StarPU, a Task-Based Runtime System

for Heterogeneous Platform Programming

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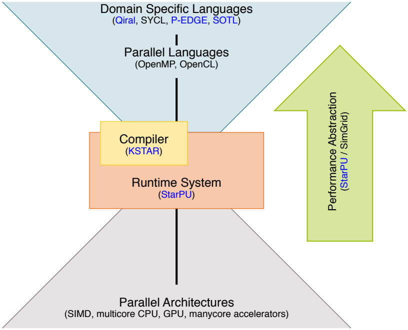
Team STORM

STatic Optimizations, Runtime Methods

- Inria Bordeaux – Sud-Ouest, LaBRI Laboratory
- Head: Denis Barthou
- Research directions
  - Expressing...
  - Adapting... ... parallelism
  - Optimizing...



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Runtime Systems for Heterogeneous Platforms

Hardware Evolution

More capabilities, more complexity

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- Higher resolutions
- 2D acceleration
- 3D rendering

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- SSD vs Disks
- Network-attached disks
- Parallel file systems

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Computing Hardware?

Technology Dilemma for the Application Programmer

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- Under-used hardware?
- Low performance?

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- Long-term viability?
- Vendor-tied code?
  - Is it worthwhile to invest into porting on such platforms?

Technology Dilemma for the Application Programmer

Answer: **Use runtime systems!**

1.1

Principles of Runtime Systems

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- Optimization

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- **MPI** (Message Passing Interface), Global Arrays
- GASPI / GPI-2
- GASNet, CCI
- Distributed Shared Memory systems
- SHMEM

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I/O

- MPI-IO
- HDF5 libraries
- Database engines

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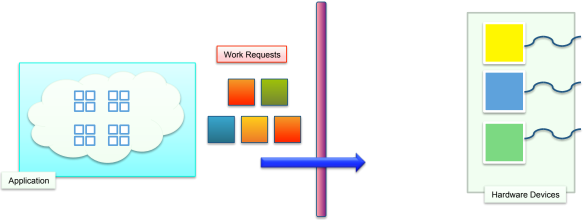
- Abstraction
  - Uniform front-end layer
  - Device-independent API
  - Targeted by applications



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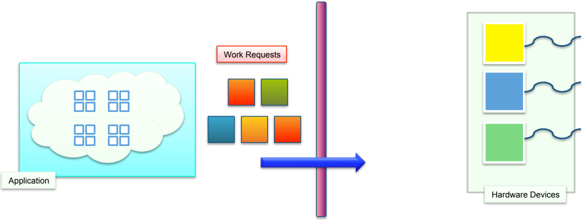

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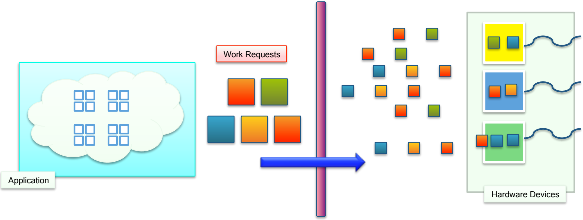
- **Decoupling applications from device specific matters**



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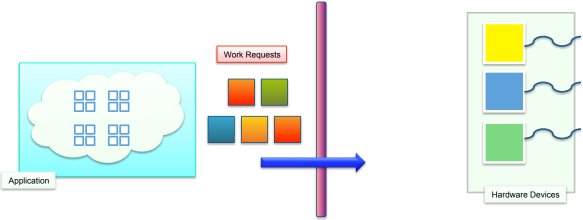

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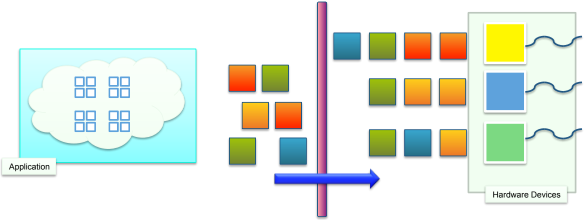
  - Spatial work mapping



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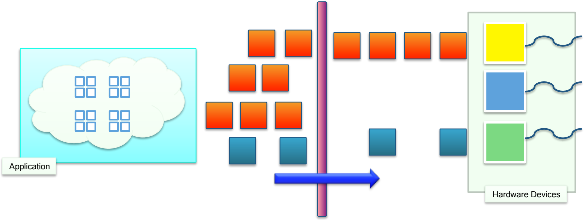

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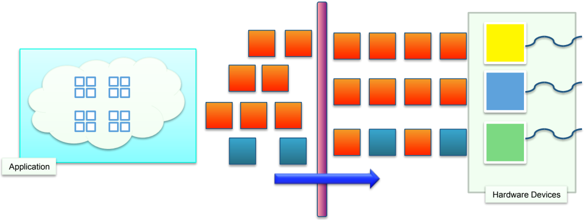
- **Plan application workload execution**



