Getting started with StarPU

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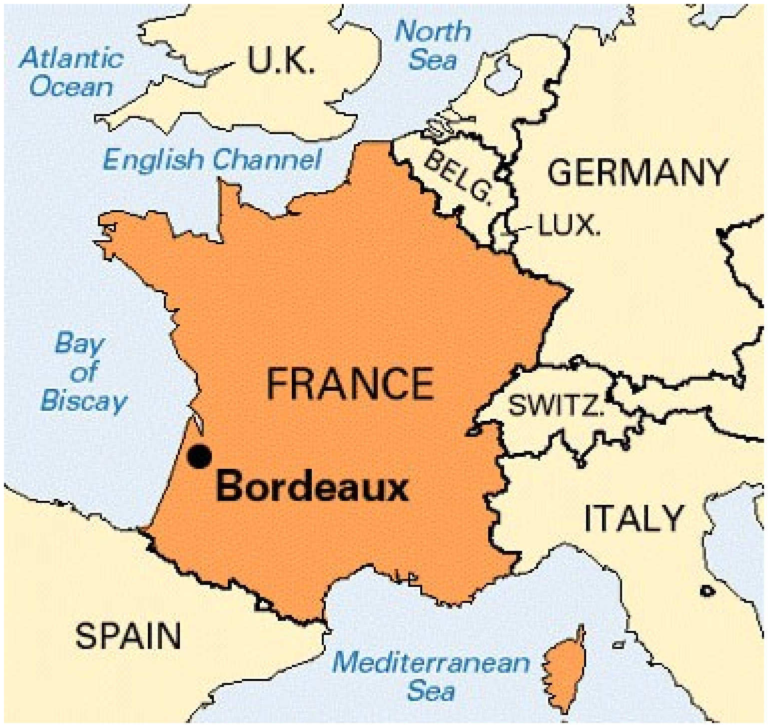
The RUNTIME Team



Doing Parallelism for centuries !

The RUNTIME Team

Research directions

- High Performance Runtime Systems for Parallel Architectures
  - "*Runtime Systems perform dynamically what cannot be not statically*"

- Main research directions
  - Exploiting shared memory machines
    - Thread scheduling over hierarchical multicore architectures
    - Task scheduling over accelerator-based machines
  - Communication over high speed networks
    - Multicore-aware communication engines
    - Multithreaded MPI implementations
  - Integration of multithreading and communication
    - Runtime support for hybrid programming

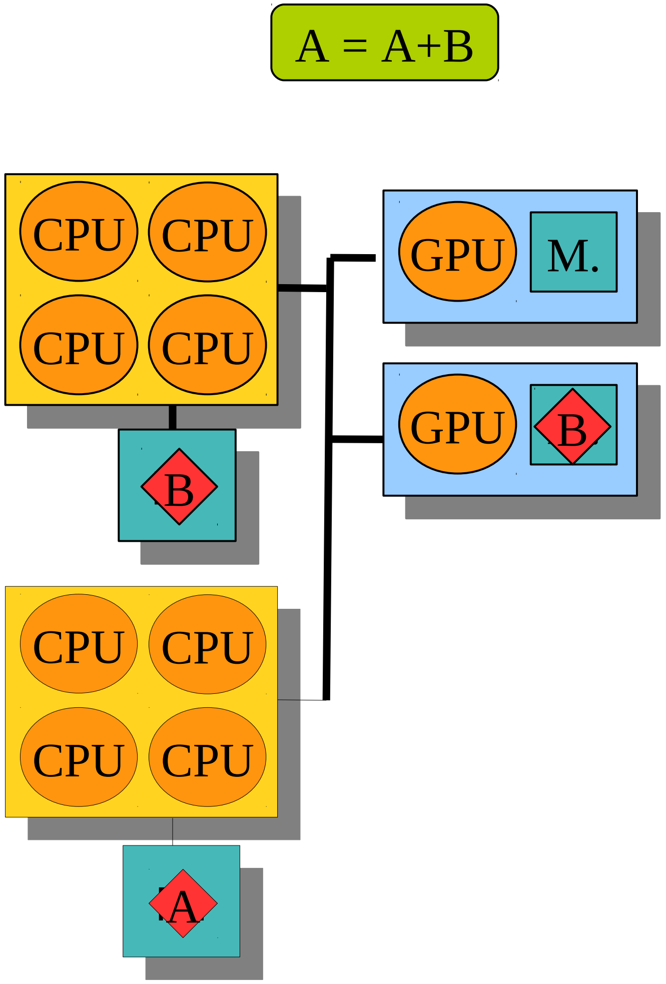
- See http://runtime.bordeaux.inria.fr/ for more information

The StarPU runtime system

Motivation

Accelerator-based architectures

- Main Challenges
  - Dynamically schedule tasks on all processing units
    - See a pool of heterogeneous cores
    - Scheduling ≠ offloading
  - Avoid unnecessary data transfers between accelerators
    - Need to keep track of data copies



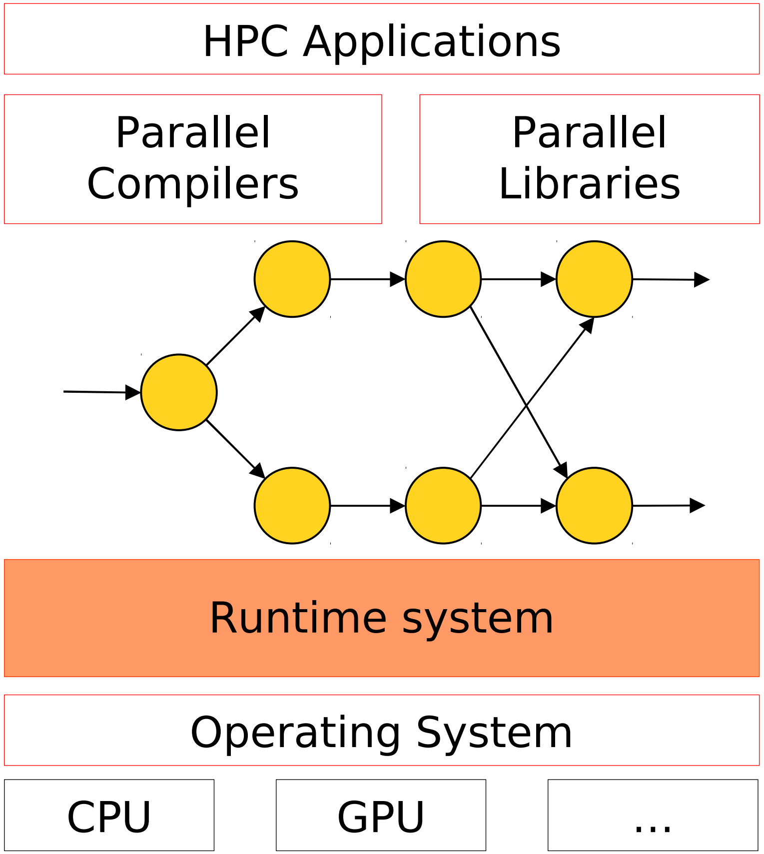
Motivation

The need for runtime systems

- “do dynamically what can’t be done statically”

- Typical duties
  - Task scheduling
  - Memory management

- Compilers and libraries generate (graphs of) parallel tasks
  - Additional information is welcome!

