StarPU: seamless computations among CPUs and GPUs

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INRIA Runtime Team-Project

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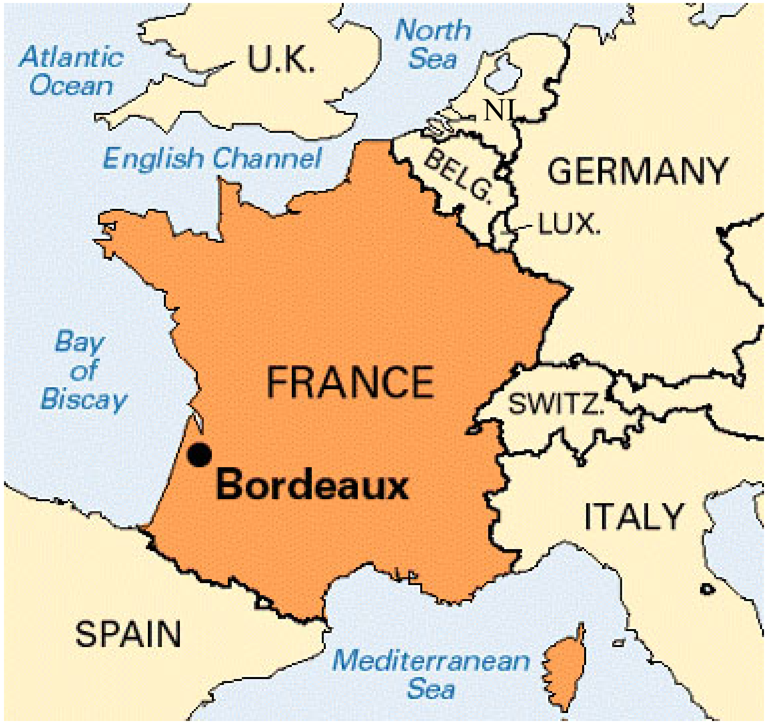
The RUNTIME Team



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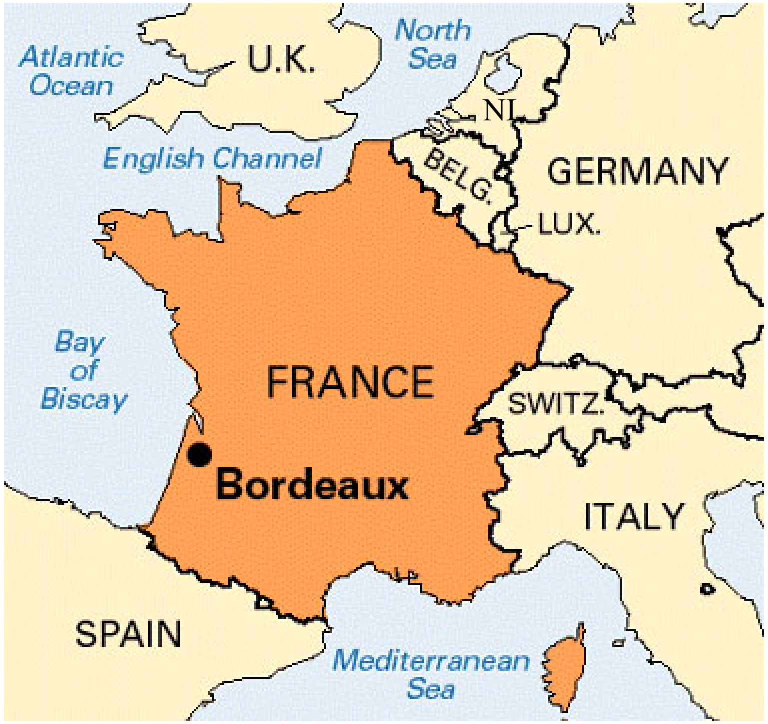

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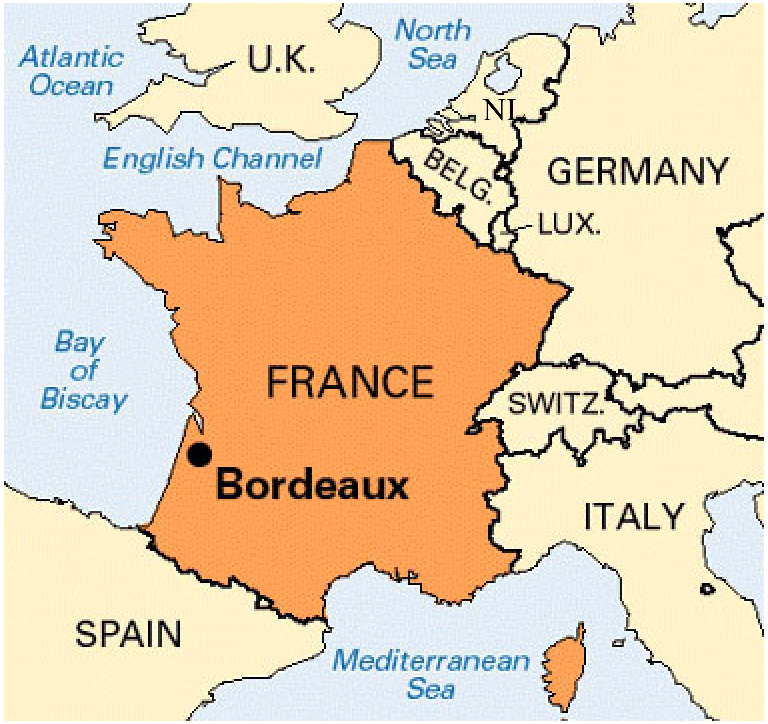
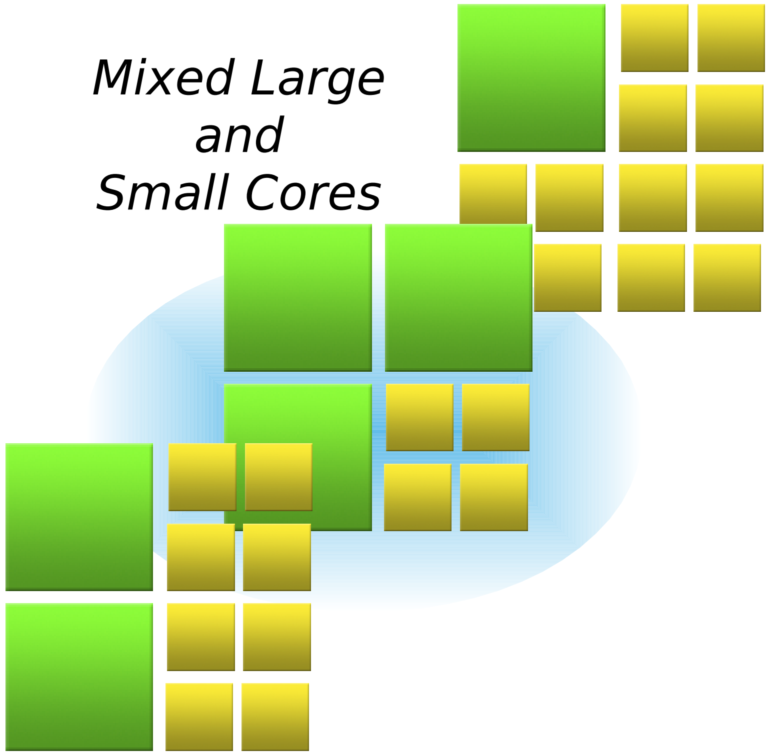


Doing Parallelism for centuries !

Introduction

Toward heterogeneous multi-core architectures

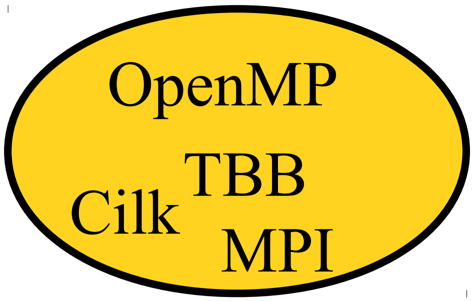
- Multicore is here
  - Hierarchical architectures
  - Manycore
- Architecture specialization
  - Now
    - Accelerators (GPGPUs, FPGAs)
    - Coprocessors (Xeon Phi)
    - Fusion
    - DSPs
    - All of the above
  - In the near Future
    - Many simple cores
    - A few full-featured cores

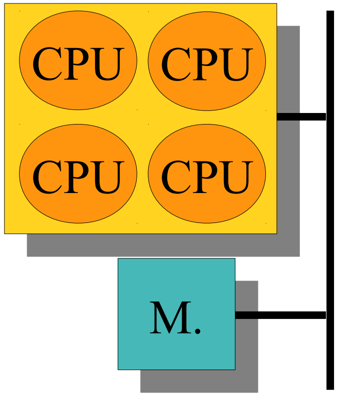


How to program these architectures?

- Multicore programming
  - pthreads, OpenMP, TBB, ...

Multicore





How to program these architectures?

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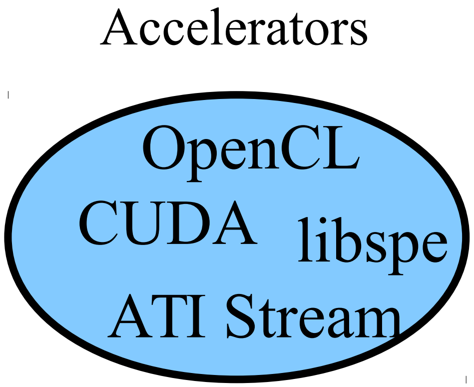
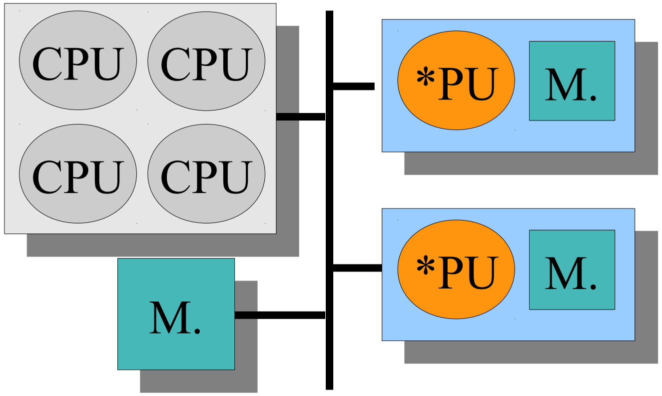
  - pthreads, OpenMP, TBB, ...
- Accelerator programming
  - Consensus on OpenCL/OpenACC?
  - (Often) Pure offloading model

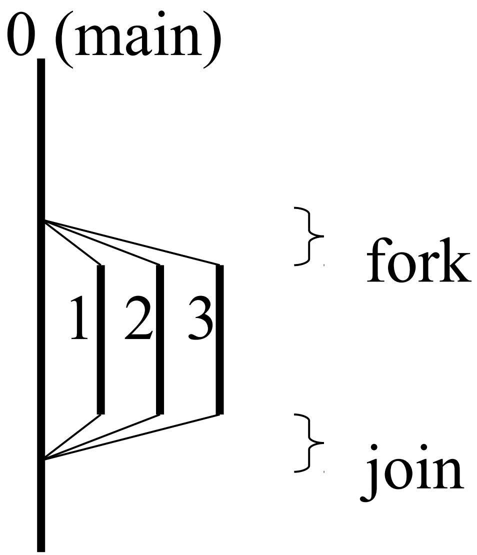




OpenMP
A portable approach to shared-memory programming

- Extension to existing languages
  - C, C++, Fortran
  - Set of programming directives
- Fork/join approach
  - Parallel sections
- Well suited to data-parallel programs
  - Parallel loops
- OpenMP 3.0 introduced *tasks*
  - Support for irregular parallelism

```
int matrix[MAX][MAX];
  ...
#pragma omp parallel for
  for (int i; i < 400; i++)
  {
     matrix[i][0] += ...
  }
```



How to program these architectures?