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  - Providing fallbacks, when possible
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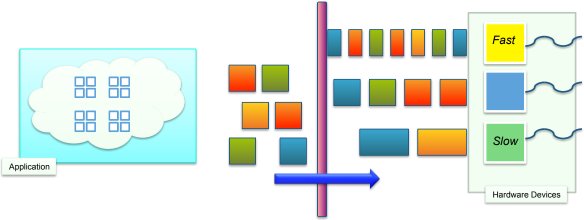

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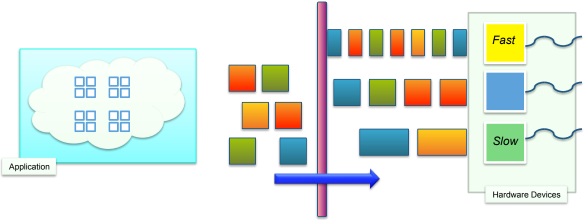

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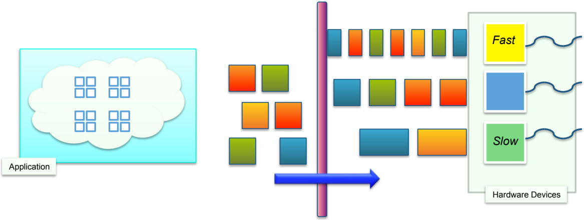
- **Cope with effective hardware aptitude and performance level**



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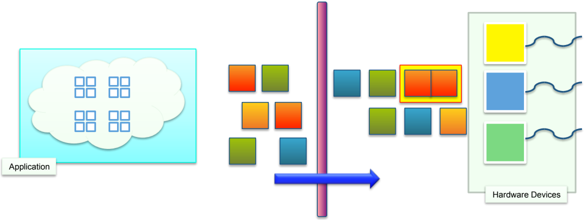

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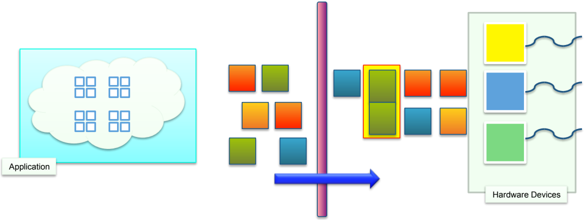

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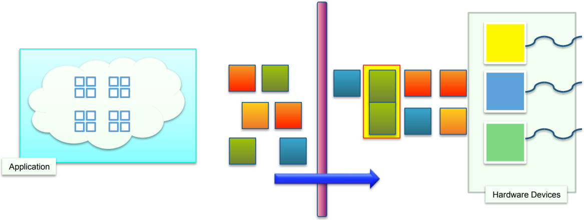
- **Out-weight the cost of an extra, intermediate software layer**



1.2

Runtime Systems for Computing

Evolution of Computing Hardware

Rupture

- The “Frequency Wall”
  - Processing units cannot run anymore faster
- Looking for other sources of performance

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- Multiply existing processing power
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Hardware Parallelism

- Multiply existing processing power
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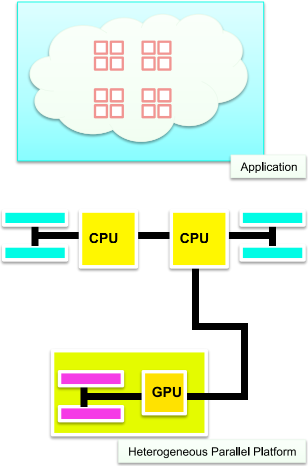
- Not a new idea...
- ...but definitely the key performance factor now

Heterogeneous Computing Platforms

Heterogeneous Association

- General purpose processor
- Specialized accelerator

Generalization



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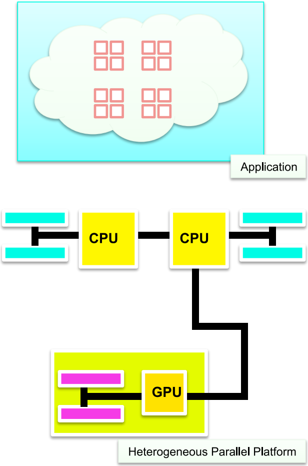

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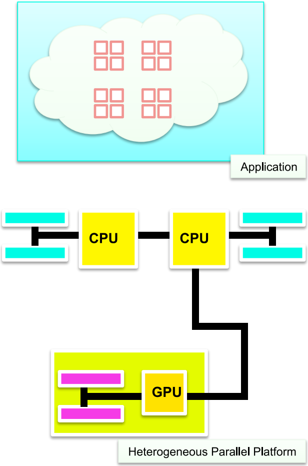

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  - Latency-optimized cores
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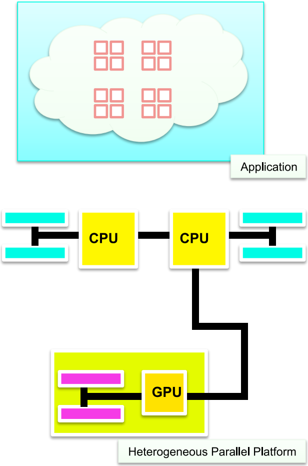