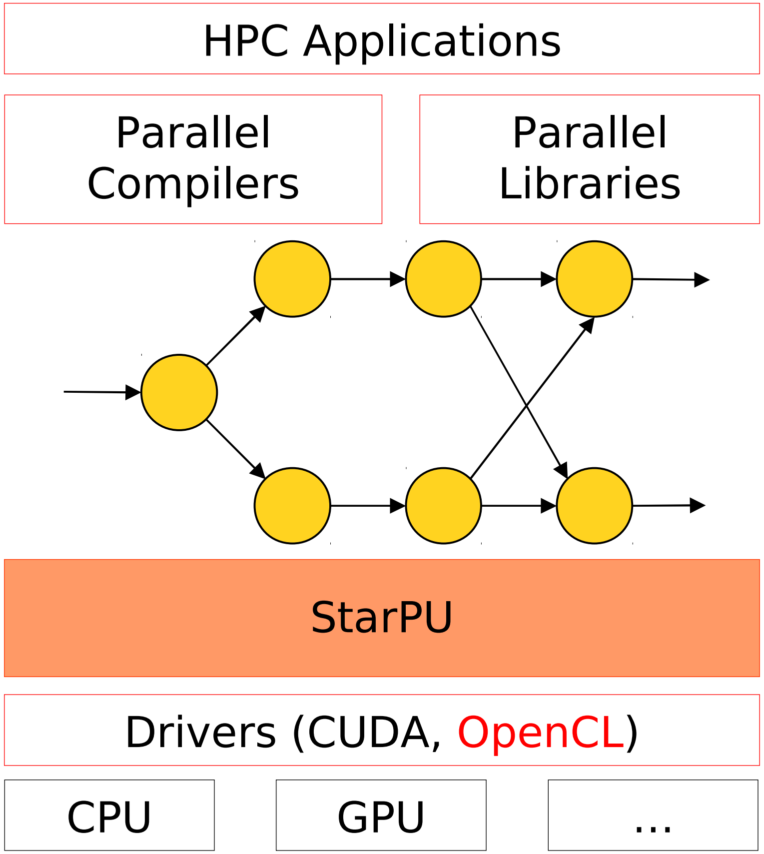


The StarPU runtime system

Memory Management

- StarPU provides a Virtual Shared Memory subsystem
  - Weak consistency
  - Replication
  - Single writer
  - High level API
    - Partitioning filters

- Input & ouput of tasks = reference to VSM data

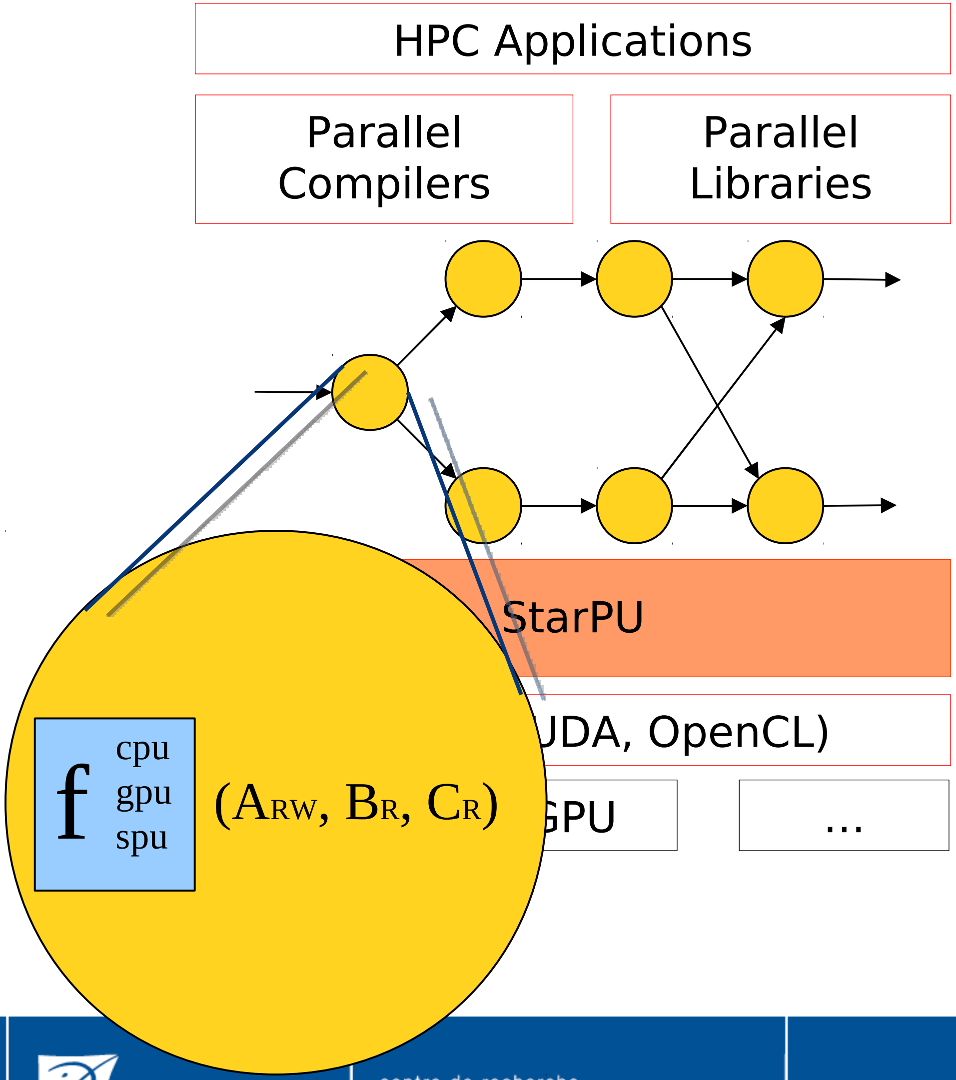


The StarPU runtime system

Task scheduling

- Tasks =
  - Data input & output
    - Reference to VSM data
  - Multiple implementations
    - E.g. CUDA + CPU implementation
  - Dependencies with other tasks
  - Scheduling hints

