, to safely access the data of a data handle from its home node, without having to unregister it.

1.2.4 Research Papers

Research papers about StarPU can be found at

`http://runtime.bordeaux.inria.fr/Publis/Keyword/STARPU.html`

Notably a good overview in the research report

`http://hal.archives-ouvertes.fr/inria-00467677`

2 Installing StarPU

StarPU can be built and installed by the standard means of the GNU autotools. The following chapter is intended to briefly remind how these tools can be used to install StarPU.

2.1 Downloading StarPU

2.1.1 Getting Sources

The latest official release tarballs of StarPU sources are available for download from `https://gforge.inria.fr/frs/?group_id=1570`.

The latest nightly development snapshot is available from `http://starpu.gforge.inria.fr/testing/`.

```
% wget http://starpu.gforge.inria.fr/testing/starpu-nightly-latest.tar.gz
```

Additionally, the code can be directly checked out of Subversion, it should be done only if you need the very latest changes (i.e. less than a day!).[1].

```
% svn checkout svn://scm.gforge.inria.fr/svn/starpu/trunk
```

2.1.2 Optional dependencies

The topology discovery library, `hwloc`, is not mandatory to use StarPU but strongly recommended. It allows to increase performance, and to perform some topology aware scheduling.

`hwloc` is available in major distributions and for most OSes and can be downloaded from `http://www.open-mpi.org/software/hwloc`.

2.2 Configuration of StarPU

2.2.1 Generating Makefiles and configuration scripts

This step is not necessary when using the tarball releases of StarPU. If you are using the source code from the svn repository, you first need to generate the configure scripts and the Makefiles. This requires the availability of `autoconf`, `automake` >= 2.60, and `makeinfo`.

```
% ./autogen.sh
```

2.2.2 Running the configuration

```
% ./configure
```

Details about options that are useful to give to `./configure` are given in Section 15.1 [Compilation configuration], page 129.

2.3 Building and Installing StarPU

2.3.1 Building

```
% make
```

[1] The client side of the software Subversion can be obtained from `http://subversion.tigris.org`. If you are running on Windows, you will probably prefer to use TortoiseSVN from `http://tortoisesvn.tigris.org/`

2.3.2 Sanity Checks

In order to make sure that StarPU is working properly on the system, it is also possible to run a test suite.

```
% make check
```

2.3.3 Installing

In order to install StarPU at the location that was specified during configuration:

```
% make install
```

Libtool interface versioning information are included in libraries names (libstarpu-1.0.so, libstarpumpi-1.0.so and libstarpufft-1.0.so).

3 Using StarPU

3.1 Setting flags for compiling and linking applications

Compiling and linking an application against StarPU may require to use specific flags or libraries (for instance `CUDA` or `libspe2`). To this end, it is possible to use the `pkg-config` tool.

If StarPU was not installed at some standard location, the path of StarPU's library must be specified in the `PKG_CONFIG_PATH` environment variable so that `pkg-config` can find it. For example if StarPU was installed in `$prefix_dir`:

```
% PKG_CONFIG_PATH=$PKG_CONFIG_PATH:$prefix_dir/lib/pkgconfig
```

The flags required to compile or link against StarPU are then accessible with the following commands[1]:

```
% pkg-config --cflags starpu-1.0  # options for the compiler
% pkg-config --libs starpu-1.0    # options for the linker
```

Also pass the `--static` option if the application is to be linked statically.

3.2 Running a basic StarPU application

Basic examples using StarPU are built in the directory `examples/basic_examples/` (and installed in `$prefix_dir/lib/starpu/examples/`). You can for example run the example `vector_scal`.

```
% ./examples/basic_examples/vector_scal
BEFORE: First element was 1.000000
AFTER: First element is 3.140000
%
```

When StarPU is used for the first time, the directory `$STARPU_HOME/.starpu/` is created, performance models will be stored in that directory (`STARPU_HOME` defaults to `$HOME`)

Please note that buses are benchmarked when StarPU is launched for the first time. This may take a few minutes, or less if `hwloc` is installed. This step is done only once per user and per machine.

3.3 Kernel threads started by StarPU

StarPU automatically binds one thread per CPU core. It does not use SMT/hyperthreading because kernels are usually already optimized for using a full core, and using hyperthreading would make kernel calibration rather random.

Since driving GPUs is a CPU-consuming task, StarPU dedicates one core per GPU

While StarPU tasks are executing, the application is not supposed to do computations in the threads it starts itself, tasks should be used instead.

TODO: add a StarPU function to bind an application thread (e.g. the main thread) to a dedicated core (and thus disable the corresponding StarPU CPU worker).

[1] It is still possible to use the API provided in the version 0.9 of StarPU by calling `pkg-config` with the `libstarpu` package. Similar packages are provided for `libstarpumpi` and `libstarpufft`.

3.4 Enabling OpenCL

When both CUDA and OpenCL drivers are enabled, StarPU will launch an OpenCL worker for NVIDIA GPUs only if CUDA is not already running on them. This design choice was necessary as OpenCL and CUDA can not run at the same time on the same NVIDIA GPU, as there is currently no interoperability between them.

To enable OpenCL, you need either to disable CUDA when configuring StarPU:

```
% ./configure --disable-cuda
```

or when running applications:

```
% STARPU_NCUDA=0 ./application
```

OpenCL will automatically be started on any device not yet used by CUDA. So on a machine running 4 GPUS, it is therefore possible to enable CUDA on 2 devices, and OpenCL on the 2 other devices by doing so:

```
% STARPU_NCUDA=2 ./application
```

4 Basic Examples

4.1 Compiling and linking options

Let's suppose StarPU has been installed in the directory `$STARPU_DIR`. As explained in Section 3.1 [Setting flags for compiling and linking applications], page 9, the variable `PKG_CONFIG_PATH` needs to be set. It is also necessary to set the variable `LD_LIBRARY_PATH` to locate dynamic libraries at runtime.

```
% PKG_CONFIG_PATH=$STARPU_DIR/lib/pkgconfig:$PKG_CONFIG_PATH
% LD_LIBRARY_PATH=$STARPU_DIR/lib:$LD_LIBRARY_PATH
```

The Makefile could for instance contain the following lines to define which options must be given to the compiler and to the linker:

```
CFLAGS          +=      $$(pkg-config --cflags starpu-1.0)
LDFLAGS         +=      $$(pkg-config --libs starpu-1.0)
```

Make sure that `pkg-config --libs starpu-1.0` actually produces some output before going further: `PKG_CONFIG_PATH` has to point to the place where `starpu-1.0.pc` was installed during `make install`.

Also pass the `--static` option if the application is to be linked statically.

4.2 Hello World

This section shows how to implement a simple program that submits a task to StarPU. You can either use the StarPU C extension (see Chapter 11 [C Extensions], page 69) or directly use the StarPU's API.

4.2.1 Hello World using the C Extension

GCC from version 4.5 permit to use the StarPU GCC plug-in (see Chapter 11 [C Extensions], page 69). This makes writing a task both simpler and less error-prone. In a nutshell, all it takes is to declare a task, declare and define its implementations (for CPU, OpenCL, and/or CUDA), and invoke the task like a regular C function. The example below defines `my_task`, which has a single implementation for CPU:

```
/* Task declaration.  */
static void my_task (int x) __attribute__ ((task));

/* Declaration of the CPU implementation of 'my_task'.  */
static void my_task_cpu (int x)
   __attribute__ ((task_implementation ("cpu", my_task)));

/* Definition of said CPU implementation.  */
static void my_task_cpu (int x)
{
  printf ("Hello, world!  With x = %d\n", x);
}

int main ()
{
  /* Initialize StarPU.  */
#pragma starpu initialize

  /* Do an asynchronous call to 'my_task'.  */
  my_task (42);

  /* Wait for the call to complete.  */
#pragma starpu wait

  /* Terminate.  */
#pragma starpu shutdown

  return 0;
}
```

The code can then be compiled and linked with GCC and the `-fplugin` flag:

```
$ gcc hello-starpu.c \
    -fplugin=`pkg-config starpu-1.0 --variable=gccplugin` \
    `pkg-config starpu-1.0 --libs`
```

As can be seen above, basic use the C extensions allows programmers to use StarPU tasks while essentially annotating "regular" C code.

4.2.2 Hello World using StarPU's API

The remainder of this section shows how to achieve the same result using StarPU's standard C API.

4.2.2.1 Required Headers

The `starpu.h` header should be included in any code using StarPU.

```
#include <starpu.h>
```

4.2.2.2 Defining a Codelet

```
struct params {
    int i;
    float f;
};
void cpu_func(void *buffers[], void *cl_arg)
{
    struct params *params = cl_arg;

    printf("Hello world (params = {%i, %f} )\n", params->i, params->f);
}

struct starpu_codelet cl =
{
    .where = STARPU_CPU,
    .cpu_funcs = { cpu_func, NULL },
    .nbuffers = 0
};
```

A codelet is a structure that represents a computational kernel. Such a codelet may contain an implementation of the same kernel on different architectures (e.g. CUDA, Cell's SPU, x86, ...).

The `nbuffers` field specifies the number of data buffers that are manipulated by the codelet: here the codelet does not access or modify any data that is controlled by our data management library. Note that the argument passed to the codelet (the `cl_arg` field of the `starpu_task` structure) does not count as a buffer since it is not managed by our data management library, but just contain trivial parameters.

We create a codelet which may only be executed on the CPUs. The `where` field is a bitmask that defines where the codelet may be executed. Here, the `STARPU_CPU` value means that only CPUs can execute this codelet (see Section 13.6 [Codelets and Tasks], page 95 for more details on this field). Note that the `where` field is optional, when unset its value is automatically set based on the availability of the different `XXX_funcs` fields. When a CPU core executes a codelet, it calls the `cpu_func` function, which *must* have the following prototype:

```
void (*cpu_func)(void *buffers[], void *cl_arg);
```

In this example, we can ignore the first argument of this function which gives a description of the input and output buffers (e.g. the size and the location of the matrices) since there is none. The second argument is a pointer to a buffer passed as an argument to the codelet by the means of the `cl_arg` field of the `starpu_task` structure.

Be aware that this may be a pointer to a *copy* of the actual buffer, and not the pointer given by the programmer: if the codelet modifies this buffer, there is no guarantee that the initial buffer will be modified as well: this for instance implies that the buffer cannot be used as a synchronization medium. If synchronization is needed, data has to be registered to StarPU, see Section 4.4 [Vector Scaling Using StarPu's API], page 20.

4.2.2.3 Submitting a Task

```
void callback_func(void *callback_arg)
{
    printf("Callback function (arg %x)\n", callback_arg);
}

int main(int argc, char **argv)
{
    /* initialize StarPU */
    starpu_init(NULL);

    struct starpu_task *task = starpu_task_create();

    task->cl = &cl; /* Pointer to the codelet defined above */

    struct params params = { 1, 2.0f };
    task->cl_arg = &params;
    task->cl_arg_size = sizeof(params);

    task->callback_func = callback_func;
    task->callback_arg = 0x42;

    /* starpu_task_submit will be a blocking call */
    task->synchronous = 1;

    /* submit the task to StarPU */
    starpu_task_submit(task);

    /* terminate StarPU */
    starpu_shutdown();

    return 0;
}
```

Before submitting any tasks to StarPU, `starpu_init` must be called. The `NULL` argument specifies that we use default configuration. Tasks cannot be submitted after the termination of StarPU by a call to `starpu_shutdown`.

In the example above, a task structure is allocated by a call to `starpu_task_create`. This function only allocates and fills the corresponding structure with the default settings (see Section 13.6 [Codelets and Tasks], page 95), but it does not submit the task to StarPU.

The `cl` field is a pointer to the codelet which the task will execute: in other words, the codelet structure describes which computational kernel should be offloaded on the different architectures, and the task structure is a wrapper containing a codelet and the piece of data on which the codelet should operate.

The optional `cl_arg` field is a pointer to a buffer (of size `cl_arg_size`) with some parameters for the kernel described by the codelet. For instance, if a codelet implements a computational kernel that multiplies its input vector by a constant, the constant could be specified by the means of this buffer, instead of registering it as a StarPU data. It must however be noted that StarPU avoids making copy whenever possible and rather passes the pointer as such, so the buffer which is pointed at must kept allocated until the task

terminates, and if several tasks are submitted with various parameters, each of them must be given a pointer to their own buffer.

Once a task has been executed, an optional callback function is be called. While the computational kernel could be offloaded on various architectures, the callback function is always executed on a CPU. The `callback_arg` pointer is passed as an argument of the callback. The prototype of a callback function must be:

```
void (*callback_function)(void *);
```

If the `synchronous` field is non-zero, task submission will be synchronous: the `starpu_task_submit` function will not return until the task was executed. Note that the `starpu_shutdown` method does not guarantee that asynchronous tasks have been executed before it returns, `starpu_task_wait_for_all` can be used to that effect, or data can be unregistered (`starpu_data_unregister(vector_handle);`), which will implicitly wait for all the tasks scheduled to work on it, unless explicitly disabled thanks to `starpu_data_set_default_sequential_consistency_flag` or `starpu_data_set_sequential_consistency_flag`.

4.2.2.4 Execution of Hello World

```
% make hello_world
cc $(pkg-config --cflags starpu-1.0)  $(pkg-config --libs starpu-1.0) hello_world.c -o hello_world
% ./hello_world
Hello world (params = {1, 2.000000} )
Callback function (arg 42)
```

4.3 Vector Scaling Using the C Extension

The previous example has shown how to submit tasks. In this section, we show how StarPU tasks can manipulate data. The version of this example using StarPU's API is given in the next sections.

The simplest way to get started writing StarPU programs is using the C language extensions provided by the GCC plug-in (see Chapter 11 [C Extensions], page 69). These extensions map directly to StarPU's main concepts: tasks, task implementations for CPU, OpenCL, or CUDA, and registered data buffers.

The example below is a vector-scaling program, that multiplies elements of a vector by a given factor[1]. For comparison, the standard C version that uses StarPU's standard C programming interface is given in the next section (see Section 4.4 [Vector Scaling Using StarPu's API], page 20).

First of all, the vector-scaling task and its simple CPU implementation has to be defined:

[1] The complete example, and additional examples, is available in the '`gcc-plugin/examples`' directory of the StarPU distribution.

```
/* Declare the ‘vector_scal’ task.  */

static void vector_scal (unsigned size, float vector[size],
                         float factor)
  __attribute__ ((task));

/* Declare and define the standard CPU implementation.  */

static void vector_scal_cpu (unsigned size, float vector[size],
                             float factor)
  __attribute__ ((task_implementation ("cpu", vector_scal)));

static void
vector_scal_cpu (unsigned size, float vector[size], float factor)
{
  unsigned i;
  for (i = 0; i < size; i++)
    vector[i] *= factor;
}
```

Next, the body of the program, which uses the task defined above, can be implemented:

```
int
main (void)
{
#pragma starpu initialize

#define NX     0x100000
#define FACTOR 3.14

  {
    float vector[NX] __attribute__ ((heap_allocated));

#pragma starpu register vector

    size_t i;
    for (i = 0; i < NX; i++)
      vector[i] = (float) i;

    vector_scal (NX, vector, FACTOR);

#pragma starpu wait
  } /* VECTOR is automatically freed here.  */

#pragma starpu shutdown

  return valid ? EXIT_SUCCESS : EXIT_FAILURE;
}
```

The `main` function above does several things:

- It initializes StarPU.
- It allocates *vector* in the heap; it will automatically be freed when its scope is left. Alternatively, good old `malloc` and `free` could have been used, but they are more error-prone and require more typing.
- It *registers* the memory pointed to by *vector*. Eventually, when OpenCL or CUDA

task implementations are added, this will allow StarPU to transfer that memory region between GPUs and the main memory. Removing this `pragma` is an error.

- It invokes the `vector_scal` task. The invocation looks the same as a standard C function call. However, it is an *asynchronous invocation*, meaning that the actual call is performed in parallel with the caller's continuation.

- It *waits* for the termination of the `vector_scal` asynchronous call.

- Finally, StarPU is shut down.

The program can be compiled and linked with GCC and the `-fplugin` flag:

```
$ gcc hello-starpu.c \
    -fplugin=‘pkg-config starpu-1.0 --variable=gccplugin‘ \
    ‘pkg-config starpu-1.0 --libs‘
```

And voilà!

4.3.1 Adding an OpenCL Task Implementation

Now, this is all fine and great, but you certainly want to take advantage of these newfangled GPUs that your lab just bought, don't you?

So, let's add an OpenCL implementation of the `vector_scal` task. We assume that the OpenCL kernel is available in a file, '`vector_scal_opencl_kernel.cl`', not shown here. The OpenCL task implementation is similar to that used with the standard C API (see Section 4.5.2 [Definition of the OpenCL Kernel], page 22). It is declared and defined in our C file like this:

```
/* Include StarPU's OpenCL integration.  */
#include <starpu_opencl.h>

/* The OpenCL programs, loaded from 'main' (see below).  */
static struct starpu_opencl_program cl_programs;

static void vector_scal_opencl (unsigned size, float vector[size],
                                float factor)
  __attribute__ ((task_implementation ("opencl", vector_scal)));

static void
vector_scal_opencl (unsigned size, float vector[size], float factor)
{
  int id, devid, err;
  cl_kernel kernel;
  cl_command_queue queue;
  cl_event event;

  /* VECTOR is GPU memory pointer, not a main memory pointer.  */
  cl_mem val = (cl_mem) vector;

  id = starpu_worker_get_id ();
  devid = starpu_worker_get_devid (id);

  /* Prepare to invoke the kernel.  In the future, this will be largely
     automated.  */
  err = starpu_opencl_load_kernel (&kernel, &queue, &cl_programs,
                                   "vector_mult_opencl", devid);
  if (err != CL_SUCCESS)
    STARPU_OPENCL_REPORT_ERROR (err);

  err = clSetKernelArg (kernel, 0, sizeof (val), &val);
  err |= clSetKernelArg (kernel, 1, sizeof (size), &size);
  err |= clSetKernelArg (kernel, 2, sizeof (factor), &factor);
  if (err)
    STARPU_OPENCL_REPORT_ERROR (err);

  size_t global = 1, local = 1;
  err = clEnqueueNDRangeKernel (queue, kernel, 1, NULL, &global,
                                &local, 0, NULL, &event);
  if (err != CL_SUCCESS)
    STARPU_OPENCL_REPORT_ERROR (err);

  clFinish (queue);
  starpu_opencl_collect_stats (event);
  clReleaseEvent (event);

  /* Done with KERNEL.  */
  starpu_opencl_release_kernel (kernel);
}
```

The OpenCL kernel itself must be loaded from `main`, sometime after the `initialize` pragma:

```
  starpu_opencl_load_opencl_from_file ("vector_scal_opencl_kernel.cl",
                                       &cl_programs, "");
```

And that's it. The `vector_scal` task now has an additional implementation, for OpenCL, which StarPU's scheduler may choose to use at run-time. Unfortunately, the `vector_scal_opencl` above still has to go through the common OpenCL boilerplate; in the future, additional extensions will automate most of it.

4.3.2 Adding a CUDA Task Implementation

Adding a CUDA implementation of the task is very similar, except that the implementation itself is typically written in CUDA, and compiled with `nvcc`. Thus, the C file only needs to contain an external declaration for the task implementation:

```
extern void vector_scal_cuda (unsigned size, float vector[size],
                              float factor)
  __attribute__ ((task_implementation ("cuda", vector_scal)));
```

The actual implementation of the CUDA task goes into a separate compilation unit, in a '`.cu`' file. It is very close to the implementation when using StarPU's standard C API (see Section 4.5.1 [Definition of the CUDA Kernel], page 22).

```
/* CUDA implementation of the 'vector_scal' task, to be compiled
   with 'nvcc'.  */

#include <starpu.h>
#include <starpu_cuda.h>
#include <stdlib.h>

static __global__ void
vector_mult_cuda (float *val, unsigned n, float factor)
{
  unsigned i = blockIdx.x * blockDim.x + threadIdx.x;

  if (i < n)
    val[i] *= factor;
}

/* Definition of the task implementation declared in the C file.   */
extern "C" void
vector_scal_cuda (size_t size, float vector[], float factor)
{
  unsigned threads_per_block = 64;
  unsigned nblocks = (size + threads_per_block - 1) / threads_per_block;

  vector_mult_cuda <<< nblocks, threads_per_block, 0,
    starpu_cuda_get_local_stream () >>> (vector, size, factor);

  cudaStreamSynchronize (starpu_cuda_get_local_stream ());
}
```

The complete source code, in the '`gcc-plugin/examples/vector_scal`' directory of the StarPU distribution, also shows how an SSE-specialized CPU task implementation can be added.

For more details on the C extensions provided by StarPU's GCC plug-in, See Chapter 11 [C Extensions], page 69.

4.4 Vector Scaling Using StarPu's API

This section shows how to achieve the same result as explained in the previous section using StarPU's standard C API.

The full source code for this example is given in Appendix A [Full source code for the 'Scaling a Vector' example], page 135.

4.4.1 Source Code of Vector Scaling

Programmers can describe the data layout of their application so that StarPU is responsible for enforcing data coherency and availability across the machine. Instead of handling complex (and non-portable) mechanisms to perform data movements, programmers only declare which piece of data is accessed and/or modified by a task, and StarPU makes sure that when a computational kernel starts somewhere (e.g. on a GPU), its data are available locally.

Before submitting those tasks, the programmer first needs to declare the different pieces of data to StarPU using the `starpu_*_data_register` functions. To ease the development of applications for StarPU, it is possible to describe multiple types of data layout. A type of data layout is called an **interface**. There are different predefined interfaces available in StarPU: here we will consider the **vector interface**.

The following lines show how to declare an array of `NX` elements of type `float` using the vector interface:

```
float vector[NX];

starpu_data_handle_t vector_handle;
starpu_vector_data_register(&vector_handle, 0, (uintptr_t)vector, NX,
                            sizeof(vector[0]));
```

The first argument, called the **data handle**, is an opaque pointer which designates the array in StarPU. This is also the structure which is used to describe which data is used by a task. The second argument is the node number where the data originally resides. Here it is 0 since the `vector` array is in the main memory. Then comes the pointer `vector` where the data can be found in main memory, the number of elements in the vector and the size of each element. The following shows how to construct a StarPU task that will manipulate the vector and a constant factor.

```
float factor = 3.14;
struct starpu_task *task = starpu_task_create();

task->cl = &cl;                      /* Pointer to the codelet defined below */
task->handles[0] = vector_handle;    /* First parameter of the codelet */
task->cl_arg = &factor;
task->cl_arg_size = sizeof(factor);
task->synchronous = 1;

starpu_task_submit(task);
```

Since the factor is a mere constant float value parameter, it does not need a preliminary registration, and can just be passed through the `cl_arg` pointer like in the previous example.

The vector parameter is described by its handle. There are two fields in each element of the `buffers` array. `handle` is the handle of the data, and `mode` specifies how the kernel will access the data (`STARPU_R` for read-only, `STARPU_W` for write-only and `STARPU_RW` for read and write access).

The definition of the codelet can be written as follows:

```
void scal_cpu_func(void *buffers[], void *cl_arg)
{
    unsigned i;
    float *factor = cl_arg;

    /* length of the vector */
    unsigned n = STARPU_VECTOR_GET_NX(buffers[0]);
    /* CPU copy of the vector pointer */
    float *val = (float *)STARPU_VECTOR_GET_PTR(buffers[0]);

    for (i = 0; i < n; i++)
        val[i] *= *factor;
}

struct starpu_codelet cl = {
    .where = STARPU_CPU,
    .cpu_funcs = { scal_cpu_func, NULL },
    .nbuffers = 1,
    .modes = { STARPU_RW }
};
```

The first argument is an array that gives a description of all the buffers passed in the `task->handles` array. The size of this array is given by the `nbuffers` field of the codelet structure. For the sake of genericity, this array contains pointers to the different interfaces describing each buffer. In the case of the **vector interface**, the location of the vector (resp. its length) is accessible in the `ptr` (resp. `nx`) of this array. Since the vector is accessed in a read-write fashion, any modification will automatically affect future accesses to this vector made by other tasks.

The second argument of the `scal_cpu_func` function contains a pointer to the parameters of the codelet (given in `task->cl_arg`), so that we read the constant factor from this pointer.

4.4.2 Execution of Vector Scaling

```
% make vector_scal
cc $(pkg-config --cflags starpu-1.0)  $(pkg-config --libs starpu-1.0)  vector_scal.c   -o vector_scal
% ./vector_scal
0.000000 3.000000 6.000000 9.000000 12.000000
```

4.5 Vector Scaling on an Hybrid CPU/GPU Machine

Contrary to the previous examples, the task submitted in this example may not only be executed by the CPUs, but also by a CUDA device.

4.5.1 Definition of the CUDA Kernel

The CUDA implementation can be written as follows. It needs to be compiled with a CUDA compiler such as nvcc, the NVIDIA CUDA compiler driver. It must be noted that the vector pointer returned by STARPU_VECTOR_GET_PTR is here a pointer in GPU memory, so that it can be passed as such to the `vector_mult_cuda` kernel call.

```
#include <starpu.h>
#include <starpu_cuda.h>

static __global__ void vector_mult_cuda(float *val, unsigned n,
                                        float factor)
{
    unsigned i =  blockIdx.x*blockDim.x + threadIdx.x;
    if (i < n)
        val[i] *= factor;
}

extern "C" void scal_cuda_func(void *buffers[], void *_args)
{
    float *factor = (float *)_args;

    /* length of the vector */
    unsigned n = STARPU_VECTOR_GET_NX(buffers[0]);
    /* CUDA copy of the vector pointer */
    float *val = (float *)STARPU_VECTOR_GET_PTR(buffers[0]);
    unsigned threads_per_block = 64;
    unsigned nblocks = (n + threads_per_block-1) / threads_per_block;

    vector_mult_cuda<<<nblocks,threads_per_block, 0, starpu_cuda_get_local_stream()>>>(val, n, *factor);

    cudaStreamSynchronize(starpu_cuda_get_local_stream());
}
```

4.5.2 Definition of the OpenCL Kernel

The OpenCL implementation can be written as follows. StarPU provides tools to compile a OpenCL kernel stored in a file.

```
__kernel void vector_mult_opencl(__global float* val, int nx, float factor)
{
        const int i = get_global_id(0);
        if (i < nx) {
                val[i] *= factor;
        }
}
```

Contrary to CUDA and CPU, `STARPU_VECTOR_GET_DEV_HANDLE` has to be used, which returns a `cl_mem` (which is not a device pointer, but an OpenCL handle), which can be passed as such to the OpenCL kernel. The difference is important when using partitioning, see Section 5.4 [Partitioning Data], page 30.

```
#include <starpu.h>
#include <starpu_opencl.h>

extern struct starpu_opencl_program programs;

void scal_opencl_func(void *buffers[], void *_args)
{
    float *factor = _args;
    int id, devid, err;
    cl_kernel kernel;
    cl_command_queue queue;
    cl_event event;

    /* length of the vector */
    unsigned n = STARPU_VECTOR_GET_NX(buffers[0]);
    /* OpenCL copy of the vector pointer */
    cl_mem val = (cl_mem) STARPU_VECTOR_GET_DEV_HANDLE(buffers[0]);

    id = starpu_worker_get_id();
    devid = starpu_worker_get_devid(id);

    err = starpu_opencl_load_kernel(&kernel, &queue, &programs,
                  "vector_mult_opencl", devid);   /* Name of the codelet defined above */
    if (err != CL_SUCCESS) STARPU_OPENCL_REPORT_ERROR(err);

    err = clSetKernelArg(kernel, 0, sizeof(val), &val);
    err |= clSetKernelArg(kernel, 1, sizeof(n), &n);
    err |= clSetKernelArg(kernel, 2, sizeof(*factor), factor);
    if (err) STARPU_OPENCL_REPORT_ERROR(err);

    {
        size_t global=n;
        size_t local=1;
        err = clEnqueueNDRangeKernel(queue, kernel, 1, NULL, &global, &local, 0, NULL, &event);
        if (err != CL_SUCCESS) STARPU_OPENCL_REPORT_ERROR(err);
    }

    clFinish(queue);
    starpu_opencl_collect_stats(event);
    clReleaseEvent(event);

    starpu_opencl_release_kernel(kernel);
}
```

4.5.3 Definition of the Main Code

The CPU implementation is the same as in the previous section.

Here is the source of the main application. You can notice the value of the field `where` for the codelet. We specify `STARPU_CPU|STARPU_CUDA|STARPU_OPENCL` to indicate to StarPU that the codelet can be executed either on a CPU or on a CUDA or an OpenCL device.

```
#include <starpu.h>

#define NX 2048

extern void scal_cuda_func(void *buffers[], void *_args);
extern void scal_cpu_func(void *buffers[], void *_args);
extern void scal_opencl_func(void *buffers[], void *_args);

/* Definition of the codelet */
static struct starpu_codelet cl = {
    .where = STARPU_CPU|STARPU_CUDA|STARPU_OPENCL; /* It can be executed on a CPU, */
                                    /* on a CUDA device, or on an OpenCL device */
    .cuda_funcs = { scal_cuda_func, NULL},
    .cpu_funcs = {scal_cpu_func, NULL },
    .opencl_funcs = { scal_opencl_func, NULL },
    .nbuffers = 1,
    .modes = { STARPU_RW }
}

#ifdef STARPU_USE_OPENCL
/* The compiled version of the OpenCL program */
struct starpu_opencl_program programs;
#endif

int main(int argc, char **argv)
{
    float *vector;
    int i, ret;
    float factor=3.0;
    struct starpu_task *task;
    starpu_data_handle_t vector_handle;

    starpu_init(NULL);                              /* Initialising StarPU */

#ifdef STARPU_USE_OPENCL
    starpu_opencl_load_opencl_from_file(
            "examples/basic_examples/vector_scal_opencl_codelet.cl",
            &programs, NULL);
#endif

    vector = malloc(NX*sizeof(vector[0]));
    assert(vector);
    for(i=0 ; i<NX ; i++) vector[i] = i;
```

```
    /* Registering data within StarPU */
    starpu_vector_data_register(&vector_handle, 0, (uintptr_t)vector,
                                NX, sizeof(vector[0]));

    /* Definition of the task */
    task = starpu_task_create();
    task->cl = &cl;
    task->handles[0] = vector_handle;
    task->cl_arg = &factor;
    task->cl_arg_size = sizeof(factor);
```

```
    /* Submitting the task */
    ret = starpu_task_submit(task);
    if (ret == -ENODEV) {
            fprintf(stderr, "No worker may execute this task\n");
            return 1;
    }

    /* Waiting for its termination */
    starpu_task_wait_for_all();

    /* Update the vector in RAM */
    starpu_data_acquire(vector_handle, STARPU_R);
```

```
    /* Access the data */
    for(i=0 ; i<NX; i++) {
      fprintf(stderr, "%f ", vector[i]);
    }
    fprintf(stderr, "\n");

    /* Release the RAM view of the data before unregistering it and shutting down StarPU */
    starpu_data_release(vector_handle);
    starpu_data_unregister(vector_handle);
    starpu_shutdown();

    return 0;
}
```

4.5.4 Execution of Hybrid Vector Scaling

The Makefile given at the beginning of the section must be extended to give the rules to compile the CUDA source code. Note that the source file of the OpenCL kernel does not need to be compiled now, it will be compiled at run-time when calling the function `starpu_opencl_load_opencl_from_file()` (see [starpu_opencl_load_opencl_from_file], page 112).

```
CFLAGS  += $(shell pkg-config --cflags starpu-1.0)
LDFLAGS += $(shell pkg-config --libs starpu-1.0)
CC       = gcc

vector_scal: vector_scal.o vector_scal_cpu.o vector_scal_cuda.o vector_scal_opencl.o

%.o: %.cu
       nvcc $(CFLAGS) $< -c $
clean:
       rm -f vector_scal *.o
```

```
% make
```

and to execute it, with the default configuration:

```
% ./vector_scal
0.000000 3.000000 6.000000 9.000000 12.000000
```

or for example, by disabling CPU devices:

```
% STARPU_NCPUS=0 ./vector_scal
0.000000 3.000000 6.000000 9.000000 12.000000
```

or by disabling CUDA devices (which may permit to enable the use of OpenCL, see Section 3.4 [Enabling OpenCL], page 10):

```
% STARPU_NCUDA=0 ./vector_scal
0.000000 3.000000 6.000000 9.000000 12.000000
```

5 Advanced Examples

5.1 Using multiple implementations of a codelet

One may want to write multiple implementations of a codelet for a single type of device and let StarPU choose which one to run. As an example, we will show how to use SSE to scale a vector. The codelet can be written as follows:

```
#include <xmmintrin.h>

void scal_sse_func(void *buffers[], void *cl_arg)
{
    float *vector = (float *) STARPU_VECTOR_GET_PTR(buffers[0]);
    unsigned int n = STARPU_VECTOR_GET_NX(buffers[0]);
    unsigned int n_iterations = n/4;
    if (n % 4 != 0)
        n_iterations++;

    __m128 *VECTOR = (__m128*) vector;
    __m128 factor __attribute__((aligned(16)));
    factor = _mm_set1_ps(*(float *) cl_arg);

    unsigned int i;
    for (i = 0; i < n_iterations; i++)
        VECTOR[i] = _mm_mul_ps(factor, VECTOR[i]);
}
```

```
struct starpu_codelet cl = {
    .where = STARPU_CPU,
    .cpu_funcs = { scal_cpu_func, scal_sse_func, NULL },
    .nbuffers = 1,
    .modes = { STARPU_RW }
};
```

Schedulers which are multi-implementation aware (only `dmda`, `heft` and `pheft` for now) will use the performance models of all the implementations it was given, and pick the one that seems to be the fastest.