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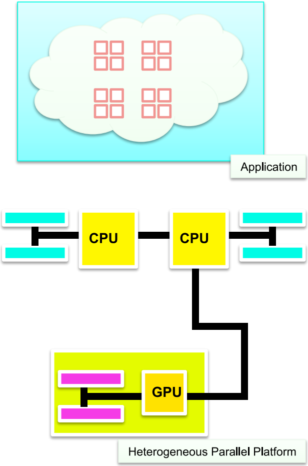
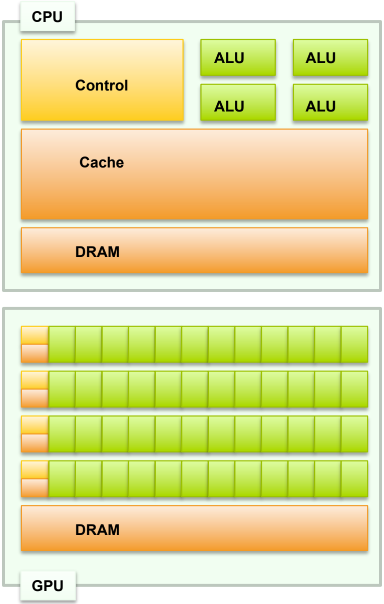
- **Overall increased parallelism diversity**
  - Multiprocessors, multicores
  - Vector processing extensions
  - Accelerators



Example: CPU vs GPU Hardware

Multiple strategies for multiple purposes

- **CPU**
  - Strategy
    - Large caches
    - Large control
  - Purpose
    - Complex codes, branching
    - Complex memory access patterns
  - World Rally Championship car
- **GPU**
  - Strategy
    - Lot of computing power
    - Simplified control
  - Purpose
    - Regular data parallel codes
    - Simple memory access patterns
  - Formula One car



Accelerators

Special purpose computing devices
(or general purpose GPUs)

- (initially) a discrete expansion card
- Rationale: dye area trade-off

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Single Instruction Multiple Threads (SIMT)

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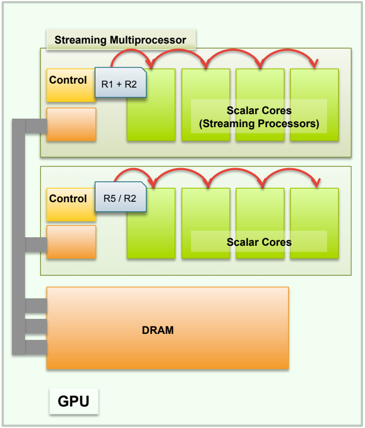

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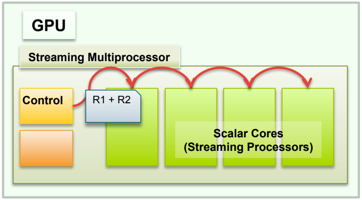
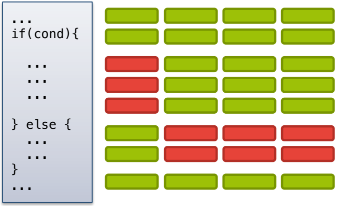
SIMT is distinct from SIMD

- Allows flows to diverge
- … but better avoid it!





Problematics

Unified computing runtime system for heterogeneous platforms

- Portability of performance
  - Abstraction
  - Adaptiveness
  - Execution Control
  - Optimization

Need a way to abstract application execution. . .

. . . into elementary, manageable objects

1.3

Abstracting Application Workload

Thread Scheduling

Reasoning on *Thread* objects?

Thread

- One instruction flow
  - Unbounded flow
  - Parallel activity
- One state/context per thread
  - Stack

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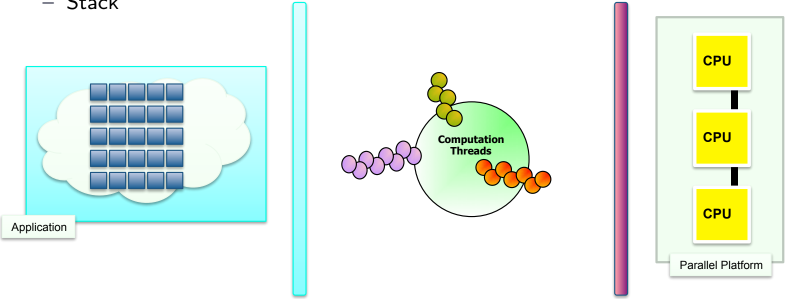

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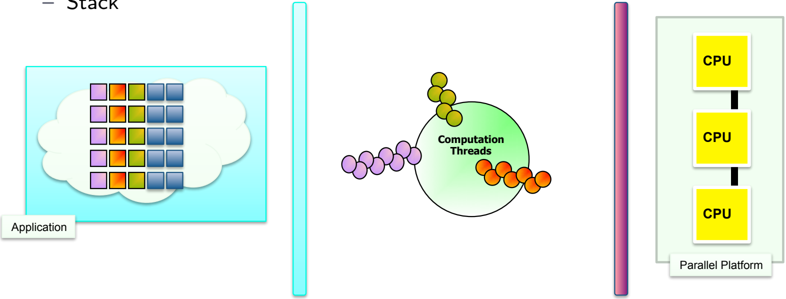