- StarPU provides an Open Scheduling platform
  - Scheduling algorithm = plug-ins



The StarPU runtime system

Development context

- History
  - Started about 2 years ago
  - StarPU main core ~ 20k lines of code
  - Written in C
  - 3 core developers
    - Cédric Augonnet, Samuel Thibault, Nathalie Furmento

- Open Source
  - Released under LGPL
  - Sources freely available
    - svn repository and nightly tarballs
    - See http://runtime.bordeaux.inria.fr/StarPU/
  - Open to external contributors

The StarPU runtime system

Supported platforms

- Supported architectures
  - Multicore CPUs (x86, PPC, ...)
  - NVIDIA GPUs
  - OpenCL devices (eg. AMD cards)
  - Cell processors (experimental)

- Supported Operating Systems
  - Linux
  - Mac OS
  - Windows

Test case

Mixing PLASMA and MAGMA

Mixing PLASMA and MAGMA with StarPU

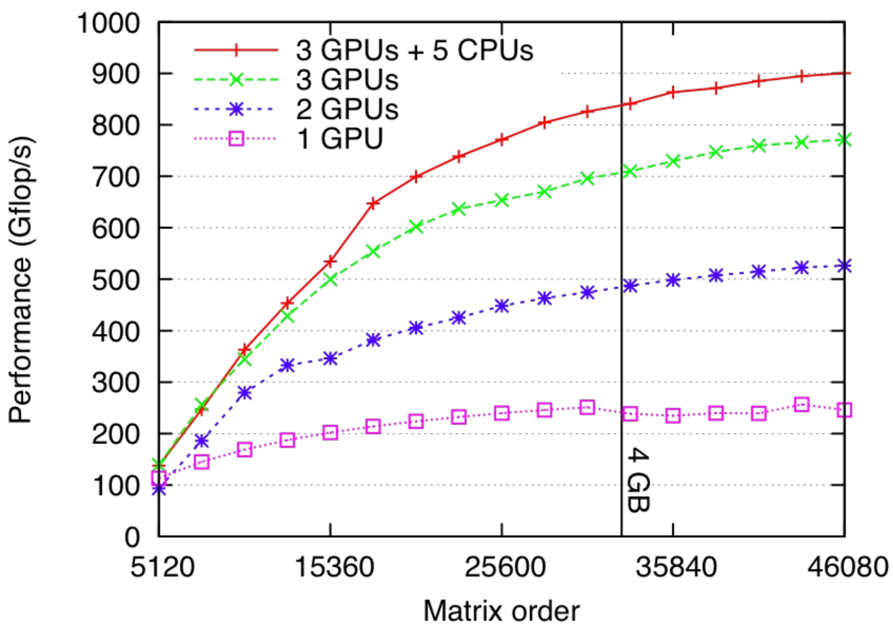
- PLASMA BLAS
  - Rely on vendors' BLAS
- MAGMA BLAS
  - Autotuned kernels
  - Rely on CUBLAS
  - Provides new kernels
- PLASMA
  - Tile algorithms
  - Dynamically scheduled tasks
    - Alternative to PLASMA's scheduer (QUARK)
    - Extend it for GPUs

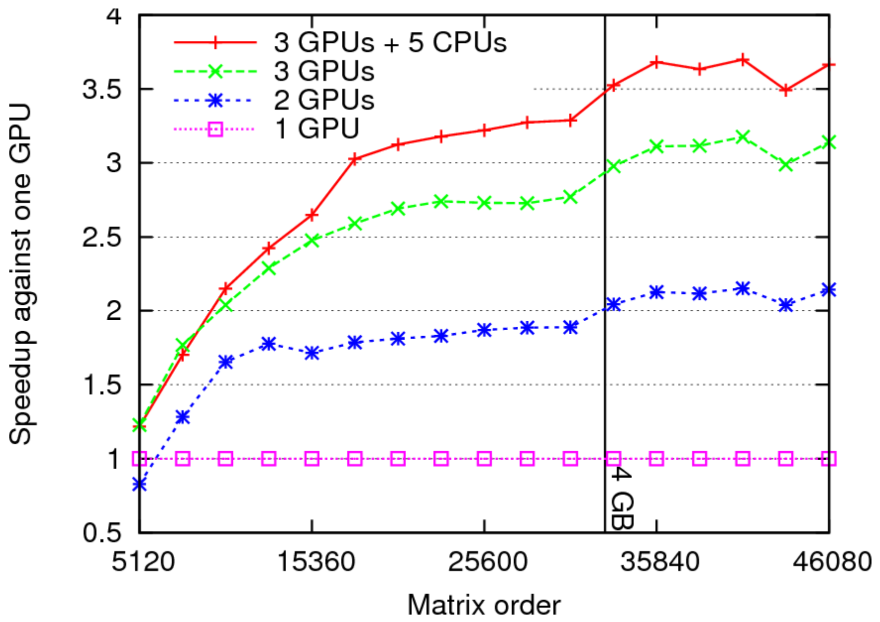
Mixing PLASMA and MAGMA with StarPU

- Methodology (~a week of work)
  - Describe data layout
    - Register all tiles to StarPU
  - Create tasks
    - Codelets : Multi-versionned functions
      - PLASMA kernels on CPU
      - MAGMA kernels on GPU
    - Access registered tiles
  - Dynamically submit a DAG of tasks
    - Automatic dependencies
    - No mapping decision

Mixing PLASMA and MAGMA with StarPU

- Cholesky decomposition
  - 5 CPUs (Nehalem) + 3 GPUs (FX5800)
  - Efficiency > 100%