5.2 Enabling implementation according to capabilities

Some implementations may not run on some devices. For instance, some CUDA devices do not support double floating point precision, and thus the kernel execution would just fail; or the device may not have enough shared memory for the implementation being used. The `can_execute` field of the `struct starpu_codelet` structure permits to express this. For instance:

```
static int can_execute(unsigned workerid, struct starpu_task *task, unsigned nimpl)
{
  const struct cudaDeviceProp *props;
  if (starpu_worker_get_type(workerid) == STARPU_CPU_WORKER)
    return 1;
  /* Cuda device */
  props = starpu_cuda_get_device_properties(workerid);
  if (props->major >= 2 || props->minor >= 3)
    /* At least compute capability 1.3, supports doubles */
    return 1;
  /* Old card, does not support doubles */
  return 0;
}

struct starpu_codelet cl = {
    .where = STARPU_CPU|STARPU_CUDA,
    .can_execute = can_execute,
    .cpu_funcs = {cpu_func, NULL },
    .cuda_funcs = { gpu_func, NULL }
    .nbuffers = 1,
    .modes = { STARPU_RW }
};
```

This can be essential e.g. when running on a machine which mixes various models of CUDA devices, to take benefit from the new models without crashing on old models.

Note: the `can_execute` function is called by the scheduler each time it tries to match a task with a worker, and should thus be very fast. The `starpu_cuda_get_device_properties` provides a quick access to CUDA properties of CUDA devices to achieve such efficiency.

Another example is compiling CUDA code for various compute capabilities, resulting with two CUDA functions, e.g. `scal_gpu_13` for compute capability 1.3, and `scal_gpu_20` for compute capability 2.0. Both functions can be provided to StarPU by using `cuda_funcs`, and `can_execute` can then be used to rule out the `scal_gpu_20` variant on a CUDA device which will not be able to execute it:

```
static int can_execute(unsigned workerid, struct starpu_task *task, unsigned nimpl)
{
  const struct cudaDeviceProp *props;
  if (starpu_worker_get_type(workerid) == STARPU_CPU_WORKER)
    return 1;
  /* Cuda device */
  if (nimpl == 0)
    /* Trying to execute the 1.3 capability variant, we assume it is ok in all cases.  */
    return 1;
  /* Trying to execute the 2.0 capability variant, check that the card can do it.  */
  props = starpu_cuda_get_device_properties(workerid);
  if (props->major >= 2 || props->minor >= 0)
    /* At least compute capability 2.0, can run it */
    return 1;
  /* Old card, does not support 2.0, will not be able to execute the 2.0 variant.  */
  return 0;
}

struct starpu_codelet cl = {
    .where = STARPU_CPU|STARPU_CUDA,
    .can_execute = can_execute,
    .cpu_funcs = { cpu_func, NULL },
    .cuda_funcs = { scal_gpu_13, scal_gpu_20, NULL },
    .nbuffers = 1,
    .modes = { STARPU_RW }
};
```

Note: the most generic variant should be provided first, as some schedulers are not able to try the different variants.

5.3 Task and Worker Profiling

A full example showing how to use the profiling API is available in the StarPU sources in the directory `examples/profiling/`.

```
struct starpu_task *task = starpu_task_create();
task->cl = &cl;
task->synchronous = 1;
/* We will destroy the task structure by hand so that we can
 * query the profiling info before the task is destroyed. */
task->destroy = 0;

/* Submit and wait for completion (since synchronous was set to 1) */
starpu_task_submit(task);

/* The task is finished, get profiling information */
struct starpu_task_profiling_info *info = task->profiling_info;

/* How much time did it take before the task started ? */
double delay += starpu_timing_timespec_delay_us(&info->submit_time, &info->start_time);

/* How long was the task execution ? */
double length += starpu_timing_timespec_delay_us(&info->start_time, &info->end_time);

/* We don't need the task structure anymore */
starpu_task_destroy(task);
```

```
/* Display the occupancy of all workers during the test */
int worker;
for (worker = 0; worker < starpu_worker_get_count(); worker++)
{
        struct starpu_worker_profiling_info worker_info;
        int ret = starpu_worker_get_profiling_info(worker, &worker_info);
        STARPU_ASSERT(!ret);

        double total_time = starpu_timing_timespec_to_us(&worker_info.total_time);
        double executing_time = starpu_timing_timespec_to_us(&worker_info.executing_time);
        double sleeping_time = starpu_timing_timespec_to_us(&worker_info.sleeping_time);

        float executing_ratio = 100.0*executing_time/total_time;
        float sleeping_ratio = 100.0*sleeping_time/total_time;

        char workername[128];
        starpu_worker_get_name(worker, workername, 128);
        fprintf(stderr, "Worker %s:\n", workername);
        fprintf(stderr, "\ttotal time: %.2lf ms\n", total_time*1e-3);
        fprintf(stderr, "\texec time: %.2lf ms (%.2f %%)\n", executing_time*1e-3,
                executing_ratio);
        fprintf(stderr, "\tblocked time: %.2lf ms (%.2f %%)\n", sleeping_time*1e-3,
                sleeping_ratio);
}
```

5.4 Partitioning Data

An existing piece of data can be partitioned in sub parts to be used by different tasks, for instance:

```
int vector[NX];
starpu_data_handle_t handle;

/* Declare data to StarPU */
starpu_vector_data_register(&handle, 0, (uintptr_t)vector, NX, sizeof(vector[0]));

/* Partition the vector in PARTS sub-vectors */
starpu_filter f =
{
    .filter_func = starpu_block_filter_func_vector,
    .nchildren = PARTS
};
starpu_data_partition(handle, &f);
```

The task submission then uses `starpu_data_get_sub_data` to retrive the sub-handles to be passed as tasks parameters.

```
/* Submit a task on each sub-vector */
for (i=0; i<starpu_data_get_nb_children(handle); i++) {
    /* Get subdata number i (there is only 1 dimension) */
    starpu_data_handle_t sub_handle = starpu_data_get_sub_data(handle, 1, i);
    struct starpu_task *task = starpu_task_create();

    task->handles[0] = sub_handle;
    task->cl = &cl;
    task->synchronous = 1;
    task->cl_arg = &factor;
    task->cl_arg_size = sizeof(factor);

    starpu_task_submit(task);
}
```

Partitioning can be applied several times, see `examples/basic_examples/mult.c` and `examples/filters/`.

Wherever the whole piece of data is already available, the partitioning will be done in-place, i.e. without allocating new buffers but just using pointers inside the existing copy. This is particularly important to be aware of when using OpenCL, wherethe kernel parameters are not pointers, but handles. The kernel thus needs to be also passed the offset within the OpenCL buffer:

```
void opencl_func(void *buffers[], void *cl_arg)
{
    cl_mem vector = (cl_mem) STARPU_VECTOR_GET_DEV_HANDLE(buffers[0]);
    unsigned offset = STARPU_BLOCK_GET_OFFSET(buffers[0]);

    ...
    clSetKernelArg(kernel, 0, sizeof(vector), &vector);
    clSetKernelArg(kernel, 1, sizeof(offset), &offset);
    ...
}
```

And the kernel has to shift from the pointer passed by the OpenCL driver:

```
__kernel void opencl_kernel(__global int *vector, unsigned offset)
{
    block = (__global void *)block + offset;
    ...
}
```

5.5 Performance model example

To achieve good scheduling, StarPU scheduling policies need to be able to estimate in advance the duration of a task. This is done by giving to codelets a performance model, by defining a `starpu_perfmodel` structure and providing its address in the `model` field of the `struct starpu_codelet` structure. The `symbol` and `type` fields of `starpu_perfmodel` are mandatory, to give a name to the model, and the type of the model, since there are several kinds of performance models.

- Measured at runtime (`STARPU_HISTORY_BASED` model type). This assumes that for a given set of data input/output sizes, the performance will always be about the same.

This is very true for regular kernels on GPUs for instance (<0.1% error), and just a bit less true on CPUs (~=1% error). This also assumes that there are few different sets of data input/output sizes. StarPU will then keep record of the average time of previous executions on the various processing units, and use it as an estimation. History is done per task size, by using a hash of the input and ouput sizes as an index. It will also save it in `~/.starpu/sampling/codelets` for further executions, and can be observed by using the `starpu_perfmodel_display` command, or drawn by using the`starpu_perfmodel_plot`. The models are indexed by machine name. To share the models between machines (e.g. for a homogeneous cluster), use `export STARPU_HOSTNAME=some_global_name`. Measurements are only done when using a task scheduler which makes use of it, such as `heft` or `dmda`.

The following is a small code example.

If e.g. the code is recompiled with other compilation options, or several variants of the code are used, the symbol string should be changed to reflect that, in order to recalibrate a new model from zero. The symbol string can even be constructed dynamically at execution time, as long as this is done before submitting any task using it.

```
static struct starpu_perfmodel mult_perf_model = {
    .type = STARPU_HISTORY_BASED,
    .symbol = "mult_perf_model"
};

struct starpu_codelet cl = {
    .where = STARPU_CPU,
    .cpu_funcs = { cpu_mult, NULL },
    .nbuffers = 3,
    .modes = { STARPU_R, STARPU_R, STARPU_W },
    /* for the scheduling policy to be able to use performance models */
    .model = &mult_perf_model
};
```

- Measured at runtime and refined by regression (`STARPU_*REGRESSION_BASED` model type). This still assumes performance regularity, but can work with various data input sizes, by applying regression over observed execution times. STARPU_REGRESSION_BASED uses an a*n^b regression form, STARPU_NL_REGRESSION_BASED uses an a*n^b+c (more precise than STARPU_REGRESSION_BASED, but costs a lot more to compute). For instance, `tests/perfmodels/regression_based.c` uses a regression-based performance model for the `memset` operation. Of course, the application has to issue tasks with varying size so that the regression can be computed. StarPU will not trust the regression unless there is at least 10% difference between the minimum and maximum observed input size. For non-linear regression, since computing it is quite expensive, it is only done at termination of the application. This means that the first execution uses history-based performance model to perform scheduling.
- Provided as an estimation from the application itself (`STARPU_COMMON` model type and `cost_function` field), see for instance `examples/common/blas_model.h` and `examples/common/blas_model.c`.
- Provided explicitly by the application (`STARPU_PER_ARCH` model type): the `.per_`

`arch[arch][nimpl].cost_function` fields have to be filled with pointers to functions which return the expected duration of the task in micro-seconds, one per architecture.

For the `STARPU_HISTORY_BASED` and `STARPU_*REGRESSION_BASE`, the total size of task data (both input and output) is used as an index by default. The `size_base` field of `struct starpu_perfmodel` however permits the application to override that, when for instance some of the data do not matter for task cost (e.g. mere reference table), or when using sparse structures (in which case it is the number of non-zeros which matter), or when there is some hidden parameter such as the number of iterations, etc.

How to use schedulers which can benefit from such performance model is explained in Section 6.5 [Task scheduling policy], page 44.

The same can be done for task power consumption estimation, by setting the `power_model` field the same way as the `model` field. Note: for now, the application has to give to the power consumption performance model a name which is different from the execution time performance model.

The application can request time estimations from the StarPU performance models by filling a task structure as usual without actually submitting it. The data handles can be created by calling `starpu_data_register` functions with a `NULL` pointer (and need to be unregistered as usual) and the desired data sizes. The `starpu_task_expected_length` and `starpu_task_expected_power` functions can then be called to get an estimation of the task duration on a given arch. `starpu_task_destroy` needs to be called to destroy the dummy task afterwards. See `tests/perfmodels/regression_based.c` for an example.

5.6 Theoretical lower bound on execution time

For kernels with history-based performance models, StarPU can very easily provide a theoretical lower bound for the execution time of a whole set of tasks. See for instance `examples/lu/lu_example.c`: before submitting tasks, call `starpu_bound_start`, and after complete execution, call `starpu_bound_stop`. `starpu_bound_print_lp` or `starpu_bound_print_mps` can then be used to output a Linear Programming problem corresponding to the schedule of your tasks. Run it through `lp_solve` or any other linear programming solver, and that will give you a lower bound for the total execution time of your tasks. If StarPU was compiled with the glpk library installed, `starpu_bound_compute` can be used to solve it immediately and get the optimized minimum, in ms. Its `integer` parameter allows to decide whether integer resolution should be computed and returned too.

The `deps` parameter tells StarPU whether to take tasks and implicit data dependencies into account. It must be understood that the linear programming problem size is quadratic with the number of tasks and thus the time to solve it will be very long, it could be minutes for just a few dozen tasks. You should probably use `lp_solve -timeout 1 test.pl -wmps test.mps` to convert the problem to MPS format and then use a better solver, `glpsol` might be better than `lp_solve` for instance (the `--pcost` option may be useful), but sometimes doesn't manage to converge. `cbc` might look slower, but it is parallel. Be sure to try at least all the `-B` options of `lp_solve`. For instance, we often just use `lp_solve -cc -B1 -Bb -Bg -Bp -Bf -Br -BG -Bd -Bs -BB -Bo -Bc -Bi` , and the `-gr` option can also be quite useful.

Setting `deps` to 0 will only take into account the actual computations on processing units. It however still properly takes into account the varying performances of kernels and

processing units, which is quite more accurate than just comparing StarPU performances with the fastest of the kernels being used.

The `prio` parameter tells StarPU whether to simulate taking into account the priorities as the StarPU scheduler would, i.e. schedule prioritized tasks before less prioritized tasks, to check to which extend this results to a less optimal solution. This increases even more computation time.

Note that for simplicity, all this however doesn't take into account data transfers, which are assumed to be completely overlapped.

5.7 Insert Task Utility

StarPU provides the wrapper function `starpu_insert_task` to ease the creation and submission of tasks.

`int starpu_insert_task` (*struct starpu_codelet *cl, ...*) [Function]

Create and submit a task corresponding to *cl* with the following arguments. The argument list must be zero-terminated.

The arguments following the codelets can be of the following types:

- `STARPU_R`, `STARPU_W`, `STARPU_RW`, `STARPU_SCRATCH`, `STARPU_REDUX` an access mode followed by a data handle;
- the specific values `STARPU_VALUE`, `STARPU_CALLBACK`, `STARPU_CALLBACK_ARG`, `STARPU_CALLBACK_WITH_ARG`, `STARPU_PRIORITY`, followed by the appropriated objects as defined below.

Parameters to be passed to the codelet implementation are defined through the type `STARPU_VALUE`. The function `starpu_codelet_unpack_args` must be called within the codelet implementation to retrieve them.

`STARPU_VALUE` [Macro]

this macro is used when calling `starpu_insert_task`, and must be followed by a pointer to a constant value and the size of the constant

`STARPU_CALLBACK` [Macro]

this macro is used when calling `starpu_insert_task`, and must be followed by a pointer to a callback function

`STARPU_CALLBACK_ARG` [Macro]

this macro is used when calling `starpu_insert_task`, and must be followed by a pointer to be given as an argument to the callback function

`STARPU_CALLBACK_WITH_ARG` [Macro]

this macro is used when calling `starpu_insert_task`, and must be followed by two pointers: one to a callback function, and the other to be given as an argument to the callback function; this is equivalent to using both `STARPU_CALLBACK` and `STARPU_CALLBACK_WITH_ARG`

`STARPU_PRIORITY` [Macro]

this macro is used when calling `starpu_insert_task`, and must be followed by a integer defining a priority level

`void starpu_codelet_pack_args (`*char **arg_buffer*, *size_t *arg_buffer_size*, ...`)` [Function]

Pack arguments of type `STARPU_VALUE` into a buffer which can be given to a codelet and later unpacked with the function `starpu_codelet_unpack_args` defined below.

`void starpu_codelet_unpack_args (`*void *cl_arg*, ...`)` [Function]

Retrieve the arguments of type `STARPU_VALUE` associated to a task automatically created using the function `starpu_insert_task` defined above.

Here the implementation of the codelet:

```
void func_cpu(void *descr[], void *_args)
{
        int *x0 = (int *)STARPU_VARIABLE_GET_PTR(descr[0]);
        float *x1 = (float *)STARPU_VARIABLE_GET_PTR(descr[1]);
        int ifactor;
        float ffactor;

        starpu_codelet_unpack_args(_args, &ifactor, &ffactor);
        *x0 = *x0 * ifactor;
        *x1 = *x1 * ffactor;
}

struct starpu_codelet mycodelet = {
        .where = STARPU_CPU,
        .cpu_funcs = { func_cpu, NULL },
        .nbuffers = 2,
        .modes = { STARPU_RW, STARPU_RW }
};
```

And the call to the `starpu_insert_task` wrapper:

```
starpu_insert_task(&mycodelet,
                   STARPU_VALUE, &ifactor, sizeof(ifactor),
                   STARPU_VALUE, &ffactor, sizeof(ffactor),
                   STARPU_RW, data_handles[0], STARPU_RW, data_handles[1],
                   0);
```

The call to `starpu_insert_task` is equivalent to the following code:

```
struct starpu_task *task = starpu_task_create();
task->cl = &mycodelet;
task->handles[0] = data_handles[0];
task->handles[1] = data_handles[1];
char *arg_buffer;
size_t arg_buffer_size;
starpu_codelet_pack_args(&arg_buffer, &arg_buffer_size,
                    STARPU_VALUE, &ifactor, sizeof(ifactor),
                    STARPU_VALUE, &ffactor, sizeof(ffactor),
                    0);
task->cl_arg = arg_buffer;
task->cl_arg_size = arg_buffer_size;
int ret = starpu_task_submit(task);
```

If some part of the task insertion depends on the value of some computation, the `STARPU_DATA_ACQUIRE_CB` macro can be very convenient. For instance, assuming that the index variable `i` was registered as handle `i_handle`:

```
/* Compute which portion we will work on, e.g. pivot */
starpu_insert_task(&which_index, STARPU_W, i_handle, 0);
```

```
/* And submit the corresponding task */
STARPU_DATA_ACQUIRE_CB(i_handle, STARPU_R, starpu_insert_task(&work, STARPU_RW, A_handle[i], 0));
```

The `STARPU_DATA_ACQUIRE_CB` macro submits an asynchronous request for acquiring data `i` for the main application, and will execute the code given as third parameter when it is acquired. In other words, as soon as the value of `i` computed by the `which_index` codelet can be read, the portion of code passed as third parameter of `STARPU_DATA_ACQUIRE_CB` will be executed, and is allowed to read from `i` to use it e.g. as an index. Note that this macro is only avaible when compiling StarPU with the compiler `gcc`.

5.8 Data reduction

In various cases, some piece of data is used to accumulate intermediate results. For instances, the dot product of a vector, maximum/minimum finding, the histogram of a photograph, etc. When these results are produced along the whole machine, it would not be efficient to accumulate them in only one place, incurring data transmission each and access concurrency.

StarPU provides a `STARPU_REDUX` mode, which permits to optimize that case: it will allocate a buffer on each memory node, and accumulate intermediate results there. When the data is eventually accessed in the normal `STARPU_R` mode, StarPU will collect the intermediate results in just one buffer.

For this to work, the user has to use the `starpu_data_set_reduction_methods` to declare how to initialize these buffers, and how to assemble partial results.

For instance, `cg` uses that to optimize its dot product: it first defines the codelets for initialization and reduction:

```
struct starpu_codelet bzero_variable_cl =
{
        .cpu_funcs = { bzero_variable_cpu, NULL },
        .cuda_funcs = { bzero_variable_cuda, NULL },
        .nbuffers = 1,
}

static void accumulate_variable_cpu(void *descr[], void *cl_arg)
{
        double *v_dst = (double *)STARPU_VARIABLE_GET_PTR(descr[0]);
        double *v_src = (double *)STARPU_VARIABLE_GET_PTR(descr[1]);
        *v_dst = *v_dst + *v_src;
}

static void accumulate_variable_cuda(void *descr[], void *cl_arg)
{
        double *v_dst = (double *)STARPU_VARIABLE_GET_PTR(descr[0]);
        double *v_src = (double *)STARPU_VARIABLE_GET_PTR(descr[1]);
        cublasaxpy(1, (double)1.0, v_src, 1, v_dst, 1);
        cudaStreamSynchronize(starpu_cuda_get_local_stream());
}

struct starpu_codelet accumulate_variable_cl =
{
        .cpu_funcs = { accumulate_variable_cpu, NULL },
        .cuda_funcs = { accumulate_variable_cuda, NULL },
        .nbuffers = 1,
}
```

and attaches them as reduction methods for its dtq handle:

```
starpu_data_set_reduction_methods(dtq_handle,
        &accumulate_variable_cl, &bzero_variable_cl);
```

and dtq_handle can now be used in STARPU_REDUX mode for the dot products with partitioned vectors:

```
int dots(starpu_data_handle v1, starpu_data_handle v2,
         starpu_data_handle s, unsigned nblocks)
{
    starpu_insert_task(&bzero_variable_cl, STARPU_W, s, 0);
    for (b = 0; b < nblocks; b++)
        starpu_insert_task(&dot_kernel_cl,
            STARPU_RW, s,
            STARPU_R, starpu_data_get_sub_data(v1, 1, b),
            STARPU_R, starpu_data_get_sub_data(v2, 1, b),
            0);
}
```

The cg example also uses reduction for the blocked gemv kernel, leading to yet more relaxed dependencies and more parallelism.

5.9 Parallel Tasks

StarPU can leverage existing parallel computation libraries by the means of parallel tasks. A parallel task is a task which gets worked on by a set of CPUs (called a parallel or combined worker) at the same time, by using an existing parallel CPU implementation of the computation to be achieved. This can also be useful to improve the load balance between slow CPUs and fast GPUs: since CPUs work collectively on a single task, the completion time of tasks on CPUs become comparable to the completion time on GPUs, thus relieving from granularity discrepancy concerns. Hwloc support needs to be enabled to get good performance, otherwise StarPU will not know how to better group cores.

Two modes of execution exist to accomodate with existing usages.

5.9.1 Fork-mode parallel tasks

In the Fork mode, StarPU will call the codelet function on one of the CPUs of the combined worker. The codelet function can use starpu_combined_worker_get_size() to get the number of threads it is allowed to start to achieve the computation. The CPU binding mask is already enforced, so that threads created by the function will inherit the mask, and thus execute where StarPU expected. For instance, using OpenMP (full source is available in examples/openmp/vector_scal.c):

```
void scal_cpu_func(void *buffers[], void *_args)
{
    unsigned i;
    float *factor = _args;
    struct starpu_vector_interface *vector = buffers[0];
    unsigned n = STARPU_VECTOR_GET_NX(vector);
    float *val = (float *)STARPU_VECTOR_GET_PTR(vector);

#pragma omp parallel for num_threads(starpu_combined_worker_get_size())
    for (i = 0; i < n; i++)
        val[i] *= *factor;
```

```
}

static struct starpu_codelet cl =
{
    .modes = { STARPU_RW },
    .where = STARPU_CPU,
    .type = STARPU_FORKJOIN,
    .max_parallelism = INT_MAX,
    .cpu_funcs = {scal_cpu_func, NULL},
    .nbuffers = 1,
};
```

Other examples include for instance calling a BLAS parallel CPU implementation (see `examples/mult/xgemm.c`).

5.9.2 SPMD-mode parallel tasks

In the SPMD mode, StarPU will call the codelet function on each CPU of the combined worker. The codelet function can use `starpu_combined_worker_get_size()` to get the total number of CPUs involved in the combined worker, and thus the number of calls that are made in parallel to the function, and `starpu_combined_worker_get_rank()` to get the rank of the current CPU within the combined worker. For instance:

```
static void func(void *buffers[], void *args)
{
    unsigned i;
    float *factor = _args;
    struct starpu_vector_interface *vector = buffers[0];
    unsigned n = STARPU_VECTOR_GET_NX(vector);
    float *val = (float *)STARPU_VECTOR_GET_PTR(vector);

    /* Compute slice to compute */
    unsigned m = starpu_combined_worker_get_size();
    unsigned j = starpu_combined_worker_get_rank();
    unsigned slice = (n+m-1)/m;

    for (i = j * slice; i < (j+1) * slice && i < n; i++)
        val[i] *= *factor;
}

static struct starpu_codelet cl =
{
    .modes = { STARPU_RW },
    .where = STARP_CPU,
    .type = STARPU_SPMD,
    .max_parallelism = INT_MAX,
    .cpu_funcs = { func, NULL },
    .nbuffers = 1,
}
```

Of course, this trivial example will not really benefit from parallel task execution, and was only meant to be simple to understand. The benefit comes when the computation to be done is so that threads have to e.g. exchange intermediate results, or write to the data in a complex but safe way in the same buffer.

5.9.3 Parallel tasks performance

To benefit from parallel tasks, a parallel-task-aware StarPU scheduler has to be used. When exposed to codelets with a Fork or SPMD flag, the `pheft` (parallel-heft) and `pgreedy` (parallel greedy) schedulers will indeed also try to execute tasks with several CPUs. It will automatically try the various available combined worker sizes and thus be able to avoid choosing a large combined worker if the codelet does not actually scale so much.

5.9.4 Combined worker sizes

By default, StarPU creates combined workers according to the architecture structure as detected by hwloc. It means that for each object of the hwloc topology (NUMA node, socket, cache, ...) a combined worker will be created. If some nodes of the hierarchy have a big arity (e.g. many cores in a socket without a hierarchy of shared caches), StarPU will create combined workers of intermediate sizes.

5.9.5 Concurrent parallel tasks

Unfortunately, many environments and librairies do not support concurrent calls.

For instance, most OpenMP implementations (including the main ones) do not support concurrent `pragma omp parallel` statements without nesting them in another `pragma omp parallel` statement, but StarPU does not yet support creating its CPU workers by using such pragma.

Other parallel libraries are also not safe when being invoked concurrently from different threads, due to the use of global variables in their sequential sections for instance.

The solution is then to use only one combined worker at a time. This can be done by setting `single_combined_worker` to 1 in the `starpu_conf` structure, or setting the `STARPU_SINGLE_COMBINED_WORKER` environment variable to 1. StarPU will then run only one parallel task at a time.

5.10 Debugging

StarPU provides several tools to help debugging aplications. Execution traces can be generated and displayed graphically, see Section 7.2.1 [Generating traces], page 51. Some gdb helpers are also provided to show the whole StarPU state:

```
(gdb) source tools/gdbinit
(gdb) help starpu
```

5.11 The multiformat interface

It may be interesting to represent the same piece of data using two different data structures: one that would only be used on CPUs, and one that would only be used on GPUs. This can be done by using the multiformat interface. StarPU will be able to convert data from one data structure to the other when needed. Note that the heft scheduler is the only one optimized for this interface. The user must provide StarPU with conversion codelets:

```
#define NX 1024
struct point array_of_structs[NX];
starpu_data_handle_t handle;

/*
 * The conversion of a piece of data is itself a task, though it is created,
 * submitted and destroyed by StarPU internals and not by the user. Therefore,
 * we have to define two codelets.
 * Note that for now the conversion from the CPU format to the GPU format has to
 * be executed on the GPU, and the conversion from the GPU to the CPU has to be
 * executed on the CPU.
 */
#ifdef STARPU_USE_OPENCL
void cpu_to_opencl_opencl_func(void *buffers[], void *args);
struct starpu_codelet cpu_to_opencl_cl = {
    .where = STARPU_OPENCL,
    .opencl_funcs = { cpu_to_opencl_opencl_func, NULL },
    .nbuffers = 1,
    .modes = { STARPU_RW }
};

void opencl_to_cpu_func(void *buffers[], void *args);
struct starpu_codelet opencl_to_cpu_cl = {
    .where = STARPU_CPU,
    .cpu_funcs = { opencl_to_cpu_func, NULL },
    .nbuffers = 1,
    .modes = { STARPU_RW }
};
#endif

struct starpu_multiformat_data_interface_ops format_ops = {
#ifdef STARPU_USE_OPENCL
    .opencl_elemsize = 2 * sizeof(float),
    .cpu_to_opencl_cl = &cpu_to_opencl_cl,
    .opencl_to_cpu_cl = &opencl_to_cpu_cl,
#endif
    .cpu_elemsize = 2 * sizeof(float),
    ...
};
starpu_multiformat_data_register(handle, 0, &array_of_structs, NX, &format_ops);
```

Kernels can be written almost as for any other interface. Note that STARPU_MULTIFORMAT_GET_CPU_PTR shall only be used for CPU kernels. CUDA kernels must use STARPU_MULTIFORMAT_GET_CUDA_PTR, and OpenCL kernels must use STARPU_MULTIFORMAT_GET_OPENCL_PTR. STARPU_MULTIFORMAT_GET_NX may be used in any kind of kernel.

```
static void
multiformat_scal_cpu_func(void *buffers[], void *args)
{
    struct point *aos;
    unsigned int n;

    aos = STARPU_MULTIFORMAT_GET_CPU_PTR(buffers[0]);
    n = STARPU_MULTIFORMAT_GET_NX(buffers[0]);
    ...
}

extern "C" void multiformat_scal_cuda_func(void *buffers[], void *_args)
{
    unsigned int n;
    struct struct_of_arrays *soa;

    soa = (struct struct_of_arrays *) STARPU_MULTIFORMAT_GET_CUDA_PTR(buffers[0]);
    n = STARPU_MULTIFORMAT_GET_NX(buffers[0]);

    ...
}
```

A full example may be found in `examples/basic_examples/multiformat.c`.

5.12 On-GPU rendering

Graphical-oriented applications need to draw the result of their computations, typically on the very GPU where these happened. Technologies such as OpenGL/CUDA interoperability permit to let CUDA directly work on the OpenGL buffers, making them thus immediately ready for drawing, by mapping OpenGL buffer, textures or renderbuffer objects into CUDA. To achieve this with StarPU, it simply needs to be given the CUDA pointer at registration, for instance:

```
for (workerid = 0; workerid < starpu_worker_get_count(); workerid++)
        if (starpu_worker_get_type(workerid) == STARPU_CUDA_WORKER)
                break;

cudaSetDevice(starpu_worker_get_devid(workerid));
cudaGraphicsResourceGetMappedPointer((void**)&output, &num_bytes, resource);
starpu_vector_data_register(&handle, starpu_worker_get_memory_node(workerid), output, num_bytes / sizeof(float

starpu_insert_task(&cl, STARPU_RW, handle, 0);

starpu_data_unregister(handle);

cudaSetDevice(starpu_worker_get_devid(workerid));
cudaGraphicsUnmapResources(1, &resource, 0);

/* Now display it */
```

5.13 More examples

More examples are available in the StarPU sources in the `examples/` directory. Simple examples include:

`incrementer/`:
: Trivial incrementation test.

`basic_examples/`:
: Simple documented Hello world (as shown in Section 4.2 [Hello World], page 11), vector/scalar product (as shown in Section 4.5 [Vector Scaling on an Hybrid CPU/GPU Machine], page 21), matrix product examples (as shown in Section 5.5 [Performance model example], page 31), an example using the blocked matrix data interface, an example using the variable data interface, and an example using different formats on CPUs and GPUs.

`matvecmult/`:
: OpenCL example from NVidia, adapted to StarPU.

`axpy/`:
: AXPY CUBLAS operation adapted to StarPU.

`fortran/`:
: Example of Fortran bindings.

More advanced examples include:

`filters/`:
: Examples using filters, as shown in Section 5.4 [Partitioning Data], page 30.

`lu/`:
: LU matrix factorization, see for instance `xlu_implicit.c`

`cholesky/`:
: Cholesky matrix factorization, see for instance `cholesky_implicit.c`.

6 How to optimize performance with StarPU

TODO: improve!

Simply encapsulating application kernels into tasks already permits to seamlessly support CPU and GPUs at the same time. To achieve good performance, a few additional changes are needed.

6.1 Data management

When the application allocates data, whenever possible it should use the `starpu_malloc` function, which will ask CUDA or OpenCL to make the allocation itself and pin the corresponding allocated memory. This is needed to permit asynchronous data transfer, i.e. permit data transfer to overlap with computations. Otherwise, the trace will show that the `DriverCopyAsync` state takes a lot of time, this is because CUDA or OpenCL then reverts to synchronous transfers.

By default, StarPU leaves replicates of data wherever they were used, in case they will be re-used by other tasks, thus saving the data transfer time. When some task modifies some data, all the other replicates are invalidated, and only the processing unit which ran that task will have a valid replicate of the data. If the application knows that this data will not be re-used by further tasks, it should advise StarPU to immediately replicate it to a desired list of memory nodes (given through a bitmask). This can be understood like the write-through mode of CPU caches.

```
starpu_data_set_wt_mask(img_handle, 1<<0);
```

will for instance request to always automatically transfer a replicate into the main memory (node 0), as bit 0 of the write-through bitmask is being set.

```
starpu_data_set_wt_mask(img_handle, ~0U);
```

will request to always automatically broadcast the updated data to all memory nodes.

Setting the write-through mask to `~0U` can also be useful to make sure all memory nodes always have a copy of the data, so that it is never evicted when memory gets scarse.

Implicit data dependency computation can become expensive if a lot of tasks access the same piece of data. If no dependency is required on some piece of data (e.g. because it is only accessed in read-only mode, or because write accesses are actually commutative), use the `starpu_data_set_sequential_consistency_flag` function to disable implicit dependencies on that data.

In the same vein, accumulation of results in the same data can become a bottleneck. The use of the `STARPU_REDUX` mode permits to optimize such accumulation (see Section 5.8 [Data reduction], page 36).

6.2 Task granularity

Like any other runtime, StarPU has some overhead to manage tasks. Since it does smart scheduling and data management, that overhead is not always neglectable. The order of

magnitude of the overhead is typically a couple of microseconds. The amount of work that a task should do should thus be somewhat bigger, to make sure that the overhead becomes neglectible. The offline performance feedback can provide a measure of task length, which should thus be checked if bad performance are observed.