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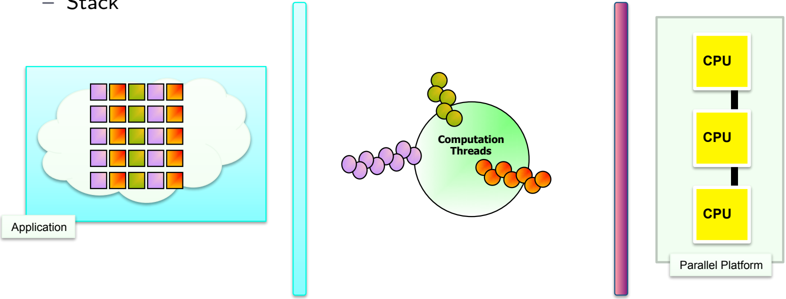

Threads: Resources vs Needs

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- Threads express explicit resource request
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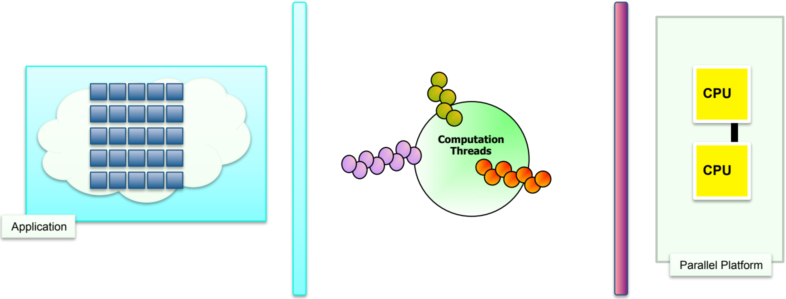

Threads: Resources Miss-subscription

Software vs hardware mismatch

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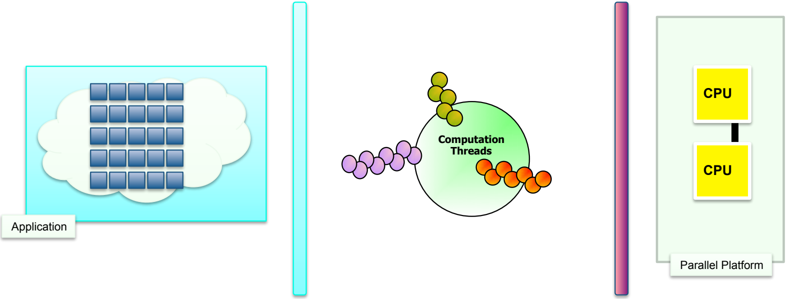

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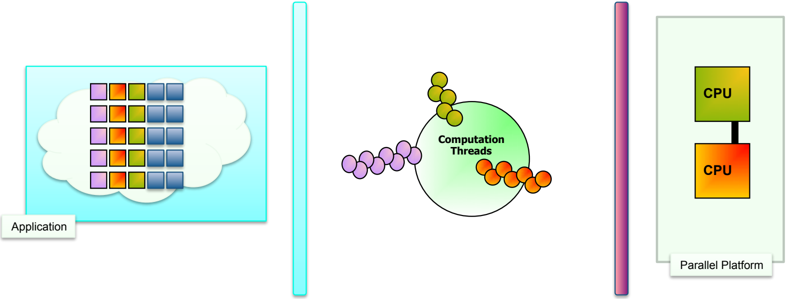

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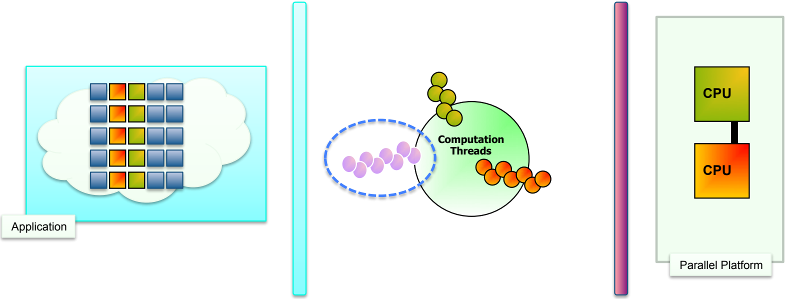

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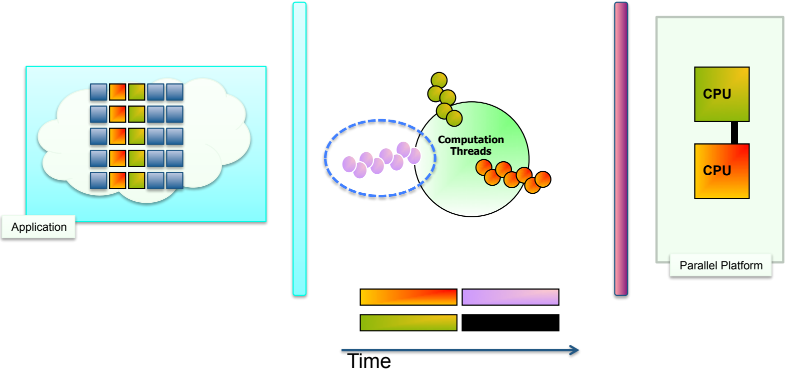

Threads: Lack of Semantics

What does a thread really do?