Mixing PLASMA and MAGMA with StarPU

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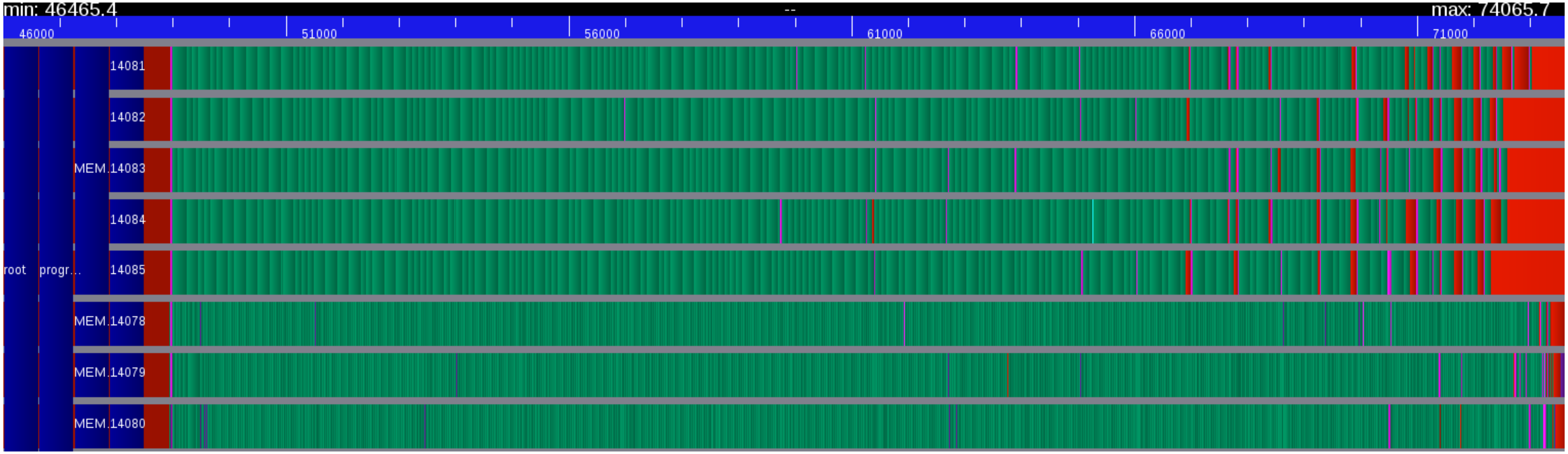
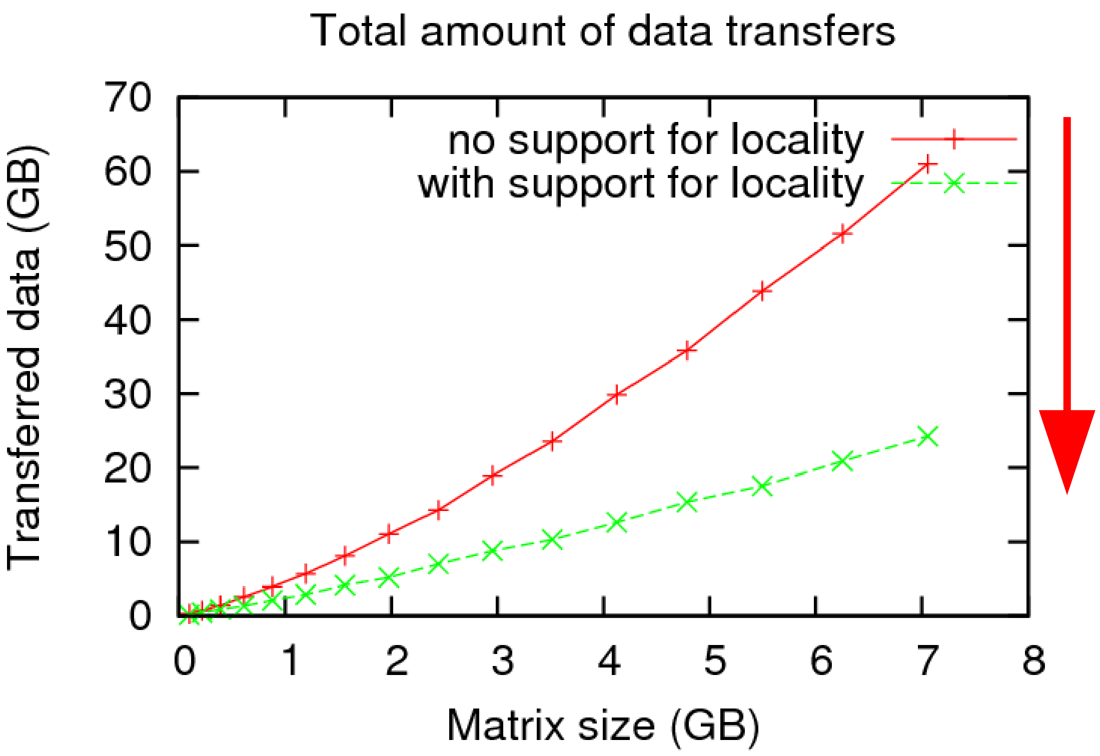


Mixing PLASMA and MAGMA with StarPU

- Memory transfers during Cholesky decomposition



~2.5x less transfers

Installing StarPU

Downloading StarPU

Getting sources

- Access SVN sources (via svn or https)
  - svn checkout svn://scm.gforge.inria.fr/svn/starpu/trunk
  - svn checkout --username anonsvn https://scm.gforge.inria.fr/svn/starpu/trunk
  - Password : anonsvn
  - Requires : Autoconf (>= 2.60) & Automake
  - Run ./autogen.sh to generate a ./configure script

- Nightly Tarball
  - http://starpu.gforge.inria.fr/testing/starpu-nightly-latest.tar.gz
  - Useful when autotools are not available (or recent enough)

Optional dependency with hwloc

Topology discovery external library

- hwloc
  - Topology discovery library
  - Portable !
  - Initially developped in the RUNTIME team
- StarPU & hwloc
  - Not mandatory but strongly recommended
    - Increase performance
    - Topology aware scheduling
- Getting hwloc
  - Available in major distributions and for most OS
  - Download from http://www.open-mpi.org/software/hwloc

Configuring and Compiling StarPU

- Standard installation procedure
  - ./configure
  - or ./configure --prefix=$HOME/StarPU/
  - --enable-verbose to get some debug messages
  - --help to get a summary of options

- Compiling
  - make -j
  - make install

- Sanity checks
  - make check

Installing StarPU

- make install
- Environment variables (typically added into ~/.bashrc)
  - export STARPUDIR=<StarPU's installation directory>
    export LD_LIBRARY_PATH=${LD_LIBRARY_PATH}:$STARPUDIR/lib/
    export PATH=${PATH}:$STARPUDIR/bin/
  - export PKG_CONFIG_PATH=${PKG_CONFIG_PATH}:$STARPUDIR/lib/pkgconfig/
- Using pkg-config
  - pkg-config --cflags libstarpu : compiler flags
  - pkg-config --libs libstarpu : linker flags
  - Example for libs
    - -L/home/gonnet/StarPU/trunk/target/lib -L/usr/local/cuda//lib64/ -lstarpu -lcuda

Installing StarPU (2)

- When StarPU is used for the first time
  - $HOME/.StarPU/ is created
    - Contains performance models
  - **Buses are benchmarked when StarPU is launched for the time**
    - **May take a few minutes!**
      - Faster if hwloc is installed
    - Only once per user and per machine