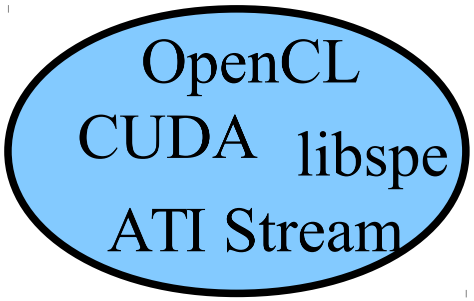
Accelerator programming

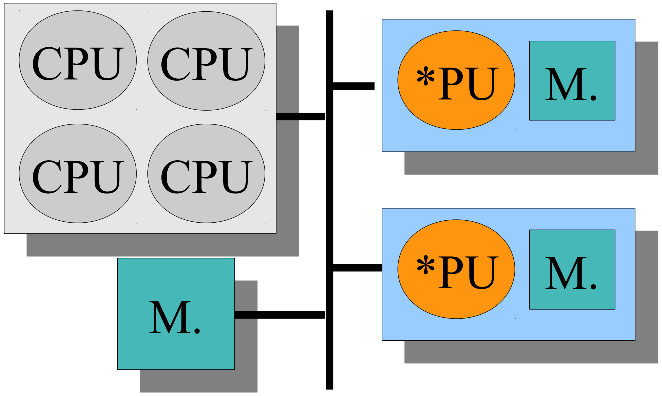
- OpenMP extension

```
int matrix[MAX][MAX];
  ...
#pragma omp target device(acc0)
   map(matrix)
#pragma omp parallel for
  for (int i; i < 400; i++)
  {
     matrix[i][0] += ...
  }
```

- Still quite hand-tuned

Accelerators





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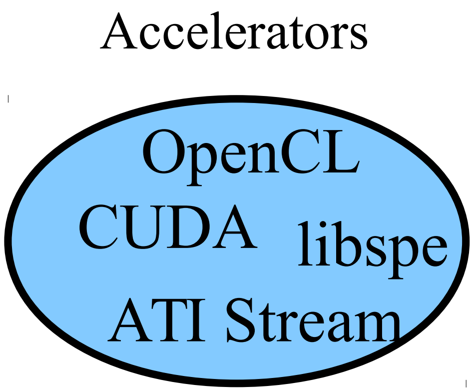
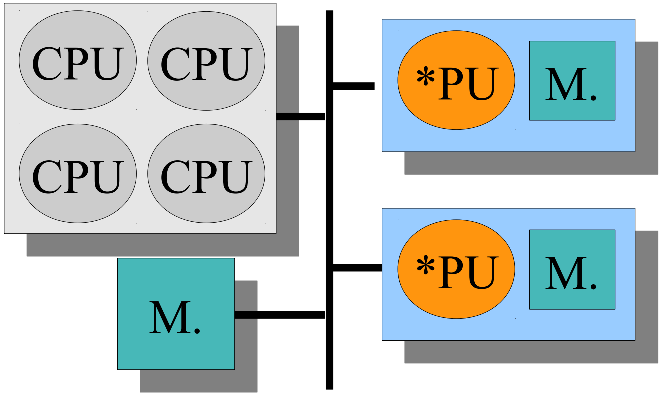


Accelerator programming

- OpenACC

```
int matrix[MAX][MAX];
  ...
#pragma acc kernels copy(matrix)
  for (int i; i < 400; i++)
  {
     matrix[i][0] += ...
  }
```

- Again quite hand-tuned



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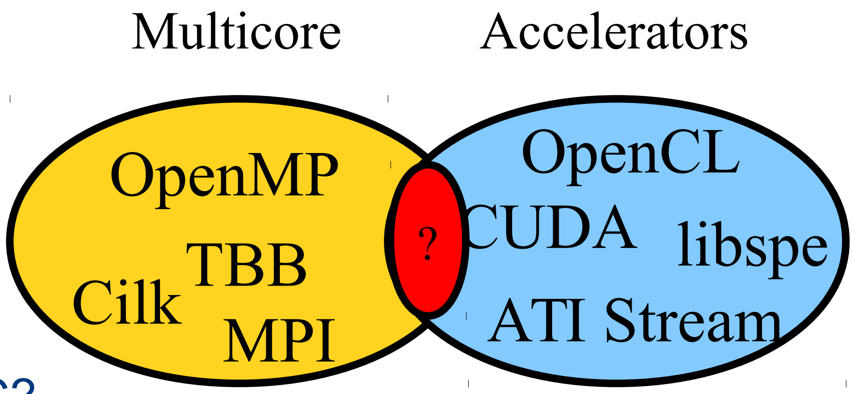
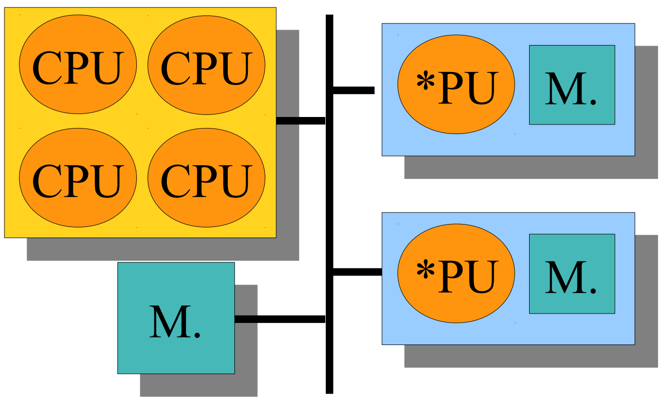


- Accelerator programming
  - Consensus on OpenCL/OpenACC?
  - (Often) Pure offloading model

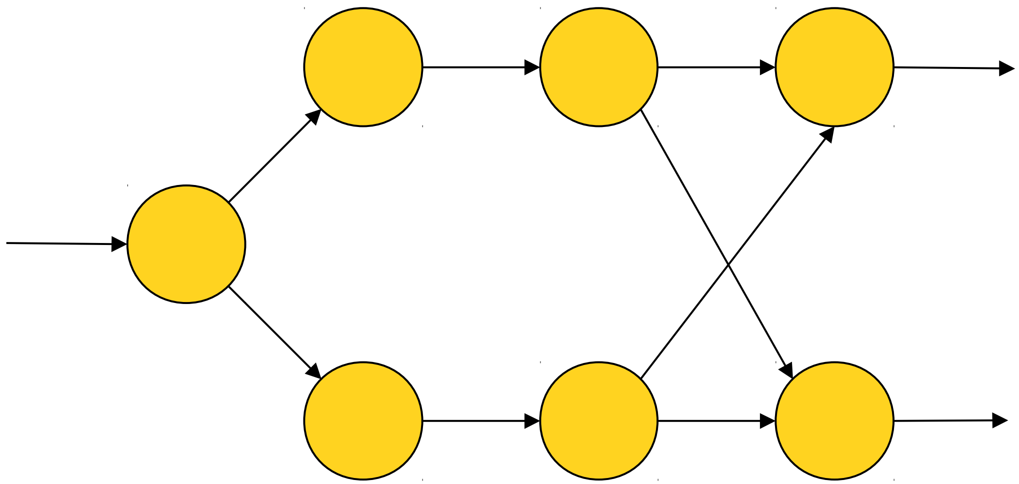
- Hybrid models?
  - **Take advantage of all resources ☺**
  - **Complex interactions and distribution ☹**



Task graphs

- Well-studied expression of parallelism
- Departs from usual sequential programming

Really ?



Task management

Implicit task dependencies

- Right-Looking Cholesky decomposition (from PLASMA)

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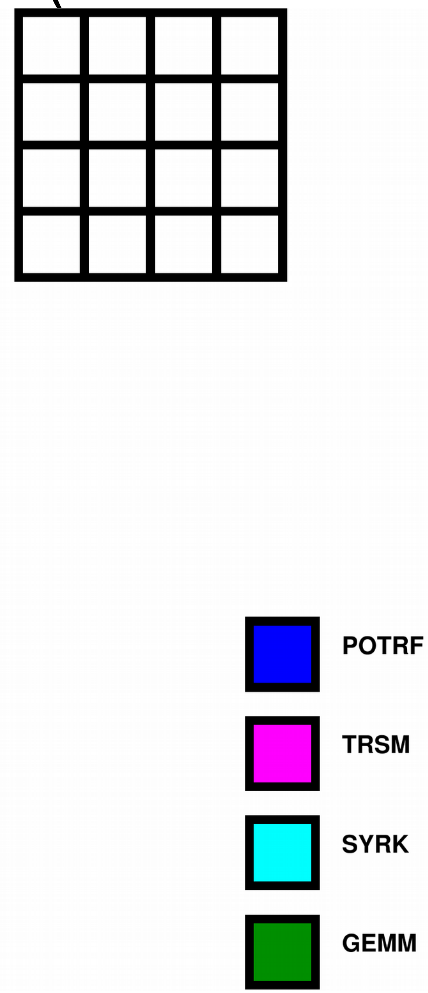

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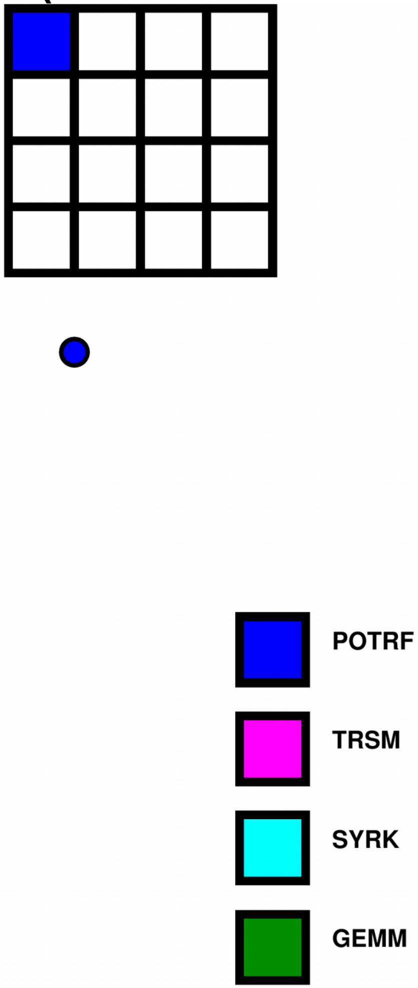

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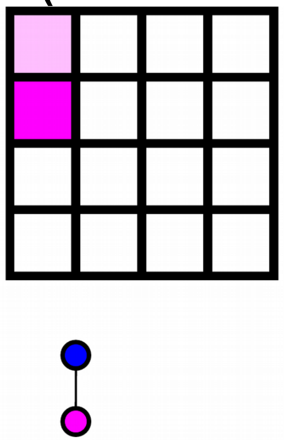

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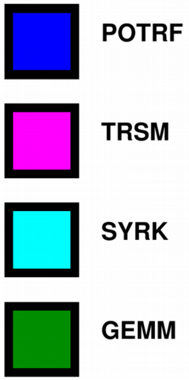

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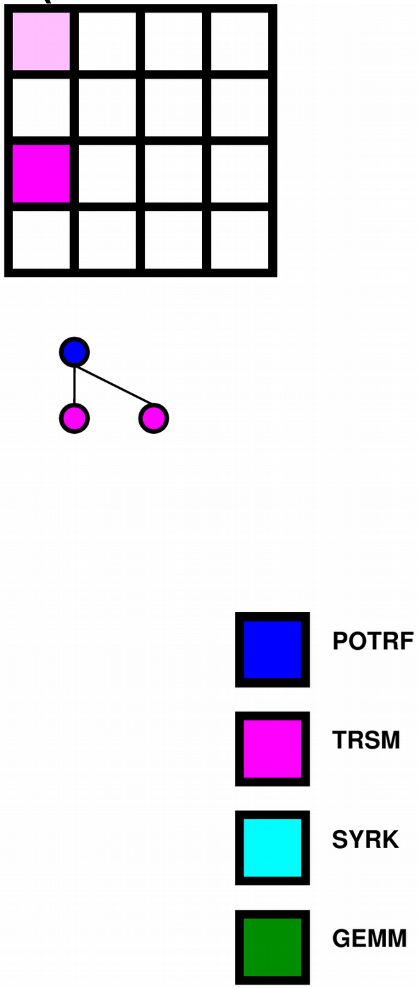

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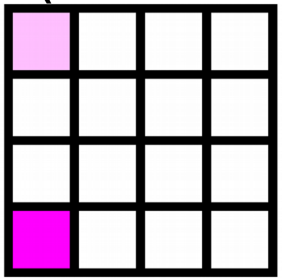

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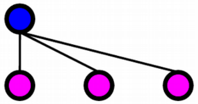

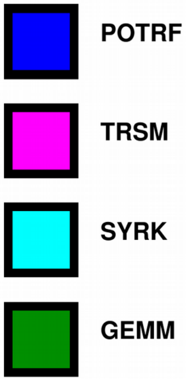

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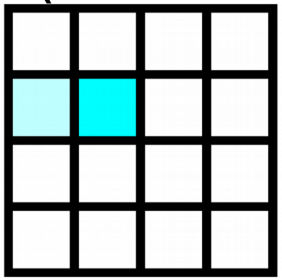

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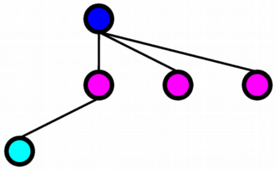

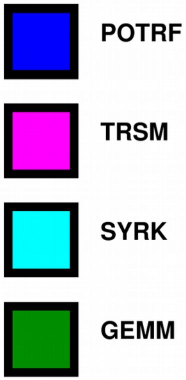

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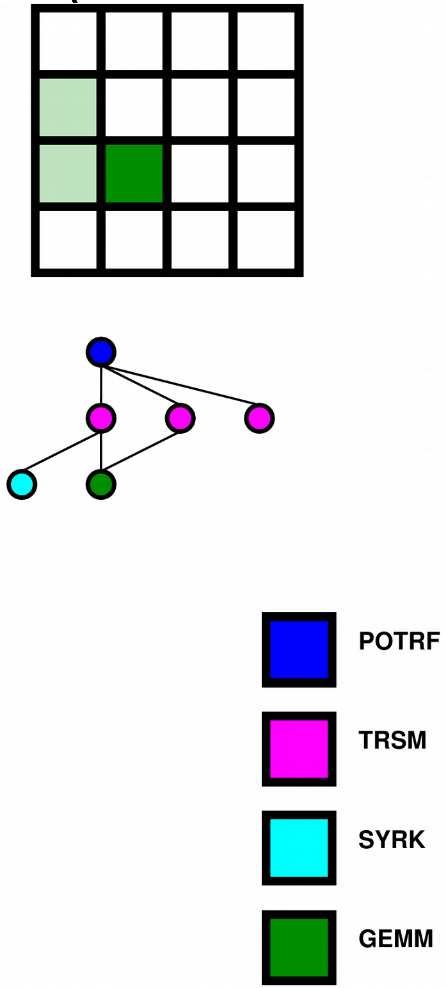

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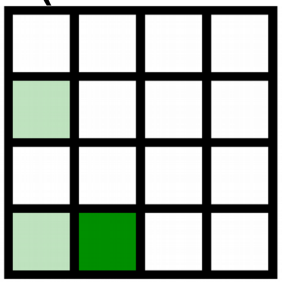

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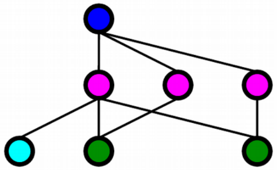