- Resource usage?
- Inter-thread constraints
- Chaining constraints, ordering?

Planning Issues

- Unbounded computation
- System-controlled context switches

Consequences

- Heavy synchronizations: barriers
- User-managed fine-grain synchronizations: locks, mutexes
- Little to no help from runtime system

Threads: Load Balancing Issues

Keeping every hardware unit busy

- Irregular application, workload
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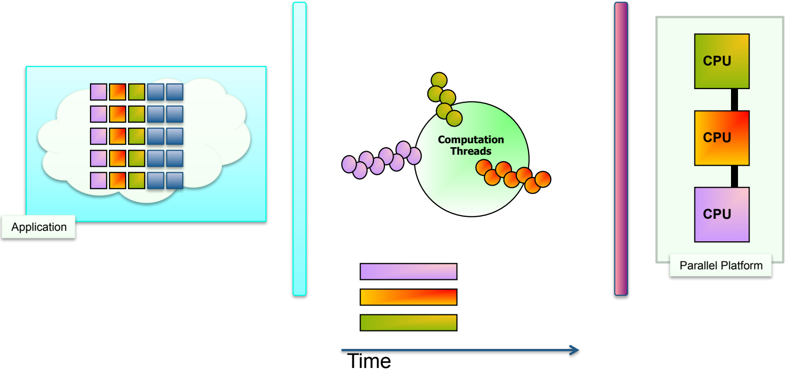

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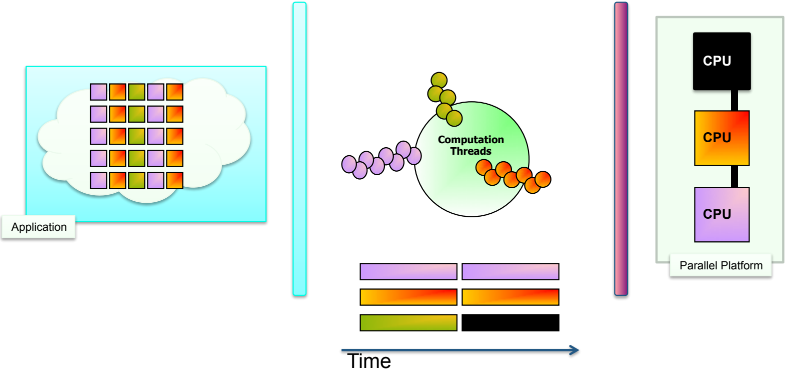

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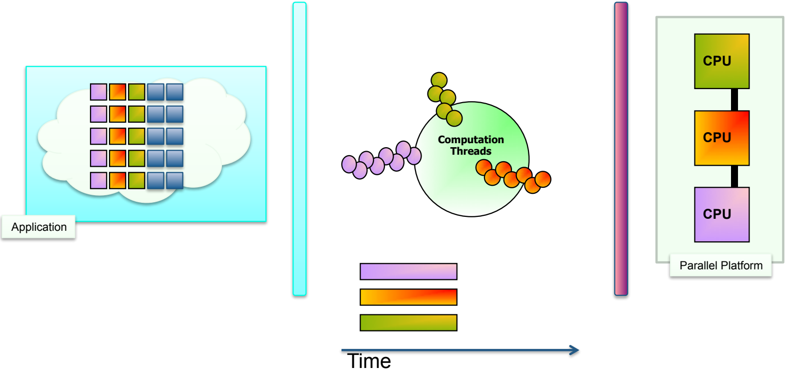

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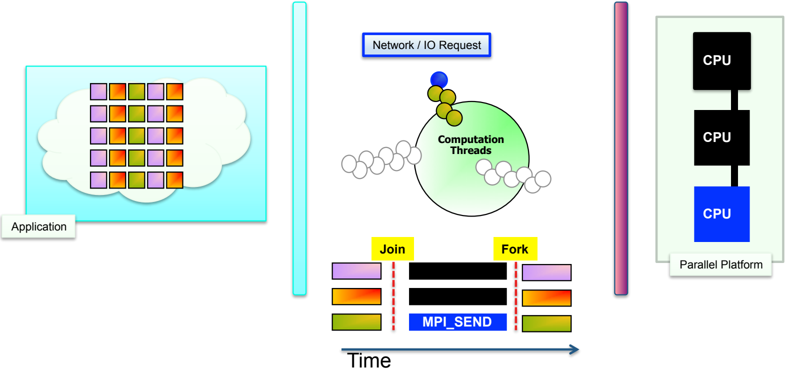
- Thread-level idle time reduction?