6.3 Task submission

To let StarPU make online optimizations, tasks should be submitted asynchronously as much as possible. Ideally, all the tasks should be submitted, and mere calls to `starpu_task_wait_for_all` or `starpu_data_unregister` be done to wait for termination. StarPU will then be able to rework the whole schedule, overlap computation with communication, manage accelerator local memory usage, etc.

6.4 Task priorities

By default, StarPU will consider the tasks in the order they are submitted by the application. If the application programmer knows that some tasks should be performed in priority (for instance because their output is needed by many other tasks and may thus be a bottleneck if not executed early enough), the `priority` field of the task structure should be set to transmit the priority information to StarPU.

6.5 Task scheduling policy

By default, StarPU uses the `eager` simple greedy scheduler. This is because it provides correct load balance even if the application codelets do not have performance models. If your application codelets have performance models (see Section 5.5 [Performance model example], page 31 for examples showing how to do it), you should change the scheduler thanks to the `STARPU_SCHED` environment variable. For instance `export STARPU_SCHED=dmda` . Use `help` to get the list of available schedulers.

The **eager** scheduler uses a central task queue, from which workers draw tasks to work on. This however does not permit to prefetch data since the scheduling decision is taken late. If a task has a non-0 priority, it is put at the front of the queue.

The **prio** scheduler also uses a central task queue, but sorts tasks by priority (between -5 and 5).

The **random** scheduler distributes tasks randomly according to assumed worker overall performance.

The **ws** (work stealing) scheduler schedules tasks on the local worker by default. When a worker becomes idle, it steals a task from the most loaded worker.

The **dm** (deque model) scheduler uses task execution performance models into account to perform an HEFT-similar scheduling strategy: it schedules tasks where their termination time will be minimal.

The **dmda** (deque model data aware) scheduler is similar to dm, it also takes into account data transfer time.

The **dmdar** (deque model data aware ready) scheduler is similar to dmda, it also sorts tasks on per-worker queues by number of already-available data buffers.

The **dmdas** (deque model data aware sorted) scheduler is similar to dmda, it also supports arbitrary priority values.

The **heft** (heterogeneous earliest finish time) scheduler is similar to dmda, it also supports task bundles.

The **pheft** (parallel HEFT) scheduler is similar to heft, it also supports parallel tasks (still experimental).

The **pgreedy** (parallel greedy) scheduler is similar to greedy, it also supports parallel tasks (still experimental).

6.6 Performance model calibration

Most schedulers are based on an estimation of codelet duration on each kind of processing unit. For this to be possible, the application programmer needs to configure a performance model for the codelets of the application (see Section 5.5 [Performance model example], page 31 for instance). History-based performance models use on-line calibration. StarPU will automatically calibrate codelets which have never been calibrated yet, and save the result in `~/.starpu/sampling/codelets`. The models are indexed by machine name. To share the models between machines (e.g. for a homogeneous cluster), use `export STARPU_HOSTNAME=some_global_name`. To force continuing calibration, use `export STARPU_CALIBRATE=1` . This may be necessary if your application has not-so-stable performance. StarPU will force calibration (and thus ignore the current result) until 10 (_STARPU_CALIBRATION_MINIMUM) measurements have been made on each architecture, to avoid badly scheduling tasks just because the first measurements were not so good. Details on the current performance model status can be obtained from the `starpu_perfmodel_display` command: the `-l` option lists the available performance models, and the `-s` option permits to choose the performance model to be displayed. The result looks like:

```
$ starpu_perfmodel_display -s starpu_dlu_lu_model_22
performance model for cpu
# hash    size     mean          dev           n
880805ba  98304    2.731309e+02  6.010210e+01  1240
b50b6605  393216   1.469926e+03  1.088828e+02  1240
5c6c3401  1572864  1.125983e+04  3.265296e+03  1240
```

Which shows that for the LU 22 kernel with a 1.5MiB matrix, the average execution time on CPUs was about 11ms, with a 3ms standard deviation, over 1240 samples. It is a good idea to check this before doing actual performance measurements.

A graph can be drawn by using the `starpu_perfmodel_plot`:

```
$ starpu_perfmodel_plot -s starpu_dlu_lu_model_22
98304 393216 1572864
$ gnuplot starpu_starpu_dlu_lu_model_22.gp
$ gv starpu_starpu_dlu_lu_model_22.eps
```

If a kernel source code was modified (e.g. performance improvement), the calibration information is stale and should be dropped, to re-calibrate from start. This can be done by using `export STARPU_CALIBRATE=2`.

Note: due to CUDA limitations, to be able to measure kernel duration, calibration mode needs to disable asynchronous data transfers. Calibration thus disables data transfer / computation overlapping, and should thus not be used for eventual benchmarks. Note 2:

history-based performance models get calibrated only if a performance-model-based scheduler is chosen.

6.7 Task distribution vs Data transfer

Distributing tasks to balance the load induces data transfer penalty. StarPU thus needs to find a balance between both. The target function that the `dmda` scheduler of StarPU tries to minimize is `alpha * T_execution + beta * T_data_transfer`, where `T_execution` is the estimated execution time of the codelet (usually accurate), and `T_data_transfer` is the estimated data transfer time. The latter is estimated based on bus calibration before execution start, i.e. with an idle machine, thus without contention. You can force bus recalibration by running `starpu_calibrate_bus`. The beta parameter defaults to 1, but it can be worth trying to tweak it by using `export STARPU_SCHED_BETA=2` for instance, since during real application execution, contention makes transfer times bigger. This is of course imprecise, but in practice, a rough estimation already gives the good results that a precise estimation would give.

6.8 Data prefetch

The `heft`, `dmda` and `pheft` scheduling policies perform data prefetch (see Section 15.2.2.3 [STARPU_PREFETCH], page 133): as soon as a scheduling decision is taken for a task, requests are issued to transfer its required data to the target processing unit, if needeed, so that when the processing unit actually starts the task, its data will hopefully be already available and it will not have to wait for the transfer to finish.

The application may want to perform some manual prefetching, for several reasons such as excluding initial data transfers from performance measurements, or setting up an initial statically-computed data distribution on the machine before submitting tasks, which will thus guide StarPU toward an initial task distribution (since StarPU will try to avoid further transfers).

This can be achieved by giving the `starpu_data_prefetch_on_node` function the handle and the desired target memory node.

6.9 Power-based scheduling

If the application can provide some power performance model (through the `power_model` field of the codelet structure), StarPU will take it into account when distributing tasks. The target function that the `dmda` scheduler minimizes becomes `alpha * T_execution + beta * T_data_transfer + gamma * Consumption` , where `Consumption` is the estimated task consumption in Joules. To tune this parameter, use `export STARPU_SCHED_GAMMA=3000` for instance, to express that each Joule (i.e kW during 1000us) is worth 3000us execution time penalty. Setting `alpha` and `beta` to zero permits to only take into account power consumption.

This is however not sufficient to correctly optimize power: the scheduler would simply tend to run all computations on the most energy-conservative processing unit. To account for the consumption of the whole machine (including idle processing units), the idle power of the machine should be given by setting `export STARPU_IDLE_POWER=200` for 200W, for instance. This value can often be obtained from the machine power supplier.

The power actually consumed by the total execution can be displayed by setting `export STARPU_PROFILING=1 STARPU_WORKER_STATS=1` .

6.10 Profiling

A quick view of how many tasks each worker has executed can be obtained by setting `export STARPU_WORKER_STATS=1` This is a convenient way to check that execution did happen on accelerators without penalizing performance with the profiling overhead.

A quick view of how much data transfers have been issued can be obtained by setting `export STARPU_BUS_STATS=1` .

More detailed profiling information can be enabled by using `export STARPU_PROFILING=1` or by calling `starpu_profiling_status_set` from the source code. Statistics on the execution can then be obtained by using `export STARPU_BUS_STATS=1` and `export STARPU_WORKER_STATS=1` . More details on performance feedback are provided by the next chapter.

6.11 CUDA-specific optimizations

Due to CUDA limitations, StarPU will have a hard time overlapping its own communications and the codelet computations if the application does not use a dedicated CUDA stream for its computations. StarPU provides one by the use of `starpu_cuda_get_local_stream()` which should be used by all CUDA codelet operations. For instance:

```
func <<<grid,block,0,starpu_cuda_get_local_stream()>>> (foo, bar);
cudaStreamSynchronize(starpu_cuda_get_local_stream());
```

StarPU already does appropriate calls for the CUBLAS library.

Unfortunately, some CUDA libraries do not have stream variants of kernels. That will lower the potential for overlapping.

6.12 Performance debugging

To get an idea of what is happening, a lot of performance feedback is available, detailed in the next chapter. The various informations should be checked for.

- What does the Gantt diagram look like? (see Section 7.2.2 [Gantt diagram], page 52)
  - If it's mostly green (running tasks), then the machine is properly utilized, and perhaps the codelets are just slow. Check their performance, see Section 7.3 [Codelet performance], page 53.
  - If it's mostly purple (FetchingInput), tasks keep waiting for data transfers, do you perhaps have far more communication than computation? Did you properly use CUDA streams to make sure communication can be overlapped? Did you use data-locality aware schedulers to avoid transfers as much as possible?
  - If it's mostly red (Blocked), tasks keep waiting for dependencies, do you have enough parallelism? It might be a good idea to check what the DAG looks like (see Section 7.2.3 [DAG], page 52).
  - If only some workers are completely red (Blocked), for some reason the scheduler didn't assign tasks to them. Perhaps the performance model is bogus, check it

(see Section 7.3 [Codelet performance], page 53). Do all your codelets have a performance model? When some of them don't, the schedulers switches to a greedy algorithm which thus performs badly.

7 Performance feedback

7.1 On-line performance feedback

7.1.1 Enabling on-line performance monitoring

In order to enable online performance monitoring, the application can call `starpu_profiling_status_set(STARPU_PROFILING_ENABLE)`. It is possible to detect whether monitoring is already enabled or not by calling `starpu_profiling_status_get()`. Enabling monitoring also reinitialize all previously collected feedback. The `STARPU_PROFILING` environment variable can also be set to 1 to achieve the same effect.

Likewise, performance monitoring is stopped by calling `starpu_profiling_status_set(STARPU_PROFILING_DISABLE)`. Note that this does not reset the performance counters so that the application may consult them later on.

More details about the performance monitoring API are available in section Section 13.10 [Profiling API], page 107.

7.1.2 Per-task feedback

If profiling is enabled, a pointer to a `starpu_task_profiling_info` structure is put in the `.profiling_info` field of the `starpu_task` structure when a task terminates. This structure is automatically destroyed when the task structure is destroyed, either automatically or by calling `starpu_task_destroy`.

The `starpu_task_profiling_info` structure indicates the date when the task was submitted (`submit_time`), started (`start_time`), and terminated (`end_time`), relative to the initialization of StarPU with `starpu_init`. It also specifies the identifier of the worker that has executed the task (`workerid`). These date are stored as `timespec` structures which the user may convert into micro-seconds using the `starpu_timing_timespec_to_us` helper function.

It it worth noting that the application may directly access this structure from the callback executed at the end of the task. The `starpu_task` structure associated to the callback currently being executed is indeed accessible with the `starpu_get_current_task()` function.

7.1.3 Per-codelet feedback

The `per_worker_stats` field of the `struct starpu_codelet` structure is an array of counters. The i-th entry of the array is incremented every time a task implementing the codelet is executed on the i-th worker. This array is not reinitialized when profiling is enabled or disabled.

7.1.4 Per-worker feedback

The second argument returned by the `starpu_worker_get_profiling_info` function is a `starpu_worker_profiling_info` structure that gives statistics about the specified worker. This structure specifies when StarPU started collecting profiling information for that worker (`start_time`), the duration of the profiling measurement interval (`total_time`), the time spent executing kernels (`executing_time`), the time spent sleeping because there is no

task to execute at all (`sleeping_time`), and the number of tasks that were executed while profiling was enabled. These values give an estimation of the proportion of time spent do real work, and the time spent either sleeping because there are not enough executable tasks or simply wasted in pure StarPU overhead.

Calling `starpu_worker_get_profiling_info` resets the profiling information associated to a worker.

When an FxT trace is generated (see Section 7.2.1 [Generating traces], page 51), it is also possible to use the `starpu_workers_activity` script (described in Section 7.2.4 [starpu-workers-activity], page 52) to generate a graphic showing the evolution of these values during the time, for the different workers.

7.1.5 Bus-related feedback

TODO: ajouter STARPU_BUS_STATS

The bus speed measured by StarPU can be displayed by using the `starpu_machine_display` tool, for instance:

```
StarPU has found:
        3 CUDA devices
                CUDA 0 (Tesla C2050 02:00.0)
                CUDA 1 (Tesla C2050 03:00.0)
                CUDA 2 (Tesla C2050 84:00.0)
from    to RAM          to CUDA 0       to CUDA 1       to CUDA 2
RAM     0.000000        5176.530428     5176.492994     5191.710722
CUDA 0  4523.732446     0.000000        2414.074751     2417.379201
CUDA 1  4523.718152     2414.078822     0.000000        2417.375119
CUDA 2  4534.229519     2417.069025     2417.060863     0.000000
```

7.1.6 StarPU-Top interface

StarPU-Top is an interface which remotely displays the on-line state of a StarPU application and permits the user to change parameters on the fly.

Variables to be monitored can be registered by calling the `starpu_top_add_data_boolean`, `starpu_top_add_data_integer`, `starpu_top_add_data_float` functions, e.g.:

```
starpu_top_data *data = starpu_top_add_data_integer("mynum", 0, 100, 1);
```

The application should then call `starpu_top_init_and_wait` to give its name and wait for StarPU-Top to get a start request from the user. The name is used by StarPU-Top to quickly reload a previously-saved layout of parameter display.

```
starpu_top_init_and_wait("the application");
```

The new values can then be provided thanks to `starpu_top_update_data_boolean`, `starpu_top_update_data_integer`, `starpu_top_update_data_float`, e.g.:

```
starpu_top_update_data_integer(data, mynum);
```

Updateable parameters can be registered thanks to `starpu_top_register_parameter_boolean`, `starpu_top_register_parameter_integer`, `starpu_top_register_parameter_float`, e.g.:

```
float alpha;
starpu_top_register_parameter_float("alpha", &alpha, 0, 10, modif_hook);
```

`modif_hook` is a function which will be called when the parameter is being modified, it can for instance print the new value:

```
void modif_hook(struct starpu_top_param *d) {
    fprintf(stderr,"%s has been modified: %f\n", d->name, alpha);
}
```

Task schedulers should notify StarPU-Top when it has decided when a task will be scheduled, so that it can show it in its Gantt chart, for instance:

```
starpu_top_task_prevision(task, workerid, begin, end);
```

Starting StarPU-Top[1] and the application can be done two ways:

- The application is started by hand on some machine (and thus already waiting for the start event). In the Preference dialog of StarPU-Top, the SSH checkbox should be unchecked, and the hostname and port (default is 2011) on which the application is already running should be specified. Clicking on the connection button will thus connect to the already-running application.
- StarPU-Top is started first, and clicking on the connection button will start the application itself (possibly on a remote machine). The SSH checkbox should be checked, and a command line provided, e.g.:

  ```
  ssh myserver STARPU_SCHED=heft ./application
  ```

  If port 2011 of the remote machine can not be accessed directly, an ssh port bridge should be added:

  ```
  ssh -L 2011:localhost:2011 myserver STARPU_SCHED=heft ./application
  ```

  and "localhost" should be used as IP Address to connect to.

7.2 Off-line performance feedback

7.2.1 Generating traces with FxT

StarPU can use the FxT library (see `https://savannah.nongnu.org/projects/fkt/`) to generate traces with a limited runtime overhead.

You can either get a tarball:

```
% wget http://download.savannah.gnu.org/releases/fkt/fxt-0.2.2.tar.gz
```

or use the FxT library from CVS (autotools are required):

[1] StarPU-Top is started via the binary `starpu_top`.

```
% cvs -d :pserver:anonymous@cvs.sv.gnu.org:/sources/fkt co FxT
% ./bootstrap
```

Compiling and installing the FxT library in the `$FXTDIR` path is done following the standard procedure:

```
% ./configure --prefix=$FXTDIR
% make
% make install
```

In order to have StarPU to generate traces, StarPU should be configured with the `--with-fxt` option:

```
$ ./configure --with-fxt=$FXTDIR
```

Or you can simply point the `PKG_CONFIG_PATH` to `$FXTDIR/lib/pkgconfig` and pass `--with-fxt` to `./configure`

When FxT is enabled, a trace is generated when StarPU is terminated by calling `starpu_shutdown()`). The trace is a binary file whose name has the form `prof_file_XXX_YYY` where `XXX` is the user name, and `YYY` is the pid of the process that used StarPU. This file is saved in the `/tmp/` directory by default, or by the directory specified by the `STARPU_FXT_PREFIX` environment variable.

7.2.2 Creating a Gantt Diagram

When the FxT trace file `filename` has been generated, it is possible to generate a trace in the Paje format by calling:

```
% starpu_fxt_tool -i filename
```

Or alternatively, setting the `STARPU_GENERATE_TRACE` environment variable to 1 before application execution will make StarPU do it automatically at application shutdown.

This will create a `paje.trace` file in the current directory that can be inspected with the ViTE trace visualizing open-source tool. More information about ViTE is available at `http://vite.gforge.inria.fr/`. It is possible to open the `paje.trace` file with ViTE by using the following command:

```
% vite paje.trace
```

7.2.3 Creating a DAG with graphviz

When the FxT trace file `filename` has been generated, it is possible to generate a task graph in the DOT format by calling:

```
$ starpu_fxt_tool -i filename
```

This will create a `dag.dot` file in the current directory. This file is a task graph described using the DOT language. It is possible to get a graphical output of the graph by using the graphviz library:

```
$ dot -Tpdf dag.dot -o output.pdf
```

7.2.4 Monitoring activity

When the FxT trace file `filename` has been generated, it is possible to generate an activity trace by calling:

```
$ starpu_fxt_tool -i filename
```

This will create an `activity.data` file in the current directory. A profile of the application showing the activity of StarPU during the execution of the program can be generated:

```
$ starpu_workers_activity activity.data
```

This will create a file named `activity.eps` in the current directory. This picture is composed of two parts. The first part shows the activity of the different workers. The green sections indicate which proportion of the time was spent executed kernels on the processing unit. The red sections indicate the proportion of time spent in StartPU: an important overhead may indicate that the granularity may be too low, and that bigger tasks may be appropriate to use the processing unit more efficiently. The black sections indicate that the processing unit was blocked because there was no task to process: this may indicate a lack of parallelism which may be alleviated by creating more tasks when it is possible.

The second part of the `activity.eps` picture is a graph showing the evolution of the number of tasks available in the system during the execution. Ready tasks are shown in black, and tasks that are submitted but not schedulable yet are shown in grey.

7.3 Performance of codelets

The performance model of codelets (described in Section 5.5 [Performance model example], page 31) can be examined by using the `starpu_perfmodel_display` tool:

```
$ starpu_perfmodel_display -l
file: <malloc_pinned.hannibal>
file: <starpu_slu_lu_model_21.hannibal>
file: <starpu_slu_lu_model_11.hannibal>
file: <starpu_slu_lu_model_22.hannibal>
file: <starpu_slu_lu_model_12.hannibal>
```

Here, the codelets of the lu example are available. We can examine the performance of the 22 kernel (in micro-seconds):

```
$ starpu_perfmodel_display -s starpu_slu_lu_model_22
performance model for cpu
# hash      size       mean          dev           n
57618ab0    19660800   2.851069e+05  1.829369e+04  109
performance model for cuda_0
# hash      size       mean          dev           n
57618ab0    19660800   1.164144e+04  1.556094e+01  315
performance model for cuda_1
# hash      size       mean          dev           n
57618ab0    19660800   1.164271e+04  1.330628e+01  360
performance model for cuda_2
# hash      size       mean          dev           n
57618ab0    19660800   1.166730e+04  3.390395e+02  456
```

We can see that for the given size, over a sample of a few hundreds of execution, the GPUs are about 20 times faster than the CPUs (numbers are in us). The standard deviation is extremely low for the GPUs, and less than 10% for CPUs.

The `starpu_regression_display` tool does the same for regression-based performance models. It also writes a `.gp` file in the current directory, to be run in the `gnuplot` tool, which shows the corresponding curve.

The same can also be achieved by using StarPU's library API, see Section 13.9 [Performance Model API], page 104 and notably the `starpu_load_history_debug` function. The source code of the `starpu_perfmodel_display` tool can be a useful example.

7.4 Theoretical lower bound on execution time

See Section 5.6 [Theoretical lower bound on execution time], page 33 for an example on how to use this API. It permits to record a trace of what tasks are needed to complete the application, and then, by using a linear system, provide a theoretical lower bound of the execution time (i.e. with an ideal scheduling).

The computed bound is not really correct when not taking into account dependencies, but for an application which have enough parallelism, it is very near to the bound computed with dependencies enabled (which takes a huge lot more time to compute), and thus provides a good-enough estimation of the ideal execution time.

`void starpu_bound_start (int deps, int prio)` [Function]
Start recording tasks (resets stats). *deps* tells whether dependencies should be recorded too (this is quite expensive)

`void starpu_bound_stop (void)` [Function]
Stop recording tasks

`void starpu_bound_print_dot (FILE *output)` [Function]
Print the DAG that was recorded

`void starpu_bound_compute (double *res, double *integer_res, int integer)` [Function]
Get theoretical upper bound (in ms) (needs glpk support detected by `configure` script)

`void starpu_bound_print_lp (FILE *output)` [Function]
Emit the Linear Programming system on *output* for the recorded tasks, in the lp format

`void starpu_bound_print_mps (FILE *output)` [Function]
Emit the Linear Programming system on *output* for the recorded tasks, in the mps format

`void starpu_bound_print (FILE *output, int integer)` [Function]
Emit statistics of actual execution vs theoretical upper bound. *integer* permits to choose between integer solving (which takes a long time but is correct), and relaxed solving (which provides an approximate solution).

8 Tips and Tricks to know about

8.1 How to initialize a computation library once for each worker?

Some libraries need to be initialized once for each concurrent instance that may run on the machine. For instance, a C++ computation class which is not thread-safe by itself, but for which several instanciated objects of that class can be used concurrently. This can be used in StarPU by initializing one such object per worker. For instance, the libstarpufft example does the following to be able to use FFTW.

Some global array stores the instanciated objects:

```
fftw_plan plan_cpu[STARPU_NMAXWORKERS];
```

At initialisation time of libstarpu, the objects are initialized:

```
int workerid;
for (workerid = 0; workerid < starpu_worker_get_count(); workerid++) {
    switch (starpu_worker_get_type(workerid)) {
        case STARPU_CPU_WORKER:
            plan_cpu[workerid] = fftw_plan(...);
            break;
    }
}
```

And in the codelet body, they are used:

```
static void fft(void *descr[], void *_args)
{
    int workerid = starpu_worker_get_id();
    fftw_plan plan = plan_cpu[workerid];
    ...

    fftw_execute(plan, ...);
}
```

Another way to go which may be needed is to execute some code from the workers themselves thanks to `starpu_execute_on_each_worker`. This may be required by CUDA to behave properly due to threading issues. For instance, StarPU's `starpu_helper_cublas_init` looks like the following to call `cublasInit` from the workers themselves:

```
static void init_cublas_func(void *args STARPU_ATTRIBUTE_UNUSED)
{
    cublasStatus cublasst = cublasInit();
    cublasSetKernelStream(starpu_cuda_get_local_stream());
}
void starpu_helper_cublas_init(void)
{
    starpu_execute_on_each_worker(init_cublas_func, NULL, STARPU_CUDA);
}
```

9 StarPU MPI support

The integration of MPI transfers within task parallelism is done in a very natural way by the means of asynchronous interactions between the application and StarPU. This is implemented in a separate libstarpumpi library which basically provides "StarPU" equivalents of `MPI_*` functions, where `void *` buffers are replaced with `starpu_data_handle_t`s, and all GPU-RAM-NIC transfers are handled efficiently by StarPU-MPI. The user has to use the usual `mpirun` command of the MPI implementation to start StarPU on the different MPI nodes.

An MPI Insert Task function provides an even more seamless transition to a distributed application, by automatically issuing all required data transfers according to the task graph and an application-provided distribution.

9.1 The API

9.1.1 Compilation

The flags required to compile or link against the MPI layer are then accessible with the following commands:

```
% pkg-config --cflags starpumpi-1.0  # options for the compiler
% pkg-config --libs starpumpi-1.0    # options for the linker
```

Also pass the `--static` option if the application is to be linked statically.

9.1.2 Initialisation

`int starpu_mpi_initialize` (*void*) [Function]
Initializes the starpumpi library. This must be called between calling `starpu_init` and other `starpu_mpi` functions. This function does not call `MPI_Init`, it should be called beforehand.

`int starpu_mpi_initialize_extended` (*int *rank*, *int *world_size*) [Function]
Initializes the starpumpi library. This must be called between calling `starpu_init` and other `starpu_mpi` functions. This function calls `MPI_Init`, and therefore should be prefered to the previous one for MPI implementations which are not thread-safe. Returns the current MPI node rank and world size.

`int starpu_mpi_shutdown` (*void*) [Function]
Cleans the starpumpi library. This must be called between calling `starpu_mpi` functions and `starpu_shutdown`. `MPI_Finalize` will be called if StarPU-MPI has been initialized by calling `starpu_mpi_initialize_extended`.

9.1.3 Communication

The standard point to point communications of MPI have been implemented. The semantic is similar to the MPI one, but adapted to the DSM provided by StarPU. A MPI request will only be submitted when the data is available in the main memory of the node submitting the request.

`int starpu_mpi_send` (*starpu_data_handle_t* `data_handle`, *int* `dest`, *int* `mpi_tag`, *MPI_Comm* `comm`) [Function]

Performs a standard-mode, blocking send of *data_handle* to the node *dest* using the message tag `mpi_tag` within the communicator *comm*.

`int starpu_mpi_recv` (*starpu_data_handle_t* `data_handle`, *int* `source`, *int* `mpi_tag`, *MPI_Comm* `comm`, *MPI_Status* *`status`) [Function]

Performs a standard-mode, blocking receive in *data_handle* from the node *source* using the message tag `mpi_tag` within the communicator *comm*.

`int starpu_mpi_isend` (*starpu_data_handle_t* `data_handle`, *starpu_mpi_req* *`req`, *int* `dest`, *int* `mpi_tag`, *MPI_Comm* `comm`) [Function]

Posts a standard-mode, non blocking send of *data_handle* to the node *dest* using the message tag `mpi_tag` within the communicator *comm*. After the call, the pointer to the request *req* can be used to test the completion of the communication.

`int starpu_mpi_irecv` (*starpu_data_handle_t* `data_handle`, *starpu_mpi_req* *`req`, *int* `source`, *int* `mpi_tag`, *MPI_Comm* `comm`) [Function]

Posts a nonblocking receive in *data_handle* from the node *source* using the message tag `mpi_tag` within the communicator *comm*. After the call, the pointer to the request *req* can be used to test the completion of the communication.

`int starpu_mpi_isend_detached` (*starpu_data_handle_t* `data_handle`, *int* `dest`, *int* `mpi_tag`, *MPI_Comm* `comm`, *void* (*`callback`)(*void* *), *void* *`arg`) [Function]

Posts a standard-mode, non blocking send of *data_handle* to the node *dest* using the message tag `mpi_tag` within the communicator *comm*. On completion, the *callback* function is called with the argument *arg*.

`int starpu_mpi_irecv_detached` (*starpu_data_handle_t* `data_handle`, *int* `source`, *int* `mpi_tag`, *MPI_Comm* `comm`, *void* (*`callback`)(*void* *), *void* *`arg`) [Function]

Posts a nonblocking receive in *data_handle* from the node *source* using the message tag `mpi_tag` within the communicator *comm*. On completion, the *callback* function is called with the argument *arg*.

`int starpu_mpi_wait` (*starpu_mpi_req* *`req`, *MPI_Status* *`status`) [Function]

Returns when the operation identified by request *req* is complete.

`int starpu_mpi_test` (*starpu_mpi_req* *`req`, *int* *`flag`, *MPI_Status* *`status`) [Function]

If the operation identified by *req* is complete, set *flag* to 1. The *status* object is set to contain information on the completed operation.

`int starpu_mpi_barrier` (*MPI_Comm* `comm`) [Function]

Blocks the caller until all group members of the communicator *comm* have called it.

`int starpu_mpi_isend_detached_unlock_tag (`*starpu_data_handle_t* **`data_handle`**, *int* **`dest`**, *int* **`mpi_tag`**, *MPI_Comm* **`comm`**, *starpu_tag_t* **`tag`**`)` [Function]

Posts a standard-mode, non blocking send of *data_handle* to the node *dest* using the message tag `mpi_tag` within the communicator *comm*. On completion, *tag* is unlocked.

`int starpu_mpi_irecv_detached_unlock_tag (`*starpu_data_handle_t* **`data_handle`**, *int* **`source`**, *int* **`mpi_tag`**, *MPI_Comm* **`comm`**, *starpu_tag_t* **`tag`**`)` [Function]

Posts a nonblocking receive in *data_handle* from the node *source* using the message tag `mpi_tag` within the communicator *comm*. On completion, *tag* is unlocked.

`int starpu_mpi_isend_array_detached_unlock_tag (`*unsigned* **`array_size`**, *starpu_data_handle_t* ***`data_handle`**, *int* ***`dest`**, *int* ***`mpi_tag`**, *MPI_Comm* ***`comm`**, *starpu_tag_t* **`tag`**`)` [Function]

Posts *array_size* standard-mode, non blocking send of the data of data *data_handle[x]* to the node *dest[x]* using the message tag `mpi_tag[x]` within the communicator *comm[x]*. On completion of the all the requests, *tag* is unlocked.

`int starpu_mpi_irecv_array_detached_unlock_tag (`*unsigned* **`array_size`**, *starpu_data_handle_t* ***`data_handle`**, *int* ***`source`**, *int* ***`mpi_tag`**, *MPI_Comm* ***`comm`**, *starpu_tag_t* **`tag`**`)` [Function]

Posts *array_size* nonblocking receive in *data_handle[x]* from the node *source[x]* using the message tag `mpi_tag[x]` within the communicator *comm[x]*. On completion of the all the requests, *tag* is unlocked.

9.2 Simple Example

```
void increment_token(void)
{
    struct starpu_task *task = starpu_task_create();

    task->cl = &increment_cl;
    task->handles[0] = token_handle;

    starpu_task_submit(task);
}
```

```
int main(int argc, char **argv)
{
    int rank, size;

    starpu_init(NULL);
    starpu_mpi_initialize_extended(&rank, &size);

    starpu_vector_data_register(&token_handle, 0, (uintptr_t)&token, 1, sizeof(unsigned));

    unsigned nloops = NITER;
    unsigned loop;

    unsigned last_loop = nloops - 1;
    unsigned last_rank = size - 1;
```

```
for (loop = 0; loop < nloops; loop++) {
    int tag = loop*size + rank;

    if (loop == 0 && rank == 0)
    {
        token = 0;
        fprintf(stdout, "Start with token value %d\n", token);
    }
    else
    {
        starpu_mpi_irecv_detached(token_handle, (rank+size-1)%size, tag,
                MPI_COMM_WORLD, NULL, NULL);
    }

    increment_token();

    if (loop == last_loop && rank == last_rank)
    {
        starpu_data_acquire(token_handle, STARPU_R);
        fprintf(stdout, "Finished: token value %d\n", token);
        starpu_data_release(token_handle);
    }
    else
    {
        starpu_mpi_isend_detached(token_handle, (rank+1)%size, tag+1,
                MPI_COMM_WORLD, NULL, NULL);
    }
}

starpu_task_wait_for_all();
```

```
starpu_mpi_shutdown();
starpu_shutdown();

if (rank == last_rank)
{
    fprintf(stderr, "[%d] token = %d == %d * %d ?\n", rank, token, nloops, size);
    STARPU_ASSERT(token == nloops*size);
}
```

9.3 MPI Insert Task Utility

To save the programmer from having to explicit all communications, StarPU provides an "MPI Insert Task Utility". The principe is that the application decides a distribution of the data over the MPI nodes by allocating it and notifying StarPU of that decision, i.e. tell StarPU which MPI node "owns" which data. All MPI nodes then process the whole task graph, and StarPU automatically determines which node actually execute which task, as well as the required MPI transfers.

`int starpu_data_set_tag` (*starpu_data_handle_t* `handle`, *int* `tag`) [Function]
Tell StarPU-MPI which MPI tag to use when exchanging the data.

`int starpu_data_get_tag` (*starpu_data_handle_t* `handle`) [Function]
Returns the MPI tag to be used when exchanging the data.

`int starpu_data_set_rank` (*starpu_data_handle_t* `handle`, *int* `rank`) [Function]
Tell StarPU-MPI which MPI node "owns" a given data, that is, the node which will always keep an up-to-date value, and will by default execute tasks which write to it.

`int starpu_data_get_rank` (*starpu_data_handle_t* `handle`) [Function]
Returns the last value set by `starpu_data_set_rank`.

`STARPU_EXECUTE_ON_NODE` [Macro]
this macro is used when calling `starpu_mpi_insert_task`, and must be followed by a integer value which specified the node on which to execute the codelet.

`STARPU_EXECUTE_ON_DATA` [Macro]
this macro is used when calling `starpu_mpi_insert_task`, and must be followed by a data handle to specify that the node owning the given data will execute the codelet.

`int starpu_mpi_insert_task` (*MPI_Comm* `comm`, *struct starpu_codelet* *`codelet`, ...) [Function]
Create and submit a task corresponding to *codelet* with the following arguments. The argument list must be zero-terminated.