A trivial example : scaling a vector

Scaling a vector

Launching StarPU

- Makefile flags
  - CFLAGS += $$(pkg-config --cflags libstarpu)
  - LDFLAGS+=$$(pkg-config --libs libstarpu)

- Headers
  - #include <starpu.h>

- (De)Initialize StarPU
  - starpu_init(NULL);
  - starpu_shutdown();

Scaling a vector

Data registration

- Register a piece of data to StarPU
  - ```
    float array[NX];
    for (unsigned i = 0; i < NX; i++)
        array[i] = 1.0f;

    starpu_data_handle vector_handle;
    starpu_vector_data_register(&vector_handle, 0,
            array, NX, sizeof(vector[0]));
    ```
- Unregister data
  - `starpu_data_unregister(vector_handle);`
    ```

Scaling a vector

Defining a codelet

- CPU kernel

```
void scal_cpu_func(void *buffers[], void *cl_arg)
{
   struct starpu_vector_interface_s *vector = buffers[0];

   unsigned n = vector->nx;
   float *val = (float *)vector->ptr;

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

Scaling a vector

Defining a codelet (2)

- CUDA kernel (compiled with nvcc, in a separate .cu file)

```
__global__ void vector_mult_cuda(float *val, unsigned n, float factor)
{
	for(unsigned i = 0 ; i < n ; i++) val[i] *= factor;
}

extern "C" void scal_cuda_func(void *buffers[], void *cl_arg)
{
	float *factor = (float *)cl_arg;
	struct starpu_vector_interface_s *vector = buffers[0];
	unsigned n = vector->nx;
	float *val = (float *)vector->ptr;

	vector_mult_cuda<<<1,1>>>(val, n, *factor);
	cudaThreadSynchronize();
}
```

Scaling a vector

Defining a codelet (3)

- Codelet = multi-versionned kernel
  - Function pointers to the different kernels
  - Number of data managed by StarPU

```
starpu_codelet scal_cl = {
    .where = STARPU_CPU | STARPU_CUDA,
    .cpu_func = scal_cpu_func,
    .cuda_func = scal_cuda_func,
    .nbuffers = 1
};
```

Scaling a vector

Defining a task

- Define a task that scales the vector by a constant

```
struct starpu_task *task = starpu_task_create();
task->cl = &scal_cl;

task->buffers[0].handle = vector_handle;
task->buffers[0].mode = STARPU_RW;

float factor = 3.14;
task->cl_arg = &factor;
task->cl_arg_size = sizeof(factor);

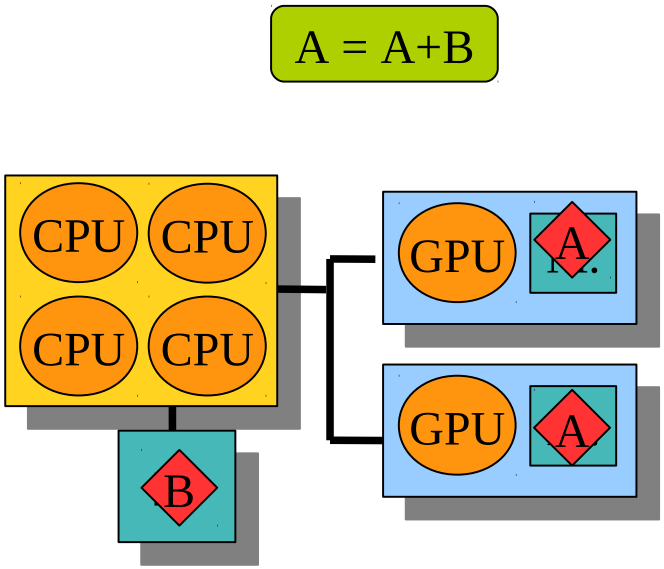
starpu_task_submit(task);
starpu_task_wait(task);
```

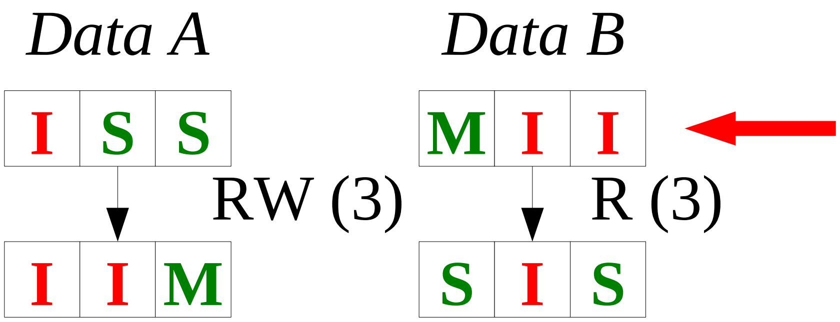
Data Management

StarPU data interfaces

StarPU data coherency protocol

- Memory nodes
  - Each worker is associated to a node
  - Multiple workers may share a node
- Data coherency
  - Keep track of replicates
  - Discard invalid replicates
- MSI coherency protocol
  - M : Modified
  - S : Shared
  - I : Invalid





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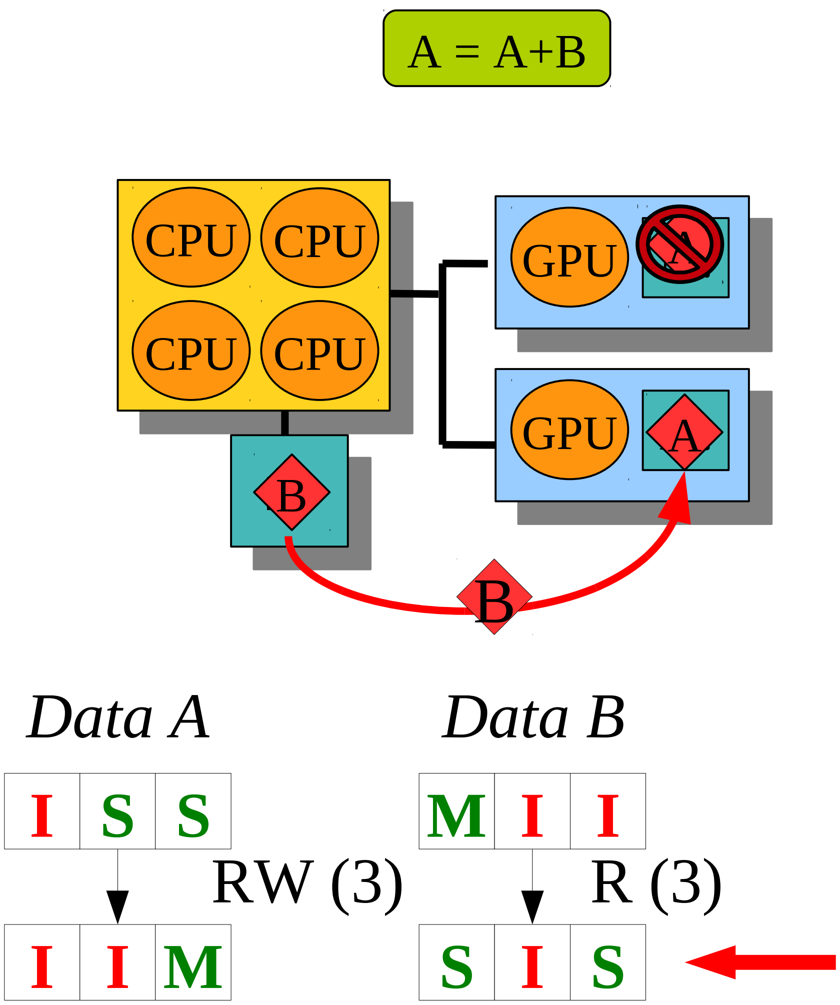