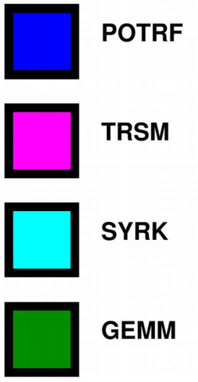

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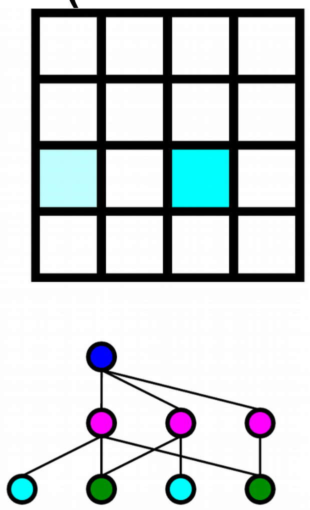

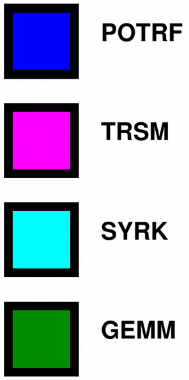

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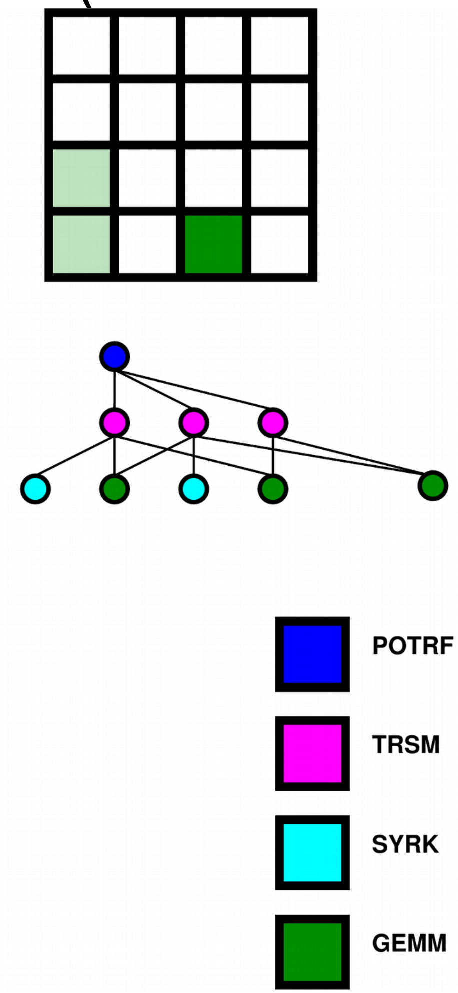

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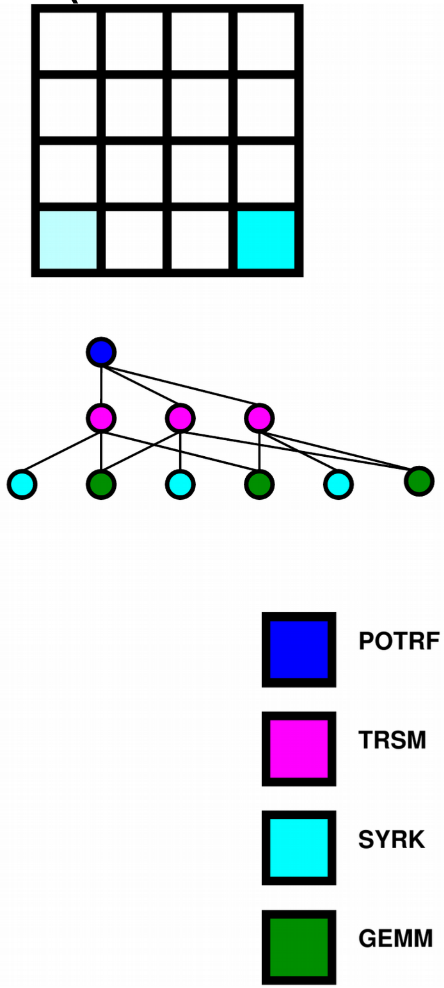

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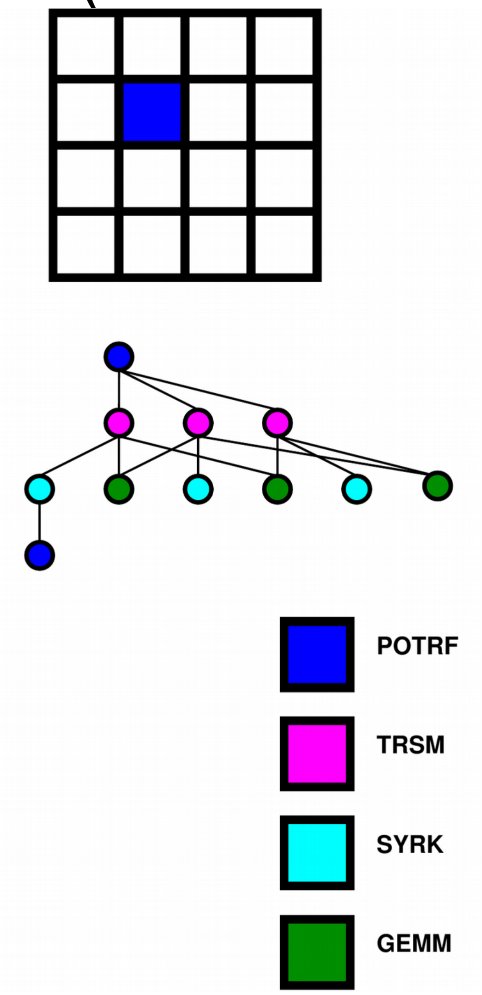

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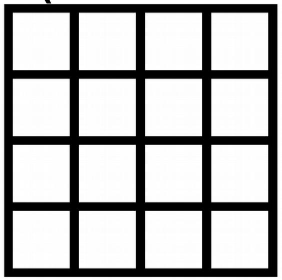

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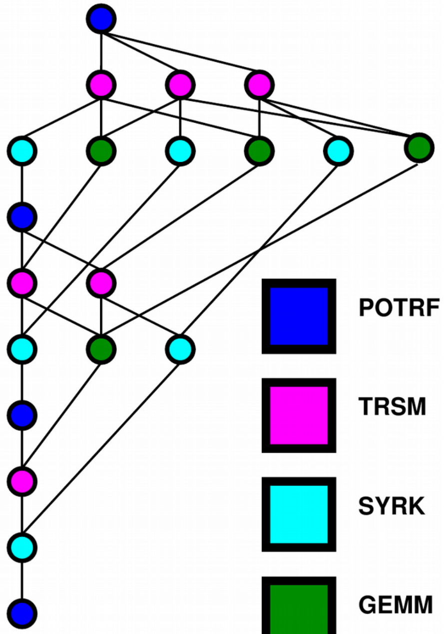
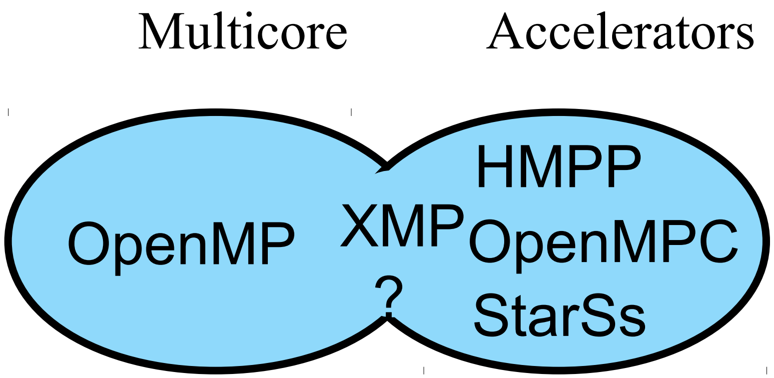
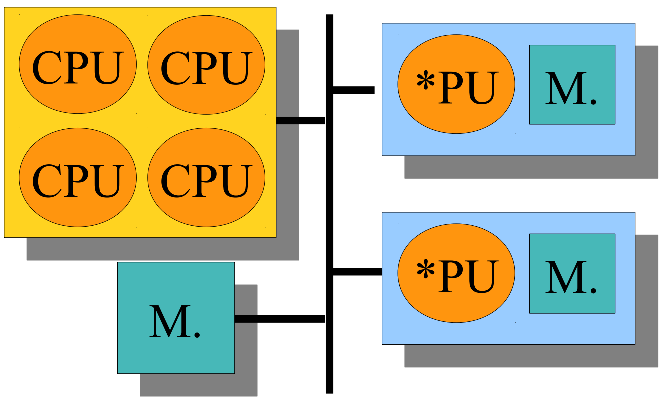


How to program these architectures?

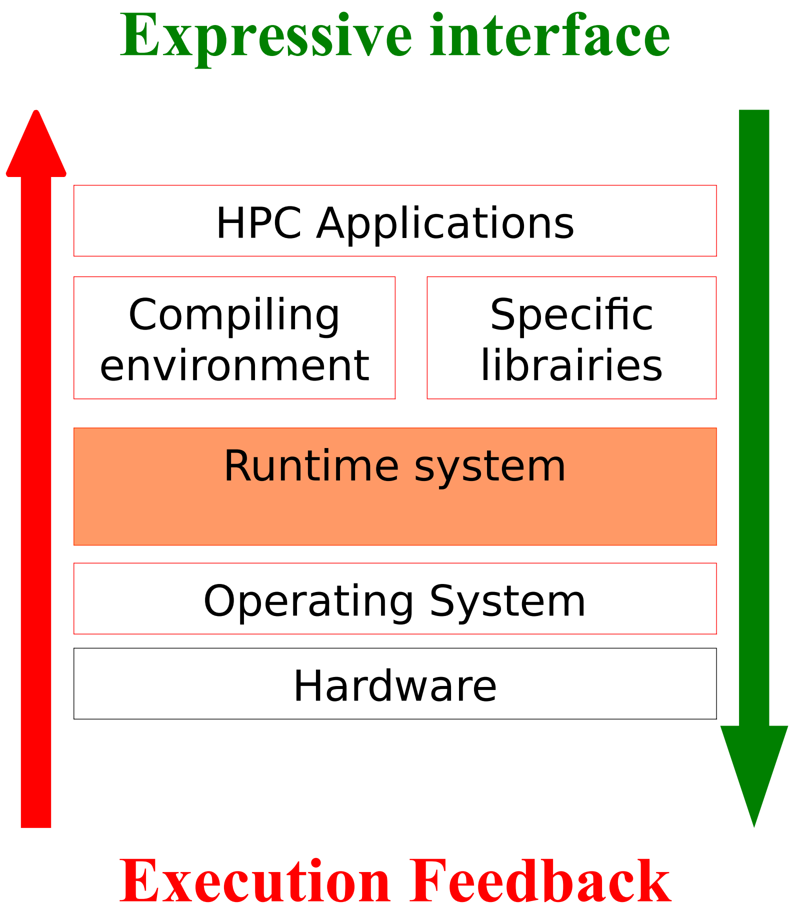
- A uniform way
  - Use a single (or a combination of) high-level programming language to deal with network + multicore + accelerators
  - Increasing number of directive-based languages
    - Use simple directives... and good compilers!
      - XcalableMP
      - HMPP
      - StarSs
  - Much better potential for *composability*
    - If compiler is clever!





Challenging issues at all stages

- Applications
  - Programming paradigm
  - BLAS kernels, FFT, …
- Compilers
  - Languages
  - Code generation/optimization
- Runtime systems
  - Resources management
  - Task scheduling
- Architecture
  - Memory interconnect



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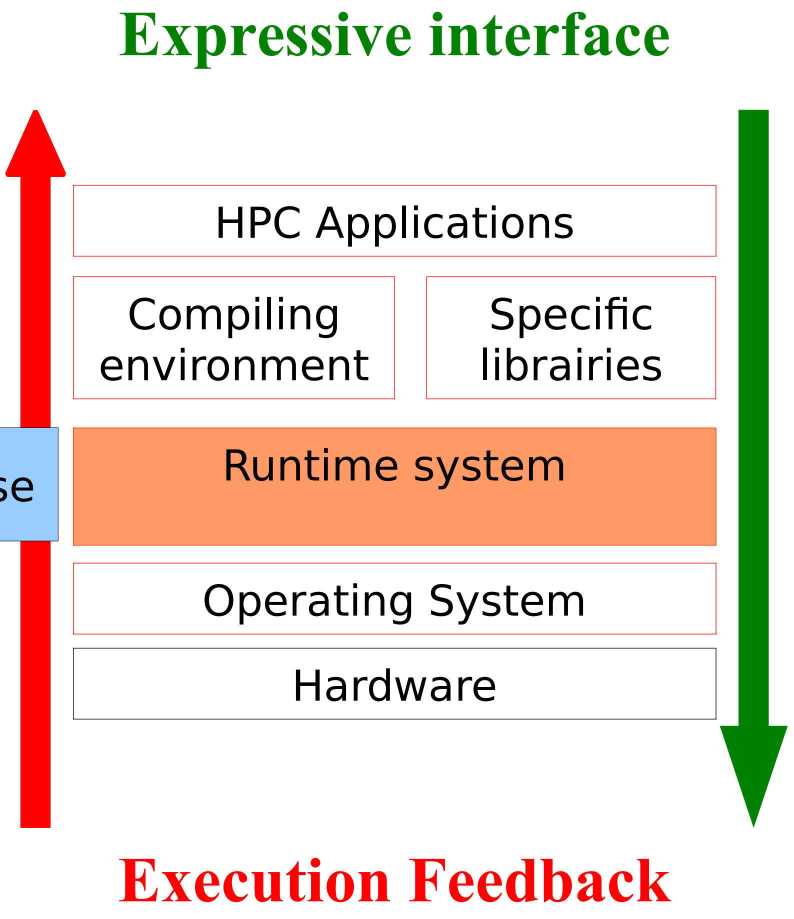
Scheduling expertise