The arguments following the codelets are the same types as for the function `starpu_insert_task` defined in Section 5.7 [Insert Task Utility], page 34. The extra argument `STARPU_EXECUTE_ON_NODE` followed by an integer allows to specify the MPI node to execute the codelet. It is also possible to specify that the node owning a specific data will execute the codelet, by using `STARPU_EXECUTE_ON_DATA` followed by a data handle.

The internal algorithm is as follows:

1. Find out whether we (as an MPI node) are to execute the codelet because we own the data to be written to. If different nodes own data to be written to, the argument `STARPU_EXECUTE_ON_NODE` or `STARPU_EXECUTE_ON_DATA` has to be used to specify which MPI node will execute the task.
2. Send and receive data as requested. Nodes owning data which need to be read by the task are sending them to the MPI node which will execute it. The latter receives them.

3. Execute the codelet. This is done by the MPI node selected in the 1st step of the algorithm.

4. In the case when different MPI nodes own data to be written to, send written data back to their owners.

The algorithm also includes a cache mechanism that allows not to send data twice to the same MPI node, unless the data has been modified.

`void starpu_mpi_get_data_on_node` (*MPI_Comm* `comm`, *starpu_data_handle_t* `data_handle`, *int* `node`) [Function]

Transfer data *data_handle* to MPI node *node*, sending it from its owner if needed. At least the target node and the owner have to call the function.

Here an stencil example showing how to use `starpu_mpi_insert_task`. One first needs to define a distribution function which specifies the locality of the data. Note that that distribution information needs to be given to StarPU by calling `starpu_data_set_rank`.

```
/* Returns the MPI node number where data is */
int my_distrib(int x, int y, int nb_nodes) {
  /* Block distrib */
  return ((int)(x / sqrt(nb_nodes) + (y / sqrt(nb_nodes)) * sqrt(nb_nodes))) % nb_nodes;

  // /* Other examples useful for other kinds of computations */
  // /* / distrib */
  // return (x+y) % nb_nodes;

  // /* Block cyclic distrib */
  // unsigned side = sqrt(nb_nodes);
  // return x % side + (y % side) * size;
}
```

Now the data can be registered within StarPU. Data which are not owned but will be needed for computations can be registered through the lazy allocation mechanism, i.e. with a `home_node` set to -1. StarPU will automatically allocate the memory when it is used for the first time.

One can note an optimization here (the `else if` test): we only register data which will be needed by the tasks that we will execute.

```
unsigned matrix[X][Y];
starpu_data_handle_t data_handles[X][Y];

for(x = 0; x < X; x++) {
    for (y = 0; y < Y; y++) {
        int mpi_rank = my_distrib(x, y, size);
         if (mpi_rank == my_rank)
            /* Owning data */
            starpu_variable_data_register(&data_handles[x][y], 0,
                                          (uintptr_t)&(matrix[x][y]), sizeof(unsigned));
        else if (my_rank == my_distrib(x+1, y, size) || my_rank == my_distrib(x-1, y, size)
              || my_rank == my_distrib(x, y+1, size) || my_rank == my_distrib(x, y-1, size))
            /* I don't own that index, but will need it for my computations */
            starpu_variable_data_register(&data_handles[x][y], -1,
                                          (uintptr_t)NULL, sizeof(unsigned));
        else
            /* I know it's useless to allocate anything for this */
            data_handles[x][y] = NULL;
        if (data_handles[x][y])
            starpu_data_set_rank(data_handles[x][y], mpi_rank);
    }
}
```

Now `starpu_mpi_insert_task()` can be called for the different steps of the application.

```
for(loop=0 ; loop<niter; loop++)
    for (x = 1; x < X-1; x++)
        for (y = 1; y < Y-1; y++)
            starpu_mpi_insert_task(MPI_COMM_WORLD, &stencil5_cl,
                                   STARPU_RW, data_handles[x][y],
                                   STARPU_R, data_handles[x-1][y],
                                   STARPU_R, data_handles[x+1][y],
                                   STARPU_R, data_handles[x][y-1],
                                   STARPU_R, data_handles[x][y+1],
                                   0);
starpu_task_wait_for_all();
```

I.e. all MPI nodes process the whole task graph, but as mentioned above, for each task, only the MPI node which owns the data being written to (here, `data_handles[x][y]`) will actually run the task. The other MPI nodes will automatically send the required data.

9.4 MPI Collective Operations

`int starpu_mpi_scatter_detached` (*starpu_data_handle_t* *`data_handles`, *int* `count`, *int* `root`, *MPI_Comm* `comm`) [Function]

Scatter data among processes of the communicator based on the ownership of the data. For each data of the array *data_handles*, the process *root* sends the data to the process owning this data. Processes receiving data must have valid data handles to receive them.

`int starpu_mpi_gather_detached` (*starpu_data_handle_t* *`data_handles`, *int* `count`, *int* `root`, *MPI_Comm* `comm`) [Function]

Gather data from the different processes of the communicator onto the process *root*. Each process owning data handle in the array *data_handles* will send them to the process *root*. The process *root* must have valid data handles to receive the data.

```
if (rank == root)
{
    /* Allocate the vector */
    vector = malloc(nblocks * sizeof(float *));
    for(x=0 ; x<nblocks ; x++)
    {
        starpu_malloc((void **)&vector[x], block_size*sizeof(float));
    }
}

/* Allocate data handles and register data to StarPU */
data_handles = malloc(nblocks*sizeof(starpu_data_handle_t *));
for(x = 0; x < nblocks ;  x++)
{
    int mpi_rank = my_distrib(x, nodes);
    if (rank == root) {
        starpu_vector_data_register(&data_handles[x], 0, (uintptr_t)vector[x],
                                    blocks_size, sizeof(float));
    }
    else if ((mpi_rank == rank) || ((rank == mpi_rank+1 || rank == mpi_rank-1))) {
        /* I own that index, or i will need it for my computations */
        starpu_vector_data_register(&data_handles[x], -1, (uintptr_t)NULL,
                                   block_size, sizeof(float));
    }
    else {
        /* I know it's useless to allocate anything for this */
        data_handles[x] = NULL;
    }
    if (data_handles[x]) {
        starpu_data_set_rank(data_handles[x], mpi_rank);
    }
}

/* Scatter the matrix among the nodes */
starpu_mpi_scatter_detached(data_handles, nblocks, root, MPI_COMM_WORLD);

/* Calculation */
for(x = 0; x < nblocks ;  x++) {
    if (data_handles[x]) {
        int owner = starpu_data_get_rank(data_handles[x]);
        if (owner == rank) {
            starpu_insert_task(&cl, STARPU_RW, data_handles[x], 0);
        }
    }
}

/* Gather the matrix on main node */
starpu_mpi_gather_detached(data_handles, nblocks, 0, MPI_COMM_WORLD);
```

10 StarPU FFT support

StarPU provides `libstarpufft`, a library whose design is very similar to both fftw and cufft, the difference being that it takes benefit from both CPUs and GPUs. It should however be noted that GPUs do not have the same precision as CPUs, so the results may different by a negligible amount

float, double and long double precisions are available, with the fftw naming convention:

1. double precision structures and functions are named e.g. `starpufft_execute`
2. float precision structures and functions are named e.g. `starpufftf_execute`
3. long double precision structures and functions are named e.g. `starpufftl_execute`

The documentation below uses names for double precision, replace `starpufft_` with `starpufftf_` or `starpufftl_` as appropriate.

Only complex numbers are supported at the moment.

The application has to call `starpu_init` before calling starpufft functions.

Either main memory pointers or data handles can be provided.

1. To provide main memory pointers, use `starpufft_start` or `starpufft_execute`. Only one FFT can be performed at a time, because StarPU will have to register the data on the fly. In the `starpufft_start` case, `starpufft_cleanup` needs to be called to unregister the data.
2. To provide data handles (which is preferrable), use `starpufft_start_handle` (preferred) or `starpufft_execute_handle`. Several FFTs Several FFT tasks can be submitted for a given plan, which permits e.g. to start a series of FFT with just one plan. `starpufft_start_handle` is preferrable since it does not wait for the task completion, and thus permits to enqueue a series of tasks.

10.1 Compilation

The flags required to compile or link against the FFT library are accessible with the following commands:

```
% pkg-config --cflags starpufft-1.0  # options for the compiler
% pkg-config --libs starpufft-1.0    # options for the linker
```

Also pass the `--static` option if the application is to be linked statically.

10.2 Initialisation

`void * starpufft_malloc` (*size_t* `n`) [Function]

Allocates memory for *n* bytes. This is preferred over `malloc`, since it allocates pinned memory, which allows overlapped transfers.

`void * starpufft_free` (*void* `*p`) [Function]

Release memory previously allocated.

`struct starpufft_plan * starpufft_plan_dft_1d` (*int* `n`, *int* `sign`, *unsigned* `flags`) [Function]

Initializes a plan for 1D FFT of size *n*. *sign* can be `STARPUFFT_FORWARD` or `STARPUFFT_INVERSE`. *flags* must be 0.

`struct starpufft_plan * starpufft_plan_dft_2d` (*int* `n`, *int* `m`, *int* `sign`, *unsigned* `flags`) [Function]

Initializes a plan for 2D FFT of size (n, m). *sign* can be `STARPUFFT_FORWARD` or `STARPUFFT_INVERSE`. *flags* must be 0.

`struct starpu_task * starpufft_start` (*starpufft_plan* `p`, *void* *`in`, *void* *`out`) [Function]

Start an FFT previously planned as p, using *in* and *out* as input and output. This only submits the task and does not wait for it. The application should call `starpufft_cleanup` to unregister the data.

`struct starpu_task * starpufft_start_handle` (*starpufft_plan* `p`, *starpu_data_handle_t* `in`, *starpu_data_handle_t* `out`) [Function]

Start an FFT previously planned as p, using data handles *in* and *out* as input and output (assumed to be vectors of elements of the expected types). This only submits the task and does not wait for it.

`void starpufft_execute` (*starpufft_plan* `p`, *void* *`in`, *void* *`out`) [Function]

Execute an FFT previously planned as p, using *in* and *out* as input and output. This submits and waits for the task.

`void starpufft_execute_handle` (*starpufft_plan* `p`, *starpu_data_handle_t* `in`, *starpu_data_handle_t* `out`) [Function]

Execute an FFT previously planned as p, using data handles *in* and *out* as input and output (assumed to be vectors of elements of the expected types). This submits and waits for the task.

`void starpufft_cleanup` (*starpufft_plan* `p`) [Function]

Releases data for plan p, in the `starpufft_start` case.

`void starpufft_destroy_plan` (*starpufft_plan* `p`) [Function]

Destroys plan p, i.e. release all CPU (fftw) and GPU (cufft) resources.

11 C Extensions

When GCC plug-in support is available, StarPU builds a plug-in for the GNU Compiler Collection (GCC), which defines extensions to languages of the C family (C, C++, Objective-C) that make it easier to write StarPU code[1].

Those extensions include syntactic sugar for defining tasks and their implementations, invoking a task, and manipulating data buffers. Use of these extensions can be made conditional on the availability of the plug-in, leading to valid C sequential code when the plug-in is not used (see Section 11.4 [Conditional Extensions], page 73).

When StarPU has been installed with its GCC plug-in, programs that use these extensions can be compiled this way:

```
$ gcc -c -fplugin=‘pkg-config starpu-1.0 --variable=gccplugin‘ foo.c
```

When the plug-in is not available, the above `pkg-config` command returns the empty string.

In addition, the `-fplugin-arg-starpu-verbose` flag can be used to obtain feedback from the compiler as it analyzes the C extensions used in source files.

This section describes the C extensions implemented by StarPU's GCC plug-in. It does not require detailed knowledge of the StarPU library.

Note: as of StarPU 1.0.0rc4, this is still an area under development and subject to change.

11.1 Defining Tasks

The StarPU GCC plug-in views *tasks* as "extended" C functions:

1. tasks may have several implementations—e.g., one for CPUs, one written in OpenCL, one written in CUDA;
2. tasks may have several implementations of the same target—e.g., several CPU implementations;
3. when a task is invoked, it may run in parallel, and StarPU is free to choose any of its implementations.

Tasks and their implementations must be *declared*. These declarations are annotated with *attributes* (see Section "Attribute Syntax" in *Using the GNU Compiler Collection (GCC)*): the declaration of a task is a regular C function declaration with an additional `task` attribute, and task implementations are declared with a `task_implementation` attribute.

The following function attributes are provided:

`task`
: Declare the given function as a StarPU task. Its return type must be `void`, and it must not be defined—instead, a definition will automatically be provided by the compiler.

  Under the hood, declaring a task leads to the declaration of the corresponding `codelet` (see Section 1.2.1 [Codelet and Tasks], page 3). If one or more task

[1] This feature is only available for GCC 4.5 and later; it is known to work with GCC 4.5, 4.6, and 4.7. You may need to install a specific `-dev` package of your distro, such as `gcc-4.6-plugin-dev` on Debian and derivatives. In addition, the plug-in's test suite is only run when GNU Guile is found at `configure`-time. Building the GCC plug-in can be disabled by configuring with `--disable-gcc-extensions`.

implementations are declared in the same compilation unit, then the codelet and the function itself are also defined; they inherit the scope of the task.

Scalar arguments to the task are passed by value and copied to the target device if need be—technically, they are passed as the `cl_arg` buffer (see Section 13.6 [Codelets and Tasks], page 95).

Pointer arguments are assumed to be registered data buffers—the `buffers` argument of a task (see Section 13.6 [Codelets and Tasks], page 95); `const`-qualified pointer arguments are viewed as read-only buffers (`STARPU_R`), and non-`const`-qualified buffers are assumed to be used read-write (`STARPU_RW`). In addition, the `output` type attribute can be as a type qualifier for output pointer or array parameters (`STARPU_W`).

`task_implementation (`*target*`, `*task*`)`

Declare the given function as an implementation of *task* to run on *target*. *target* must be a string, currently one of `"cpu"`, `"opencl"`, or `"cuda"`.

Here is an example:

```
#define __output  __attribute__ ((output))

static void matmul (const float *A, const float *B,
                    __output float *C,
                    unsigned nx, unsigned ny, unsigned nz)
  __attribute__ ((task));

static void matmul_cpu (const float *A, const float *B,
                        __output float *C,
                        unsigned nx, unsigned ny, unsigned nz)
  __attribute__ ((task_implementation ("cpu", matmul)));


static void
matmul_cpu (const float *A, const float *B, __output float *C,
            unsigned nx, unsigned ny, unsigned nz)
{
  unsigned i, j, k;

  for (j = 0; j < ny; j++)
    for (i = 0; i < nx; i++)
      {
        for (k = 0; k < nz; k++)
          C[j * nx + i] += A[j * nz + k] * B[k * nx + i];
      }
}
```

A `matmult` task is defined; it has only one implementation, `matmult_cpu`, which runs on the CPU. Variables A and B are input buffers, whereas C is considered an input/output buffer.

CUDA and OpenCL implementations can be declared in a similar way:

```
static void matmul_cuda (const float *A, const float *B, float *C,
                         unsigned nx, unsigned ny, unsigned nz)
  __attribute__ ((task_implementation ("cuda", matmul)));

static void matmul_opencl (const float *A, const float *B, float *C,
                           unsigned nx, unsigned ny, unsigned nz)
  __attribute__ ((task_implementation ("opencl", matmul)));
```

The CUDA and OpenCL implementations typically either invoke a kernel written in CUDA or OpenCL (for similar code, see Section A.3 [CUDA Kernel], page 138, and see Section A.4 [OpenCL Kernel], page 138), or call a library function that uses CUDA or OpenCL under the hood, such as CUBLAS functions:

```
static void
matmul_cuda (const float *A, const float *B, float *C,
             unsigned nx, unsigned ny, unsigned nz)
{
  cublasSgemm ('n', 'n', nx, ny, nz,
               1.0f, A, 0, B, 0,
               0.0f, C, 0);
  cudaStreamSynchronize (starpu_cuda_get_local_stream ());
}
```

A task can be invoked like a regular C function:

```
matmul (&A[i * zdim * bydim + k * bzdim * bydim],
        &B[k * xdim * bzdim + j * bxdim * bzdim],
        &C[i * xdim * bydim + j * bxdim * bydim],
        bxdim, bydim, bzdim);
```

This leads to an *asynchronous invocation*, whereby `matmult`'s implementation may run in parallel with the continuation of the caller.

The next section describes how memory buffers must be handled in StarPU-GCC code. For a complete example, see the `gcc-plugin/examples` directory of the source distribution, and Section 4.3 [Vector Scaling Using the C Extension], page 15.

11.2 Initialization, Termination, and Synchronization

The following pragmas allow user code to control StarPU's life time and to synchronize with tasks.

`#pragma starpu initialize`
: Initialize StarPU. This call is compulsory and is *never* added implicitly. One of the reasons this has to be done explicitly is that it provides greater control to user code over its resource usage.

`#pragma starpu shutdown`
: Shut down StarPU, giving it an opportunity to write profiling info to a file on disk, for instance (see Section 7.2 [Off-line], page 51).

`#pragma starpu wait`
: Wait for all task invocations to complete, as with `starpu_wait_for_all` (see Section 13.6 [Codelets and Tasks], page 95).

11.3 Registered Data Buffers

Data buffers such as matrices and vectors that are to be passed to tasks must be *registered*. Registration allows StarPU to handle data transfers among devices—e.g., transferring an input buffer from the CPU's main memory to a task scheduled to run a GPU (see Section 1.2.2 [StarPU Data Management Library], page 4).

The following pragmas are provided:

`#pragma starpu register` *`ptr`* `[`*`size`*`]`
: Register *ptr* as a *size*-element buffer. When *ptr* has an array type whose size is known, *size* may be omitted.

`#pragma starpu unregister` *`ptr`*
: Unregister the previously-registered memory area pointed to by *ptr*. As a side-effect, *ptr* points to a valid copy in main memory.

`#pragma starpu acquire` *`ptr`*
: Acquire in main memory an up-to-date copy of the previously-registered memory area pointed to by *ptr*, for read-write access.

`#pragma starpu release` *`ptr`*
: Release the previously-register memory area pointed to by *ptr*, making it available to the tasks.

Additionally, the `heap_allocated` variable attribute offers a simple way to allocate storage for arrays on the heap:

`heap_allocated`
: This attributes applies to local variables with an array type. Its effect is to automatically allocate the array's storage on the heap, using `starpu_malloc` under the hood (see Section 13.3.2 [Basic Data Library API], page 81). The heap-allocated array is automatically freed when the variable's scope is left, as with automatic variables.

The following example illustrates use of the `heap_allocated` attribute:

```
extern void cholesky(unsigned nblocks, unsigned size,
                     float mat[nblocks][nblocks][size])
  __attribute__ ((task));

int
main (int argc, char *argv[])
{
#pragma starpu initialize

  /* ... */

  int nblocks, size;
  parse_args (&nblocks, &size);

  /* Allocate an array of the required size on the heap,
     and register it.  */
```

```
  {
    float matrix[nblocks][nblocks][size]
      __attribute__ ((heap_allocated));

#pragma starpu register matrix

    cholesky (nblocks, size, matrix);

#pragma starpu wait
#pragma starpu unregister matrix

  }   /* MATRIX is automatically freed here.  */

#pragma starpu shutdown

  return EXIT_SUCCESS;
}
```

11.4 Using C Extensions Conditionally

The C extensions described in this chapter are only available when GCC and its StarPU plug-in are in use. Yet, it is possible to make use of these extensions when they are available—leading to hybrid CPU/GPU code—and discard them when they are not available—leading to valid sequential code.

To that end, the GCC plug-in defines a C preprocessor macro when it is being used:

`STARPU_GCC_PLUGIN` [Macro]

Defined for code being compiled with the StarPU GCC plug-in. When defined, this macro expands to an integer denoting the version of the supported C extensions.

The code below illustrates how to define a task and its implementations in a way that allows it to be compiled without the GCC plug-in:

```
/* The macros below abstract over the attributes specific to
   StarPU-GCC and the name of the CPU implementation.  */
#ifdef STARPU_GCC_PLUGIN
# define __task  __attribute__ ((task))
# define CPU_TASK_IMPL(task)  task ## _cpu
#else
# define __task
# define CPU_TASK_IMPL(task)  task
#endif

#include <stdlib.h>

static void matmul (const float *A, const float *B, float *C,
                    unsigned nx, unsigned ny, unsigned nz) __task;

#ifdef STARPU_GCC_PLUGIN

static void matmul_cpu (const float *A, const float *B, float *C,
```

```
                        unsigned nx, unsigned ny, unsigned nz)
  __attribute__ ((task_implementation ("cpu", matmul)));

#endif


static void
CPU_TASK_IMPL (matmul) (const float *A, const float *B, float *C,
                        unsigned nx, unsigned ny, unsigned nz)
{
  /* Code of the CPU kernel here...  */
}

int
main (int argc, char *argv[])
{
  /* The pragmas below are simply ignored when StarPU-GCC
     is not used.  */
#pragma starpu initialize

  float A[123][42][7], B[123][42][7], C[123][42][7];

#pragma starpu register A
#pragma starpu register B
#pragma starpu register C

  /* When StarPU-GCC is used, the call below is asynchronous;
     otherwise, it is synchronous.  */
  matmul (A, B, C, 123, 42, 7);

#pragma starpu wait
#pragma starpu shutdown

  return EXIT_SUCCESS;
}
```

Note that attributes such as `task` are simply ignored by GCC when the StarPU plug-in is not loaded, so the `__task` macro could be omitted altogether. However, `gcc -Wall` emits a warning for unknown attributes, which can be inconvenient, and other compilers may be unable to parse the attribute syntax. Thus, using macros such as `__task` above is recommended.

12 SOCL OpenCL Extensions

SOCL is an extension that aims at implementing the OpenCL standard on top of StarPU. It allows to gives a (relatively) clean and standardized API to StarPU. By allowing OpenCL applications to use StarPU transparently, it provides users with the latest StarPU enhancements without any further development, and allows these OpenCL applications to easily fall back to another OpenCL implementation.

This section does not require detailed knowledge of the StarPU library.

Note: as of StarPU 1.0.0rc4, this is still an area under development and subject to change.

TODO

13 StarPU Basic API

13.1 Initialization and Termination

`int starpu_init (struct starpu_conf *conf)` [Function]

This is StarPU initialization method, which must be called prior to any other StarPU call. It is possible to specify StarPU's configuration (e.g. scheduling policy, number of cores, ...) by passing a non-null argument. Default configuration is used if the passed argument is `NULL`.

Upon successful completion, this function returns 0. Otherwise, `-ENODEV` indicates that no worker was available (so that StarPU was not initialized).

`struct starpu_conf` [Data Type]

This structure is passed to the `starpu_init` function in order to configure StarPU. When the default value is used, StarPU automatically selects the number of processing units and takes the default scheduling policy. The environment variables overwrite the equivalent parameters.

`const char *sched_policy_name` (default = NULL)
: This is the name of the scheduling policy. This can also be specified with the `STARPU_SCHED` environment variable.

`struct starpu_sched_policy *sched_policy` (default = NULL)
: This is the definition of the scheduling policy. This field is ignored if `sched_policy_name` is set.

`int ncpus` (default = -1)
: This is the number of CPU cores that StarPU can use. This can also be specified with the `STARPU_NCPUS` environment variable.

`int ncuda` (default = -1)
: This is the number of CUDA devices that StarPU can use. This can also be specified with the `STARPU_NCUDA` environment variable.

`int nopencl` (default = -1)
: This is the number of OpenCL devices that StarPU can use. This can also be specified with the `STARPU_NOPENCL` environment variable.

`int nspus` (default = -1)
: This is the number of Cell SPUs that StarPU can use. This can also be specified with the `STARPU_NGORDON` environment variable.

`unsigned use_explicit_workers_bindid` (default = 0)
: If this flag is set, the `workers_bindid` array indicates where the different workers are bound, otherwise StarPU automatically selects where to bind the different workers. This can also be specified with the `STARPU_WORKERS_CPUID` environment variable.

`unsigned workers_bindid[STARPU_NMAXWORKERS]`
: If the `use_explicit_workers_bindid` flag is set, this array indicates where to bind the different workers. The i-th entry of the `workers_`

`bindid` indicates the logical identifier of the processor which should execute the i-th worker. Note that the logical ordering of the CPUs is either determined by the OS, or provided by the `hwloc` library in case it is available.

`unsigned use_explicit_workers_cuda_gpuid` (default = 0)
If this flag is set, the CUDA workers will be attached to the CUDA devices specified in the `workers_cuda_gpuid` array. Otherwise, StarPU affects the CUDA devices in a round-robin fashion. This can also be specified with the `STARPU_WORKERS_CUDAID` environment variable.

`unsigned workers_cuda_gpuid[STARPU_NMAXWORKERS]`
If the `use_explicit_workers_cuda_gpuid` flag is set, this array contains the logical identifiers of the CUDA devices (as used by `cudaGetDevice`).

`unsigned use_explicit_workers_opencl_gpuid` (default = 0)
If this flag is set, the OpenCL workers will be attached to the OpenCL devices specified in the `workers_opencl_gpuid` array. Otherwise, StarPU affects the OpenCL devices in a round-robin fashion. This can also be specified with the `STARPU_WORKERS_OPENCLID` environment variable.

`unsigned workers_opencl_gpuid[STARPU_NMAXWORKERS]`
If the `use_explicit_workers_opencl_gpuid` flag is set, this array contains the logical identifiers of the OpenCL devices to be used.

`int calibrate` (default = 0)
If this flag is set, StarPU will calibrate the performance models when executing tasks. If this value is equal to -1, the default value is used. This can also be specified with the `STARPU_CALIBRATE` environment variable.

`int single_combined_worker` (default = 0)
By default, StarPU parallel tasks concurrently. Some parallel libraries (e.g. most OpenMP implementations) however do not support concurrent calls to parallel code. In such case, setting this flag makes StarPU only start one parallel task at a time. This can also be specified with the `STARPU_SINGLE_COMBINED_WORKER` environment variable.

`int disable_asynchronous_copy` (default = 0)
This flag should be set to 1 to disable asynchronous copies between CPUs and accelerators. This can also be specified with the `DISABLE_STARPU_ASYNCHRONOUS_COPY` environment variable. The AMD implementation of OpenCL is known to fail when copying data asynchronously. When using this implementation, it is therefore necessary to disable asynchronous data transfers.

`int starpu_conf_init` (*struct starpu_conf *conf*) [Function]
This function initializes the *conf* structure passed as argument with the default values. In case some configuration parameters are already specified through environment variables, `starpu_conf_init` initializes the fields of the structure according to the environment variables. For instance if `STARPU_CALIBRATE` is set, its value is put in the `.ncuda` field of the structure passed as argument.

Upon successful completion, this function returns 0. Otherwise, `-EINVAL` indicates that the argument was NULL.

`void starpu_shutdown (`*void*`)` [Function]
This is StarPU termination method. It must be called at the end of the application: statistics and other post-mortem debugging information are not guaranteed to be available until this method has been called.

`int starpu_asynchronous_copy_disabled ()` [Function]
Return 1 if asynchronous data transfers between CPU and accelerators are disabled.

13.2 Workers' Properties

`enum starpu_archtype` [Data Type]
The different values are:

```
STARPU_CPU_WORKER
STARPU_CUDA_WORKER
STARPU_OPENCL_WORKER
STARPU_GORDON_WORKER
```

`unsigned starpu_worker_get_count (`*void*`)` [Function]
This function returns the number of workers (i.e. processing units executing StarPU tasks). The returned value should be at most `STARPU_NMAXWORKERS`.

`int starpu_worker_get_count_by_type (`*enum starpu_archtype type*`)` [Function]
Returns the number of workers of the given type indicated by the argument. A positive (or null) value is returned in case of success, `-EINVAL` indicates that the type is not valid otherwise.

`unsigned starpu_cpu_worker_get_count (`*void*`)` [Function]
This function returns the number of CPUs controlled by StarPU. The returned value should be at most `STARPU_MAXCPUS`.

`unsigned starpu_cuda_worker_get_count (`*void*`)` [Function]
This function returns the number of CUDA devices controlled by StarPU. The returned value should be at most `STARPU_MAXCUDADEVS`.

`unsigned starpu_opencl_worker_get_count (`*void*`)` [Function]
This function returns the number of OpenCL devices controlled by StarPU. The returned value should be at most `STARPU_MAXOPENCLDEVS`.

`unsigned starpu_spu_worker_get_count (`*void*`)` [Function]
This function returns the number of Cell SPUs controlled by StarPU.

`int starpu_worker_get_id (`*void*`)` [Function]
This function returns the identifier of the current worker, i.e the one associated to the calling thread. The returned value is either -1 if the current context is not a StarPU worker (i.e. when called from the application outside a task or a callback), or an integer between 0 and `starpu_worker_get_count() - 1`.

`int starpu_worker_get_ids_by_type (`*enum starpu_archtype* `type`, *int* `*workerids`, *int* `maxsize`) [Function]

This function gets the list of identifiers of workers with the given type. It fills the workerids array with the identifiers of the workers that have the type indicated in the first argument. The maxsize argument indicates the size of the workids array. The returned value gives the number of identifiers that were put in the array. `-ERANGE` is returned is maxsize is lower than the number of workers with the appropriate type: in that case, the array is filled with the maxsize first elements. To avoid such overflows, the value of maxsize can be chosen by the means of the `starpu_worker_get_count_by_type` function, or by passing a value greater or equal to `STARPU_NMAXWORKERS`.

`int starpu_worker_get_devid (`*int* `id`) [Function]

This functions returns the device id of the given worker. The worker should be identified with the value returned by the `starpu_worker_get_id` function. In the case of a CUDA worker, this device identifier is the logical device identifier exposed by CUDA (used by the `cudaGetDevice` function for instance). The device identifier of a CPU worker is the logical identifier of the core on which the worker was bound; this identifier is either provided by the OS or by the `hwloc` library in case it is available.

`enum starpu_archtype starpu_worker_get_type (`*int* `id`) [Function]

This function returns the type of processing unit associated to a worker. The worker identifier is a value returned by the `starpu_worker_get_id` function). The returned value indicates the architecture of the worker: `STARPU_CPU_WORKER` for a CPU core, `STARPU_CUDA_WORKER` for a CUDA device, `STARPU_OPENCL_WORKER` for a OpenCL device, and `STARPU_GORDON_WORKER` for a Cell SPU. The value returned for an invalid identifier is unspecified.

`void starpu_worker_get_name (`*int* `id`, *char* `*dst`, *size_t* `maxlen`) [Function]

This function allows to get the name of a given worker. StarPU associates a unique human readable string to each processing unit. This function copies at most the *maxlen* first bytes of the unique string associated to a worker identified by its identifier *id* into the *dst* buffer. The caller is responsible for ensuring that the *dst* is a valid pointer to a buffer of *maxlen* bytes at least. Calling this function on an invalid identifier results in an unspecified behaviour.

`unsigned starpu_worker_get_memory_node (`*unsigned* `workerid`) [Function]

This function returns the identifier of the memory node associated to the worker identified by *workerid*.

`enum starpu_node_kind` [Data Type]

todo

`STARPU_UNUSED`
`STARPU_CPU_RAM`
`STARPU_CUDA_RAM`
`STARPU_OPENCL_RAM`
`STARPU_SPU_LS`

`enum starpu_node_kind starpu_node_get_kind (uint32_t node)` [Function]
Returns the type of the given node as defined by `enum starpu_node_kind`. For example, when defining a new data interface, this function should be used in the allocation function to determine on which device the memory needs to be allocated.

13.3 Data Library

This section describes the data management facilities provided by StarPU.

We show how to use existing data interfaces in Section 13.4 [Data Interfaces], page 84, but developers can design their own data interfaces if required.

13.3.1 Introduction

Data management is done at a high-level in StarPU: rather than accessing a mere list of contiguous buffers, the tasks may manipulate data that are described by a high-level construct which we call data interface.

An example of data interface is the "vector" interface which describes a contiguous data array on a spefic memory node. This interface is a simple structure containing the number of elements in the array, the size of the elements, and the address of the array in the appropriate address space (this address may be invalid if there is no valid copy of the array in the memory node). More informations on the data interfaces provided by StarPU are given in Section 13.4 [Data Interfaces], page 84.

When a piece of data managed by StarPU is used by a task, the task implementation is given a pointer to an interface describing a valid copy of the data that is accessible from the current processing unit.

Every worker is associated to a memory node which is a logical abstraction of the address space from which the processing unit gets its data. For instance, the memory node associated to the different CPU workers represents main memory (RAM), the memory node associated to a GPU is DRAM embedded on the device. Every memory node is identified by a logical index which is accessible from the `starpu_worker_get_memory_node` function. When registering a piece of data to StarPU, the specified memory node indicates where the piece of data initially resides (we also call this memory node the home node of a piece of data).

13.3.2 Basic Data Library API

`int starpu_malloc (void **A, size_t dim)` [Function]
This function allocates data of the given size in main memory. It will also try to pin it in CUDA or OpenCL, so that data transfers from this buffer can be asynchronous, and thus permit data transfer and computation overlapping. The allocated buffer must be freed thanks to the `starpu_free` function.

`int starpu_free (void *A)` [Function]
This function frees memory which has previously allocated with `starpu_malloc`.

`enum starpu_access_mode` [Data Type]
This datatype describes a data access mode. The different available modes are:

`STARPU_R`: read-only mode.
`STARPU_W`: write-only mode.
`STARPU_RW`: read-write mode.
This is equivalent to `STARPU_R|STARPU_W`.

`STARPU_SCRATCH`: scratch memory.
A temporary buffer is allocated for the task, but StarPU does not enforce data consistency—i.e. each device has its own buffer, independently from each other (even for CPUs), and no data transfer is ever performed. This is useful for temporary variables to avoid allocating/freeing buffers inside each task.