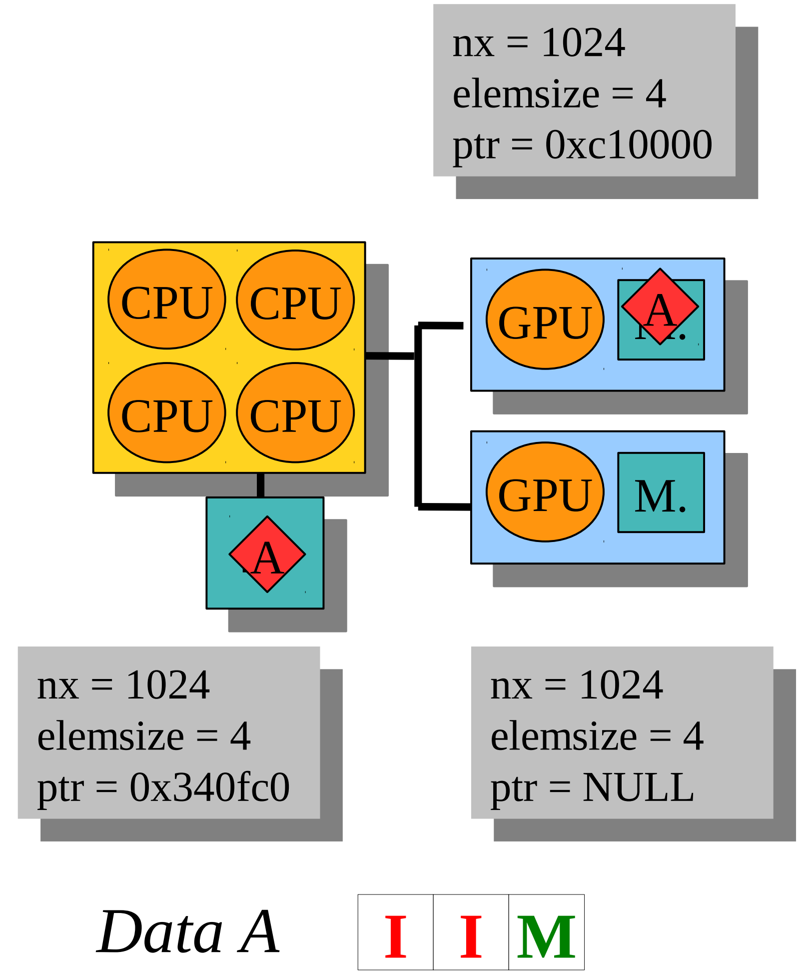
StarPU data interfaces

StarPU data interfaces

- Each piece of data is described by a structure
  - Example : vector interface

```
struct starpu_vector_interface_s {
    unsigned nx;
    unsigned elemsize;
    uintptr_t ptr;
}
```

  - StarPU ensures that interfaces are coherent

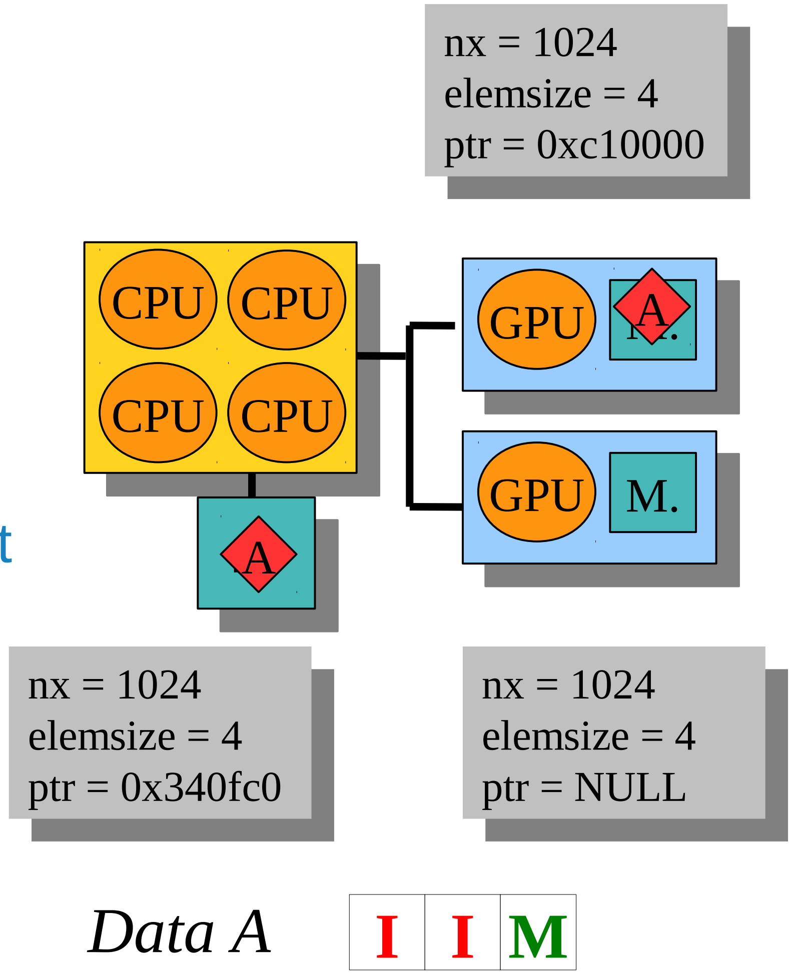


- StarPU tasks are passed pointers to these interfaces
  - Coherency protocol is independent from the type of interface

StarPU data interfaces

StarPU data interfaces

- Various interfaces are available
  - Variable, Vector, Matrix, CSR ....
- Defining a new interface
  - C structure
  - struct starpu_data_interface_ops_t
    - Transfer between nodes
    - Allocate on node
    - Get data size …