Overview of StarPU

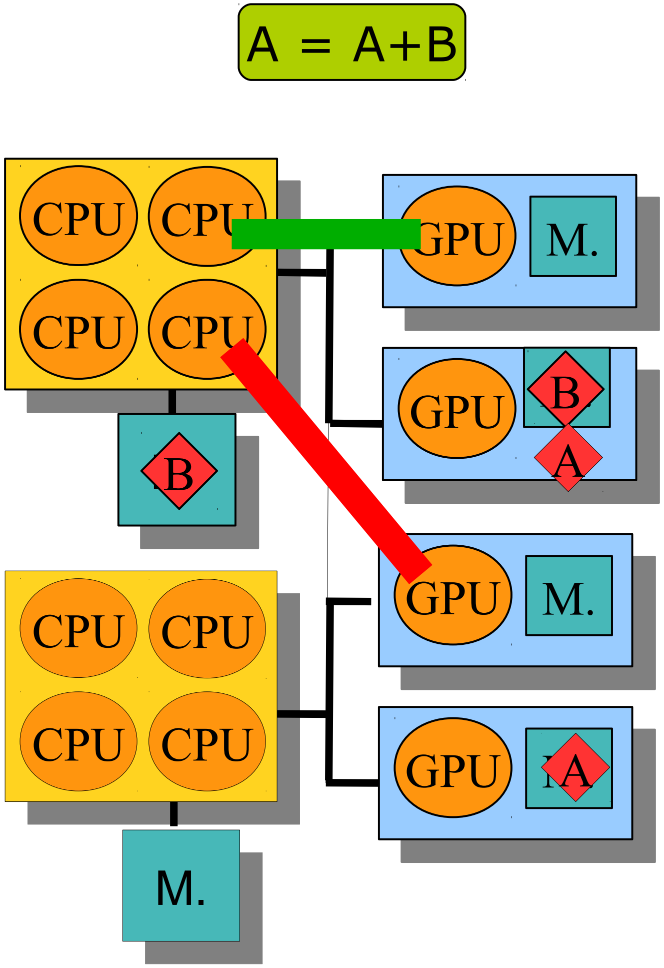
Rationale

Task scheduling

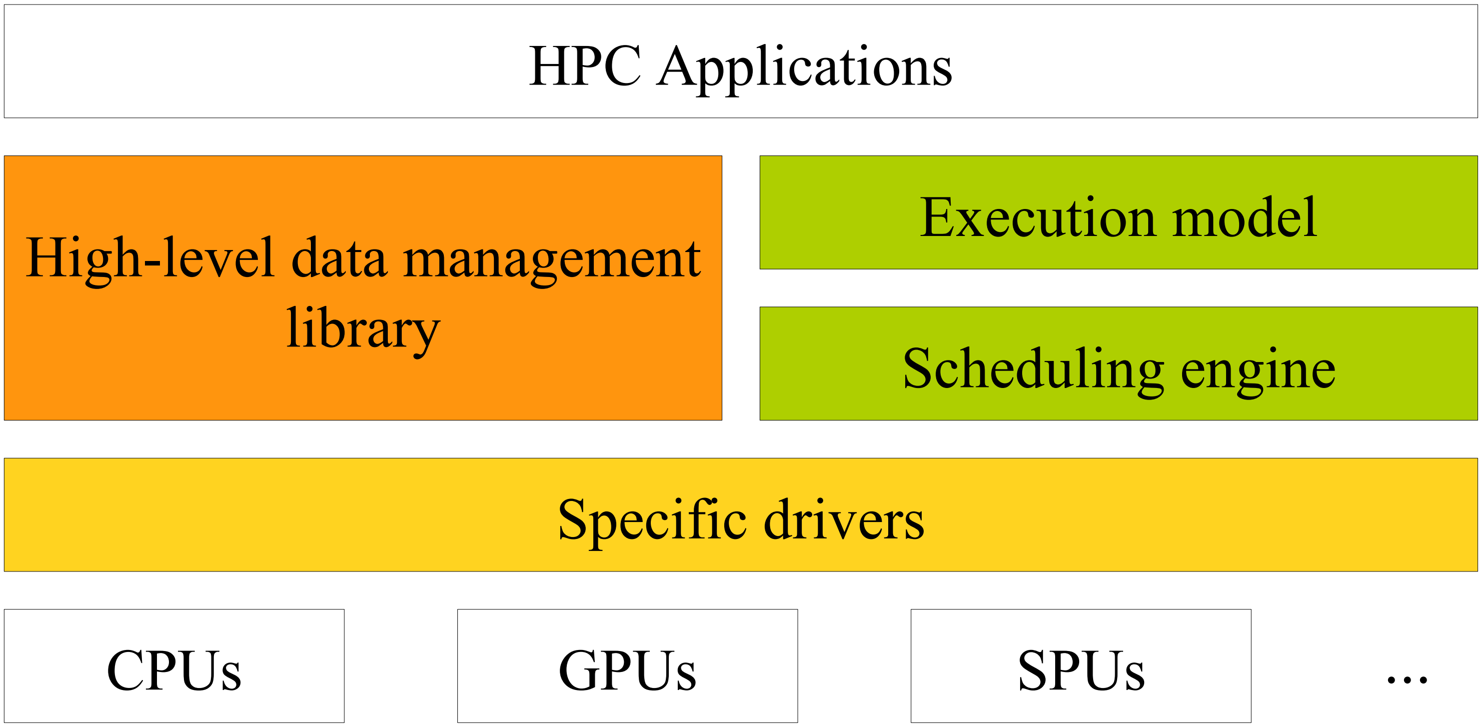
- Dynamic
- On all kinds of PU
  - General purpose
  - Accelerators/specialized

Memory transfer

- Eliminate redundant transfers
- Software VSM (Virtual Shared Memory)



The StarPU runtime system



Mastering CPUs, GPUs, SPUs … ***PUs → StarPU**

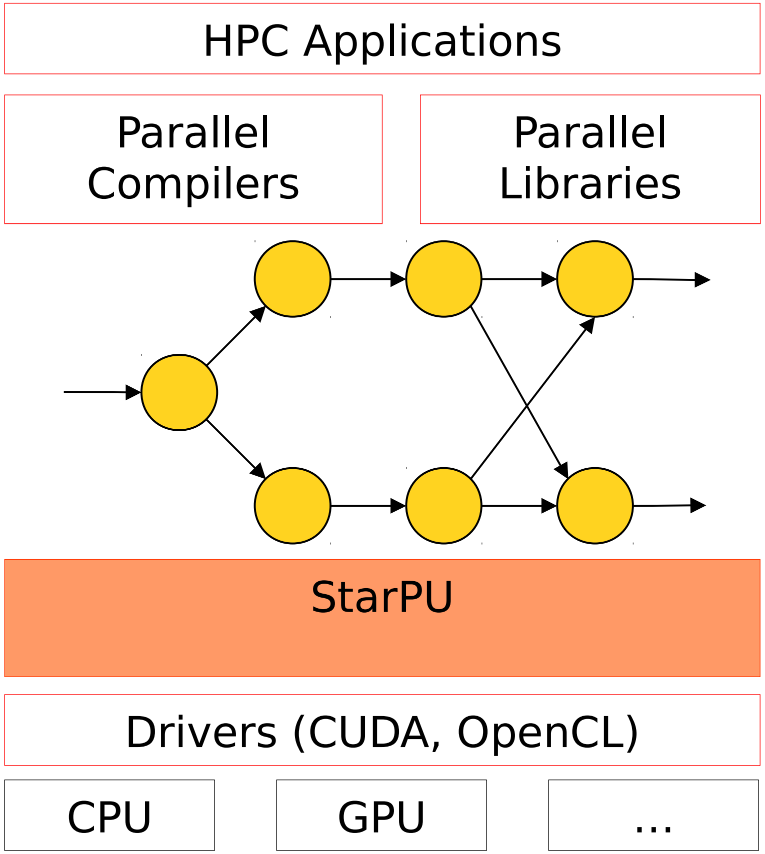
The StarPU runtime system

The need for runtime systems

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

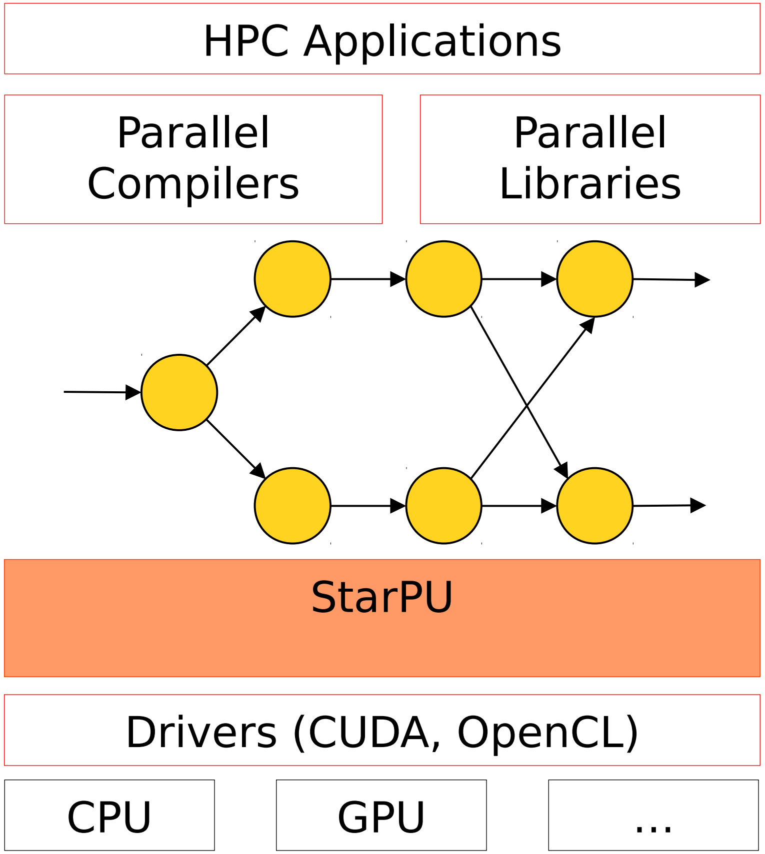
- Compilers and libraries generate (graphs of) tasks
  - Additional information is welcome!

- StarPU provides
  - Task scheduling
  - Memory management



Data management

- StarPU provides a Virtual Shared Memory (VSM) subsystem
  - Replication
  - Weak consistency
  - Single writer
  - High level API
    - Partitioning filters
- Input & ouput of tasks = reference to VSM data