Currently, no behavior is defined concerning the relation with the `STARPU_R` and `STARPU_W` modes and the value provided at registration—i.e., the value of the scratch buffer is undefined at entry of the codelet function. It is being considered for future extensions at least to define the initial value. For now, data to be used in `SCRATCH` mode should be registered with node `-1` and a `NULL` pointer, since the value of the provided buffer is simply ignored for now.

`STARPU_REDUX` reduction mode.

`starpu_data_handle_t` [Data Type]
StarPU uses `starpu_data_handle_t` as an opaque handle to manage a piece of data. Once a piece of data has been registered to StarPU, it is associated to a `starpu_data_handle_t` which keeps track of the state of the piece of data over the entire machine, so that we can maintain data consistency and locate data replicates for instance.

`void starpu_data_register` (*starpu_data_handle_t* ***handleptr***, *uint32_t* ***home_node***, *void* ***data_interface***, *struct starpu_data_interface_ops* ***ops***) [Function]
Register a piece of data into the handle located at the *handleptr* address. The *data_interface* buffer contains the initial description of the data in the home node. The *ops* argument is a pointer to a structure describing the different methods used to manipulate this type of interface. See [struct starpu_data_interface_ops], page 117 for more details on this structure.

If `home_node` is -1, StarPU will automatically allocate the memory when it is used for the first time in write-only mode. Once such data handle has been automatically allocated, it is possible to access it using any access mode.

Note that StarPU supplies a set of predefined types of interface (e.g. vector or matrix) which can be registered by the means of helper functions (e.g. `starpu_vector_data_register` or `starpu_matrix_data_register`).

`void starpu_data_register_same` (*starpu_data_handle_t* ***handledst***, *starpu_data_handle_t* ***handlesrc***) [Function]
Register a new piece of data into the handle *handledst* with the same interface as the handle *handlesrc*.

`void starpu_data_unregister` (*starpu_data_handle_t* ***handle***) [Function]
This function unregisters a data handle from StarPU. If the data was automatically allocated by StarPU because the home node was -1, all automatically allocated buffers

are freed. Otherwise, a valid copy of the data is put back into the home node in the buffer that was initially registered. Using a data handle that has been unregistered from StarPU results in an undefined behaviour.

`void starpu_data_unregister_no_coherency (`*starpu_data_handle_t* **`handle`**`)` [Function]
This is the same as starpu_data_unregister, except that StarPU does not put back a valid copy into the home node, in the buffer that was initially registered.

`void starpu_data_invalidate (`*starpu_data_handle_t* **`handle`**`)` [Function]
Destroy all replicates of the data handle. After data invalidation, the first access to the handle must be performed in write-only mode. Accessing an invalidated data in read-mode results in undefined behaviour.

`void starpu_data_set_wt_mask (`*starpu_data_handle_t* **`handle`**`,` [Function]
uint32_t **`wt_mask`**`)`
This function sets the write-through mask of a given data, i.e. a bitmask of nodes where the data should be always replicated after modification. It also prevents the data from being evicted from these nodes when memory gets scarse.

`int starpu_data_prefetch_on_node (`*starpu_data_handle_t* **`handle`**`,` [Function]
unsigned **`node`**`,` *unsigned* **`async`**`)`
Issue a prefetch request for a given data to a given node, i.e. requests that the data be replicated to the given node, so that it is available there for tasks. If the *async* parameter is 0, the call will block until the transfer is achieved, else the call will return as soon as the request is scheduled (which may however have to wait for a task completion).

`starpu_data_handle_t starpu_data_lookup (`*const void* ***ptr**`)` [Function]
Return the handle corresponding to the data pointed to by the *ptr* host pointer.

`int starpu_data_request_allocation (`*starpu_data_handle_t* [Function]
`handle``,` *uint32_t* **`node`**`)`
Explicitly ask StarPU to allocate room for a piece of data on the specified memory node.

`void starpu_data_query_status (`*starpu_data_handle_t* **`handle`**`,` *int* [Function]
`memory_node``,` *int* ***`is_allocated`**`,` *int* ***`is_valid`**`,` *int* ***`is_requested`**`)`
Query the status of the handle on the specified memory node.

`void starpu_data_advise_as_important (`*starpu_data_handle_t* [Function]
`handle``,` *unsigned* **`is_important`**`)`
This function allows to specify that a piece of data can be discarded without impacting the application.

`void starpu_data_set_reduction_methods (`*starpu_data_handle_t* [Function]
`handle``,` *struct starpu_codelet* ***`redux_cl`**`,` *struct starpu_codelet* ***`init_cl`**`)`
This sets the codelets to be used for the *handle* when it is accessed in REDUX mode. Per-worker buffers will be initialized with the *init_cl* codelet, and reduction between per-worker buffers will be done with the *redux_cl* codelet.

13.3.3 Access registered data from the application

`int starpu_data_acquire` (*starpu_data_handle_t* **`handle`**, *enum starpu_access_mode* **`mode`**) [Function]

The application must call this function prior to accessing registered data from main memory outside tasks. StarPU ensures that the application will get an up-to-date copy of the data in main memory located where the data was originally registered, and that all concurrent accesses (e.g. from tasks) will be consistent with the access mode specified in the *mode* argument. `starpu_data_release` must be called once the application does not need to access the piece of data anymore. Note that implicit data dependencies are also enforced by `starpu_data_acquire`, i.e. `starpu_data_acquire` will wait for all tasks scheduled to work on the data, unless that they have not been disabled explictly by calling `starpu_data_set_default_sequential_consistency_flag` or `starpu_data_set_sequential_consistency_flag`. `starpu_data_acquire` is a blocking call, so that it cannot be called from tasks or from their callbacks (in that case, `starpu_data_acquire` returns `-EDEADLK`). Upon successful completion, this function returns 0.

`int starpu_data_acquire_cb` (*starpu_data_handle_t* **`handle`**, *enum starpu_access_mode* **`mode`**, *void* (**`callback`**)(*void **), *void* ***`arg`**) [Function]

`starpu_data_acquire_cb` is the asynchronous equivalent of `starpu_data_release`. When the data specified in the first argument is available in the appropriate access mode, the callback function is executed. The application may access the requested data during the execution of this callback. The callback function must call `starpu_data_release` once the application does not need to access the piece of data anymore. Note that implicit data dependencies are also enforced by `starpu_data_acquire_cb` in case they are enabled. Contrary to `starpu_data_acquire`, this function is non-blocking and may be called from task callbacks. Upon successful completion, this function returns 0.

`STARPU_DATA_ACQUIRE_CB` (*starpu_data_handle_t* **`handle`**, *enum starpu_access_mode* **`mode`**, *code*) [Macro]

`STARPU_DATA_ACQUIRE_CB` is the same as `starpu_data_acquire_cb`, except that the code to be executed in a callback is directly provided as a macro parameter, and the data handle is automatically released after it. This permits to easily execute code which depends on the value of some registered data. This is non-blocking too and may be called from task callbacks.

`void starpu_data_release` (*starpu_data_handle_t* **`handle`**) [Function]

This function releases the piece of data acquired by the application either by `starpu_data_acquire` or by `starpu_data_acquire_cb`.

13.4 Data Interfaces

13.4.1 Registering Data

There are several ways to register a memory region so that it can be managed by StarPU. The functions below allow the registration of vectors, 2D matrices, 3D matrices as well as BCSR and CSR sparse matrices.

`void starpu_void_data_register (`*starpu_data_handle_t* `*handle`) [Function]

Register a void interface. There is no data really associated to that interface, but it may be used as a synchronization mechanism. It also permits to express an abstract piece of data that is managed by the application internally: this makes it possible to forbid the concurrent execution of different tasks accessing the same "void" data in read-write concurrently.

`void starpu_variable_data_register (`*starpu_data_handle_t* `*handle`, *uint32_t* `home_node`, *uintptr_t* `ptr`, *size_t* `size`) [Function]

Register the *size*-byte element pointed to by *ptr*, which is typically a scalar, and initialize *handle* to represent this data item.

```
float var;
starpu_data_handle_t var_handle;
starpu_variable_data_register(&var_handle, 0, (uintptr_t)&var, sizeof(var));
```

`void starpu_vector_data_register (`*starpu_data_handle_t* `*handle`, *uint32_t* `home_node`, *uintptr_t* `ptr`, *uint32_t* `nx`, *size_t* `elemsize`) [Function]

Register the *nx* *elemsize*-byte elements pointed to by *ptr* and initialize *handle* to represent it.

```
float vector[NX];
starpu_data_handle_t vector_handle;
starpu_vector_data_register(&vector_handle, 0, (uintptr_t)vector, NX,
                            sizeof(vector[0]));
```

`void starpu_matrix_data_register (`*starpu_data_handle_t* `*handle`, *uint32_t* `home_node`, *uintptr_t* `ptr`, *uint32_t* `ld`, *uint32_t* `nx`, *uint32_t* `ny`, *size_t* `elemsize`) [Function]

Register the *nx*x*ny* 2D matrix of *elemsize*-byte elements pointed by *ptr* and initialize *handle* to represent it. *ld* specifies the number of elements between rows. a value greater than *nx* adds padding, which can be useful for alignment purposes.

```
float *matrix;
starpu_data_handle_t matrix_handle;
matrix = (float*)malloc(width * height * sizeof(float));
starpu_matrix_data_register(&matrix_handle, 0, (uintptr_t)matrix,
                            width, width, height, sizeof(float));
```

`void starpu_block_data_register (`*starpu_data_handle_t* `*handle`, *uint32_t* `home_node`, *uintptr_t* `ptr`, *uint32_t* `ldy`, *uint32_t* `ldz`, *uint32_t* `nx`, *uint32_t* `ny`, *uint32_t* `nz`, *size_t* `elemsize`) [Function]

Register the *nx*x*ny*x*nz* 3D matrix of *elemsize*-byte elements pointed by *ptr* and initialize *handle* to represent it. Again, *ldy* and *ldz* specify the number of elements between rows and between z planes.

```
float *block;
starpu_data_handle_t block_handle;
block = (float*)malloc(nx*ny*nz*sizeof(float));
starpu_block_data_register(&block_handle, 0, (uintptr_t)block,
                           nx, nx*ny, nx, ny, nz, sizeof(float));
```

`void starpu_bcsr_data_register (`*starpu_data_handle_t* ***handle***, *uint32_t* ***home_node***, *uint32_t* ***nnz***, *uint32_t* ***nrow***, *uintptr_t* ***nzval***, *uint32_t* ****colind***, *uint32_t* ****rowptr***, *uint32_t* ***firstentry***, *uint32_t* ***r***, *uint32_t* ***c***, *size_t* ***elemsize***`)` [Function]

This variant of `starpu_data_register` uses the BCSR (Blocked Compressed Sparse Row Representation) sparse matrix interface. Register the sparse matrix made of *nnz* non-zero values of size *elemsize* stored in *nzval* and initializes *handle* to represent it. Blocks have size *r* * *c*. *nrow* is the number of rows (in terms of blocks), *colind* is the list of positions of the non-zero entries on the row, *rowptr* is the index (in nzval) of the first entry of the row. *fristentry* is the index of the first entry of the given arrays (usually 0 or 1).

`void starpu_csr_data_register (`*starpu_data_handle_t* ***handle***, *uint32_t* ***home_node***, *uint32_t* ***nnz***, *uint32_t* ***nrow***, *uintptr_t* ***nzval***, *uint32_t* ****colind***, *uint32_t* ****rowptr***, *uint32_t* ***firstentry***, *size_t* ***elemsize***`)` [Function]

This variant of `starpu_data_register` uses the CSR (Compressed Sparse Row Representation) sparse matrix interface. TODO

`void * starpu_data_get_interface_on_node (`*starpu_data_handle_t* ***handle***, *unsigned* ***memory_node***`)` [Function]

Return the interface associated with *handle* on *memory_node*.

13.4.2 Accessing Data Interfaces

Each data interface is provided with a set of field access functions. The ones using a `void *` parameter aimed to be used in codelet implementations (see for example the code in Section 4.4 [Vector Scaling Using StarPu's API], page 20).

`enum starpu_data_interface_id` [Data Type]

The different values are:

`STARPU_MATRIX_INTERFACE_ID`
`STARPU_BLOCK_INTERFACE_ID`
`STARPU_VECTOR_INTERFACE_ID`
`STARPU_CSR_INTERFACE_ID`
`STARPU_BCSR_INTERFACE_ID`
`STARPU_VARIABLE_INTERFACE_ID`
`STARPU_VOID_INTERFACE_ID`
`STARPU_MULTIFORMAT_INTERFACE_ID`
`STARPU_NINTERFACES_ID`: number of data interfaces

13.4.2.1 Handle

`void * starpu_handle_to_pointer (`*starpu_data_handle_t* **`handle`**`,` *uint32_t* **`node`**`)` [Function]
Return the pointer associated with *handle* on node *node* or `NULL` if *handle*'s interface does not support this operation or data for this handle is not allocated on that node.

`void * starpu_handle_get_local_ptr (`*starpu_data_handle_t* **`handle`**`)` [Function]
Return the local pointer associated with *handle* or `NULL` if *handle*'s interface does not have data allocated locally

`enum starpu_data_interface_id starpu_handle_get_interface_id (`*starpu_data_handle_t* **`handle`**`)` [Function]
Return the unique identifier of the interface associated with the given *handle*.

13.4.2.2 Variable Data Interfaces

`size_t starpu_variable_get_elemsize (`*starpu_data_handle_t* **`handle`**`)` [Function]
Return the size of the variable designated by *handle*.

`uintptr_t starpu_variable_get_local_ptr (`*starpu_data_handle_t* **`handle`**`)` [Function]
Return a pointer to the variable designated by *handle*.

`STARPU_VARIABLE_GET_PTR (`*void* ***`interface`**`)` [Macro]
Return a pointer to the variable designated by *interface*.

`STARPU_VARIABLE_GET_ELEMSIZE (`*void* ***`interface`**`)` [Macro]
Return the size of the variable designated by *interface*.

13.4.2.3 Vector Data Interfaces

`uint32_t starpu_vector_get_nx (`*starpu_data_handle_t* **`handle`**`)` [Function]
Return the number of elements registered into the array designated by *handle*.

`size_t starpu_vector_get_elemsize (`*starpu_data_handle_t* **`handle`**`)` [Function]
Return the size of each element of the array designated by *handle*.

`uintptr_t starpu_vector_get_local_ptr (`*starpu_data_handle_t* **`handle`**`)` [Function]
Return the local pointer associated with *handle*.

`STARPU_VECTOR_GET_PTR (`*void* ***`interface`**`)` [Macro]
Return a pointer to the array designated by *interface*, valid on CPUs and CUDA only. For OpenCL, the device handle and offset need to be used instead.

`STARPU_VECTOR_GET_DEV_HANDLE (`*void* ***`interface`**`)` [Macro]
Return a device handle for the array designated by *interface*, to be used on OpenCL. the offset documented below has to be used in addition to this.

`STARPU_VECTOR_GET_OFFSET` (*void *interface*) [Macro]
Return the offset in the array designated by *interface*, to be used with the device handle.

`STARPU_VECTOR_GET_NX` (*void *interface*) [Macro]
Return the number of elements registered into the array designated by *interface*.

`STARPU_VECTOR_GET_ELEMSIZE` (*void *interface*) [Macro]
Return the size of each element of the array designated by *interface*.

13.4.2.4 Matrix Data Interfaces

`uint32_t starpu_matrix_get_nx` (*starpu_data_handle_t handle*) [Function]
Return the number of elements on the x-axis of the matrix designated by *handle*.

`uint32_t starpu_matrix_get_ny` (*starpu_data_handle_t handle*) [Function]
Return the number of elements on the y-axis of the matrix designated by *handle*.

`uint32_t starpu_matrix_get_local_ld` (*starpu_data_handle_t handle*) [Function]
Return the number of elements between each row of the matrix designated by *handle*. Maybe be equal to nx when there is no padding.

`uintptr_t starpu_matrix_get_local_ptr` (*starpu_data_handle_t handle*) [Function]
Return the local pointer associated with *handle*.

`size_t starpu_matrix_get_elemsize` (*starpu_data_handle_t handle*) [Function]
Return the size of the elements registered into the matrix designated by *handle*.

`STARPU_MATRIX_GET_PTR` (*void *interface*) [Macro]
Return a pointer to the matrix designated by *interface*, valid on CPUs and CUDA devices only. For OpenCL devices, the device handle and offset need to be used instead.

`STARPU_MATRIX_GET_DEV_HANDLE` (*void *interface*) [Macro]
Return a device handle for the matrix designated by *interface*, to be used on OpenCL. The offset documented below has to be used in addition to this.

`STARPU_MATRIX_GET_OFFSET` (*void *interface*) [Macro]
Return the offset in the matrix designated by *interface*, to be used with the device handle.

`STARPU_MATRIX_GET_NX` (*void *interface*) [Macro]
Return the number of elements on the x-axis of the matrix designated by *interface*.

`STARPU_MATRIX_GET_NY` (*void *interface*) [Macro]
Return the number of elements on the y-axis of the matrix designated by *interface*.

`STARPU_MATRIX_GET_LD` (*void *interface*) [Macro]
Return the number of elements between each row of the matrix designated by *interface*. May be equal to nx when there is no padding.

`STARPU_MATRIX_GET_ELEMSIZE` (*void *interface*) [Macro]
Return the size of the elements registered into the matrix designated by *interface*.

13.4.2.5 Block Data Interfaces

`uint32_t starpu_block_get_nx` (*starpu_data_handle_t* **handle**) [Function]
Return the number of elements on the x-axis of the block designated by *handle*.

`uint32_t starpu_block_get_ny` (*starpu_data_handle_t* **handle**) [Function]
Return the number of elements on the y-axis of the block designated by *handle*.

`uint32_t starpu_block_get_nz` (*starpu_data_handle_t* **handle**) [Function]
Return the number of elements on the z-axis of the block designated by *handle*.

`uint32_t starpu_block_get_local_ldy` (*starpu_data_handle_t* **handle**) [Function]
Return the number of elements between each row of the block designated by *handle*, in the format of the current memory node.

`uint32_t starpu_block_get_local_ldz` (*starpu_data_handle_t* **handle**) [Function]
Return the number of elements between each z plane of the block designated by *handle*, in the format of the current memory node.

`uintptr_t starpu_block_get_local_ptr` (*starpu_data_handle_t* **handle**) [Function]
Return the local pointer associated with *handle*.

`size_t starpu_block_get_elemsize` (*starpu_data_handle_t* **handle**) [Function]
Return the size of the elements of the block designated by *handle*.

`STARPU_BLOCK_GET_PTR` (*void *interface*) [Macro]
Return a pointer to the block designated by *interface*.

`STARPU_BLOCK_GET_DEV_HANDLE` (*void *interface*) [Macro]
Return a device handle for the block designated by *interface*, to be used on OpenCL. The offset document below has to be used in addition to this.

`STARPU_BLOCK_GET_OFFSET` (*void *interface*) [Macro]
Return the offset in the block designated by *interface*, to be used with the device handle.

`STARPU_BLOCK_GET_NX` (*void *interface*) [Macro]
Return the number of elements on the x-axis of the block designated by *handle*.

`STARPU_BLOCK_GET_NY` (*void *interface*) [Macro]
Return the number of elements on the y-axis of the block designated by *handle*.

`STARPU_BLOCK_GET_NZ` (*void *interface*) [Macro]
Return the number of elements on the z-axis of the block designated by *handle*.

STARPU_BLOCK_GET_LDY (*void *interface*) [Macro]
Return the number of elements between each row of the block designated by *interface*. May be equal to nx when there is no padding.

STARPU_BLOCK_GET_LDZ (*void *interface*) [Macro]
Return the number of elements between each z plane of the block designated by *interface*. May be equal to nx*ny when there is no padding.

STARPU_BLOCK_GET_ELEMSIZE (*void *interface*) [Macro]
Return the size of the elements of the matrix designated by *interface*.

13.4.2.6 BCSR Data Interfaces

uint32_t starpu_bcsr_get_nnz (*starpu_data_handle_t handle*) [Function]
Return the number of non-zero elements in the matrix designated by *handle*.

uint32_t starpu_bcsr_get_nrow (*starpu_data_handle_t handle*) [Function]
Return the number of rows (in terms of blocks of size r*c) in the matrix designated by *handle*.

uint32_t starpu_bcsr_get_firstentry (*starpu_data_handle_t handle*) [Function]
Return the index at which all arrays (the column indexes, the row pointers...) of the matrix desginated by *handle* start.

uintptr_t starpu_bcsr_get_local_nzval (*starpu_data_handle_t handle*) [Function]
Return a pointer to the non-zero values of the matrix designated by *handle*.

uint32_t * starpu_bcsr_get_local_colind (*starpu_data_handle_t handle*) [Function]
Return a pointer to the column index, which holds the positions of the non-zero entries in the matrix designated by *handle*.

uint32_t * starpu_bcsr_get_local_rowptr (*starpu_data_handle_t handle*) [Function]
Return the row pointer array of the matrix designated by *handle*.

uint32_t starpu_bcsr_get_r (*starpu_data_handle_t handle*) [Function]
Return the number of rows in a block.

uint32_t starpu_bcsr_get_c (*starpu_data_handle_t handle*) [Function]
Return the numberof columns in a block.

size_t starpu_bcsr_get_elemsize (*starpu_data_handle_t handle*) [Function]
Return the size of the elements in the matrix designated by *handle*.

STARPU_BCSR_GET_NNZ (*void *interface*) [Macro]
Return the number of non-zero values in the matrix designated by *interface*.

STARPU_BCSR_GET_NZVAL (*void *interface*) [Macro]
Return a pointer to the non-zero values of the matrix designated by *interface*.

`STARPU_BCSR_GET_COLIND` (*void *interface*) [Macro]
Return a pointer to the column index of the matrix designated by *interface*.

`STARPU_BCSR_GET_ROWPTR` (*void *interface*) [Macro]
Return a pointer to the row pointer array of the matrix designated by *interface*.

13.4.2.7 CSR Data Interfaces

`uint32_t starpu_csr_get_nnz` (*starpu_data_handle_t* **handle**) [Function]
Return the number of non-zero values in the matrix designated by *handle*.

`uint32_t starpu_csr_get_nrow` (*starpu_data_handle_t* **handle**) [Function]
Return the size of the row pointer array of the matrix designated by *handle*.

`uint32_t starpu_csr_get_firstentry` (*starpu_data_handle_t* **handle**) [Function]
Return the index at which all arrays (the column indexes, the row pointers...) of the matrix designated by *handle* start.

`uintptr_t starpu_csr_get_local_nzval` (*starpu_data_handle_t* **handle**) [Function]
Return a local pointer to the non-zero values of the matrix designated by *handle*.

`uint32_t * starpu_csr_get_local_colind` (*starpu_data_handle_t* **handle**) [Function]
Return a local pointer to the column index of the matrix designated by *handle*.

`uint32_t * starpu_csr_get_local_rowptr` (*starpu_data_handle_t* **handle**) [Function]
Return a local pointer to the row pointer array of the matrix designated by *handle*.

`size_t starpu_csr_get_elemsize` (*starpu_data_handle_t* **handle**) [Function]
Return the size of the elements registered into the matrix designated by *handle*.

`STARPU_CSR_GET_NNZ` (*void *interface*) [Macro]
Return the number of non-zero values in the matrix designated by *interface*.

`STARPU_CSR_GET_NROW` (*void *interface*) [Macro]
Return the size of the row pointer array of the matrix designated by *interface*.

`STARPU_CSR_GET_NZVAL` (*void *interface*) [Macro]
Return a pointer to the non-zero values of the matrix designated by *interface*.

`STARPU_CSR_GET_COLIND` (*void *interface*) [Macro]
Return a pointer to the column index of the matrix designated by *interface*.

`STARPU_CSR_GET_ROWPTR` (*void *interface*) [Macro]
Return a pointer to the row pointer array of the matrix designated by *interface*.

`STARPU_CSR_GET_FIRSTENTRY` (*void *interface*) [Macro]
Return the index at which all arrays (the column indexes, the row pointers...) of the *interface* start.

`STARPU_CSR_GET_ELEMSIZE` (*void *interface*) [Macro]
Return the size of the elements registered into the matrix designated by *interface*.

13.5 Data Partition

13.5.1 Basic API

`struct starpu_data_filter` [Data Type]

The filter structure describes a data partitioning operation, to be given to the `starpu_data_partition` function, see [starpu_data_partition], page 92 for an example. The different fields are:

`void (*filter_func)(void *father_interface, void* child_interface, struct starpu_data_filter *, unsigned id, unsigned nparts)`
: This function fills the `child_interface` structure with interface information for the `id`-th child of the parent `father_interface` (among `nparts`).

`unsigned nchildren`
: This is the number of parts to partition the data into.

`unsigned (*get_nchildren)(struct starpu_data_filter *, starpu_data_handle_t initial_handle)`
: This returns the number of children. This can be used instead of `nchildren` when the number of children depends on the actual data (e.g. the number of blocks in a sparse matrix).

`struct starpu_data_interface_ops *(*get_child_ops)(struct starpu_data_filter *, unsigned id)`
: In case the resulting children use a different data interface, this function returns which interface is used by child number `id`.

`unsigned filter_arg`
: Allow to define an additional parameter for the filter function.

`void *filter_arg_ptr`
: Allow to define an additional pointer parameter for the filter function, such as the sizes of the different parts.

`void starpu_data_partition (`*starpu_data_handle_t* ***initial_handle***`, struct starpu_data_filter *`***f***`)` [Function]

This requests partitioning one StarPU data *initial_handle* into several subdata according to the filter *f*, as shown in the following example:

```
struct starpu_data_filter f = {
    .filter_func = starpu_vertical_block_filter_func,
    .nchildren = nslicesx,
    .get_nchildren = NULL,
    .get_child_ops = NULL
};
starpu_data_partition(A_handle, &f);
```

`void starpu_data_unpartition (`*starpu_data_handle_t* ***root_data***`, uint32_t gathering_node)` [Function]

This unapplies one filter, thus unpartitioning the data. The pieces of data are collected back into one big piece in the *gathering_node* (usually 0).

```
starpu_data_unpartition(A_handle, 0);
```

`int starpu_data_get_nb_children` (*starpu_data_handle_t* **handle**) [Function]
This function returns the number of children.

`starpu_data_handle_t starpu_data_get_child` [Function]
(*starpu_data_handle_t* **handle**, *unsigned* **i**)
Return the *i*th child of the given *handle*, which must have been partitionned beforehand.

`starpu_data_handle_t starpu_data_get_sub_data` [Function]
(*starpu_data_handle_t* **root_data**, *unsigned* **depth**, ...)
After partitioning a StarPU data by applying a filter, `starpu_data_get_sub_data` can be used to get handles for each of the data portions. *root_data* is the parent data that was partitioned. *depth* is the number of filters to traverse (in case several filters have been applied, to e.g. partition in row blocks, and then in column blocks), and the subsequent parameters are the indexes. The function returns a handle to the subdata.

```
h = starpu_data_get_sub_data(A_handle, 1, taskx);
```

`starpu_data_handle_t starpu_data_vget_sub_data` [Function]
(*starpu_data_handle_t* **root_data**, *unsigned* **depth**, *va_list* **pa**)
This function is similar to `starpu_data_get_sub_data` but uses a va_list for the parameter list.

`void starpu_data_map_filters` (*starpu_data_handle_t* **root_data**, [Function]
unsigned **nfilters**, ...)
Applies *nfilters* filters to the handle designated by *root_handle* recursively. *nfilters* pointers to variables of the type starpu_data_filter should be given.

`void starpu_data_vmap_filters` (*starpu_data_handle_t* **root_data**, [Function]
unsigned **nfilters**, *va_list* **pa**)
Applies *nfilters* filters to the handle designated by *root_handle* recursively. It uses a va_list of pointers to variables of the typer starpu_data_filter.

13.5.2 Predefined filter functions

This section gives a partial list of the predefined partitioning functions. Examples on how to use them are shown in Section 5.4 [Partitioning Data], page 30. The complete list can be found in `starpu_data_filters.h` .

13.5.2.1 Partitioning BCSR Data

`void starpu_canonical_block_filter_bcsr` (*void* [Function]
father_interface*, *void* **child_interface*, *struct starpu_data_filter* **f*, *unsigned* **id, *unsigned* **nparts**)
This partitions a block-sparse matrix into dense matrices.

`void starpu_vertical_block_filter_func_csr (`*void *father_interface*, *void *child_interface*, *struct starpu_data_filter *f*, *unsigned id*, *unsigned nparts*`)` [Function]

This partitions a block-sparse matrix into vertical block-sparse matrices.

13.5.2.2 Partitioning BLAS interface

`void starpu_block_filter_func (`*void *father_interface*, *void *child_interface*, *struct starpu_data_filter *f*, *unsigned id*, *unsigned nparts*`)` [Function]

This partitions a dense Matrix into horizontal blocks.

`void starpu_vertical_block_filter_func (`*void *father_interface*, *void *child_interface*, *struct starpu_data_filter *f*, *unsigned id*, *unsigned nparts*`)` [Function]

This partitions a dense Matrix into vertical blocks.

13.5.2.3 Partitioning Vector Data

`void starpu_block_filter_func_vector (`*void *father_interface*, *void *child_interface*, *struct starpu_data_filter *f*, *unsigned id*, *unsigned nparts*`)` [Function]

Return in `*child_interface` the *id*th element of the vector represented by *father_interface* once partitioned in *nparts* chunks of equal size.

`void starpu_vector_list_filter_func (`*void *father_interface*, *void *child_interface*, *struct starpu_data_filter *f*, *unsigned id*, *unsigned nparts*`)` [Function]

Return in `*child_interface` the *id*th element of the vector represented by *father_interface* once partitioned into *nparts* chunks according to the `filter_arg_ptr` field of `*f`.

The `filter_arg_ptr` field must point to an array of *nparts* `uint32_t` elements, each of which specifies the number of elements in each chunk of the partition.

`void starpu_vector_divide_in_2_filter_func (`*void *father_interface*, *void *child_interface*, *struct starpu_data_filter *f*, *unsigned id*, *unsigned nparts*`)` [Function]

Return in `*child_interface` the *id*th element of the vector represented by *father_interface* once partitioned in two chunks of equal size, ignoring *nparts*. Thus, *id* must be `0` or `1`.

13.5.2.4 Partitioning Block Data

`void starpu_block_filter_func_block (`*void *father_interface*, *void *child_interface*, *struct starpu_data_filter *f*, *unsigned id*, *unsigned nparts*`)` [Function]

This partitions a 3D matrix along the X axis.

13.6 Codelets and Tasks

This section describes the interface to manipulate codelets and tasks.

`enum starpu_codelet_type` [Data Type]

Describes the type of parallel task. The different values are:

`STARPU_SEQ` (default) for classical sequential tasks.

`STARPU_SPMD` for a parallel task whose threads are handled by StarPU, the code has to use `starpu_combined_worker_get_size` and `starpu_combined_worker_get_rank` to distribute the work

`STARPU_FORKJOIN` for a parallel task whose threads are started by the codelet function, which has to use `starpu_combined_worker_get_size` to determine how many threads should be started.

See Section 5.9 [Parallel Tasks], page 37 for details.

`STARPU_CPU` [Macro]

This macro is used when setting the field `where` of a `struct starpu_codelet` to specify the codelet may be executed on a CPU processing unit.

`STARPU_CUDA` [Macro]

This macro is used when setting the field `where` of a `struct starpu_codelet` to specify the codelet may be executed on a CUDA processing unit.

`STARPU_SPU` [Macro]

This macro is used when setting the field `where` of a `struct starpu_codelet` to specify the codelet may be executed on a SPU processing unit.

`STARPU_GORDON` [Macro]

This macro is used when setting the field `where` of a `struct starpu_codelet` to specify the codelet may be executed on a Cell processing unit.

`STARPU_OPENCL` [Macro]

This macro is used when setting the field `where` of a `struct starpu_codelet` to specify the codelet may be executed on a OpenCL processing unit.

`STARPU_MULTIPLE_CPU_IMPLEMENTATIONS` [Macro]

Setting the field `cpu_func` of a `struct starpu_codelet` with this macro indicates the codelet will have several implementations. The use of this macro is deprecated. One should always only define the field `cpu_funcs`.

`STARPU_MULTIPLE_CUDA_IMPLEMENTATIONS` [Macro]

Setting the field `cuda_func` of a `struct starpu_codelet` with this macro indicates the codelet will have several implementations. The use of this macro is deprecated. One should always only define the field `cuda_funcs`.

`STARPU_MULTIPLE_OPENCL_IMPLEMENTATIONS` [Macro]

Setting the field `opencl_func` of a `struct starpu_codelet` with this macro indicates the codelet will have several implementations. The use of this macro is deprecated. One should always only define the field `opencl_funcs`.

`struct starpu_codelet` [Data Type]

The codelet structure describes a kernel that is possibly implemented on various targets. For compatibility, make sure to initialize the whole structure to zero.

`uint32_t where` (optional)
: Indicates which types of processing units are able to execute the codelet. The different values `STARPU_CPU`, `STARPU_CUDA`, `STARPU_SPU`, `STARPU_GORDON`, `STARPU_OPENCL` can be combined to specify on which types of processing units the codelet can be executed. `STARPU_CPU|STARPU_CUDA` for instance indicates that the codelet is implemented for both CPU cores and CUDA devices while `STARPU_GORDON` indicates that it is only available on Cell SPUs. If the field is unset, its value will be automatically set based on the availability of the `XXX_funcs` fields defined below.

`int (*can_execute)(unsigned workerid, struct starpu_task *task, unsigned nimpl)` (optional)
: Defines a function which should return 1 if the worker designated by *workerid* can execute the *nimpl*th implementation of the given *task*, 0 otherwise.