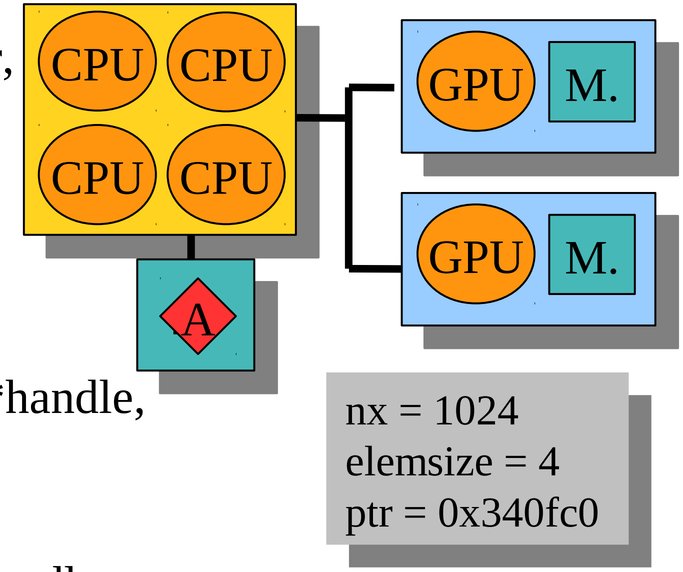


StarPU data interfaces

StarPU data interfaces

- Registering a piece of data
  - Generic method

```
starpu_data_register(starpu_data_handle *handleptr,
            uint32_t home_node, void *interface,
            struct starpu_data_interface_ops_t *ops);
```



  - Wrappers are available for existing interfaces

```
starpu_variable_data_register(starpu_data_handle *handle,
            uint32_t home_node,
            uintptr_t ptr, size_t elemsize);

starpu_vector_data_register(starpu_data_handle *handle,
            uint32_t home_node,
            uintptr_t ptr, uint32_t nx, size_t elemsize);

starpu_csr_data_register(starpu_data_handle *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);
```

StarPU data interfaces

Manipulating registered data

- Use handle to manipulate a registered piece of data
  - Task description
  - starpu_data_unregister(handle)

- Interactions between StarPU and the application are possible
  - int foo = 42;
    starpu_variable_register(&handle, 0, &foo, sizeof(foo));
    ...
    starpu_data_sync_with_mem(handle, STARPU_RW);
    foo = 12;
    starpu_data_release(handle);
    ...
  - See starpu_data_sync_with_mem_non_blocking for an asynchronous method

Task Management

Task management

Codelets

- struct starpu_codelet_t

- Describe multi-versionned kernels
  - Where can the kernels be executed ?
    - eg. STARPU_CPU | STARPU_CUDA | STARPU_OPENCL
  - Per-architecture implementation
    - Function pointers
      - **Running on the host !**
      - eg. use CUDA runtime API
    - Common interface
      - void cpu_func(void *buffers[], void *cl_arg);
  - Specify the number of buffers accessed by the codelet
    - Only data managed by StarPU
    - Use cl_arg for constant arguments
  - Optional: Performance model

Task management

Performance models

- struct starpu_perfmodel_t

- Different types of performance models
  - STARPU_COMMON
    - a single model + relative speedups
  - STARPU_PER_ARCH
    - per processing-unit performance models
  - STARPU_REGRESSION_BASED
    - Specify the type of regression with the starpu_regression_model_t structure
      - Online Linear models (eg. a*size^3)
      - Offline Non-linear models (eg. a*size^3 + b)
  - STARPU_HISTORY_BASED
    - History based performance models
    - Updated every time a task is executed
    - For regular applications

- Automatically calibrated (STARPU_CALIBRATE env. variable)

Task management

Performance models

- Using performance models is almost transparent
  - Automatically calibrated by StarPU
  - Associate each codelet with a unique identifier (symbol)

```
struct starpu_permmodel_t sgemm_model = {
        .type = STARPU_HISTORY_BASED,
        .symbol = "sgemm"
};

starpu_codelet sgemm_cl = {
        .where = STARPU_CPU|STARPU_CUDA,
        .cpu_func = cpu_sgemm,
        .cuda_func = cuda_sgemm,
        .nbuffers = 3,
        .model = &sgemm_model
};
```

Task management

The task structure

- struct starpu_task

- Task description
  - struct starpu_codelet_t *cl
    - void *cl_arg : constant argument passed to the codelet
  - Buffers array (accessed data + access mode)

```
task->buffers[0]->handle = vector_handle;
task->buffers[0]->mode = STARPU_RW;
```

  - void (*callback_func)(void *);
    - void *callback_arg;
    - Should not be a blocking call !
  - Extra hints for the scheduler
    - eg. priority level

Task management

Task API

- Create tasks
  - Dynamically allocated by starpu_task_create
  - Otherwise, initialized by starpu_task_init

- Submit a task
  - starpu_task_submit(task)
    - blocking if task->synchronous = 1

- Wait for task termination
  - starpu_task_wait(task);
  - starpu_task_wait_for_all();

- Destroy tasks
  - starpu_task_destroy(task);
    - automatically called if task->destroy = 1
  - starpu_task_deinit(task);

Task management

Explicit task dependencies

- Submit tasks within task callbacks

- Task dependencies
  - starpu_task *deps[2] = {taskA, taskB}
    void starpu_task_declare_deps_array(taskC, 2, &deps);
  - TaskC depends on taskA and taskB
  - Must be declared prior to the submission of taskC !

- Tag dependencies
  - task->tag_id logically identifies a task if task->use_tag is set
    - taskA->tag_id = 0x2000;
      taskB->tag_id = 0x42;
      starpu_tag_declare_deps(0x42, 0x2000)
    - TaskB depends on taskA
  - starpu_tag_wait(0x42)
    - Wait for taskB (taskB must have been submitted)

Task management

Implicit task dependencies

- StarPU can discover data dependencies automatically
  - Sequential data consistency
    - Match the behaviour a of sequential code
  - Example : f1(Ar); f2(Ar); g1(Arw); g2(Arw); h1(Ar); h2(Ar);
    - f1 and f2 can be done in parallel
    - g1 depends on {f1,f2}
    - g2 depends on g1
    - h1 and h2 can be done in parallel, but depends on g2

- Enabled by default for all data handles
  - void starpu_data_set_default_sequential_consistency_flag(unsigned flag);