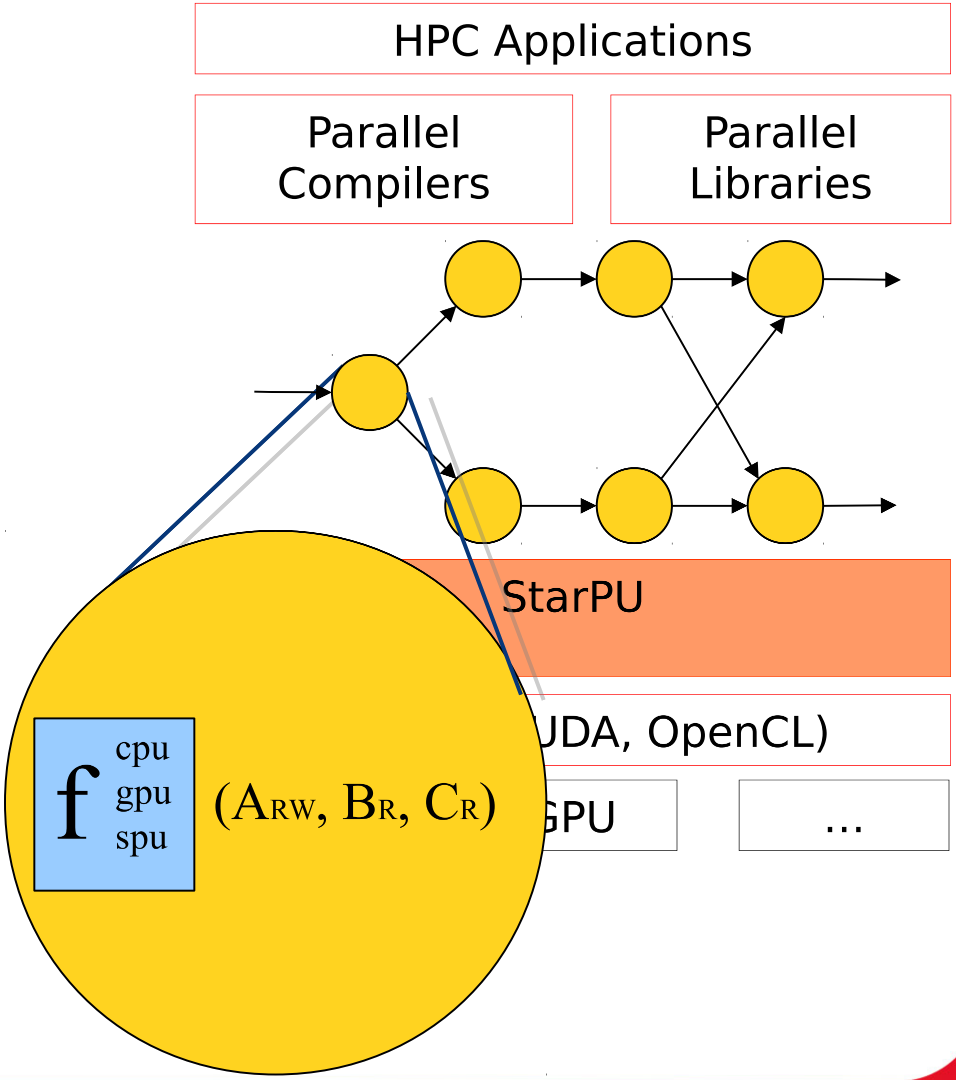


The StarPU runtime system

Task scheduling

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

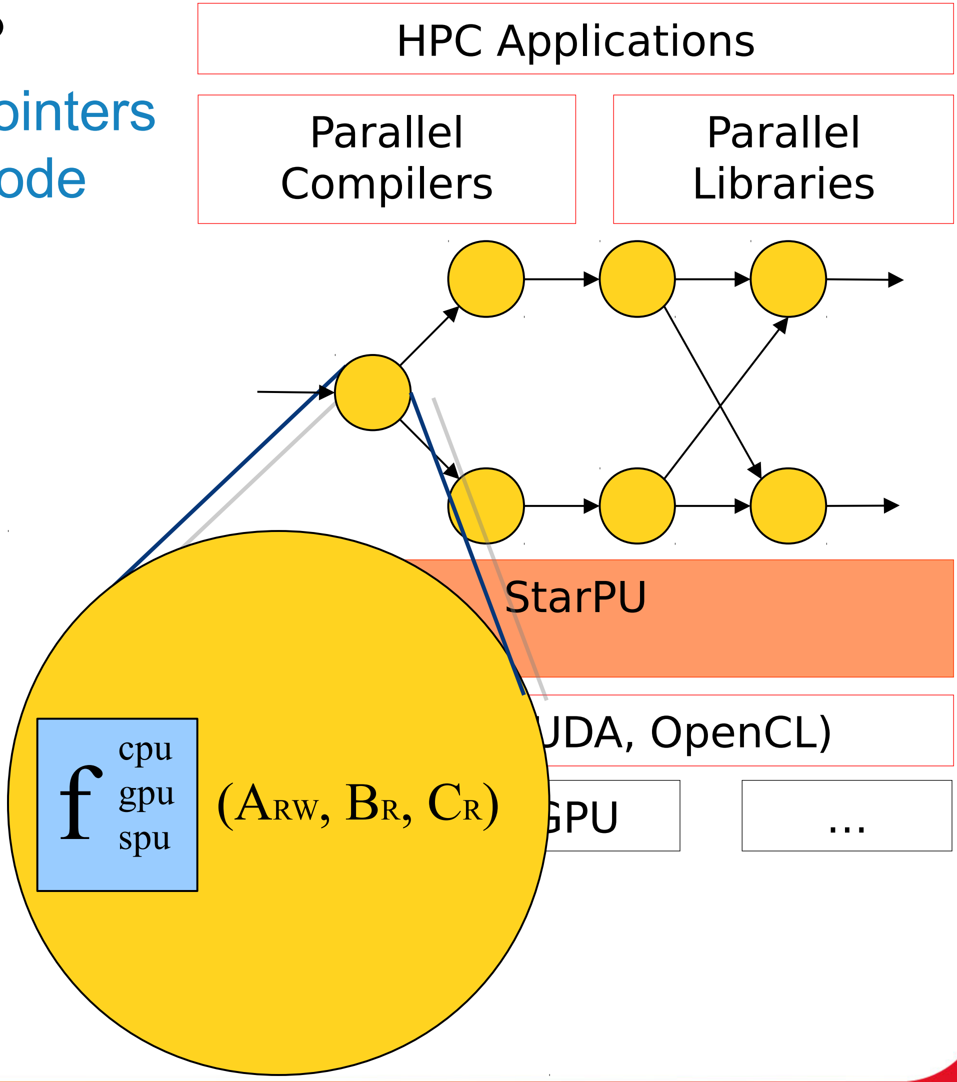
- StarPU provides an Open Scheduling platform
  - Scheduling algorithm = plug-ins



The StarPU runtime system

Task scheduling

- Who generates the code ?
  - StarPU Task ~= function pointers
  - StarPU doesn't generate code
- Libraries era
  - PLASMA + MAGMA
  - FFTW + CUFFT...
- Rely on compilers
  - PGI accelerators
  - CAPS HMPP...



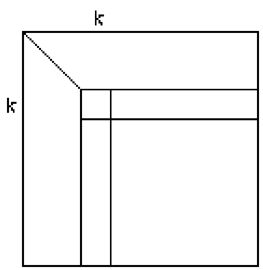
Task management

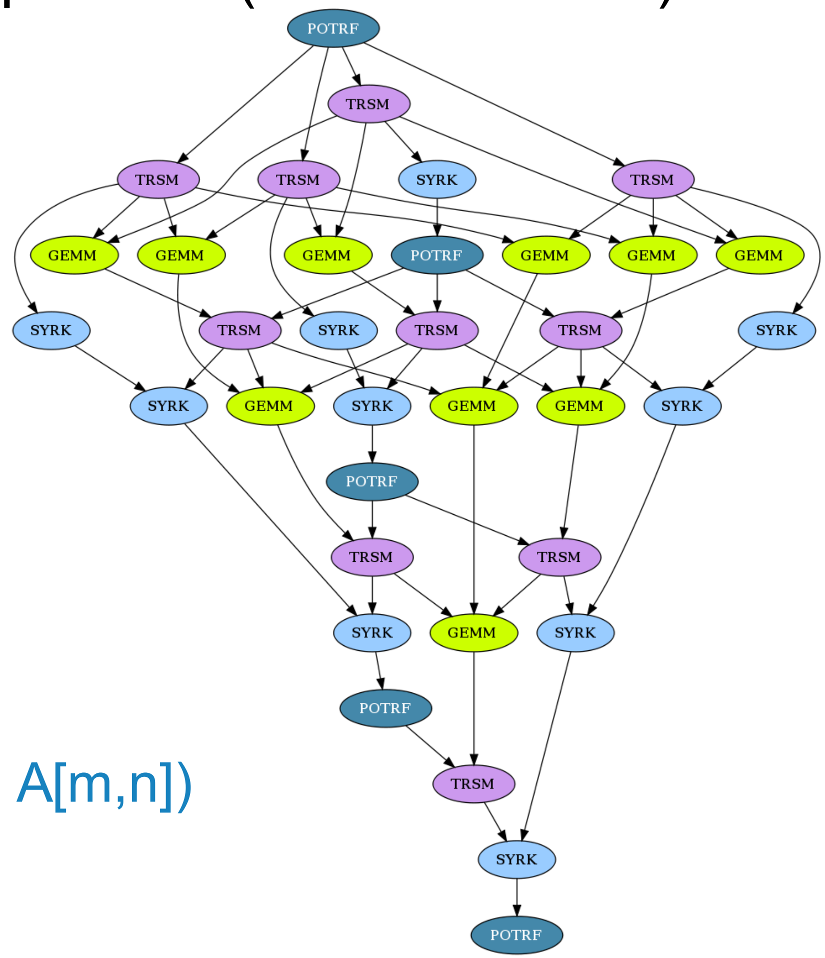
Implicit task dependencies

- 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 (m = k+1 .. tiles – 1)
        SYRK(A[m,k], A[m,m])

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



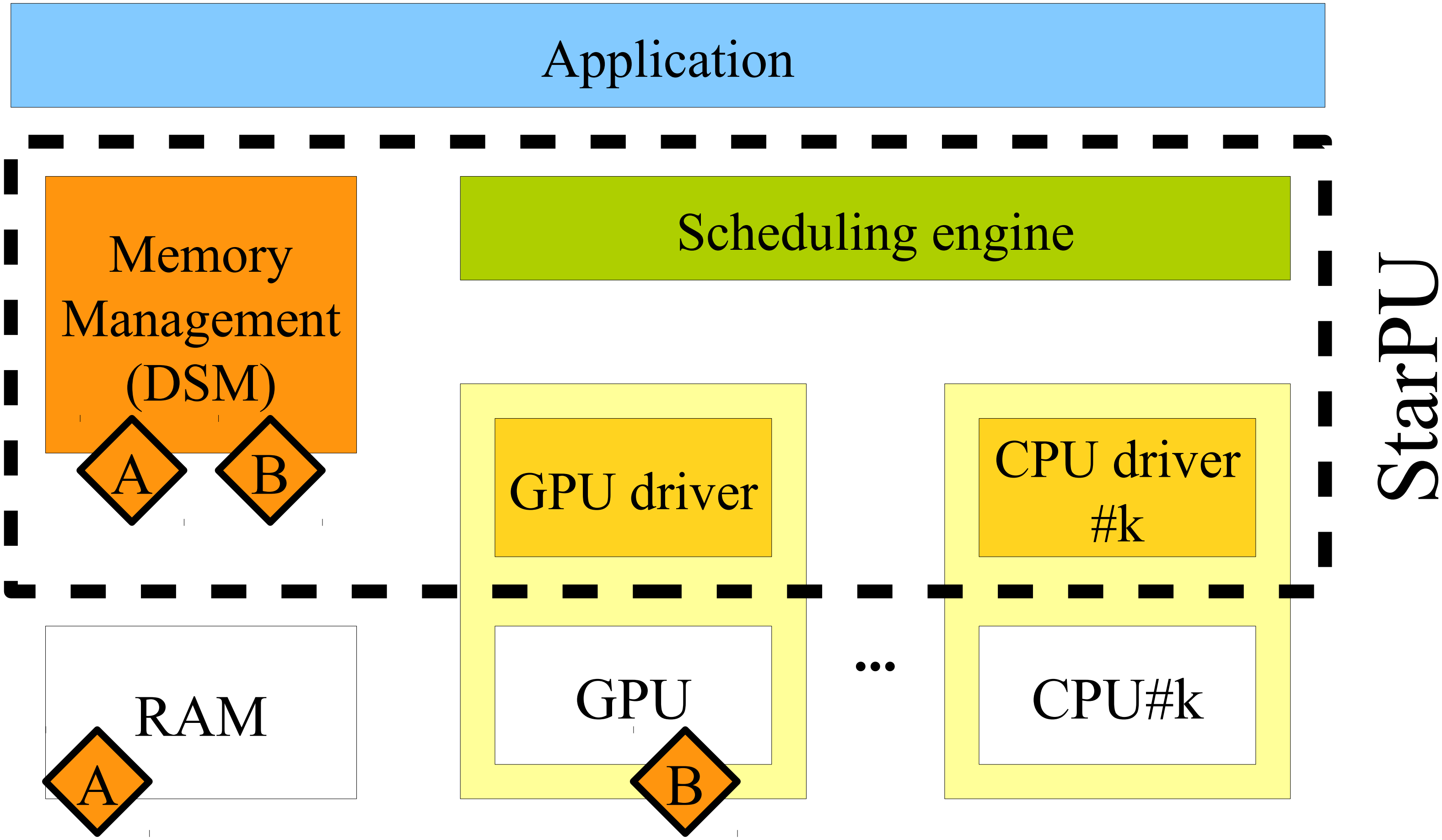


The StarPU runtime system

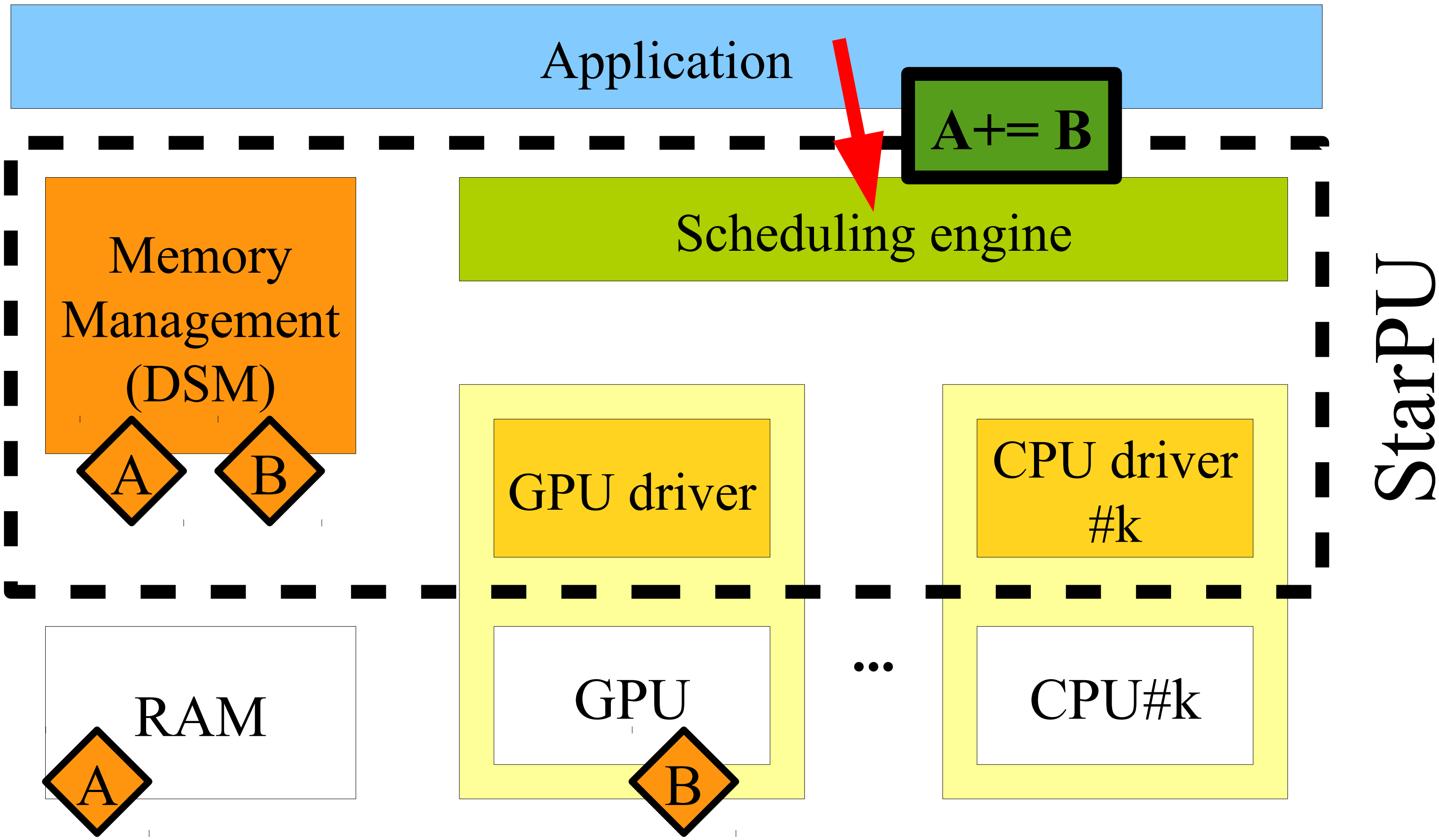
Development context

- History
  - Started about 6 years ago
    - PhD Thesis of Cédric Augonnet
  - StarPU main core ~ 40k lines of code
  - Written in C
- Open Source
  - Released under LGPL
  - Sources freely available
    - svn repository and nightly tarballs
    - See http://runtime.bordeaux.inria.fr/StarPU/
  - Open to external contributors
- [HPPC'08]
- [Europar'09] – [CCPE'11],... >400 citations