`enum starpu_codelet_type type` (optional)
: The default is `STARPU_SEQ`, i.e. usual sequential implementation. Other values (`STARPU_SPMD` or `STARPU_FORKJOIN` declare that a parallel implementation is also available. See Section 5.9 [Parallel Tasks], page 37 for details.

`int max_parallelism` (optional)
: If a parallel implementation is available, this denotes the maximum combined worker size that StarPU will use to execute parallel tasks for this codelet.

`starpu_cpu_func_t cpu_func` (optional)
: This field has been made deprecated. One should use instead the `cpu_funcs` field.

`starpu_cpu_func_t cpu_funcs[STARPU_MAXIMPLEMENTATIONS]` (optional)
: Is an array of function pointers to the CPU implementations of the codelet. It must be terminated by a NULL value. The functions prototype must be: `void cpu_func(void *buffers[], void *cl_arg)`. The first argument being the array of data managed by the data management library, and the second argument is a pointer to the argument passed from the `cl_arg` field of the `starpu_task` structure. If the `where` field is set, then the `cpu_funcs` field is ignored if `STARPU_CPU` does not appear in the `where` field, it must be non-null otherwise.

`starpu_cuda_func_t cuda_func` (optional)
: This field has been made deprecated. One should use instead the `cuda_funcs` field.

`starpu_cuda_func_t cuda_funcs[STARPU_MAXIMPLEMENTATIONS]` (optional)
: Is an array of function pointers to the CUDA implementations of the codelet. It must be terminated by a NULL value. *The functions must be*

host-functions written in the CUDA runtime API. Their prototype must be: `void cuda_func(void *buffers[], void *cl_arg);`. If the `where` field is set, then the `cuda_funcs` field is ignored if `STARPU_CUDA` does not appear in the `where` field, it must be non-null otherwise.

`starpu_opencl_func_t opencl_func` (optional)
This field has been made deprecated. One should use instead the `opencl_funcs` field.

`starpu_opencl_func_t opencl_funcs[STARPU_MAXIMPLEMENTATIONS]` (optional)
Is an array of function pointers to the OpenCL implementations of the codelet. It must be terminated by a NULL value. The functions prototype must be: `void opencl_func(void *buffers[], void *cl_arg);`. If the `where` field is set, then the `opencl_funcs` field is ignored if `STARPU_OPENCL` does not appear in the `where` field, it must be non-null otherwise.

`uint8_t gordon_func` (optional)
This field has been made deprecated. One should use instead the `gordon_funcs` field.

`uint8_t gordon_funcs[STARPU_MAXIMPLEMENTATIONS]` (optional)
Is an array of index of the Cell SPU implementations of the codelet within the Gordon library. It must be terminated by a NULL value. See Gordon documentation for more details on how to register a kernel and retrieve its index.

`unsigned nbuffers`
Specifies the number of arguments taken by the codelet. These arguments are managed by the DSM and are accessed from the `void *buffers[]` array. The constant argument passed with the `cl_arg` field of the `starpu_task` structure is not counted in this number. This value should not be above `STARPU_NMAXBUFS`.

`enum starpu_access_mode modes[STARPU_NMAXBUFS]`
Is an array of `enum starpu_access_mode`. It describes the required access modes to the data neeeded by the codelet (e.g. `STARPU_RW`). The number of entries in this array must be specified in the `nbuffers` field (defined above), and should not exceed `STARPU_NMAXBUFS`. If unsufficient, this value can be set with the `--enable-maxbuffers` option when configuring StarPU.

`struct starpu_perfmodel *model` (optional)
This is a pointer to the task duration performance model associated to this codelet. This optional field is ignored when set to `NULL`.

`struct starpu_perfmodel *power_model` (optional)
This is a pointer to the task power consumption performance model associated to this codelet. This optional field is ignored when set to `NULL`. In the case of parallel codelets, this has to account for all processing units involved in the parallel execution.

`unsigned long per_worker_stats[STARPU_NMAXWORKERS]` (optional)
: Statistics collected at runtime: this is filled by StarPU and should not be accessed directly, but for example by calling the `starpu_display_codelet_stats` function (See [starpu_display_codelet_stats], page 102 for details).

`const char *name` (optional)
: Define the name of the codelet. This can be useful for debugging purposes.

`void starpu_codelet_init` (*struct starpu_codelet *cl*) [Function]
: Initialize *cl* with default values. Codelets should preferably be initialized statically as shown in Section 4.2.2.2 [Defining a Codelet], page 13. However such a initialisation is not always possible, e.g. when using C++.

`enum starpu_task_status` [Data Type]
: State of a task, can be either of

`STARPU_TASK_INVALID` The task has just been initialized.
`STARPU_TASK_BLOCKED` The task has just been submitted, and its dependencies has not been checked yet.
`STARPU_TASK_READY` The task is ready for execution.
`STARPU_TASK_RUNNING` The task is running on some worker.
`STARPU_TASK_FINISHED` The task is finished executing.
`STARPU_TASK_BLOCKED_ON_TAG` The task is waiting for a tag.
`STARPU_TASK_BLOCKED_ON_TASK` The task is waiting for a task.
`STARPU_TASK_BLOCKED_ON_DATA` The task is waiting for some data.

`struct starpu_buffer_descr` [Data Type]
: This type is used to describe a data handle along with an access mode.

`starpu_data_handle_t handle` describes a data,
`enum starpu_access_mode mode` describes its access mode

`struct starpu_task` [Data Type]
: The `starpu_task` structure describes a task that can be offloaded on the various processing units managed by StarPU. It instantiates a codelet. It can either be allocated dynamically with the `starpu_task_create` method, or declared statically. In the latter case, the programmer has to zero the `starpu_task` structure and to fill the different fields properly. The indicated default values correspond to the configuration of a task allocated with `starpu_task_create`.

`struct starpu_codelet *cl`
: Is a pointer to the corresponding `struct starpu_codelet` data structure. This describes where the kernel should be executed, and supplies the appropriate implementations. When set to `NULL`, no code is executed during the tasks, such empty tasks can be useful for synchronization purposes.

`struct starpu_buffer_descr buffers[STARPU_NMAXBUFS]`
: This field has been made deprecated. One should use instead the `handles` field to specify the handles to the data accessed by the task. The access

modes are now defined in the `mode` field of the `struct starpu_codelet cl` field defined above.

`starpu_data_handle_t handles[STARPU_NMAXBUFS]`
: Is an array of `starpu_data_handle_t`. It specifies the handles to the different pieces of data accessed by the task. The number of entries in this array must be specified in the `nbuffers` field of the `struct starpu_codelet` structure, and should not exceed `STARPU_NMAXBUFS`. If unsufficient, this value can be set with the `--enable-maxbuffers` option when configuring StarPU.

`void *interfaces[STARPU_NMAXBUFS]`
: The actual data pointers to the memory node where execution will happen, managed by the DSM.

`void *cl_arg` (optional; default: `NULL`)
: This pointer is passed to the codelet through the second argument of the codelet implementation (e.g. `cpu_func` or `cuda_func`). In the specific case of the Cell processor, see the `cl_arg_size` argument.

`size_t cl_arg_size` (optional, Cell-specific)
: In the case of the Cell processor, the `cl_arg` pointer is not directly given to the SPU function. A buffer of size `cl_arg_size` is allocated on the SPU. This buffer is then filled with the `cl_arg_size` bytes starting at address `cl_arg`. In this case, the argument given to the SPU codelet is therefore not the `cl_arg` pointer, but the address of the buffer in local store (LS) instead. This field is ignored for CPU, CUDA and OpenCL codelets, where the `cl_arg` pointer is given as such.

`void (*callback_func)(void *)` (optional) (default: `NULL`)
: This is a function pointer of prototype `void (*f)(void *)` which specifies a possible callback. If this pointer is non-null, the callback function is executed *on the host* after the execution of the task. The callback is passed the value contained in the `callback_arg` field. No callback is executed if the field is set to `NULL`.

`void *callback_arg` (optional) (default: `NULL`)
: This is the pointer passed to the callback function. This field is ignored if the `callback_func` is set to `NULL`.

`unsigned use_tag` (optional) (default: `0`)
: If set, this flag indicates that the task should be associated with the tag contained in the `tag_id` field. Tag allow the application to synchronize with the task and to express task dependencies easily.

`starpu_tag_t tag_id`
: This fields contains the tag associated to the task if the `use_tag` field was set, it is ignored otherwise.

`unsigned synchronous`
: If this flag is set, the `starpu_task_submit` function is blocking and returns only when the task has been executed (or if no worker is able to process the task). Otherwise, `starpu_task_submit` returns immediately.

`int priority` (optional) (default: `STARPU_DEFAULT_PRIO`)
: This field indicates a level of priority for the task. This is an integer value that must be set between the return values of the `starpu_sched_get_min_priority` function for the least important tasks, and that of the `starpu_sched_get_max_priority` for the most important tasks (included). The `STARPU_MIN_PRIO` and `STARPU_MAX_PRIO` macros are provided for convenience and respectively returns value of `starpu_sched_get_min_priority` and `starpu_sched_get_max_priority`. Default priority is `STARPU_DEFAULT_PRIO`, which is always defined as 0 in order to allow static task initialization. Scheduling strategies that take priorities into account can use this parameter to take better scheduling decisions, but the scheduling policy may also ignore it.

`unsigned execute_on_a_specific_worker` (default: `0`)
: If this flag is set, StarPU will bypass the scheduler and directly affect this task to the worker specified by the `workerid` field.

`unsigned workerid` (optional)
: If the `execute_on_a_specific_worker` field is set, this field indicates which is the identifier of the worker that should process this task (as returned by `starpu_worker_get_id`). This field is ignored if `execute_on_a_specific_worker` field is set to 0.

`starpu_task_bundle_t bundle` (optional)
: The bundle that includes this task. If no bundle is used, this should be NULL.

`int detach` (optional) (default: `1`)
: If this flag is set, it is not possible to synchronize with the task by the means of `starpu_task_wait` later on. Internal data structures are only guaranteed to be freed once `starpu_task_wait` is called if the flag is not set.

`int destroy` (optional) (default: `0` for starpu_task_init, `1` for starpu_task_create)
: If this flag is set, the task structure will automatically be freed, either after the execution of the callback if the task is detached, or during `starpu_task_wait` otherwise. If this flag is not set, dynamically allocated data structures will not be freed until `starpu_task_destroy` is called explicitly. Setting this flag for a statically allocated task structure will result in undefined behaviour. The flag is set to 1 when the task is created by calling `starpu_task_create()`. Note that `starpu_task_wait_for_all` will not free any task.

`int regenerate` (optional)
: If this flag is set, the task will be re-submitted to StarPU once it has been executed. This flag must not be set if the destroy flag is set too.

`enum starpu_task_status status` (optional)
: Current state of the task.

`struct starpu_task_profiling_info *profiling_info` (optional)
: Profiling information for the task.

`double predicted` (output field)
: Predicted duration of the task. This field is only set if the scheduling strategy used performance models.

`double predicted_transfer` (optional)
: Predicted data transfer duration for the task in microseconds. This field is only valid if the scheduling strategy uses performance models.

`struct starpu_task *prev`
: A pointer to the previous task. This should only be used by StarPU.

`struct starpu_task *next`
: A pointer to the next task. This should only be used by StarPU.

`unsigned int mf_skip`
: This is only used for tasks that use multiformat handle. This should only be used by StarPU.

`void *starpu_private`
: This is private to StarPU, do not modify. If the task is allocated by hand (without starpu_task_create), this field should be set to NULL.

`int magic`
: This field is set when initializing a task. It prevents a task from being submitted if it has not been properly initialized.

`void starpu_task_init` (*struct starpu_task *task*) [Function]
Initialize *task* with default values. This function is implicitly called by `starpu_task_create`. By default, tasks initialized with `starpu_task_init` must be deinitialized explicitly with `starpu_task_deinit`. Tasks can also be initialized statically, using `STARPU_TASK_INITIALIZER` defined below.

`STARPU_TASK_INITIALIZER` [Macro]
It is possible to initialize statically allocated tasks with this value. This is equivalent to initializing a starpu_task structure with the `starpu_task_init` function defined above.

`struct starpu_task * starpu_task_create` (*void*) [Function]
Allocate a task structure and initialize it with default values. Tasks allocated dynamically with `starpu_task_create` are automatically freed when the task is terminated. This means that the task pointer can not be used any more once the task is submitted, since it can be executed at any time (unless dependencies make it wait) and thus freed at any time. If the destroy flag is explicitly unset, the resources used by the task have to be freed by calling `starpu_task_destroy`.

`void starpu_task_deinit` (*struct starpu_task *task*) [Function]
Release all the structures automatically allocated to execute *task*, but not the task structure itself. It is thus useful for statically allocated tasks for instance. It is called automatically by `starpu_task_destroy`. It has to be called only after explicitly waiting for the task or after `starpu_shutdown` (waiting for the callback is not enough, since starpu still manipulates the task after calling the callback).

`void starpu_task_destroy (`*struct starpu_task *`**task**`*`)` [Function]
Free the resource allocated during `starpu_task_create` and associated with *task*. This function is already called automatically after the execution of a task when the `destroy` flag of the `starpu_task` structure is set, which is the default for tasks created by `starpu_task_create`. Calling this function on a statically allocated task results in an undefined behaviour.

`int starpu_task_wait (`*struct starpu_task *`**task**`*`)` [Function]
This function blocks until *task* has been executed. It is not possible to synchronize with a task more than once. It is not possible to wait for synchronous or detached tasks.

Upon successful completion, this function returns 0. Otherwise, `-EINVAL` indicates that the specified task was either synchronous or detached.

`int starpu_task_submit (`*struct starpu_task *`**task**`*`)` [Function]
This function submits *task* to StarPU. Calling this function does not mean that the task will be executed immediately as there can be data or task (tag) dependencies that are not fulfilled yet: StarPU will take care of scheduling this task with respect to such dependencies. This function returns immediately if the `synchronous` field of the `starpu_task` structure was set to 0, and block until the termination of the task otherwise. It is also possible to synchronize the application with asynchronous tasks by the means of tags, using the `starpu_tag_wait` function for instance.

In case of success, this function returns 0, a return value of `-ENODEV` means that there is no worker able to process this task (e.g. there is no GPU available and this task is only implemented for CUDA devices).

`int starpu_task_wait_for_all (`*void*`)` [Function]
This function blocks until all the tasks that were submitted are terminated. It does not destroy these tasks.

`struct starpu_task * starpu_task_get_current (`*void*`)` [Function]
This function returns the task currently executed by the worker, or NULL if it is called either from a thread that is not a task or simply because there is no task being executed at the moment.

`void starpu_display_codelet_stats (`*struct starpu_codelet *`**cl**`*`)` [Function]
Output on `stderr` some statistics on the codelet *cl*.

`int starpu_task_wait_for_no_ready (`*void*`)` [Function]
This function waits until there is no more ready task.

13.7 Explicit Dependencies

`void starpu_task_declare_deps_array (`*struct starpu_task *`**task**`*, *unsigned* `**ndeps**`, *struct starpu_task *`**task_array**`*[]`)` [Function]
Declare task dependencies between a *task* and an array of tasks of length *ndeps*. This function must be called prior to the submission of the task, but it may called after the submission or the execution of the tasks in the array, provided the tasks are still

valid (ie. they were not automatically destroyed). Calling this function on a task that was already submitted or with an entry of *task_array* that is not a valid task anymore results in an undefined behaviour. If *ndeps* is null, no dependency is added. It is possible to call `starpu_task_declare_deps_array` multiple times on the same task, in this case, the dependencies are added. It is possible to have redundancy in the task dependencies.

`starpu_tag_t` [Data Type]

This type defines a task logical identifer. It is possible to associate a task with a unique "tag" chosen by the application, and to express dependencies between tasks by the means of those tags. To do so, fill the `tag_id` field of the `starpu_task` structure with a tag number (can be arbitrary) and set the `use_tag` field to 1.

If `starpu_tag_declare_deps` is called with this tag number, the task will not be started until the tasks which holds the declared dependency tags are completed.

`void starpu_tag_declare_deps` (*starpu_tag_t* **`id`**, *unsigned* **`ndeps`**, ...) [Function]

Specify the dependencies of the task identified by tag *id*. The first argument specifies the tag which is configured, the second argument gives the number of tag(s) on which *id* depends. The following arguments are the tags which have to be terminated to unlock the task.

This function must be called before the associated task is submitted to StarPU with `starpu_task_submit`.

Because of the variable arity of `starpu_tag_declare_deps`, note that the last arguments *must* be of type `starpu_tag_t`: constant values typically need to be explicitly casted. Using the `starpu_tag_declare_deps_array` function avoids this hazard.

```
/*  Tag 0x1 depends on tags 0x32 and 0x52 */
starpu_tag_declare_deps((starpu_tag_t)0x1,
        2, (starpu_tag_t)0x32, (starpu_tag_t)0x52);
```

`void starpu_tag_declare_deps_array` (*starpu_tag_t* **`id`**, *unsigned* **`ndeps`**, *starpu_tag_t* ***`array`**) [Function]

This function is similar to `starpu_tag_declare_deps`, except that its does not take a variable number of arguments but an array of tags of size *ndeps*.

```
/*  Tag 0x1 depends on tags 0x32 and 0x52 */
starpu_tag_t tag_array[2] = {0x32, 0x52};
starpu_tag_declare_deps_array((starpu_tag_t)0x1, 2, tag_array);
```

`int starpu_tag_wait` (*starpu_tag_t* **`id`**) [Function]

This function blocks until the task associated to tag *id* has been executed. This is a blocking call which must therefore not be called within tasks or callbacks, but only from the application directly. It is possible to synchronize with the same tag multiple times, as long as the `starpu_tag_remove` function is not called. Note that it is still possible to synchronize with a tag associated to a task which `starpu_task` data structure was freed (e.g. if the `destroy` flag of the `starpu_task` was enabled).

`int starpu_tag_wait_array` (*unsigned* **ntags**, *starpu_tag_t* ***id**) [Function]
This function is similar to `starpu_tag_wait` except that it blocks until *all* the *ntags* tags contained in the *id* array are terminated.

`void starpu_tag_remove` (*starpu_tag_t* **id**) [Function]
This function releases the resources associated to tag *id*. It can be called once the corresponding task has been executed and when there is no other tag that depend on this tag anymore.

`void starpu_tag_notify_from_apps` (*starpu_tag_t* **id**) [Function]
This function explicitly unlocks tag *id*. It may be useful in the case of applications which execute part of their computation outside StarPU tasks (e.g. third-party libraries). It is also provided as a convenient tool for the programmer, for instance to entirely construct the task DAG before actually giving StarPU the opportunity to execute the tasks.

13.8 Implicit Data Dependencies

In this section, we describe how StarPU makes it possible to insert implicit task dependencies in order to enforce sequential data consistency. When this data consistency is enabled on a specific data handle, any data access will appear as sequentially consistent from the application. For instance, if the application submits two tasks that access the same piece of data in read-only mode, and then a third task that access it in write mode, dependencies will be added between the two first tasks and the third one. Implicit data dependencies are also inserted in the case of data accesses from the application.

`void starpu_data_set_default_sequential_consistency_flag` [Function]
(*unsigned* **flag**)
Set the default sequential consistency flag. If a non-zero value is passed, a sequential data consistency will be enforced for all handles registered after this function call, otherwise it is disabled. By default, StarPU enables sequential data consistency. It is also possible to select the data consistency mode of a specific data handle with the `starpu_data_set_sequential_consistency_flag` function.

`unsigned` [Function]
`starpu_data_get_default_sequential_consistency_flag` (*void*)
Return the default sequential consistency flag

`void starpu_data_set_sequential_consistency_flag` [Function]
(*starpu_data_handle_t* **handle**, *unsigned* **flag**)
Sets the data consistency mode associated to a data handle. The consistency mode set using this function has the priority over the default mode which can be set with `starpu_data_set_default_sequential_consistency_flag`.

13.9 Performance Model API

`enum starpu_perf_archtype` [Data Type]
Enumerates the various types of architectures. CPU types range within STARPU_CPU_DEFAULT (1 CPU), STARPU_CPU_DEFAULT+1 (2 CPUs), ...

STARPU_CPU_DEFAULT + STARPU_MAXCPUS - 1 (STARPU_MAXCPUS CPUs). CUDA types range within STARPU_CUDA_DEFAULT (GPU number 0), STARPU_CUDA_DEFAULT + 1 (GPU number 1), ..., STARPU_CUDA_DEFAULT + STARPU_MAXCUDADEVS - 1 (GPU number STARPU_MAXCUDADEVS - 1). OpenCL types range within STARPU_OPENCL_DEFAULT (GPU number 0), STARPU_OPENCL_DEFAULT + 1 (GPU number 1), ..., STARPU_OPENCL_DEFAULT + STARPU_MAXOPENCLDEVS - 1 (GPU number STARPU_MAXOPENCLDEVS - 1).

`STARPU_CPU_DEFAULT`
`STARPU_CUDA_DEFAULT`
`STARPU_OPENCL_DEFAULT`
`STARPU_GORDON_DEFAULT`

`enum starpu_perfmodel_type` [Data Type]

The possible values are:

`STARPU_PER_ARCH` for application-provided per-arch cost model functions.
`STARPU_COMMON` for application-provided common cost model function, with per-arch factor.
`STARPU_HISTORY_BASED` for automatic history-based cost model.
`STARPU_REGRESSION_BASED` for automatic linear regression-based cost model (alpha * size ^ beta).
`STARPU_NL_REGRESSION_BASED` for automatic non-linear regression-based cost mode (a * size ^ b + c).

`struct starpu_perfmodel` [Data Type]

contains all information about a performance model. At least the `type` and `symbol` fields have to be filled when defining a performance model for a codelet. If not provided, other fields have to be zero.

`type` is the type of performance model `enum starpu_perfmodel_type`: `STARPU_HISTORY_BASED`, `STARPU_REGRESSION_BASED`, `STARPU_NL_REGRESSION_BASED`: No other fields needs to be provided, this is purely history-based. `STARPU_PER_ARCH`: `per_arch` has to be filled with functions which return the cost in micro-seconds. `STARPU_COMMON`: `cost_function` has to be filled with a function that returns the cost in micro-seconds on a CPU, timing on other archs will be determined by multiplying by an arch-specific factor.

`const char *symbol`
is the symbol name for the performance model, which will be used as file name to store the model.

`double (*cost_model)(struct starpu_buffer_descr *)`
This field is deprecated. Use instead the `cost_function` field.

`double (*cost_function)(struct starpu_task *, unsigned nimpl)`
Used by `STARPU_COMMON`: takes a task and implementation number, and must return a task duration estimation in micro-seconds.

`size_t (*size_base)(struct starpu_task *, unsigned nimpl)`
: Used by `STARPU_HISTORY_BASED` and `STARPU_*REGRESSION_BASED`. If not NULL, takes a task and implementation number, and returns the size to be used as index for history and regression.

`struct starpu_per_arch_perfmodel per_arch[STARPU_NARCH_VARIATIONS][STARPU_MAXIMPLEMENTATIONS]`
: Used by `STARPU_PER_ARCH`: array of `struct starpu_per_arch_perfmodel` structures.

`unsigned is_loaded`
: Whether the performance model is already loaded from the disk.

`unsigned benchmarking`
: Whether the performance model is still being calibrated.

`pthread_rwlock_t model_rwlock`
: Lock to protect concurrency between loading from disk (W), updating the values (W), and making a performance estimation (R).

`struct starpu_regression_model` [Data Type]

`double sumlny` sum of ln(measured)
`double sumlnx` sum of ln(size)
`double sumlnx2` sum of ln(size)^2
`unsigned long minx` minimum size
`unsigned long maxx` maximum size
`double sumlnxlny` sum of ln(size)*ln(measured)
`double alpha` estimated = alpha * size ^ beta
`double beta`
`unsigned valid` whether the linear regression model is valid (i.e. enough measures)
`double a, b, c` estimaed = a size ^b + c
`unsigned nl_valid` whether the non-linear regression model is valid (i.e. enough measures)
`unsigned nsample` number of sample values for non-linear regression

`struct starpu_per_arch_perfmodel` [Data Type]

contains information about the performance model of a given arch.

`double (*cost_model)(struct starpu_buffer_descr *t)`
: This field is deprecated. Use instead the `cost_function` field.

`double (*cost_function)(struct starpu_task *task, enum starpu_perf_archtype arch, unsigned nimpl)`
: Used by `STARPU_PER_ARCH`, must point to functions which take a task, the target arch and implementation number (as mere conveniency, since the array is already indexed by these), and must return a task duration estimation in micro-seconds.

`size_t (*size_base)(struct starpu_task *, enumstarpu_perf_archtype arch, unsigned nimpl)`
: Same as in [struct starpu_perfmodel], page 105, but per-arch, in case it depends on the architecture-specific implementation.

`struct starpu_htbl32_node *history`
: The history of performance measurements.

`struct starpu_history_list *list`
: Used by `STARPU_HISTORY_BASED` and `STARPU_NL_REGRESSION_BASED`, records all execution history measures.

`struct starpu_regression_model regression`
: Used by `STARPU_HISTORY_REGRESION_BASED` and `STARPU_NL_REGRESSION_BASED`, contains the estimated factors of the regression.

`int starpu_load_history_debug` (*const char ***`symbol`**, struct starpu_perfmodel ***`model`**) [Function]
loads a given performance model. The *model* structure has to be completely zero, and will be filled with the information saved in `~/.starpu`.

`void starpu_perfmodel_debugfilepath` (*struct starpu_perfmodel ***`model`**, enum starpu_perf_archtype* **`arch`**, *char ***`path`**, *size_t* **`maxlen`**, *unsigned nimpl*) [Function]
returns the path to the debugging information for the performance model.

`void starpu_perfmodel_get_arch_name` (*enum starpu_perf_archtype* **`arch`**, *char *`archname`*, *size_t* **`maxlen`**, *unsigned nimpl*) [Function]
returns the architecture name for *arch*.

`void starpu_force_bus_sampling` (*void*) [Function]
forces sampling the bus performance model again.

`enum starpu_perf_archtype starpu_worker_get_perf_archtype` (*int* **`workerid`**) [Function]
returns the architecture type of a given worker.

`int starpu_list_models` (*FILE *`output`*) [Function]
prints a list of all performance models on *output*.

`void starpu_bus_print_bandwidth` (*FILE *`f`*) [Function]
prints a matrix of bus bandwidths on *f*.

13.10 Profiling API

`int starpu_profiling_status_set` (*int* **`status`**) [Function]
Thie function sets the profiling status. Profiling is activated by passing `STARPU_PROFILING_ENABLE` in *status*. Passing `STARPU_PROFILING_DISABLE` disables profiling. Calling this function resets all profiling measurements. When profiling is enabled, the `profiling_info` field of the `struct starpu_task` structure points to a valid `struct starpu_task_profiling_info` structure containing information about the execution of the task.

Negative return values indicate an error, otherwise the previous status is returned.

`int starpu_profiling_status_get` (*void*) [Function]
Return the current profiling status or a negative value in case there was an error.

`void starpu_set_profiling_id (int new_id)` [Function]
This function sets the ID used for profiling trace filename

`struct starpu_task_profiling_info` [Data Type]
This structure contains information about the execution of a task. It is accessible from the `.profiling_info` field of the `starpu_task` structure if profiling was enabled. The different fields are:

`struct timespec submit_time`
Date of task submission (relative to the initialization of StarPU).

`struct timespec push_start_time`
Time when the task was submitted to the scheduler.

`struct timespec push_end_time`
Time when the scheduler finished with the task submission.

`struct timespec pop_start_time`
Time when the scheduler started to be requested for a task, and eventually gave that task.

`struct timespec pop_end_time`
Time when the scheduler finished providing the task for execution.

`struct timespec acquire_data_start_time`
Time when the worker started fetching input data.

`struct timespec acquire_data_end_time`
Time when the worker finished fetching input data.

`struct timespec start_time`
Date of task execution beginning (relative to the initialization of StarPU).

`struct timespec end_time`
Date of task execution termination (relative to the initialization of StarPU).

`struct timespec release_data_start_time`
Time when the worker started releasing data.

`struct timespec release_data_end_time`
Time when the worker finished releasing data.

`struct timespec callback_start_time`
Time when the worker started the application callback for the task.

`struct timespec callback_end_time`
Time when the worker finished the application callback for the task.

`workerid` Identifier of the worker which has executed the task.

`uint64_t used_cycles`
Number of cycles used by the task, only available in the MoviSim

`uint64_t stall_cycles`
Number of cycles stalled within the task, only available in the MoviSim

`double power_consumed`
: Power consumed by the task, only available in the MoviSim

`struct starpu_worker_profiling_info` [Data Type]

This structure contains the profiling information associated to a worker. The different fields are:

`struct timespec start_time`
: Starting date for the reported profiling measurements.

`struct timespec total_time`
: Duration of the profiling measurement interval.

`struct timespec executing_time`
: Time spent by the worker to execute tasks during the profiling measurement interval.

`struct timespec sleeping_time`
: Time spent idling by the worker during the profiling measurement interval.

`int executed_tasks`
: Number of tasks executed by the worker during the profiling measurement interval.

`uint64_t used_cycles`
: Number of cycles used by the worker, only available in the MoviSim

`uint64_t stall_cycles`
: Number of cycles stalled within the worker, only available in the MoviSim

`double power_consumed`
: Power consumed by the worker, only available in the MoviSim

`int starpu_worker_get_profiling_info` (*int* `workerid`, *struct starpu_worker_profiling_info* *`worker_info`) [Function]

Get the profiling info associated to the worker identified by *workerid*, and reset the profiling measurements. If the *worker_info* argument is NULL, only reset the counters associated to worker *workerid*.

Upon successful completion, this function returns 0. Otherwise, a negative value is returned.

`struct starpu_bus_profiling_info` [Data Type]

The different fields are:

`struct timespec start_time`
: Time of bus profiling startup.

`struct timespec total_time`
: Total time of bus profiling.

`int long long transferred_bytes`
: Number of bytes transferred during profiling.

`int transfer_count`
: Number of transfers during profiling.

`int starpu_bus_get_profiling_info (int busid, struct starpu_bus_profiling_info *bus_info)` [Function]
Get the profiling info associated to the worker designated by *workerid*, and reset the profiling measurements. If worker_info is NULL, only reset the counters.

`int starpu_bus_get_count (void)` [Function]
Return the number of buses in the machine.

`int starpu_bus_get_id (int src, int dst)` [Function]
Return the identifier of the bus between *src* and *dst*

`int starpu_bus_get_src (int busid)` [Function]
Return the source point of bus *busid*

`int starpu_bus_get_dst (int busid)` [Function]
Return the destination point of bus *busid*

`double starpu_timing_timespec_delay_us (struct timespec *start, struct timespec *end)` [Function]
Returns the time elapsed between *start* and *end* in microseconds.

`double starpu_timing_timespec_to_us (struct timespec *ts)` [Function]
Converts the given timespec *ts* into microseconds.

`void starpu_bus_profiling_helper_display_summary (void)` [Function]
Displays statistics about the bus on stderr.

`void starpu_worker_profiling_helper_display_summary (void)` [Function]
Displays statistics about the workers on stderr.

13.11 CUDA extensions

`STARPU_USE_CUDA` [Macro]
This macro is defined when StarPU has been installed with CUDA support. It should be used in your code to detect the availability of CUDA as shown in Appendix A [Full source code for the 'Scaling a Vector' example], page 135.

`cudaStream_t starpu_cuda_get_local_stream (void)` [Function]
This function gets the current worker's CUDA stream. StarPU provides a stream for every CUDA device controlled by StarPU. This function is only provided for convenience so that programmers can easily use asynchronous operations within codelets without having to create a stream by hand. Note that the application is not forced to use the stream provided by `starpu_cuda_get_local_stream` and may also create its own streams. Synchronizing with `cudaThreadSynchronize()` is allowed, but will reduce the likelihood of having all transfers overlapped.

`const struct cudaDeviceProp * starpu_cuda_get_device_properties (unsigned workerid)` [Function]
This function returns a pointer to device properties for worker *workerid* (assumed to be a CUDA worker).

`size_t starpu_cuda_get_global_mem_size (int devid)` [Function]
Return the size of the global memory of CUDA device *devid*.

`void starpu_cuda_report_error (const char *func, const char *file, int line, cudaError_t status)` [Function]
Report a CUDA error.

`STARPU_CUDA_REPORT_ERROR (cudaError_t status)` [Macro]
Calls starpu_cuda_report_error, passing the current function, file and line position.

`void starpu_helper_cublas_init (void)` [Function]
This function initializes CUBLAS on every CUDA device. The CUBLAS library must be initialized prior to any CUBLAS call. Calling `starpu_helper_cublas_init` will initialize CUBLAS on every CUDA device controlled by StarPU. This call blocks until CUBLAS has been properly initialized on every device.

`void starpu_helper_cublas_shutdown (void)` [Function]
This function synchronously deinitializes the CUBLAS library on every CUDA device.

`void starpu_cublas_report_error (const char *func, const char *file, int line, cublasStatus status)` [Function]
Report a cublas error.

`STARPU_CUBLAS_REPORT_ERROR (cublasStatus status)` [Macro]
Calls starpu_cublas_report_error, passing the current function, file and line position.

13.12 OpenCL extensions

`STARPU_USE_OPENCL` [Macro]
This macro is defined when StarPU has been installed with OpenCL support. It should be used in your code to detect the availability of OpenCL as shown in Appendix A [Full source code for the 'Scaling a Vector' example], page 135.

13.12.1 Writing OpenCL kernels

`size_t starpu_opencl_get_global_mem_size (int devid)` [Function]
Return the size of global device memory in bytes.

`void starpu_opencl_get_context (int devid, cl_context *context)` [Function]
Places the OpenCL context of the device designated by *devid* into *context*.