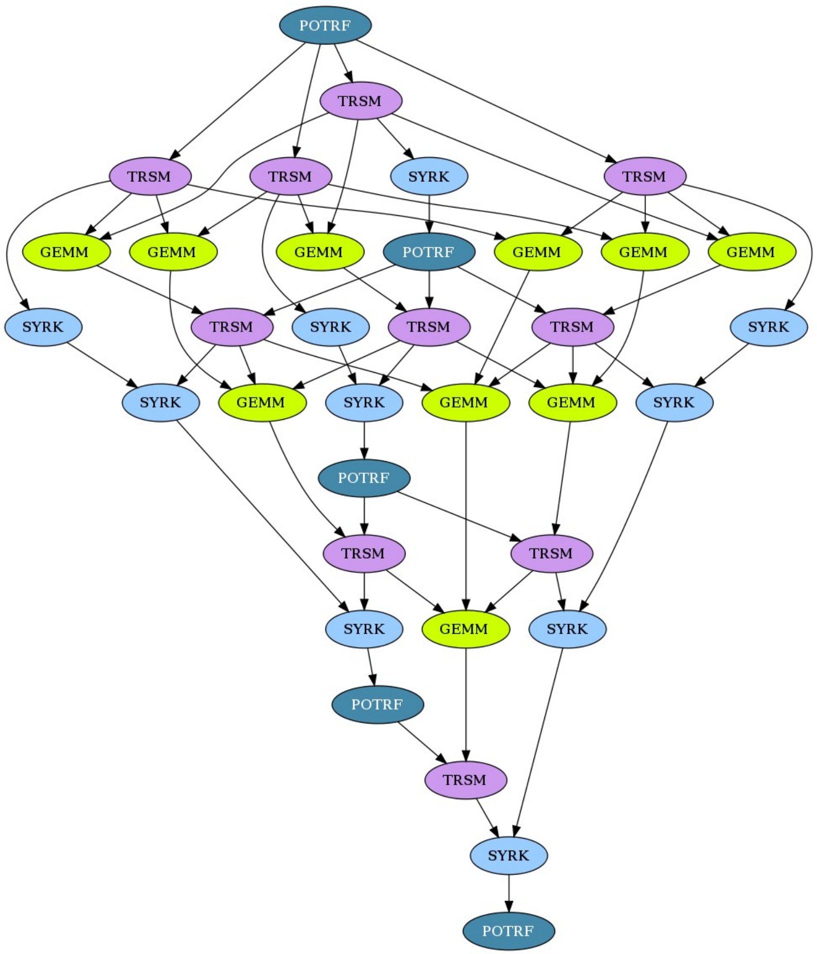
- Per-handle parameter
  - eg. RW access on accumulator should not imply a dependency
  - void starpu_data_set_sequential_consistency_flag(starpu_data_handle handle, unsigned flag);

Task management

Implicit task dependencies (2)

- Right-Looking Cholesky decomposition (from PLASMA)
  - For (k = 0 .. tiles – 1)

```
{
    POTRF(A[k,k])
    for (m = k+1 .. tiles – 1)
        TRSM(A[k,k], A[m,k])
    for (n = k+1 .. tiles – 1)
    {
        SYRK(A[n,k], A[n,n])
        for (m = k+1 .. tiles – 1)
            GEMM(A[m,k], A[n,k]
    }
}
```



Running the application

Running the application

Environment variables

- Select the number of processing units
  - STARPU_NCPUS
  - STARPU_NCUDA
  - STARPU_NOPENCL

- Select the scheduling policy
  - Run with STARPU_SCHED=help to get the different options
  - STARPU_SCHED=greedy (default)
  - STARPU_SCHED=ws
  - STARPU_SCHED=dm (use task performance models)
  - STARPU_SCHED=dmda (task + data transfer models)
    - STARPU_PREFETCH=1 is also recommended

- Calibrate performance models
  - STARPU_CALIBRATE=1
  - STARPU_CALIBRATE=2 (also erase existing models)
  - May takes a few runs to be fully calibrated
    - Possibly calibrate models on small problems !

Performance analysis

Offline performance analysis

Generate execution traces

- The FxT library
  - Low overhead tracing facility
  - Get FxT sources
    - cvs -d :pserver:anonymous@cvs.sv.gnu.org:/sources/fkt co FxT
  - Install FxT
    - ./bootstrap
      ./configure –prefix=$FXT_INSTALL_DIR
      make; make install

- Configure StarPU to generate traces
  - ./configure –with-fxt=$FXT_INSTALL_DIR

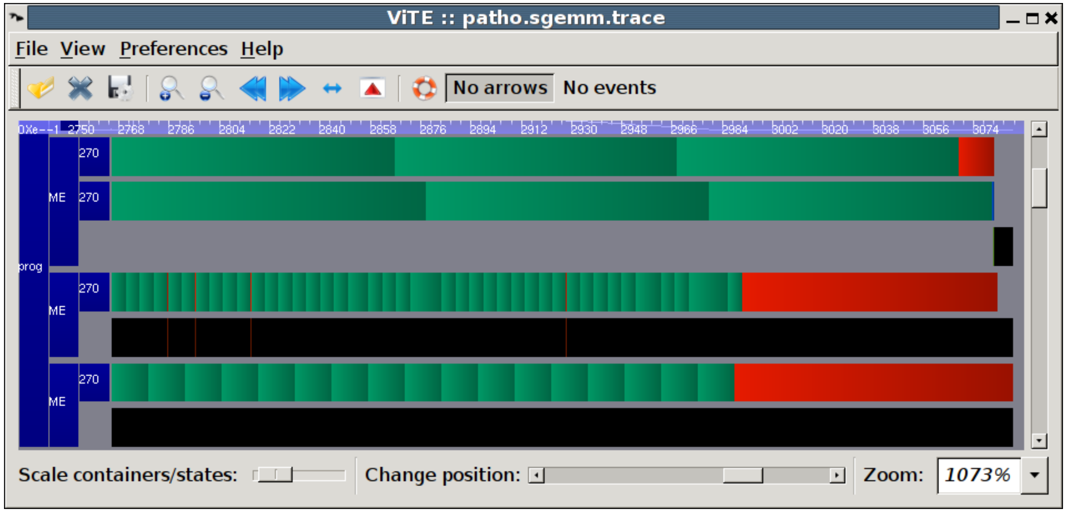
- Run the application

Offline performance analysis

Visualize execution traces

- Generate a Pajé trace
  - A file of the form /tmp/prof_file_user_<your login> should have been created
  - Call fxt_tool -i /tmp/prof_file_user_yourlogin
    - A paje.trace file should be generated in current directory

- Vite trace visualization tool
  - Freely available from http://vite.gforge.inria.fr/ (open source !)
  - vite paje.trace



2 Xeon cores

Quadro FX5800

Quadro FX4600