Threads: Outcome

Perhaps not the right semantics for end-user application development

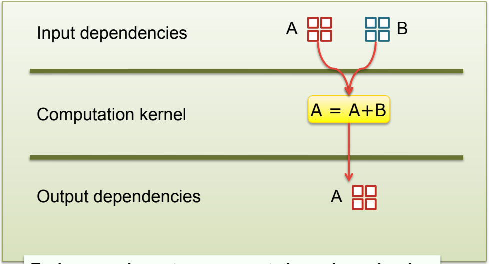
- Over-constrained concept for application programming
- Awkward object to manipulate at the runtime system level
- Not well suited to leverage theoretical scheduling results
  - Completion?
  - Other metrics?

Task Scheduling

Reasoning on *Task* objects

Common definition

- **Elementary computation**
  - Numerical kernel
  - BLAS call
  - ...
- → Potential parallel work



Task = an « elementary » computation + dependencies

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  - *No side effect* (no hidden dependencies)
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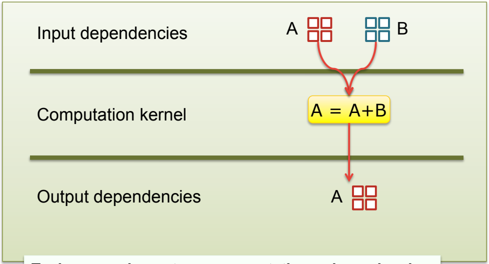

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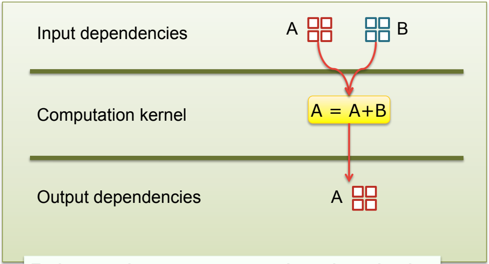

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- **Constraints**
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- → Degrees of Freedom in realizing the potential parallelism
- **Shared (often fixed) pool of worker threads**
- → Decoupled engine, to realize a potentially parallel execution

Tasks: Resources vs Needs?

A task expresses **what** to do (e.g. which computation)

The runtime remains free to decide the amount of resources to execute a task

- Rationalize resource consumption
  - Thread and associated stack reused among several tasks
- Enforce separation of concerns
  - Management code brought out of the application
- Open the way to resource allocation optimization
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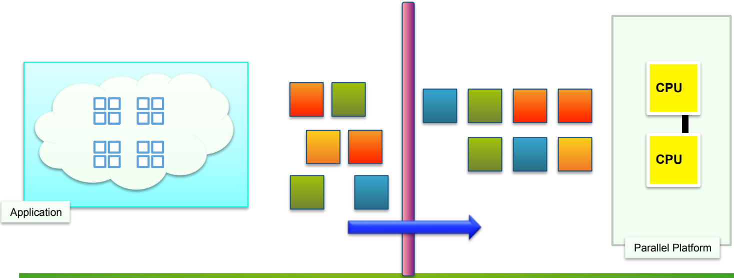

Tasks: Resources Miss-subscription?

The runtime system may initialize a pool of worker threads according to the hardware capabilities

The application submit tasks independently to the runtime, independently of the hardware capabilities

- Tasks submitted by the application according to its natural algorithm
  - Abstraction with respect to hardware
- Workers allocated according to hardware resource, topology
  - Typically one thread per core or per hardware thread
- Operating system scheduler interference largely eliminated
  - No competition between worker threads

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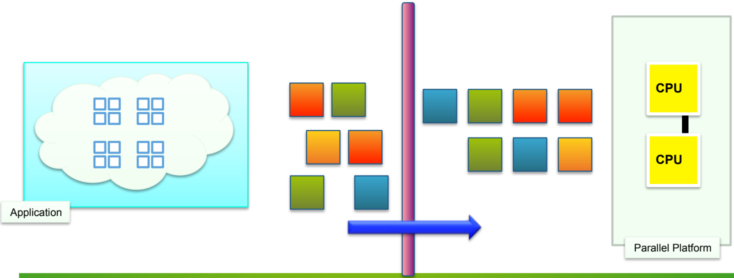

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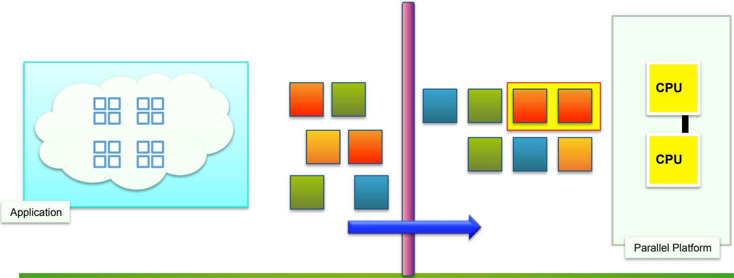