`void starpu_opencl_get_device (int devid, cl_device_id *device)` [Function]
Places the cl_device_id corresponding to *devid* in *device*.

`void starpu_opencl_get_queue (int devid, cl_command_queue *queue)` [Function]
Places the command queue of the the device designated by *devid* into *queue*.

`void starpu_opencl_get_current_context (cl_context *context)` [Function]
Return the context of the current worker.

`void starpu_opencl_get_current_queue (`*cl_command_queue* `*queue`)` [Function]
Return the computation kernel command queue of the current worker.

`int starpu_opencl_set_kernel_args (`*cl_int* `*err`, *cl_kernel* `*kernel`, ...)` [Function]
Sets the arguments of a given kernel. The list of arguments must be given as (size_t *size_of_the_argument*, cl_mem * *pointer_to_the_argument*). The last argument must be 0. Returns the number of arguments that were successfully set. In case of failure, *err* is set to the error returned by OpenCL.

13.12.2 Compiling OpenCL kernels

Source codes for OpenCL kernels can be stored in a file or in a string. StarPU provides functions to build the program executable for each available OpenCL device as a `cl_program` object. This program executable can then be loaded within a specific queue as explained in the next section. These are only helpers, Applications can also fill a `starpu_opencl_program` array by hand for more advanced use (e.g. different programs on the different OpenCL devices, for relocation purpose for instance).

`struct starpu_opencl_program` [Data Type]
Stores the OpenCL programs as compiled for the different OpenCL devices.

`cl_program programs[STARPU_MAXOPENCLDEVS]`
Stores each program for each OpenCL device.

`int starpu_opencl_load_opencl_from_file (`*const char* `*source_file_name`, *struct starpu_opencl_program* `*opencl_programs`, *const char** `build_options`)` [Function]
This function compiles an OpenCL source code stored in a file.

`int starpu_opencl_load_opencl_from_string (`*const char* `*opencl_program_source`, *struct starpu_opencl_program* `*opencl_programs`, *const char** `build_options`)` [Function]
This function compiles an OpenCL source code stored in a string.

`int starpu_opencl_unload_opencl (`*struct starpu_opencl_program* `*opencl_programs`)` [Function]
This function unloads an OpenCL compiled code.

13.12.3 Loading OpenCL kernels

`int starpu_opencl_load_kernel (`*cl_kernel* `*kernel`, *cl_command_queue* `*queue`, *struct starpu_opencl_program* `*opencl_programs`, *const char* `*kernel_name`, *int* `devid`)` [Function]
Create a kernel *kernel* for device *devid*, on its computation command queue returned in *queue*, using program *opencl_programs* and name *kernel_name*

`int starpu_opencl_release_kernel (`*cl_kernel* `kernel`)` [Function]
Release the given *kernel*, to be called after kernel execution.

13.12.4 OpenCL statistics

`int starpu_opencl_collect_stats (cl_event event)` [Function]

This function allows to collect statistics on a kernel execution. After termination of the kernels, the OpenCL codelet should call this function to pass it the even returned by `clEnqueueNDRangeKernel`, to let StarPU collect statistics about the kernel execution (used cycles, consumed power).

13.12.5 OpenCL utilities

`void starpu_opencl_display_error (const char *func, const char *file, int line, const char *msg, cl_int status)` [Function]

Given a valid error *status*, prints the corresponding error message on stdout, along with the given function name *func*, the given filename *file*, the given line number *line* and the given message *msg*.

`STARPU_OPENCL_DISPLAY_ERROR (cl_int status)` [Macro]

Call the function `starpu_opencl_display_error` with the given error *status*, the current function name, current file and line number, and a empty message.

`void starpu_opencl_report_error (const char *func, const char *file, int line, const char *msg, cl_int status)` [Function]

Call the function `starpu_opencl_display_error` and abort.

`STARPU_OPENCL_REPORT_ERROR (cl_int status)` [Macro]

Call the function `starpu_opencl_report_error` with the given error *status*, with the current function name, current file and line number, and a empty message.

`STARPU_OPENCL_REPORT_ERROR_WITH_MSG (const char *msg, cl_int status)` [Macro]

Call the function `starpu_opencl_report_error` with the given message and the given error *status*, with the current function name, current file and line number.

`cl_int starpu_opencl_allocate_memory (cl_mem *addr, size_t size, cl_mem_flags flags)` [Function]

Allocate *size* bytes of memory, stored in *addr*. *flags* must be a valid combination of cl_mem_flags values.

`cl_int starpu_opencl_copy_ram_to_opencl_async_sync (void *ptr, unsigned src_node, cl_mem buffer, unsigned dst_node, size_t size, size_t offset, cl_event *event, int *ret)` [Function]

Copy *size* bytes asynchronously from the given *ptr* on *src_node* to the given *buffer* on *dst_node*. *offset* is the offset, in bytes, in *buffer*. *event* can be used to wait for this particular copy to complete. It can be NULL. This function returns CL_SUCCESS if the copy was successful, or a valid OpenCL error code otherwise. The integer pointed to by *ret* is set to -EAGAIN if the asynchronous copy was successful, or to 0 if event was NULL.

`cl_int starpu_opencl_copy_ram_to_opencl` (*void* ***ptr***, *unsigned* ***src_node***, *cl_mem* ***buffer***, *unsigned* ***dst_node***, *size_t* ***size***, *size_t* ***offset***, *cl_event* ***event***) [Function]

Copy *size* bytes from the given *ptr* on *src_node* to the given *buffer* on *dst_node*. *offset* is the offset, in bytes, in *buffer*. *event* can be used to wait for this particular copy to complete. It can be NULL. This function returns CL_SUCCESS if the copy was successful, or a valid OpenCL error code otherwise.

`cl_int starpu_opencl_copy_opencl_to_ram_async_sync` (*cl_mem* ***buffer***, *unsigned* ***src_node***, *void* ***ptr***, *unsigned* ***dst_node***, *size_t* ***size***, *size_t* ***offset***, *cl_event* ***event***, *int* ***ret***) [Function]

Copy *size* bytes asynchronously from the given *buffer* on *src_node* to the given *ptr* on *dst_node*. *offset* is the offset, in bytes, in *buffer*. *event* can be used to wait for this particular copy to complete. It can be NULL. This function returns CL_SUCCESS if the copy was successful, or a valid OpenCL error code otherwise. The integer pointed to by *ret* is set to -EAGAIN if the asynchronous copy was successful, or to 0 if event was NULL.

`cl_int starpu_opencl_copy_opencl_to_ram` (*cl_mem* ***buffer***, *unsigned* ***src_node***, *void* ***ptr***, *unsigned* ***dst_node***, *size_t* ***size***, *size_t* ***offset***, *cl_event* ***event***) [Function]

Copy *size* bytes from the given *buffer* on *src_node* to the given *ptr* on *dst_node*. *offset* is the offset, in bytes, in *buffer*. *event* can be used to wait for this particular copy to complete. It can be NULL. This function returns CL_SUCCESS if the copy was successful, or a valid OpenCL error code otherwise.

13.13 Cell extensions

nothing yet.

13.14 Miscellaneous helpers

`int starpu_data_cpy` (*starpu_data_handle_t* ***dst_handle***, *starpu_data_handle_t* ***src_handle***, *int* ***asynchronous***, *void* (****callback_func***)(*void**), *void* ****callback_arg***) [Function]

Copy the content of the *src_handle* into the *dst_handle* handle. The *asynchronous* parameter indicates whether the function should block or not. In the case of an asynchronous call, it is possible to synchronize with the termination of this operation either by the means of implicit dependencies (if enabled) or by calling `starpu_task_wait_for_all()`. If *callback_func* is not `NULL`, this callback function is executed after the handle has been copied, and it is given the *callback_arg* pointer as argument.

`void starpu_execute_on_each_worker` (*void* (****func***)(*void **), *void* ****arg***, *uint32_t* ***where***) [Function]

This function executes the given function on a subset of workers. When calling this method, the offloaded function specified by the first argument is executed by every StarPU worker that may execute the function. The second argument is passed to the offloaded function. The last argument specifies on which types of processing units

the function should be executed. Similarly to the *where* field of the `struct starpu_codelet` structure, it is possible to specify that the function should be executed on every CUDA device and every CPU by passing `STARPU_CPU|STARPU_CUDA`. This function blocks until the function has been executed on every appropriate processing units, so that it may not be called from a callback function for instance.

14 StarPU Advanced API

14.1 Defining a new data interface

14.1.1 Data Interface API

`struct starpu_data_interface_ops` [Data Type]

Per-interface data transfer methods.

`void (*register_data_handle)(starpu_data_handle_t handle, uint32_t home_node, void *data_interface)`
Register an existing interface into a data handle.

`starpu_ssize_t (*allocate_data_on_node)(void *data_interface, uint32_t node)`
Allocate data for the interface on a given node.

`void (*free_data_on_node)(void *data_interface, uint32_t node)`
Free data of the interface on a given node.

`const struct starpu_data_copy_methods *copy_methods`
ram/cuda/spu/opencl synchronous and asynchronous transfer methods.

`void * (*handle_to_pointer)(starpu_data_handle_t handle, uint32_t node)`
Return the current pointer (if any) for the handle on the given node.

`size_t (*get_size)(starpu_data_handle_t handle)`
Return an estimation of the size of data, for performance models.

`uint32_t (*footprint)(starpu_data_handle_t handle)`
Return a 32bit footprint which characterizes the data size.

`int (*compare)(void *data_interface_a, void *data_interface_b)`
Compare the data size of two interfaces.

`void (*display)(starpu_data_handle_t handle, FILE *f)`
Dump the sizes of a handle to a file.

`int (*convert_to_gordon)(void *data_interface, uint64_t *ptr, gordon_strideSize_t *ss)`
Convert the data size to the spu size format. If no SPUs are used, this field can be seto NULL.

`enum starpu_data_interface_id interfaceid`
An identifier that is unique to each interface.

`size_t interface_size`
The size of the interface data descriptor.

`struct starpu_data_copy_methods` [Data Type]

Defines the per-interface methods.

`int {ram,cuda,opencl,spu}_to_{ram,cuda,opencl,spu}(void *src_interface, unsigned src_node, void *dst_interface, unsigned dst_node)`
: These 16 functions define how to copy data from the *src_interface* interface on the *src_node* node to the *dst_interface* interface on the *dst_node* node. They return 0 on success.

`int (*ram_to_cuda_async)(void *src_interface, unsigned src_node, void *dst_interface, unsigned dst_node, cudaStream_t stream)`
: Define how to copy data from the *src_interface* interface on the *src_node* node (in RAM) to the *dst_interface* interface on the *dst_node* node (on a CUDA device), using the given *stream*. Return 0 on success.

`int (*cuda_to_ram_async)(void *src_interface, unsigned src_node, void *dst_interface, unsigned dst_node, cudaStream_t stream)`
: Define how to copy data from the *src_interface* interface on the *src_node* node (on a CUDA device) to the *dst_interface* interface on the *dst_node* node (in RAM), using the given *stream*. Return 0 on success.

`int (*cuda_to_cuda_async)(void *src_interface, unsigned src_node, void *dst_interface, unsigned dst_node, cudaStream_t stream)`
: Define how to copy data from the *src_interface* interface on the *src_node* node (on a CUDA device) to the *dst_interface* interface on the *dst_node* node (on another CUDA device), using the given *stream*. Return 0 on success.

`int (*ram_to_opencl_async)(void *src_interface, unsigned src_node, void *dst_interface, unsigned dst_node, /* cl_event * */ void *event)`
: Define how to copy data from the *src_interface* interface on the *src_node* node (in RAM) to the *dst_interface* interface on the *dst_node* node (on an OpenCL device), using *event*, a pointer to a cl_event. Return 0 on success.

`int (*opencl_to_ram_async)(void *src_interface, unsigned src_node, void *dst_interface, unsigned dst_node, /* cl_event * */ void *event)`
: Define how to copy data from the *src_interface* interface on the *src_node* node (on an OpenCL device) to the *dst_interface* interface on the *dst_node* node (in RAM), using the given *event*, a pointer to a cl_event. Return 0 on success.

`int (*opencl_to_opencl_async)(void *src_interface, unsigned src_node, void *dst_interface, unsigned dst_node, /* cl_event * */ void *event)`
: Define how to copy data from the *src_interface* interface on the *src_node* node (on an OpenCL device) to the *dst_interface* interface on the *dst_node* node (on another OpenCL device), using the given *event*, a pointer to a cl_event. Return 0 on success.

`uint32_t starpu_crc32_be_n (`*void *`**`input`**`, size_t `**`n`**`, uint32_t `***`inputcrc`**`)` [Function]

Compute the CRC of a byte buffer seeded by the inputcrc "current state". The return value should be considered as the new "current state" for future CRC computation. This is used for computing data size footprint.

`uint32_t starpu_crc32_be` (*uint32_t* ***input***, *uint32_t* ***inputcrc***) [Function]
Compute the CRC of a 32bit number seeded by the inputcrc "current state". The return value should be considered as the new "current state" for future CRC computation. This is used for computing data size footprint.

`uint32_t starpu_crc32_string` (*char* ***str***, *uint32_t* ***inputcrc***) [Function]
Compute the CRC of a string seeded by the inputcrc "current state". The return value should be considered as the new "current state" for future CRC computation. This is used for computing data size footprint.

14.1.2 An example of data interface

`int starpu_data_interface_get_next_id ()` [Function]
Returns the next available id for a newly created data interface.

Let's define a new data interface to manage complex numbers.

```
/* interface for complex numbers */
struct starpu_complex_interface
{
        double *real;
        double *imaginary;
        int nx;
};
```

Registering such a data to StarPU is easily done using the function `starpu_data_register` (see Section 13.3.2 [Basic Data Library API], page 81). The last parameter of the function, `interface_complex_ops`, will be described below.

```
void starpu_complex_data_register(starpu_data_handle_t *handle,
     uint32_t home_node, double *real, double *imaginary, int nx)
{
        struct starpu_complex_interface complex =
        {
                .real = real,
                .imaginary = imaginary,
                .nx = nx
        };

        if (interface_complex_ops.interfaceid == -1)
        {
                interface_complex_ops.interfaceid = starpu_data_interface_get_next_id();
        }

        starpu_data_register(handleptr, home_node, &complex, &interface_complex_ops);
}
```

Different operations need to be defined for a data interface through the type `struct starpu_data_interface_ops` (see Section 14.1.1 [Data Interface API], page 117). We only define here the basic operations needed to run simple applications. The source code for the different functions can be found in the file `examples/interface/complex_interface.c`.

```
static struct starpu_data_interface_ops interface_complex_ops =
{
        .register_data_handle = complex_register_data_handle,
        .allocate_data_on_node = complex_allocate_data_on_node,
        .copy_methods = &complex_copy_methods,
        .get_size = complex_get_size,
        .footprint = complex_footprint,
        .interfaceid = -1,
        .interface_size = sizeof(struct starpu_complex_interface),
};
```

Functions need to be defined to access the different fields of the complex interface from a StarPU data handle.

```
double *starpu_complex_get_real(starpu_data_handle_t handle)
{
        struct starpu_complex_interface *complex_interface =
          (struct starpu_complex_interface *) starpu_data_get_interface_on_node(handle, 0);
        return complex_interface->real;
}

double *starpu_complex_get_imaginary(starpu_data_handle_t handle);
int starpu_complex_get_nx(starpu_data_handle_t handle);
```

Similar functions need to be defined to access the different fields of the complex interface from a `void *` pointer to be used within codelet implemetations.

```
#define STARPU_COMPLEX_GET_REAL(interface) \
        (((struct starpu_complex_interface *)(interface))->real)
#define STARPU_COMPLEX_GET_IMAGINARY(interface) \
        (((struct starpu_complex_interface *)(interface))->imaginary)
#define STARPU_COMPLEX_GET_NX(interface) \
        (((struct starpu_complex_interface *)(interface))->nx)
```

Complex data interfaces can then be registered to StarPU.

```
double real = 45.0;
double imaginary = 12.0;
starpu_complex_data_register(&handle1, 0, &real, &imaginary, 1);
starpu_insert_task(&cl_display, STARPU_R, handle1, 0);
```

and used by codelets.

```
void display_complex_codelet(void *descr[], __attribute__ ((unused)) void *_args)
{
        int nx = STARPU_COMPLEX_GET_NX(descr[0]);
        double *real = STARPU_COMPLEX_GET_REAL(descr[0]);
        double *imaginary = STARPU_COMPLEX_GET_IMAGINARY(descr[0]);
        int i;

        for(i=0 ; i<nx ; i++)
        {
                fprintf(stderr, "Complex[%d] = %3.2f + %3.2f i\n", i, real[i], imaginary[i]);
        }
}
```

The whole code for this complex data interface is available in the directory `examples/interface/`.

14.2 Multiformat Data Interface

`struct starpu_multiformat_data_interface_ops` [Data Type]

The different fields are:

`size_t cpu_elemsize`
: the size of each element on CPUs,

`size_t opencl_elemsize`
: the size of each element on OpenCL devices,

`struct starpu_codelet *cpu_to_opencl_cl`
: pointer to a codelet which converts from CPU to OpenCL

`struct starpu_codelet *opencl_to_cpu_cl`
: pointer to a codelet which converts from OpenCL to CPU

`size_t cuda_elemsize`
: the size of each element on CUDA devices,

`struct starpu_codelet *cpu_to_cuda_cl`
: pointer to a codelet which converts from CPU to CUDA

`struct starpu_codelet *cuda_to_cpu_cl`
: pointer to a codelet which converts from CUDA to CPU

`void starpu_multiformat_data_register` (*starpu_data_handle_t* ***handle***, *uint32_t* ***home_node***, *void* ***ptr***, *uint32_t* ***nobjects***, *struct starpu_multiformat_data_interface_ops* ***format_ops***) [Function]

Register a piece of data that can be represented in different ways, depending upon the processing unit that manipulates it. It allows the programmer, for instance, to use an array of structures when working on a CPU, and a structure of arrays when working on a GPU.

nobjects is the number of elements in the data. *format_ops* describes the format.

`STARPU_MULTIFORMAT_GET_CPU_PTR` (*void* ***interface***) [Macro]

returns the local pointer to the data with CPU format.

`STARPU_MULTIFORMAT_GET_CUDA_PTR` (*void *interface*) [Macro]
returns the local pointer to the data with CUDA format.

`STARPU_MULTIFORMAT_GET_OPENCL_PTR` (*void *interface*) [Macro]
returns the local pointer to the data with OpenCL format.

`STARPU_MULTIFORMAT_GET_NX` (*void *interface*) [Macro]
returns the number of elements in the data.

14.3 Task Bundles

`starpu_task_bundle_t` [Data Type]
Opaque structure describing a list of tasks that should be scheduled on the same worker whenever it's possible. It must be considered as a hint given to the scheduler as there is no guarantee that they will be executed on the same worker.

`void starpu_task_bundle_create` (*starpu_task_bundle_t *bundle*) [Function]
Factory function creating and initializing *bundle*, when the call returns, memory needed is allocated and *bundle* is ready to use.

`int starpu_task_bundle_insert` (*starpu_task_bundle_t bundle*, *struct starpu_task *task*) [Function]
Insert *task* in *bundle*. Until *task* is removed from *bundle* its expected length and data transfer time will be considered along those of the other tasks of *bundle*. This function mustn't be called if *bundle* is already closed and/or *task* is already submitted.

`int starpu_task_bundle_remove` (*starpu_task_bundle_t bundle*, *struct starpu_task *task*) [Function]
Remove *task* from *bundle*. Of course *task* must have been previously inserted *bundle*. This function mustn't be called if *bundle* is already closed and/or *task* is already submitted. Doing so would result in undefined behaviour.

`void starpu_task_bundle_close` (*starpu_task_bundle_t bundle*) [Function]
Inform the runtime that the user won't modify *bundle* anymore, it means no more inserting or removing task. Thus the runtime can destroy it when possible.

14.4 Task Lists

`struct starpu_task_list` [Data Type]
Stores a double-chained list of tasks

`void starpu_task_list_init` (*struct starpu_task_list *list*) [Function]
Initialize a list structure

`void starpu_task_list_push_front` (*struct starpu_task_list *list*, *struct starpu_task *task*) [Function]
Push a task at the front of a list

`void starpu_task_list_push_back` (*struct starpu_task_list *list*, *struct starpu_task *task*) [Function]
Push a task at the back of a list

`struct starpu_task * starpu_task_list_front` (*struct starpu_task_list *list*) [Function]
Get the front of the list (without removing it)

`struct starpu_task * starpu_task_list_back` (*struct starpu_task_list *list*) [Function]
Get the back of the list (without removing it)

`int starpu_task_list_empty` (*struct starpu_task_list *list*) [Function]
Test if a list is empty

`void starpu_task_list_erase` (*struct starpu_task_list *list*, *struct starpu_task *task*) [Function]
Remove an element from the list

`struct starpu_task * starpu_task_list_pop_front` (*struct starpu_task_list *list*) [Function]
Remove the element at the front of the list

`struct starpu_task * starpu_task_list_pop_back` (*struct starpu_task_list *list*) [Function]
Remove the element at the back of the list

`struct starpu_task * starpu_task_list_begin` (*struct starpu_task_list *list*) [Function]
Get the first task of the list.

`struct starpu_task * starpu_task_list_end` (*struct starpu_task_list *list*) [Function]
Get the end of the list.

`struct starpu_task * starpu_task_list_next` (*struct starpu_task *task*) [Function]
Get the next task of the list. This is not erase-safe.

14.5 Using Parallel Tasks

These are used by parallel tasks:

`int starpu_combined_worker_get_size` (*void*) [Function]
Return the size of the current combined worker, i.e. the total number of cpus running the same task in the case of SPMD parallel tasks, or the total number of threads that the task is allowed to start in the case of FORKJOIN parallel tasks.

`int starpu_combined_worker_get_rank` (*void*) [Function]
Return the rank of the current thread within the combined worker. Can only be used in FORKJOIN parallel tasks, to know which part of the task to work on.

Most of these are used for schedulers which support parallel tasks.

`unsigned starpu_combined_worker_get_count` (*void*) [Function]
Return the number of different combined workers.

`int starpu_combined_worker_get_id (void)` [Function]
Return the identifier of the current combined worker.

`int starpu_combined_worker_assign_workerid (int nworkers, int workerid_array[])` [Function]
Register a new combined worker and get its identifier

`int starpu_combined_worker_get_description (int workerid, int *worker_size, int **combined_workerid)` [Function]
Get the description of a combined worker

`int starpu_combined_worker_can_execute_task (unsigned workerid, struct starpu_task *task, unsigned nimpl)` [Function]
Variant of starpu_worker_can_execute_task compatible with combined workers

14.6 Defining a new scheduling policy

TODO

A full example showing how to define a new scheduling policy is available in the StarPU sources in the directory `examples/scheduler/`.

14.6.1 Scheduling Policy API

While StarPU comes with a variety of scheduling policies (see Section 6.5 [Task scheduling policy], page 44), it may sometimes be desirable to implement custom policies to address specific problems. The API described below allows users to write their own scheduling policy.

`struct starpu_machine_topology` [Data Type]

`unsigned nworkers`
Total number of workers.

`unsigned ncombinedworkers`
Total number of combined workers.

`hwloc_topology_t hwtopology`
Topology as detected by hwloc.

To maintain ABI compatibility when hwloc is not available, the field is replaced with `void *dummy`

`unsigned nhwcpus`
Total number of CPUs, as detected by the topology code. May be different from the actual number of CPU workers.

`unsigned nhwcudagpus`
Total number of CUDA devices, as detected. May be different from the actual number of CUDA workers.

`unsigned nhwopenclgpus`
Total number of OpenCL devices, as detected. May be different from the actual number of CUDA workers.

`unsigned ncpus`
: Actual number of CPU workers used by StarPU.

`unsigned ncudagpus`
: Actual number of CUDA workers used by StarPU.

`unsigned nopenclgpus`
: Actual number of OpenCL workers used by StarPU.

`unsigned ngordon_spus`
: Actual number of Gordon workers used by StarPU.

`unsigned workers_bindid[STARPU_NMAXWORKERS]`
: Indicates the successive cpu identifier that should be used to bind the workers. It is either filled according to the user's explicit parameters (from starpu_conf) or according to the STARPU_WORKERS_CPUID env. variable. Otherwise, a round-robin policy is used to distributed the workers over the cpus.

`unsigned workers_cuda_gpuid[STARPU_NMAXWORKERS]`
: Indicates the successive cpu identifier that should be used by the CUDA driver. It is either filled according to the user's explicit parameters (from starpu_conf) or according to the STARPU_WORKERS_CUDAID env. variable. Otherwise, they are taken in ID order.

`unsigned workers_opencl_gpuid[STARPU_NMAXWORKERS]`
: Indicates the successive cpu identifier that should be used by the OpenCL driver. It is either filled according to the user's explicit parameters (from starpu_conf) or according to the STARPU_WORKERS_OPENCLID env. variable. Otherwise, they are taken in ID order.

`struct starpu_sched_policy` [Data Type]

This structure contains all the methods that implement a scheduling policy. An application may specify which scheduling strategy in the `sched_policy` field of the `starpu_conf` structure passed to the `starpu_init` function. The different fields are:

`void (*init_sched)(struct starpu_machine_topology *, struct starpu_sched_policy *)`
: Initialize the scheduling policy.

`void (*deinit_sched)(struct starpu_machine_topology *, struct starpu_sched_policy *)`
: Cleanup the scheduling policy.

`int (*push_task)(struct starpu_task *)`
: Insert a task into the scheduler.

`void (*push_task_notify)(struct starpu_task *, int workerid)`
: Notify the scheduler that a task was pushed on a given worker. This method is called when a task that was explicitely assigned to a worker becomes ready and is about to be executed by the worker. This method therefore permits to keep the state of of the scheduler coherent even when StarPU bypasses the scheduling strategy.

`struct starpu_task *(*pop_task)(void)` (optional)
: Get a task from the scheduler. The mutex associated to the worker is already taken when this method is called. If this method is defined as `NULL`, the worker will only execute tasks from its local queue. In this case, the `push_task` method should use the `starpu_push_local_task` method to assign tasks to the different workers.

`struct starpu_task *(*pop_every_task)(void)`
: Remove all available tasks from the scheduler (tasks are chained by the means of the prev and next fields of the starpu_task structure). The mutex associated to the worker is already taken when this method is called. This is currently only used by the Gordon driver.

`void (*pre_exec_hook)(struct starpu_task *)` (optional)
: This method is called every time a task is starting.

`void (*post_exec_hook)(struct starpu_task *)` (optional)
: This method is called every time a task has been executed.

`const char *policy_name` (optional)
: Name of the policy.

`const char *policy_description` (optional)
: Description of the policy.

`void starpu_worker_set_sched_condition` (*int* ***workerid***, *pthread_cond_t* ***sched_cond***, *pthread_mutex_t* ***sched_mutex***) [Function]
: This function specifies the condition variable associated to a worker When there is no available task for a worker, StarPU blocks this worker on a condition variable. This function specifies which condition variable (and the associated mutex) should be used to block (and to wake up) a worker. Note that multiple workers may use the same condition variable. For instance, in the case of a scheduling strategy with a single task queue, the same condition variable would be used to block and wake up all workers. The initialization method of a scheduling strategy (`init_sched`) must call this function once per worker.

`void starpu_sched_set_min_priority` (*int* ***min_prio***) [Function]
: Defines the minimum priority level supported by the scheduling policy. The default minimum priority level is the same as the default priority level which is 0 by convention. The application may access that value by calling the `starpu_sched_get_min_priority` function. This function should only be called from the initialization method of the scheduling policy, and should not be used directly from the application.

`void starpu_sched_set_max_priority` (*int* ***max_prio***) [Function]
: Defines the maximum priority level supported by the scheduling policy. The default maximum priority level is 1. The application may access that value by calling the `starpu_sched_get_max_priority` function. This function should only be called from the initialization method of the scheduling policy, and should not be used directly from the application.

`int starpu_sched_get_min_priority` (*void*) [Function]
: Returns the current minimum priority level supported by the scheduling policy

`int starpu_sched_get_max_priority (void)` [Function]
Returns the current maximum priority level supported by the scheduling policy

`int starpu_push_local_task (int workerid, struct starpu_task *task, int back)` [Function]
The scheduling policy may put tasks directly into a worker's local queue so that it is not always necessary to create its own queue when the local queue is sufficient. If *back* not null, *task* is put at the back of the queue where the worker will pop tasks first. Setting *back* to 0 therefore ensures a FIFO ordering.

`int starpu_worker_can_execute_task (unsigned workerid, struct starpu_task *task, unsigned nimpl)` [Function]
Check if the worker specified by workerid can execute the codelet. Schedulers need to call it before assigning a task to a worker, otherwise the task may fail to execute.

`double starpu_timing_now (void)` [Function]
Return the current date in s

`double starpu_task_expected_length (struct starpu_task *task, enum starpu_perf_archtype arch, unsigned nimpl)` [Function]
Returns expected task duration in s

`double starpu_worker_get_relative_speedup (enum starpu_perf_archtype perf_archtype)` [Function]
Returns an estimated speedup factor relative to CPU speed

`double starpu_task_expected_data_transfer_time (uint32_t memory_node, struct starpu_task *task)` [Function]
Returns expected data transfer time in s

`double starpu_data_expected_transfer_time (starpu_data_handle_t handle, unsigned memory_node, enum starpu_access_mode mode)` [Function]
Predict the transfer time (in s) to move a handle to a memory node

`double starpu_task_expected_power (struct starpu_task *task, enum starpu_perf_archtype arch, unsigned nimpl)` [Function]
Returns expected power consumption in J

`double starpu_task_expected_conversion_time (struct starpu_task *task, enum starpu_perf_archtype arch, unsigned nimpl)` [Function]
Returns expected conversion time in ms (multiformat interface only)

14.6.2 Source code

```
static struct starpu_sched_policy dummy_sched_policy = {
    .init_sched = init_dummy_sched,
    .deinit_sched = deinit_dummy_sched,
    .push_task = push_task_dummy,
    .push_prio_task = NULL,
    .pop_task = pop_task_dummy,
    .post_exec_hook = NULL,
    .pop_every_task = NULL,
    .policy_name = "dummy",
    .policy_description = "dummy scheduling strategy"
};
```

14.7 Expert mode

`void starpu_wake_all_blocked_workers` (*void*) [Function]

Wake all the workers, so they can inspect data requests and task submissions again.

`int starpu_progression_hook_register` (*unsigned* (**func*)(*void* **arg*), *void* **arg*) [Function]

Register a progression hook, to be called when workers are idle.

`void starpu_progression_hook_deregister` (*int* *hook_id*) [Function]

Unregister a given progression hook.

15 Configuring StarPU

15.1 Compilation configuration

The following arguments can be given to the `configure` script.

15.1.1 Common configuration

`--enable-debug`
: Enable debugging messages.

`--enable-fast`
: Disable assertion checks, which saves computation time.

`--enable-verbose`
: Increase the verbosity of the debugging messages. This can be disabled at runtime by setting the environment variable `STARPU_SILENT` to any value.

```
% STARPU_SILENT=1 ./vector_scal
```

`--enable-coverage`
: Enable flags for the `gcov` coverage tool.

15.1.2 Configuring workers

`--enable-maxcpus=`*count*
: Use at most *count* CPU cores. This information is then available as the `STARPU_MAXCPUS` macro.

`--disable-cpu`
: Disable the use of CPUs of the machine. Only GPUs etc. will be used.

`--enable-maxcudadev=`*count*
: Use at most *count* CUDA devices. This information is then available as the `STARPU_MAXCUDADEVS` macro.

`--disable-cuda`
: Disable the use of CUDA, even if a valid CUDA installation was detected.

`--with-cuda-dir=`*prefix*
: Search for CUDA under *prefix*, which should notably contain '`include/cuda.h`'.

`--with-cuda-include-dir=`*dir*
: Search for CUDA headers under *dir*, which should notably contain `cuda.h`. This defaults to `/include` appended to the value given to `--with-cuda-dir`.

`--with-cuda-lib-dir=`*dir*
: Search for CUDA libraries under *dir*, which should notably contain the CUDA shared libraries—e.g., '`libcuda.so`'. This defaults to `/lib` appended to the value given to `--with-cuda-dir`.

`--disable-cuda-memcpy-peer`
: Explicitly disable peer transfers when using CUDA 4.0.

`--enable-maxopencldev=`*count*
: Use at most *count* OpenCL devices. This information is then available as the `STARPU_MAXOPENCLDEVS` macro.

`--disable-opencl`
: Disable the use of OpenCL, even if the SDK is detected.

`--with-opencl-dir=`*prefix*
: Search for an OpenCL implementation under *prefix*, which should notably contain '`include/CL/cl.h`' (or '`include/OpenCL/cl.h`' on Mac OS).

`--with-opencl-include-dir=`*dir*
: Search for OpenCL headers under *dir*, which should notably contain '`CL/cl.h`' (or '`OpenCL/cl.h`' on Mac OS). This defaults to `/include` appended to the value given to `--with-opencl-dir`.

`--with-opencl-lib-dir=`*dir*
: Search for an OpenCL library under *dir*, which should notably contain the OpenCL shared libraries—e.g. '`libOpenCL.so`'. This defaults to `/lib` appended to the value given to `--with-opencl-dir`.

`--enable-gordon`
: Enable the use of the Gordon runtime for Cell SPUs.

`--with-gordon-dir=`*prefix*
: Search for the Gordon SDK under *prefix*.

`--enable-maximplementations=`*count*
: Allow for at most *count* codelet implementations for the same target device. This information is then available as the `STARPU_MAXIMPLEMENTATIONS` macro.

15.1.3 Advanced configuration

`--enable-perf-debug`
: Enable performance debugging through gprof.