The StarPU runtime system
Execution model



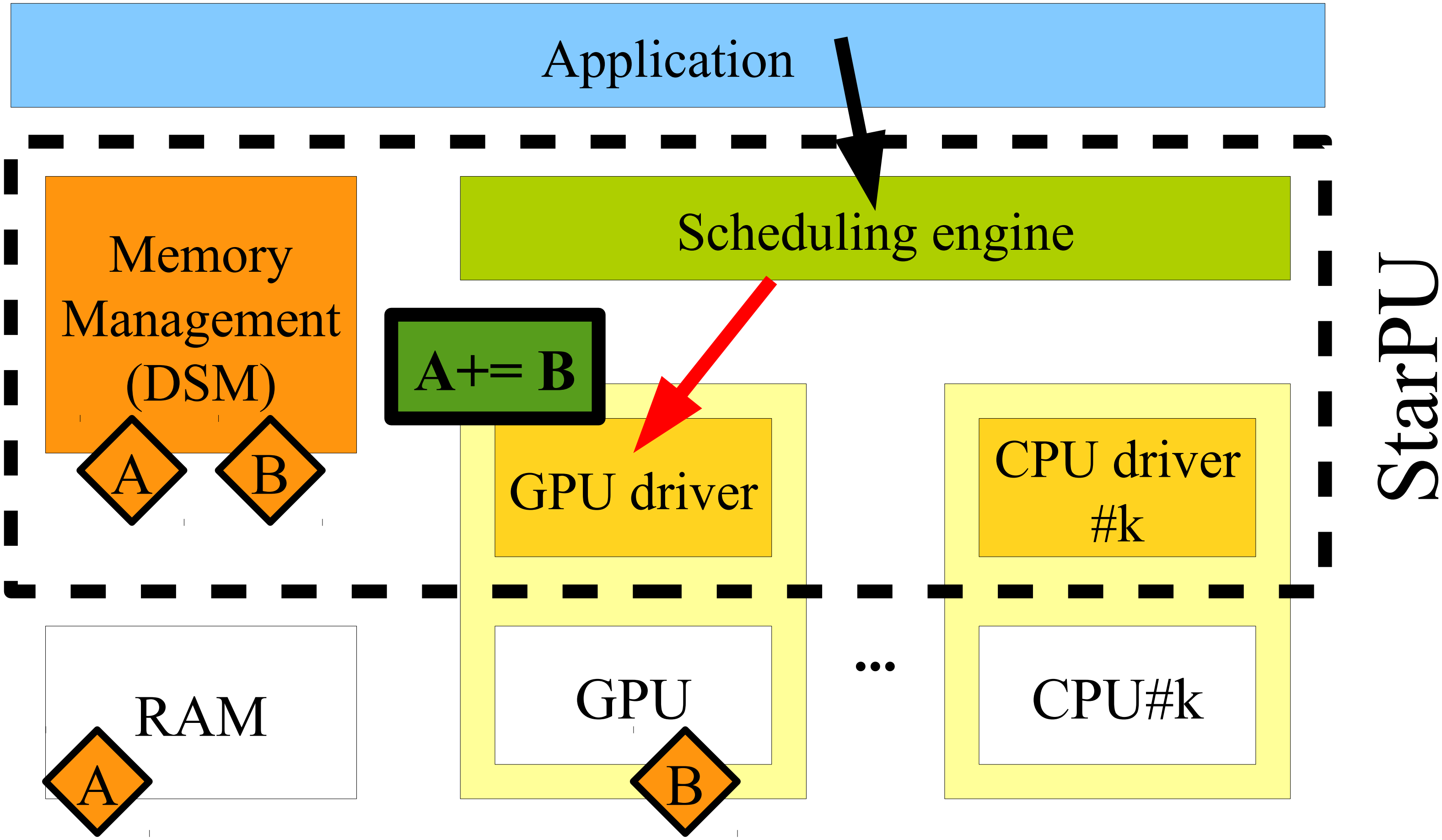
The StarPU runtime system
Execution model



Submit task « A += B »