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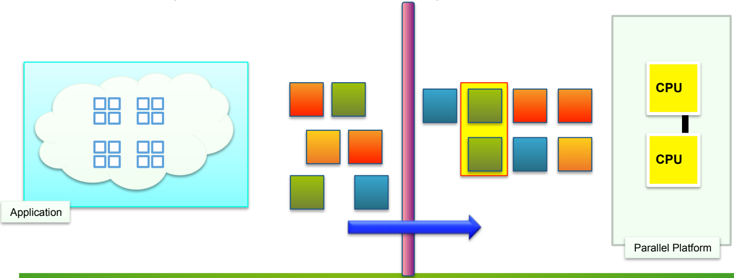

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  - Decide which pairs of tasks to execute in parallel
- No lock directly manipulated by the application

Tasks: Load Balancing Issues?

Tasks may transparently fill arising idle times as long as sufficient parallelism is available

The runtime system reacts to the situation observed at any time during the execution

- Flexibility
  - No need for all tasks to have a uniform duration
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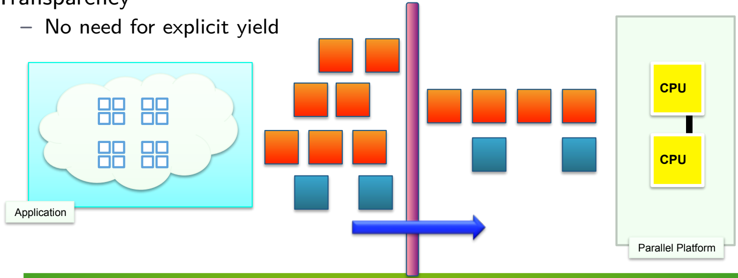

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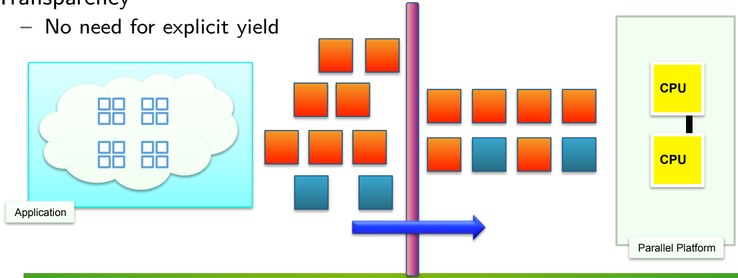

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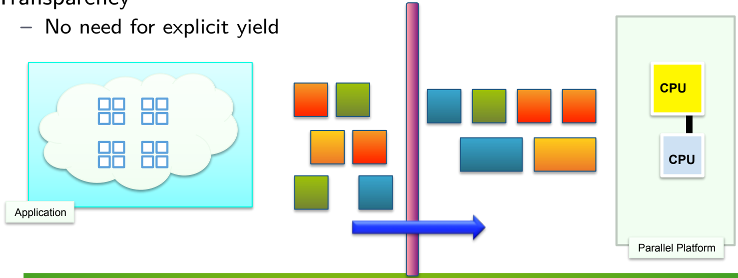

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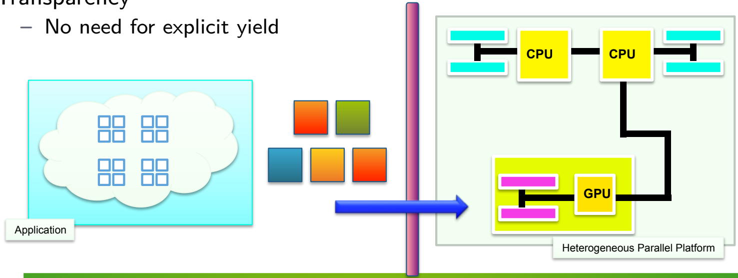

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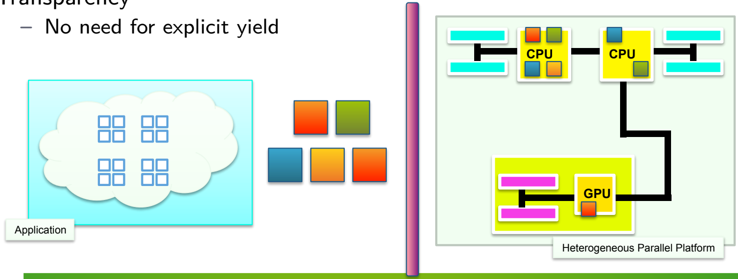


Tasks: Networking and I/O Issues?