`--enable-model-debug`
: Enable performance model debugging.

`--enable-stats`
: Enable gathering of memory transfer statistics.

`--enable-maxbuffers`
: Define the maximum number of buffers that tasks will be able to take as parameters, then available as the `STARPU_NMAXBUFS` macro.

`--enable-allocation-cache`
: Enable the use of a data allocation cache to avoid the cost of it with CUDA. Still experimental.

`--enable-opengl-render`
: Enable the use of OpenGL for the rendering of some examples.

`--enable-blas-lib`
: Specify the blas library to be used by some of the examples. The library has to be 'atlas' or 'goto'.

`--disable-starpufft`
: Disable the build of libstarpufft, even if fftw or cuFFT is available.

`--with-magma=`*prefix*
: Search for MAGMA under *prefix*. *prefix* should notably contain '`include/magmablas.h`'.

`--with-fxt=`*prefix*
: Search for FxT under *prefix*. FxT is used to generate traces of scheduling events, which can then be rendered them using ViTE (see Section 7.2 [Off-line], page 51). *prefix* should notably contain `include/fxt/fxt.h`.

`--with-perf-model-dir=`*dir*
: Store performance models under *dir*, instead of the current user's home.

`--with-mpicc=`*path*
: Use the `mpicc` compiler at *path*, for starpumpi (see Chapter 9 [StarPU MPI support], page 57).

`--with-goto-dir=`*prefix*
: Search for GotoBLAS under *prefix*.

`--with-atlas-dir=`*prefix*
: Search for ATLAS under *prefix*, which should notably contain '`include/cblas.h`'.

`--with-mkl-cflags=`*cflags*
: Use *cflags* to compile code that uses the MKL library.

`--with-mkl-ldflags=`*ldflags*
: Use *ldflags* when linking code that uses the MKL library. Note that the MKL website provides a script to determine the linking flags.

`--disable-gcc-extensions`
: Disable the GCC plug-in (see Chapter 11 [C Extensions], page 69). By default, it is enabled when the GCC compiler provides a plug-in support.

`--disable-socl`
: Disable the SOCL extension (see Chapter 12 [SOCL OpenCL Extensions], page 75). By default, it is enabled when an OpenCL implementation is found.

`--disable-starpu-top`
: Disable the StarPU-Top interface (see Section 7.1.6 [StarPU-Top], page 50). By default, it is enabled when the required dependencies are found.

15.2 Execution configuration through environment variables

Note: the values given in `starpu_conf` structure passed when calling `starpu_init` will override the values of the environment variables.

15.2.1 Configuring workers

15.2.1.1 STARPU_NCPUS – Number of CPU workers

Specify the number of CPU workers (thus not including workers dedicated to control accelerators). Note that by default, StarPU will not allocate more CPU workers than there are physical CPUs, and that some CPUs are used to control the accelerators.

15.2.1.2 STARPU_NCUDA – Number of CUDA workers

Specify the number of CUDA devices that StarPU can use. If STARPU_NCUDA is lower than the number of physical devices, it is possible to select which CUDA devices should be used by the means of the STARPU_WORKERS_CUDAID environment variable. By default, StarPU will create as many CUDA workers as there are CUDA devices.

15.2.1.3 STARPU_NOPENCL – Number of OpenCL workers

OpenCL equivalent of the STARPU_NCUDA environment variable.

15.2.1.4 STARPU_NGORDON – Number of SPU workers (Cell)

Specify the number of SPUs that StarPU can use.

15.2.1.5 STARPU_WORKERS_NOBIND – Do not bind workers to specific CPUs

Setting it to non-zero will prevent StarPU from binding its threads to CPUs. This is for instance useful when running the testsuite in parallel.

15.2.1.6 STARPU_WORKERS_CPUID – Bind workers to specific CPUs

Passing an array of integers (starting from 0) in STARPU_WORKERS_CPUID specifies on which logical CPU the different workers should be bound. For instance, if STARPU_WORKERS_CPUID = "0 1 4 5", the first worker will be bound to logical CPU #0, the second CPU worker will be bound to logical CPU #1 and so on. Note that the logical ordering of the CPUs is either determined by the OS, or provided by the hwloc library in case it is available.

Note that the first workers correspond to the CUDA workers, then come the OpenCL and the SPU, and finally the CPU workers. For example if we have STARPU_NCUDA=1, STARPU_NOPENCL=1, STARPU_NCPUS=2 and STARPU_WORKERS_CPUID = "0 2 1 3", the CUDA device will be controlled by logical CPU #0, the OpenCL device will be controlled by logical CPU #2, and the logical CPUs #1 and #3 will be used by the CPU workers.

If the number of workers is larger than the array given in STARPU_WORKERS_CPUID, the workers are bound to the logical CPUs in a round-robin fashion: if STARPU_WORKERS_CPUID = "0 1", the first and the third (resp. second and fourth) workers will be put on CPU #0 (resp. CPU #1).

This variable is ignored if the use_explicit_workers_bindid flag of the starpu_conf structure passed to starpu_init is set.

15.2.1.7 STARPU_WORKERS_CUDAID – Select specific CUDA devices

Similarly to the STARPU_WORKERS_CPUID environment variable, it is possible to select which CUDA devices should be used by StarPU. On a machine equipped with 4 GPUs, setting STARPU_WORKERS_CUDAID = "1 3" and STARPU_NCUDA=2 specifies that 2 CUDA workers

should be created, and that they should use CUDA devices #1 and #3 (the logical ordering of the devices is the one reported by CUDA).

This variable is ignored if the `use_explicit_workers_cuda_gpuid` flag of the `starpu_conf` structure passed to `starpu_init` is set.

15.2.1.8 STARPU_WORKERS_OPENCLID – Select specific OpenCL devices

OpenCL equivalent of the `STARPU_WORKERS_CUDAID` environment variable.

This variable is ignored if the `use_explicit_workers_opencl_gpuid` flag of the `starpu_conf` structure passed to `starpu_init` is set.

15.2.2 Configuring the Scheduling engine

15.2.2.1 STARPU_SCHED – Scheduling policy

Choose between the different scheduling policies proposed by StarPU: work random, stealing, greedy, with performance models, etc.

Use `STARPU_SCHED=help` to get the list of available schedulers.

15.2.2.2 STARPU_CALIBRATE – Calibrate performance models

If this variable is set to 1, the performance models are calibrated during the execution. If it is set to 2, the previous values are dropped to restart calibration from scratch. Setting this variable to 0 disable calibration, this is the default behaviour.

Note: this currently only applies to `dm`, `dmda` and `heft` scheduling policies.

15.2.2.3 STARPU_PREFETCH – Use data prefetch

This variable indicates whether data prefetching should be enabled (0 means that it is disabled). If prefetching is enabled, when a task is scheduled to be executed e.g. on a GPU, StarPU will request an asynchronous transfer in advance, so that data is already present on the GPU when the task starts. As a result, computation and data transfers are overlapped. Note that prefetching is enabled by default in StarPU.

15.2.2.4 STARPU_SCHED_ALPHA – Computation factor

To estimate the cost of a task StarPU takes into account the estimated computation time (obtained thanks to performance models). The alpha factor is the coefficient to be applied to it before adding it to the communication part.

15.2.2.5 STARPU_SCHED_BETA – Communication factor

To estimate the cost of a task StarPU takes into account the estimated data transfer time (obtained thanks to performance models). The beta factor is the coefficient to be applied to it before adding it to the computation part.

15.2.3 Miscellaneous and debug

15.2.3.1 STARPU_SILENT – Disable verbose mode

This variable allows to disable verbose mode at runtime when StarPU has been configured with the option `--enable-verbose`.

15.2.3.2 STARPU_LOGFILENAME – Select debug file name

This variable specifies in which file the debugging output should be saved to.

15.2.3.3 STARPU_FXT_PREFIX – FxT trace location

This variable specifies in which directory to save the trace generated if FxT is enabled. It needs to have a trailing '/' character.

15.2.3.4 STARPU_LIMIT_GPU_MEM – Restrict memory size on the GPUs

This variable specifies the maximum number of megabytes that should be available to the application on each GPUs. In case this value is smaller than the size of the memory of a GPU, StarPU pre-allocates a buffer to waste memory on the device. This variable is intended to be used for experimental purposes as it emulates devices that have a limited amount of memory.

15.2.3.5 STARPU_GENERATE_TRACE – Generate a Paje trace when StarPU is shut down

When set to 1, this variable indicates that StarPU should automatically generate a Paje trace when starpu_shutdown is called.

Appendix A Full source code for the 'Scaling a Vector' example

A.1 Main application

```
/*
 * This example demonstrates how to use StarPU to scale an array by a factor.
 * It shows how to manipulate data with StarPU's data management library.
 *  1- how to declare a piece of data to StarPU (starpu_vector_data_register)
 *  2- how to describe which data are accessed by a task (task->handles[0])
 *  3- how a kernel can manipulate the data (buffers[0].vector.ptr)
 */
#include <starpu.h>
#include <starpu_opencl.h>

#define    NX    2048

extern void scal_cpu_func(void *buffers[], void *_args);
extern void scal_sse_func(void *buffers[], void *_args);
extern void scal_cuda_func(void *buffers[], void *_args);
extern void scal_opencl_func(void *buffers[], void *_args);

static struct starpu_codelet cl = {
    .where = STARPU_CPU | STARPU_CUDA | STARPU_OPENCL,
    /* CPU implementation of the codelet */
    .cpu_funcs = { scal_cpu_func, scal_sse_func, NULL },
#ifdef STARPU_USE_CUDA
    /* CUDA implementation of the codelet */
    .cuda_funcs = { scal_cuda_func, NULL },
#endif
#ifdef STARPU_USE_OPENCL
    /* OpenCL implementation of the codelet */
    .opencl_funcs = { scal_opencl_func, NULL },
#endif
    .nbuffers = 1,
    .modes = { STARPU_RW }
};

#ifdef STARPU_USE_OPENCL
struct starpu_opencl_program programs;
#endif

int main(int argc, char **argv)
{
    /* We consider a vector of float that is initialized just as any of C
      * data */
    float vector[NX];
    unsigned i;
    for (i = 0; i < NX; i++)
        vector[i] = 1.0f;

    fprintf(stderr, "BEFORE: First element was %f\n", vector[0]);

    /* Initialize StarPU with default configuration */
    starpu_init(NULL);

#ifdef STARPU_USE_OPENCL
        starpu_opencl_load_opencl_from_file(
```

```
                "examples/basic_examples/vector_scal_opencl_kernel.cl", &programs, NULL);
#endif

    /* Tell StaPU to associate the "vector" vector with the "vector_handle"
     * identifier. When a task needs to access a piece of data, it should
     * refer to the handle that is associated to it.
     * In the case of the "vector" data interface:
     *  - the first argument of the registration method is a pointer to the
     *    handle that should describe the data
     *  - the second argument is the memory node where the data (ie. "vector")
     *    resides initially: 0 stands for an address in main memory, as
     *    opposed to an adress on a GPU for instance.
     *  - the third argument is the adress of the vector in RAM
     *  - the fourth argument is the number of elements in the vector
     *  - the fifth argument is the size of each element.
     */
    starpu_data_handle_t vector_handle;
    starpu_vector_data_register(&vector_handle, 0, (uintptr_t)vector,
                                NX, sizeof(vector[0]));

    float factor = 3.14;

    /* create a synchronous task: any call to starpu_task_submit will block
      * until it is terminated */
    struct starpu_task *task = starpu_task_create();
    task->synchronous = 1;

    task->cl = &cl;

    /* the codelet manipulates one buffer in RW mode */
    task->handles[0] = vector_handle;

    /* an argument is passed to the codelet, beware that this is a
     * READ-ONLY buffer and that the codelet may be given a pointer to a
     * COPY of the argument */
    task->cl_arg = &factor;
    task->cl_arg_size = sizeof(factor);

    /* execute the task on any eligible computational ressource */
    starpu_task_submit(task);

    /* StarPU does not need to manipulate the array anymore so we can stop
      * monitoring it */
    starpu_data_unregister(vector_handle);

#ifdef STARPU_USE_OPENCL
    starpu_opencl_unload_opencl(&programs);
#endif

    /* terminate StarPU, no task can be submitted after */
    starpu_shutdown();

    fprintf(stderr, "AFTER First element is %f\n", vector[0]);

    return 0;
}
```

A.2 CPU Kernel

```
#include <starpu.h>
#include <xmmintrin.h>

/* This kernel takes a buffer and scales it by a constant factor */
void scal_cpu_func(void *buffers[], void *cl_arg)
{
    unsigned i;
    float *factor = cl_arg;

    /*
     * The "buffers" array matches the task->handles array: for instance
     * task->handles[0] is a handle that corresponds to a data with
     * vector "interface", so that the first entry of the array in the
     * codelet  is a pointer to a structure describing such a vector (ie.
     * struct starpu_vector_interface *). Here, we therefore manipulate
     * the buffers[0] element as a vector: nx gives the number of elements
     * in the array, ptr gives the location of the array (that was possibly
     * migrated/replicated), and elemsize gives the size of each elements.
     */
    struct starpu_vector_interface *vector = buffers[0];

    /* length of the vector */
    unsigned n = STARPU_VECTOR_GET_NX(vector);

    /* get a pointer to the local copy of the vector: note that we have to
     * cast it in (float *) since a vector could contain any type of
     * elements so that the .ptr field is actually a uintptr_t */
    float *val = (float *)STARPU_VECTOR_GET_PTR(vector);

    /* scale the vector */
    for (i = 0; i < n; i++)
        val[i] *= *factor;
}

void scal_sse_func(void *buffers[], void *cl_arg)
{
    float *vector = (float *) STARPU_VECTOR_GET_PTR(buffers[0]);
    unsigned int n = STARPU_VECTOR_GET_NX(buffers[0]);
    unsigned int n_iterations = n/4;

    __m128 *VECTOR = (__m128*) vector;
    __m128 FACTOR __attribute__((aligned(16)));
    float factor = *(float *) cl_arg;
    FACTOR = _mm_set1_ps(factor);

    unsigned int i;
    for (i = 0; i < n_iterations; i++)
        VECTOR[i] = _mm_mul_ps(FACTOR, VECTOR[i]);

    unsigned int remainder = n%4;
    if (remainder != 0)
    {
        unsigned int start = 4 * n_iterations;
        for (i = start; i < start+remainder; ++i)
        {
            vector[i] = factor * vector[i];
        }
```

```
    }
}
```

A.3 CUDA Kernel

```
#include <starpu.h>
#include <starpu_cuda.h>

static __global__ void vector_mult_cuda(float *val, unsigned n,
                                        float factor)
{
        unsigned i =  blockIdx.x*blockDim.x + threadIdx.x;
        if (i < n)
               val[i] *= factor;
}

extern "C" void scal_cuda_func(void *buffers[], void *_args)
{
        float *factor = (float *)_args;

        /* length of the vector */
        unsigned n = STARPU_VECTOR_GET_NX(buffers[0]);
        /* local copy of the vector pointer */
        float *val = (float *)STARPU_VECTOR_GET_PTR(buffers[0]);
        unsigned threads_per_block = 64;
        unsigned nblocks = (n + threads_per_block-1) / threads_per_block;

        vector_mult_cuda<<<nblocks,threads_per_block, 0, starpu_cuda_get_local_stream()>>>(val, n, *facto

        cudaStreamSynchronize(starpu_cuda_get_local_stream());
}
```

A.4 OpenCL Kernel

A.4.1 Invoking the kernel

```
#include <starpu.h>
#include <starpu_opencl.h>

extern struct starpu_opencl_program programs;

void scal_opencl_func(void *buffers[], void *_args)
{
    float *factor = _args;
    int id, devid, err;
    cl_kernel kernel;
    cl_command_queue queue;
    cl_event event;

    /* length of the vector */
    unsigned n = STARPU_VECTOR_GET_NX(buffers[0]);
    /* OpenCL copy of the vector pointer */
    cl_mem val = (cl_mem)STARPU_VECTOR_GET_DEV_HANDLE(buffers[0]);

    id = starpu_worker_get_id();
    devid = starpu_worker_get_devid(id);

    err = starpu_opencl_load_kernel(&kernel, &queue, &programs, "vector_mult_opencl",
```

```
                                    devid);
    if (err != CL_SUCCESS) STARPU_OPENCL_REPORT_ERROR(err);

    err = clSetKernelArg(kernel, 0, sizeof(val), &val);
    err |= clSetKernelArg(kernel, 1, sizeof(n), &n);
    err |= clSetKernelArg(kernel, 2, sizeof(*factor), factor);
    if (err) STARPU_OPENCL_REPORT_ERROR(err);

    {
        size_t global=n;
        size_t local;
        size_t s;
        cl_device_id device;

        starpu_opencl_get_device(devid, &device);
        err = clGetKernelWorkGroupInfo (kernel, device, CL_KERNEL_WORK_GROUP_SIZE,
                                        sizeof(local), &local, &s);
        if (err != CL_SUCCESS) STARPU_OPENCL_REPORT_ERROR(err);
        if (local > global) local=global;

        err = clEnqueueNDRangeKernel(queue, kernel, 1, NULL, &global, &local, 0,
                                     NULL, &event);
        if (err != CL_SUCCESS) STARPU_OPENCL_REPORT_ERROR(err);
    }

    clFinish(queue);
    starpu_opencl_collect_stats(event);
    clReleaseEvent(event);

    starpu_opencl_release_kernel(kernel);
}
```

A.4.2 Source of the kernel

```
__kernel void vector_mult_opencl(__global float* val, int nx, float factor)
{
        const int i = get_global_id(0);
        if (i < nx) {
                val[i] *= factor;
        }
}
```

Appendix B GNU Free Documentation License

Version 1.3, 3 November 2008

0. PREAMBLE

The purpose of this License is to make a manual, textbook, or other functional and useful document *free* in the sense of freedom: to assure everyone the effective freedom to copy and redistribute it, with or without modifying it, either commercially or non-commercially. Secondarily, this License preserves for the author and publisher a way to get credit for their work, while not being considered responsible for modifications made by others.

This License is a kind of "copyleft", which means that derivative works of the document must themselves be free in the same sense. It complements the GNU General Public License, which is a copyleft license designed for free software.

We have designed this License in order to use it for manuals for free software, because free software needs free documentation: a free program should come with manuals providing the same freedoms that the software does. But this License is not limited to software manuals; it can be used for any textual work, regardless of subject matter or whether it is published as a printed book. We recommend this License principally for works whose purpose is instruction or reference.

1. APPLICABILITY AND DEFINITIONS

This License applies to any manual or other work, in any medium, that contains a notice placed by the copyright holder saying it can be distributed under the terms of this License. Such a notice grants a world-wide, royalty-free license, unlimited in duration, to use that work under the conditions stated herein. The "Document", below, refers to any such manual or work. Any member of the public is a licensee, and is addressed as "you". You accept the license if you copy, modify or distribute the work in a way requiring permission under copyright law.

A "Modified Version" of the Document means any work containing the Document or a portion of it, either copied verbatim, or with modifications and/or translated into another language.

A "Secondary Section" is a named appendix or a front-matter section of the Document that deals exclusively with the relationship of the publishers or authors of the Document to the Document's overall subject (or to related matters) and contains nothing that could fall directly within that overall subject. (Thus, if the Document is in part a textbook of mathematics, a Secondary Section may not explain any mathematics.) The relationship could be a matter of historical connection with the subject or with related matters, or of legal, commercial, philosophical, ethical or political position regarding them.

The "Invariant Sections" are certain Secondary Sections whose titles are designated, as being those of Invariant Sections, in the notice that says that the Document is released

under this License. If a section does not fit the above definition of Secondary then it is not allowed to be designated as Invariant. The Document may contain zero Invariant Sections. If the Document does not identify any Invariant Sections then there are none.

The "Cover Texts" are certain short passages of text that are listed, as Front-Cover Texts or Back-Cover Texts, in the notice that says that the Document is released under this License. A Front-Cover Text may be at most 5 words, and a Back-Cover Text may be at most 25 words.

A "Transparent" copy of the Document means a machine-readable copy, represented in a format whose specification is available to the general public, that is suitable for revising the document straightforwardly with generic text editors or (for images composed of pixels) generic paint programs or (for drawings) some widely available drawing editor, and that is suitable for input to text formatters or for automatic translation to a variety of formats suitable for input to text formatters. A copy made in an otherwise Transparent file format whose markup, or absence of markup, has been arranged to thwart or discourage subsequent modification by readers is not Transparent. An image format is not Transparent if used for any substantial amount of text. A copy that is not "Transparent" is called "Opaque".

Examples of suitable formats for Transparent copies include plain ASCII without markup, Texinfo input format, LaTeX input format, SGML or XML using a publicly available DTD, and standard-conforming simple HTML, PostScript or PDF designed for human modification. Examples of transparent image formats include PNG, XCF and JPG. Opaque formats include proprietary formats that can be read and edited only by proprietary word processors, SGML or XML for which the DTD and/or processing tools are not generally available, and the machine-generated HTML, PostScript or PDF produced by some word processors for output purposes only.

The "Title Page" means, for a printed book, the title page itself, plus such following pages as are needed to hold, legibly, the material this License requires to appear in the title page. For works in formats which do not have any title page as such, "Title Page" means the text near the most prominent appearance of the work's title, preceding the beginning of the body of the text.

The "publisher" means any person or entity that distributes copies of the Document to the public.

A section "Entitled XYZ" means a named subunit of the Document whose title either is precisely XYZ or contains XYZ in parentheses following text that translates XYZ in another language. (Here XYZ stands for a specific section name mentioned below, such as "Acknowledgements", "Dedications", "Endorsements", or "History".) To "Preserve the Title" of such a section when you modify the Document means that it remains a section "Entitled XYZ" according to this definition.

The Document may include Warranty Disclaimers next to the notice which states that this License applies to the Document. These Warranty Disclaimers are considered to be included by reference in this License, but only as regards disclaiming warranties: any other implication that these Warranty Disclaimers may have is void and has no effect on the meaning of this License.

2. VERBATIM COPYING

You may copy and distribute the Document in any medium, either commercially or noncommercially, provided that this License, the copyright notices, and the license notice saying this License applies to the Document are reproduced in all copies, and that you add no other conditions whatsoever to those of this License. You may not use technical measures to obstruct or control the reading or further copying of the copies you make or distribute. However, you may accept compensation in exchange for copies. If you distribute a large enough number of copies you must also follow the conditions in section 3.

You may also lend copies, under the same conditions stated above, and you may publicly display copies.

3. COPYING IN QUANTITY

   If you publish printed copies (or copies in media that commonly have printed covers) of the Document, numbering more than 100, and the Document's license notice requires Cover Texts, you must enclose the copies in covers that carry, clearly and legibly, all these Cover Texts: Front-Cover Texts on the front cover, and Back-Cover Texts on the back cover. Both covers must also clearly and legibly identify you as the publisher of these copies. The front cover must present the full title with all words of the title equally prominent and visible. You may add other material on the covers in addition. Copying with changes limited to the covers, as long as they preserve the title of the Document and satisfy these conditions, can be treated as verbatim copying in other respects.

   If the required texts for either cover are too voluminous to fit legibly, you should put the first ones listed (as many as fit reasonably) on the actual cover, and continue the rest onto adjacent pages.

   If you publish or distribute Opaque copies of the Document numbering more than 100, you must either include a machine-readable Transparent copy along with each Opaque copy, or state in or with each Opaque copy a computer-network location from which the general network-using public has access to download using public-standard network protocols a complete Transparent copy of the Document, free of added material. If you use the latter option, you must take reasonably prudent steps, when you begin distribution of Opaque copies in quantity, to ensure that this Transparent copy will remain thus accessible at the stated location until at least one year after the last time you distribute an Opaque copy (directly or through your agents or retailers) of that edition to the public.

   It is requested, but not required, that you contact the authors of the Document well before redistributing any large number of copies, to give them a chance to provide you with an updated version of the Document.

4. MODIFICATIONS

   You may copy and distribute a Modified Version of the Document under the conditions of sections 2 and 3 above, provided that you release the Modified Version under precisely this License, with the Modified Version filling the role of the Document, thus licensing distribution and modification of the Modified Version to whoever possesses a copy of it. In addition, you must do these things in the Modified Version:

   A. Use in the Title Page (and on the covers, if any) a title distinct from that of the Document, and from those of previous versions (which should, if there were any,

be listed in the History section of the Document). You may use the same title as a previous version if the original publisher of that version gives permission.

B. List on the Title Page, as authors, one or more persons or entities responsible for authorship of the modifications in the Modified Version, together with at least five of the principal authors of the Document (all of its principal authors, if it has fewer than five), unless they release you from this requirement.

C. State on the Title page the name of the publisher of the Modified Version, as the publisher.

D. Preserve all the copyright notices of the Document.

E. Add an appropriate copyright notice for your modifications adjacent to the other copyright notices.

F. Include, immediately after the copyright notices, a license notice giving the public permission to use the Modified Version under the terms of this License, in the form shown in the Addendum below.

G. Preserve in that license notice the full lists of Invariant Sections and required Cover Texts given in the Document's license notice.

H. Include an unaltered copy of this License.

I. Preserve the section Entitled "History", Preserve its Title, and add to it an item stating at least the title, year, new authors, and publisher of the Modified Version as given on the Title Page. If there is no section Entitled "History" in the Document, create one stating the title, year, authors, and publisher of the Document as given on its Title Page, then add an item describing the Modified Version as stated in the previous sentence.

J. Preserve the network location, if any, given in the Document for public access to a Transparent copy of the Document, and likewise the network locations given in the Document for previous versions it was based on. These may be placed in the "History" section. You may omit a network location for a work that was published at least four years before the Document itself, or if the original publisher of the version it refers to gives permission.

K. For any section Entitled "Acknowledgements" or "Dedications", Preserve the Title of the section, and preserve in the section all the substance and tone of each of the contributor acknowledgements and/or dedications given therein.

L. Preserve all the Invariant Sections of the Document, unaltered in their text and in their titles. Section numbers or the equivalent are not considered part of the section titles.

M. Delete any section Entitled "Endorsements". Such a section may not be included in the Modified Version.

N. Do not retitle any existing section to be Entitled "Endorsements" or to conflict in title with any Invariant Section.

O. Preserve any Warranty Disclaimers.

If the Modified Version includes new front-matter sections or appendices that qualify as Secondary Sections and contain no material copied from the Document, you may at your option designate some or all of these sections as invariant. To do this, add their

titles to the list of Invariant Sections in the Modified Version's license notice. These titles must be distinct from any other section titles.

You may add a section Entitled "Endorsements", provided it contains nothing but endorsements of your Modified Version by various parties—for example, statements of peer review or that the text has been approved by an organization as the authoritative definition of a standard.

You may add a passage of up to five words as a Front-Cover Text, and a passage of up to 25 words as a Back-Cover Text, to the end of the list of Cover Texts in the Modified Version. Only one passage of Front-Cover Text and one of Back-Cover Text may be added by (or through arrangements made by) any one entity. If the Document already includes a cover text for the same cover, previously added by you or by arrangement made by the same entity you are acting on behalf of, you may not add another; but you may replace the old one, on explicit permission from the previous publisher that added the old one.

The author(s) and publisher(s) of the Document do not by this License give permission to use their names for publicity for or to assert or imply endorsement of any Modified Version.

5. COMBINING DOCUMENTS

   You may combine the Document with other documents released under this License, under the terms defined in section 4 above for modified versions, provided that you include in the combination all of the Invariant Sections of all of the original documents, unmodified, and list them all as Invariant Sections of your combined work in its license notice, and that you preserve all their Warranty Disclaimers.

   The combined work need only contain one copy of this License, and multiple identical Invariant Sections may be replaced with a single copy. If there are multiple Invariant Sections with the same name but different contents, make the title of each such section unique by adding at the end of it, in parentheses, the name of the original author or publisher of that section if known, or else a unique number. Make the same adjustment to the section titles in the list of Invariant Sections in the license notice of the combined work.

   In the combination, you must combine any sections Entitled "History" in the various original documents, forming one section Entitled "History"; likewise combine any sections Entitled "Acknowledgements", and any sections Entitled "Dedications". You must delete all sections Entitled "Endorsements."

6. COLLECTIONS OF DOCUMENTS

   You may make a collection consisting of the Document and other documents released under this License, and replace the individual copies of this License in the various documents with a single copy that is included in the collection, provided that you follow the rules of this License for verbatim copying of each of the documents in all other respects.

   You may extract a single document from such a collection, and distribute it individually under this License, provided you insert a copy of this License into the extracted document, and follow this License in all other respects regarding verbatim copying of that document.

7. AGGREGATION WITH INDEPENDENT WORKS

   A compilation of the Document or its derivatives with other separate and independent documents or works, in or on a volume of a storage or distribution medium, is called an "aggregate" if the copyright resulting from the compilation is not used to limit the legal rights of the compilation's users beyond what the individual works permit. When the Document is included in an aggregate, this License does not apply to the other works in the aggregate which are not themselves derivative works of the Document.

   If the Cover Text requirement of section 3 is applicable to these copies of the Document, then if the Document is less than one half of the entire aggregate, the Document's Cover Texts may be placed on covers that bracket the Document within the aggregate, or the electronic equivalent of covers if the Document is in electronic form. Otherwise they must appear on printed covers that bracket the whole aggregate.

8. TRANSLATION

   Translation is considered a kind of modification, so you may distribute translations of the Document under the terms of section 4. Replacing Invariant Sections with translations requires special permission from their copyright holders, but you may include translations of some or all Invariant Sections in addition to the original versions of these Invariant Sections. You may include a translation of this License, and all the license notices in the Document, and any Warranty Disclaimers, provided that you also include the original English version of this License and the original versions of those notices and disclaimers. In case of a disagreement between the translation and the original version of this License or a notice or disclaimer, the original version will prevail.

   If a section in the Document is Entitled "Acknowledgements", "Dedications", or "History", the requirement (section 4) to Preserve its Title (section 1) will typically require changing the actual title.

9. TERMINATION

   You may not copy, modify, sublicense, or distribute the Document except as expressly provided under this License. Any attempt otherwise to copy, modify, sublicense, or distribute it is void, and will automatically terminate your rights under this License.

   However, if you cease all violation of this License, then your license from a particular copyright holder is reinstated (a) provisionally, unless and until the copyright holder explicitly and finally terminates your license, and (b) permanently, if the copyright holder fails to notify you of the violation by some reasonable means prior to 60 days after the cessation.

   Moreover, your license from a particular copyright holder is reinstated permanently if the copyright holder notifies you of the violation by some reasonable means, this is the first time you have received notice of violation of this License (for any work) from that copyright holder, and you cure the violation prior to 30 days after your receipt of the notice.

   Termination of your rights under this section does not terminate the licenses of parties who have received copies or rights from you under this License. If your rights have been terminated and not permanently reinstated, receipt of a copy of some or all of the same material does not give you any rights to use it.

10. FUTURE REVISIONS OF THIS LICENSE

    The Free Software Foundation may publish new, revised versions of the GNU Free Documentation License from time to time. Such new versions will be similar in spirit to the present version, but may differ in detail to address new problems or concerns. See http://www.gnu.org/copyleft/.

    Each version of the License is given a distinguishing version number. If the Document specifies that a particular numbered version of this License "or any later version" applies to it, you have the option of following the terms and conditions either of that specified version or of any later version that has been published (not as a draft) by the Free Software Foundation. If the Document does not specify a version number of this License, you may choose any version ever published (not as a draft) by the Free Software Foundation. If the Document specifies that a proxy can decide which future versions of this License can be used, that proxy's public statement of acceptance of a version permanently authorizes you to choose that version for the Document.

11. RELICENSING

    "Massive Multiauthor Collaboration Site" (or "MMC Site") means any World Wide Web server that publishes copyrightable works and also provides prominent facilities for anybody to edit those works. A public wiki that anybody can edit is an example of such a server. A "Massive Multiauthor Collaboration" (or "MMC") contained in the site means any set of copyrightable works thus published on the MMC site.

    "CC-BY-SA" means the Creative Commons Attribution-Share Alike 3.0 license published by Creative Commons Corporation, a not-for-profit corporation with a principal place of business in San Francisco, California, as well as future copyleft versions of that license published by that same organization.

    "Incorporate" means to publish or republish a Document, in whole or in part, as part of another Document.

    An MMC is "eligible for relicensing" if it is licensed under this License, and if all works that were first published under this License somewhere other than this MMC, and subsequently incorporated in whole or in part into the MMC, (1) had no cover texts or invariant sections, and (2) were thus incorporated prior to November 1, 2008.

    The operator of an MMC Site may republish an MMC contained in the site under CC-BY-SA on the same site at any time before August 1, 2009, provided the MMC is eligible for relicensing.

ADDENDUM: How to use this License for your documents

To use this License in a document you have written, include a copy of the License in the document and put the following copyright and license notices just after the title page:

```
Copyright (C)  year  your name.
Permission is granted to copy, distribute and/or modify this document
under the terms of the GNU Free Documentation License, Version 1.3
or any later version published by the Free Software Foundation;
with no Invariant Sections, no Front-Cover Texts, and no Back-Cover
Texts.  A copy of the license is included in the section entitled ``GNU
Free Documentation License''.
```

If you have Invariant Sections, Front-Cover Texts and Back-Cover Texts, replace the "with. . . Texts." line with this:

```
with the Invariant Sections being list their titles, with
the Front-Cover Texts being list, and with the Back-Cover Texts
being list.
```

If you have Invariant Sections without Cover Texts, or some other combination of the three, merge those two alternatives to suit the situation.

If your document contains nontrivial examples of program code, we recommend releasing these examples in parallel under your choice of free software license, such as the GNU General Public License, to permit their use in free software.

Concept Index

Function Index

Datatype Index

E

S