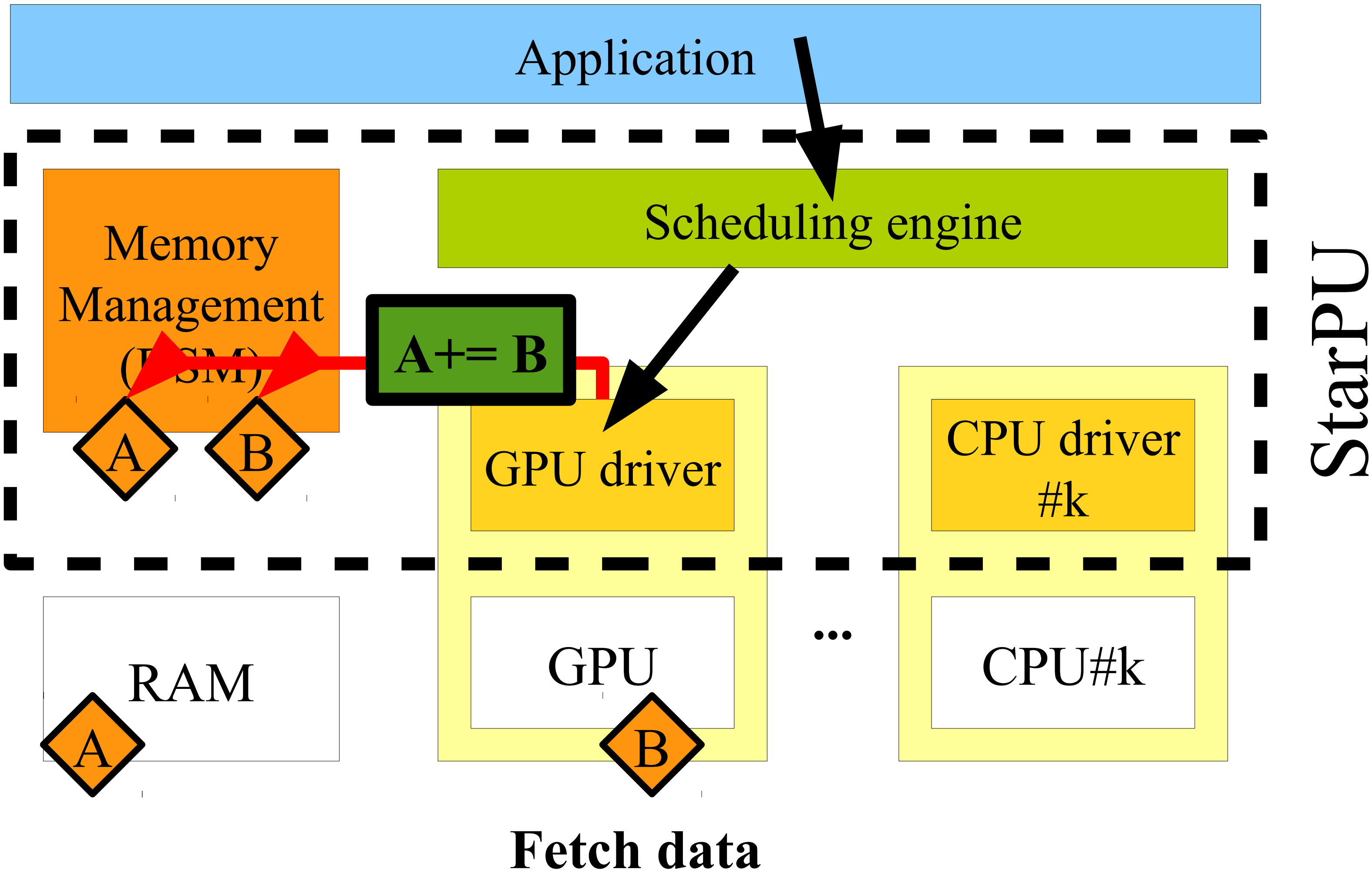
The StarPU runtime system

Execution model



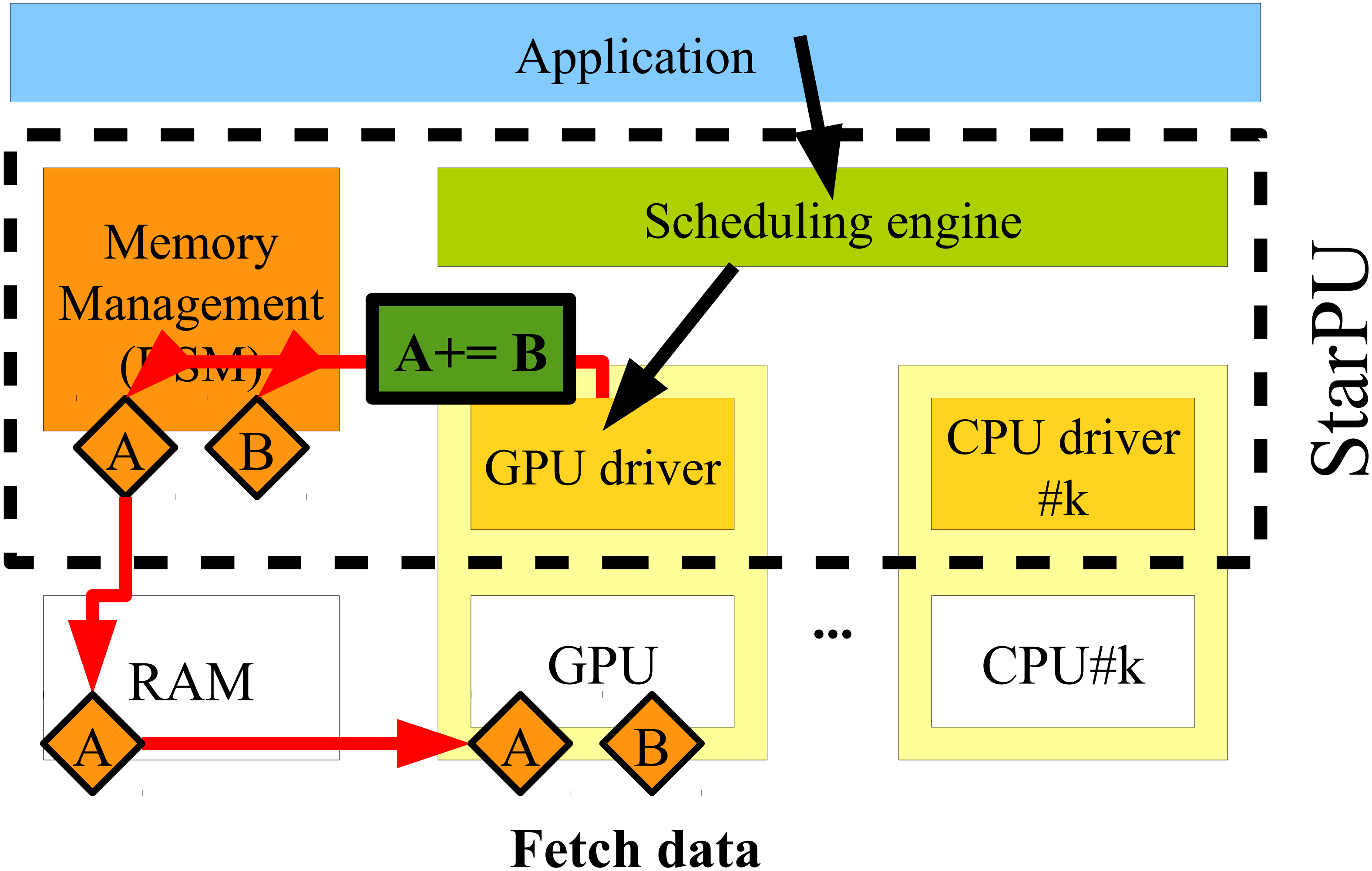
Schedule task

The StarPU runtime system
Execution model

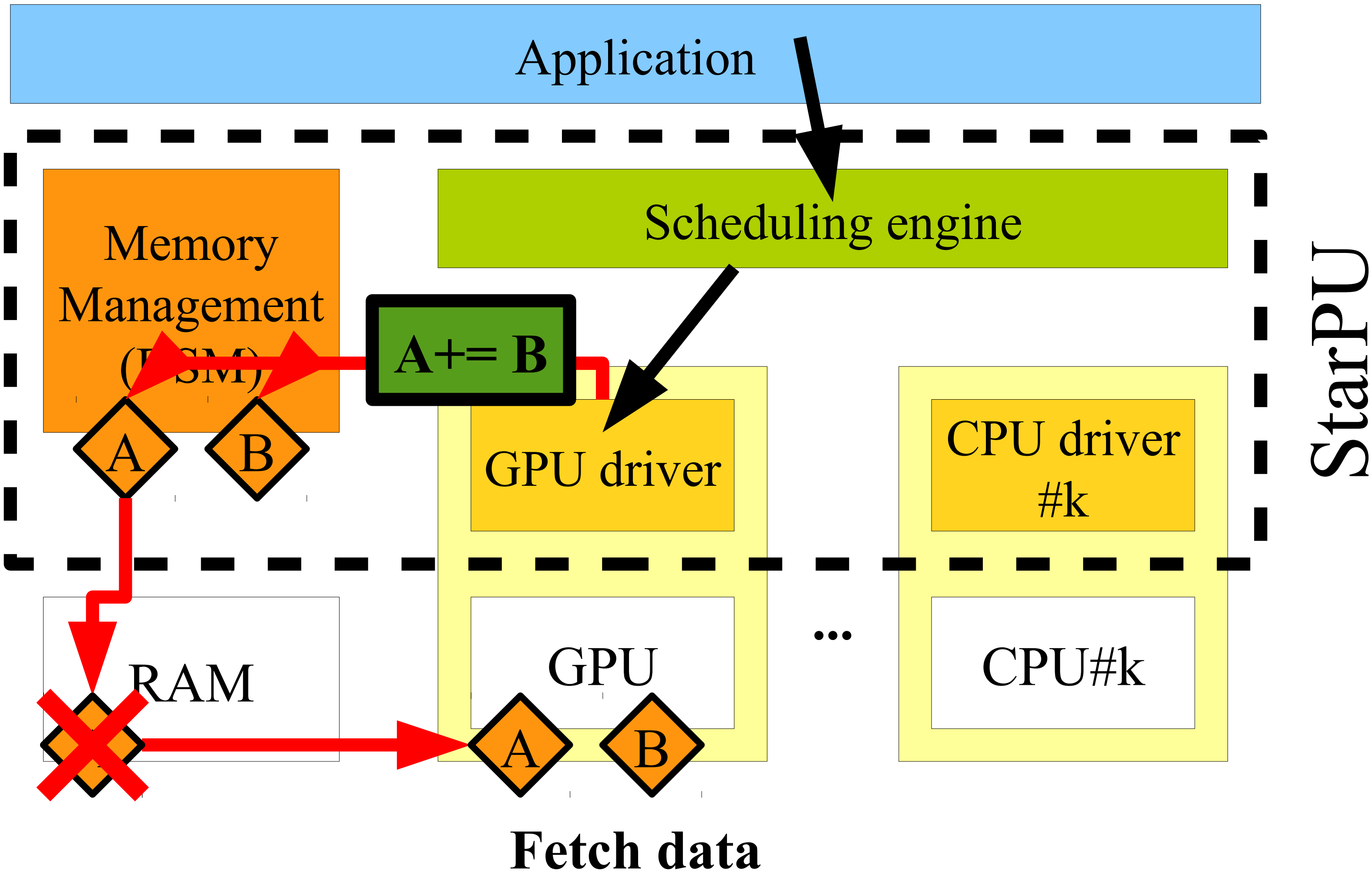


The StarPU runtime system

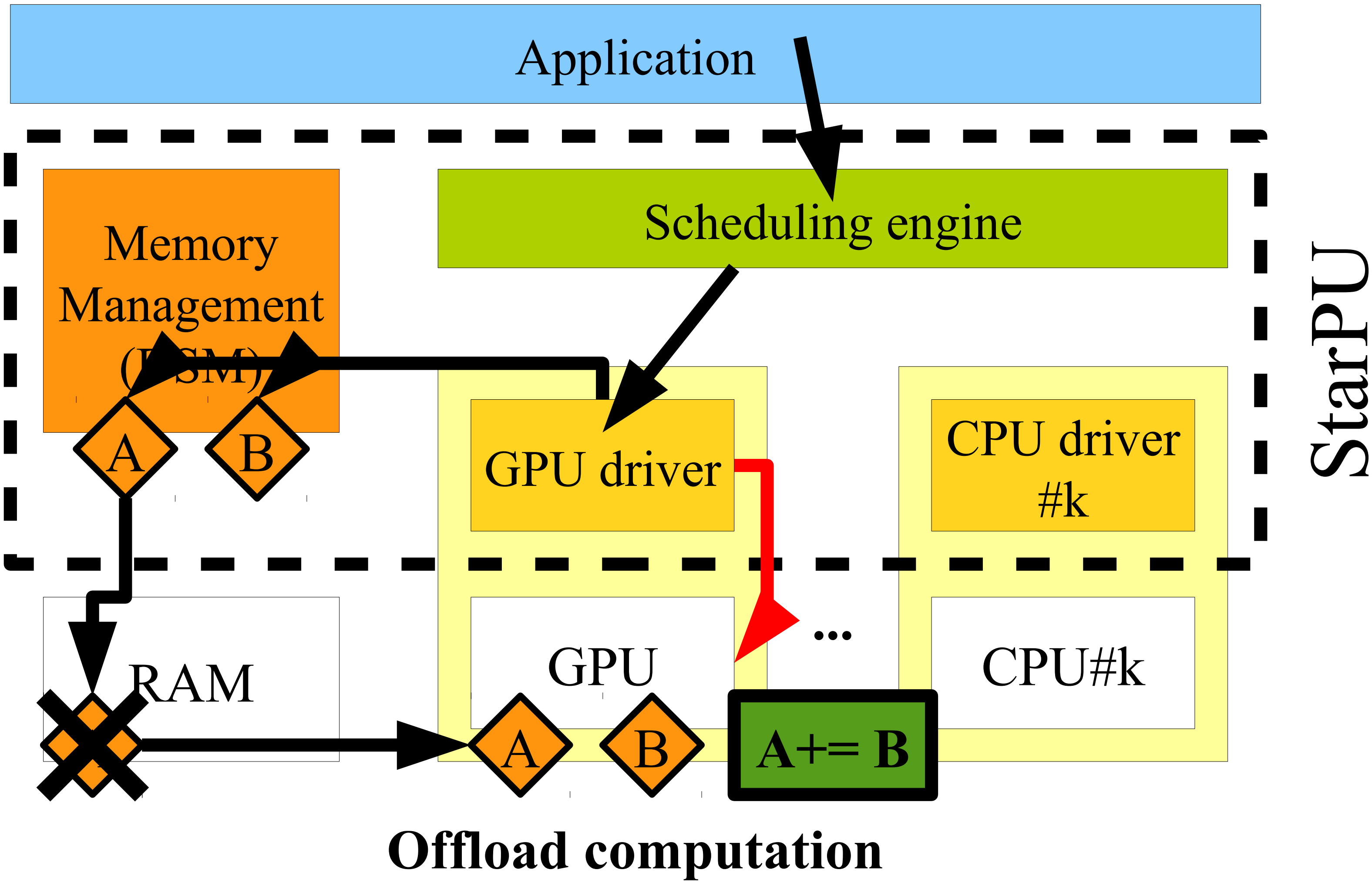
Execution model



The StarPU runtime system
Execution model

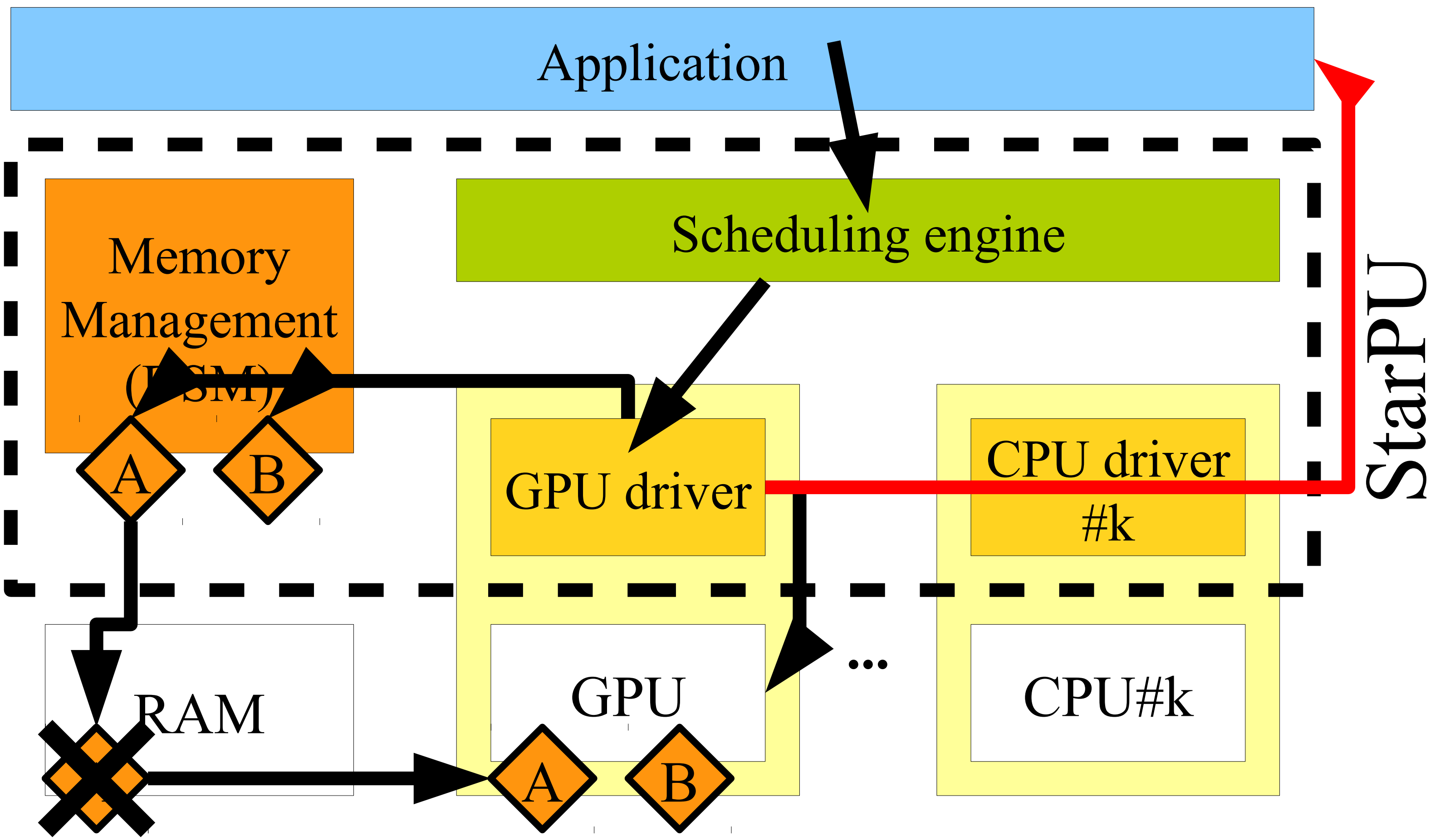


The StarPU runtime system
Execution model



The StarPU runtime system

Execution model



Optimizations

- Task pipelining
- Task execution / data transfer overlap
- GPU-GPU copies
- Data prefetch
- ...

Thus needs

- Asynchronous API with fine-grain synchronization
- Non-blocking API
- Pitched 2D copy & such
- Thread safety

Host memory mapped on GPU & vice-versa is useful, too

Programming interface

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 (4)

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

```
starpu_codelet scal_cl = {
    .cpu_func = scal_cpu_func,
    .cuda_func = scal_cuda_func,
    .opencl_func = scal_opencl_func,
    .nbuffers = 1,
    .modes = STARPU_RW
};
```

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;


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


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

Scaling a vector

Defining a task, starpu_insert_task helper

- Define a task that scales the vector by a constant

```
float factor = 3.14;

starpu_insert_task(
        &scal_cl,
        STARPU_RW, vector_handle,
        STARPU_VALUE,&factor,sizeof(factor),
        0);
```

Scaling a vector

Defining a task, gcc plugin

```
void scale_vector(int size, float vector[size], float factor)
    __attribute__((task));
void scale_vector_cpu(int size, float vector[size], float factor)
    __attribute__((task_implementation("cpu", scale_vector))) ;
void scale_vector_cpu(int size, float vector[size], float factor)
    { … }
int main(void) {
    static float input[NX];
#pragma starpu register input
    scale_vector(NX, input, 42);


#pragma starpu wait
#pragma starpu unregister input
}
```

Scaling a vector

Defining a task, gcc plugin

```
void scale_vector(int size, float vector[size], float factor)
      __attribute__((task));
void scale_vector_cpu(int size, float vector[size], float factor)
      __attribute__((task_implementation("cpu", scale_vector))) ;
void scale_vector_cpu(int size, float vector[size], float factor)
      { … }
int main(void) {
      static float input[NX];
#pragma starpu register input
      scale_vector(NX, input, 42);
      frob_vector(NX, input, out1);
      shred_vector(NX, input, out2);
#pragma starpu wait
#pragma starpu unregister input
}
```

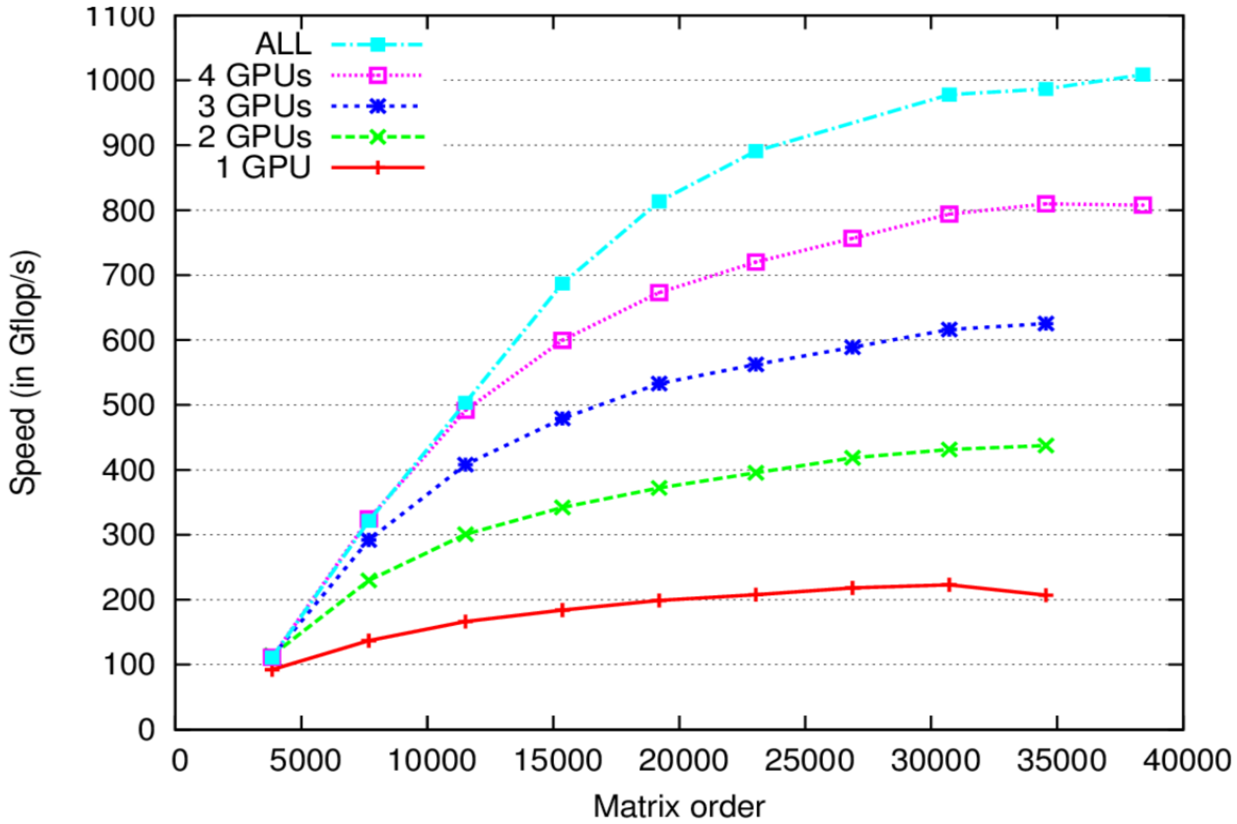
Scaling a vector

Defining a task, gcc plugin

```
void scale_vector(int size, float vector[size], float factor)
      __attribute__((task));
void scale_vector_opencl(int size, float vector[size], float factor)
      __attribute__((task_implementation("opencl", scale_vector))) ;
#pragma starpu opencl scale_vector_opencl \
      "vector-scale.cl" "vector_scal_kern" \
      group_size ngroups ;
```

Mixing PLASMA and MAGMA with StarPU

- QR decomposition
  - Mordor8 (UTK) : 16 CPUs (AMD) + 4 GPUs (C1060)



Mixing PLASMA and MAGMA with StarPU

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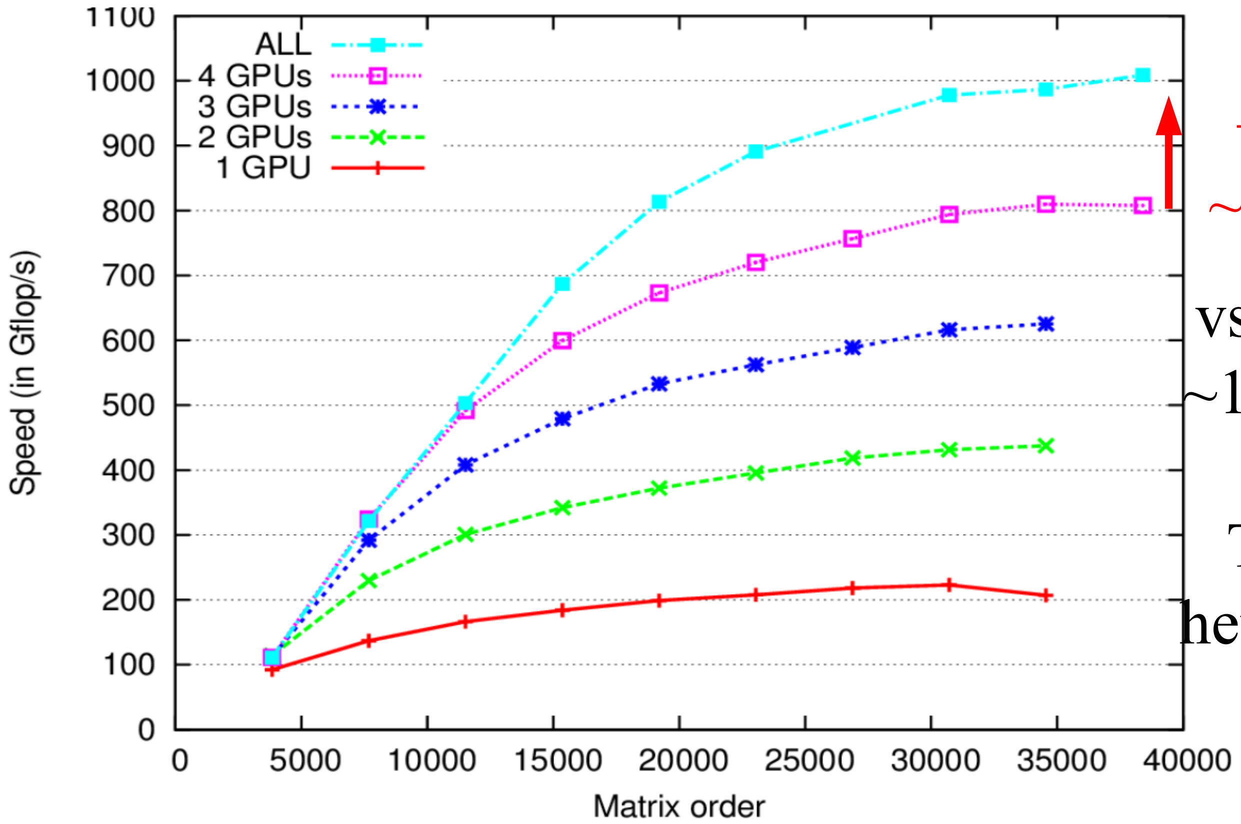


+12 CPUs ~200GFlops

vs measured ~150Gflops !

Thanks to heterogeneity

Mixing PLASMA and MAGMA with StarPU

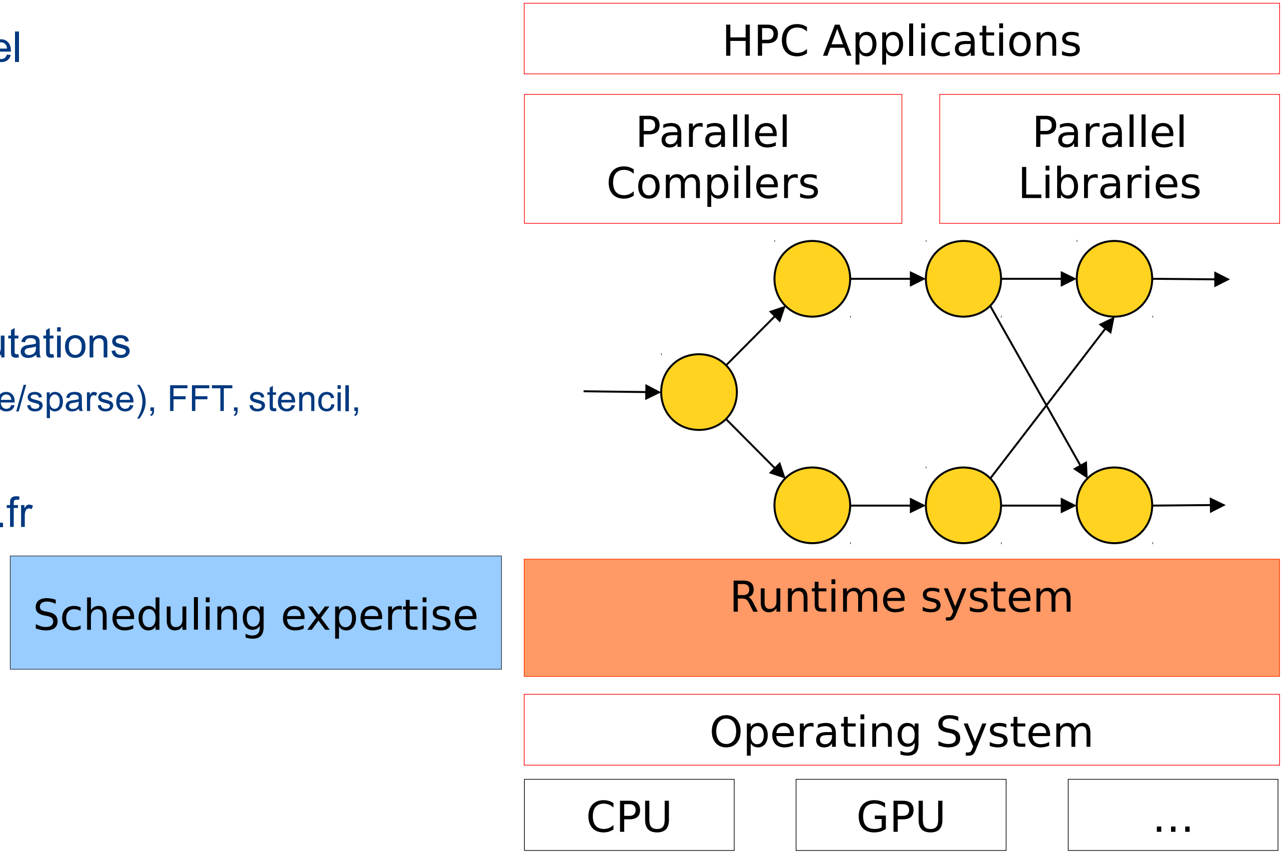
- « Super-Linear » efficiency in QR?
  - Kernel efficiency
    - sgeqrt
      - CPU: 9 Gflops GPU: 30 Gflops (Speedup : ~3)
    - stsqrt
      - CPU: 12Gflops GPU: 37 Gflops (Speedup: ~3)
    - somqr
      - CPU: 8.5 Gflops GPU: 227 Gflops (Speedup: ~27)
    - Sssmqr
      - CPU: 10Gflops GPU: 285Gflops (Speedup: ~28)
  - Task distribution observed on StarPU
    - sgeqrt: 20% of tasks on GPUs
    - Sssmqr: 92.5% of tasks on GPUs
  - Taking advantage of heterogeneity !
    - Only do what you are good for
    - Don't do what you are not good for

Conclusion

Summary

Tasks

- Nice programming model
- Runtime playground
- Scheduling playground
- Algorithmic playground
- Used for various computations
  - Cholesky/QR/LU (dense/sparse), FFT, stencil, CG, FMM...
- http://starpu.gforge.inria.fr



Conclusion

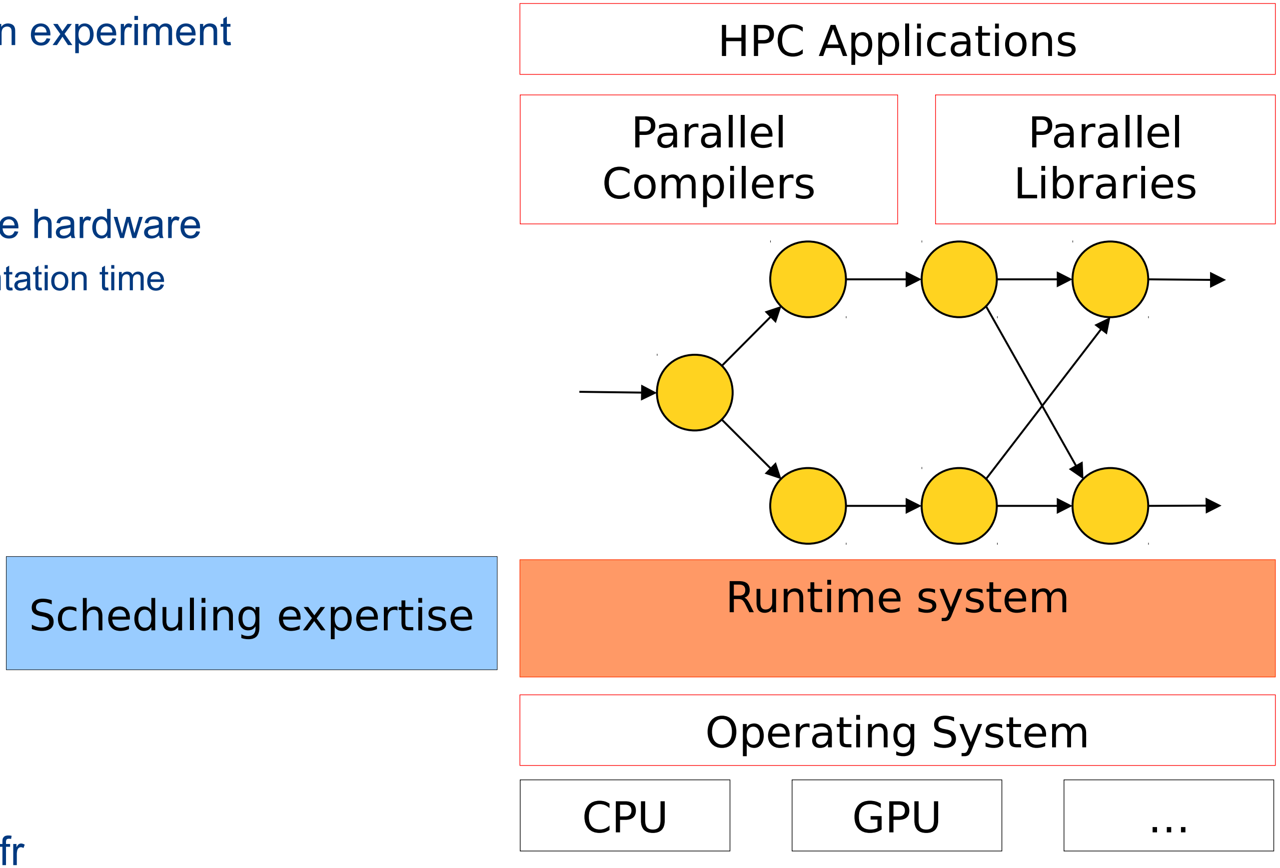
Summary

Scheduling researchers can experiment and tune various heuristics

- On actual applications
- Without even needing the hardware
    - And with fast experimentation time

Optimize

- Completion time
- Memory consumption
- Energy consumption
- …



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