Potential 1-to-1 relationship between tasks and network/IO requests

- Network/IO request may start as soon as the task producing the data has been completed

- Tasks may be triggered as the result of network/IO requests completion

- Significant difference with fork-join models, MPI+X
  - Transparent interoperability
  - Avoid deferred network/IO requests until next join
  - Avoid custom network/IO requests management inside the application code

Tasks: Outcome

Task = Characterizable work

- **Well-defined**
  - Workload
  - Completion
  - Dependencies
  - **Similar to the pure function concept from Functional programming domain**
- **Suitable object for modelling**
  - Constraints
  - Degrees of freedom
  - **Large corpus of task scheduling theory**
- **Enforcing separation of concerns**
  - Application specialist
  - Kernel(s) specialist
  - Scheduling theoretician specialist
  - Runtime-system specialist

Programming Modern Platforms using Tasks

See second part: Programming Modern Platforms with the StarPU Task-Based Runtime System

Rich set of existing task-based programming models and associated runtime systems

- DuctTeip
- Legion
- OCR
- OpenMP 4.x
- OmpSs
- ParalleX
- PaRSEC
- Swan
- Uintah/Kokkos
- XKaapi
- ...

2

The StarPU Task-Based Runtime System

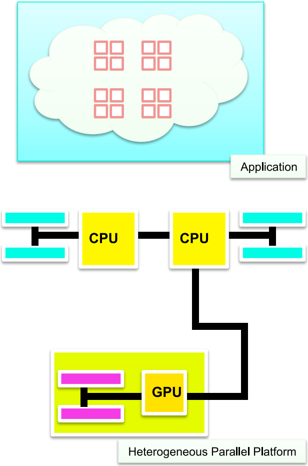
Heterogeneous Parallel Platforms

Heterogeneous Association

- General purpose processor
- Specialized accelerator

Generalization

- Distributed cores, discrete accelerators
  - Standalone GPUs
  - Intel Xeon Phi (KNC)
- Integrated cores
  - Intel Skylake / Kaby Lake
  - Intel Xeon Phi (KNL)
  - AMD Fusion
  - nVidia Tegra, ARM big.LITTLE
- Combination of various units
  - Latency-optimized cores
  - Throughput-optimized cores
  - Energy-optimized cores



Task Scheduling

Task

- Elementary computation
  - Some kernel
- → Potential parallel work
- Constraints
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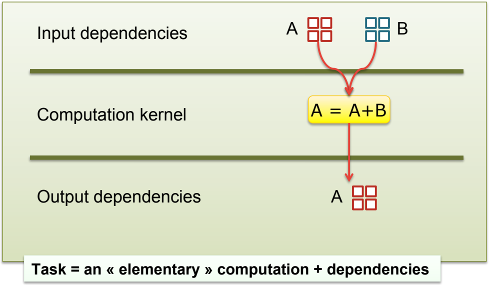

- → Degrees of Freedom in realizing the potential parallelism

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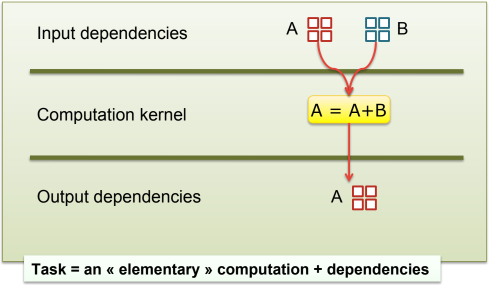

Expressing tasks?

- Divide and conquer: Cilk (recursive tasks)
- Dependencies compiler: PaRSEC (parameterized task graph)
- **Sequential task flow**: StarPU (directed acyclic task graph)

StarPU Programming Model: Sequential Task Flow

- Express parallelism…
- … using the natural program flow

- **Submit** tasks in the sequential flow of the program…
- … then let the runtime schedule the tasks asynchronously

Sequential Task Flow Graph Building

Example: Cholesky Decomposition

```
for (j = 0; j < N; j++) {
  POTRF (   A[j][j]);
  for (i = j+1; i < N; i++)
    TRSM (   A[i][j],   A[j][j]);
  for (i = j+1; i < N; i++) {
    SYRK (   A[i][i],   A[i][j]);
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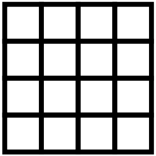

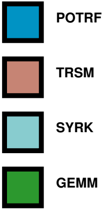

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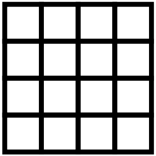

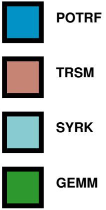

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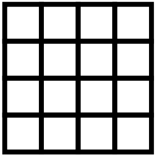

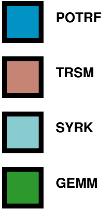

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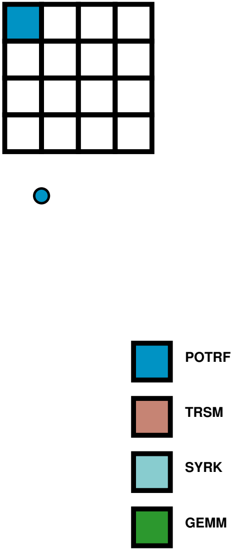

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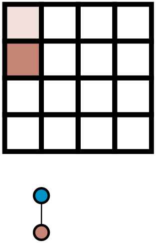

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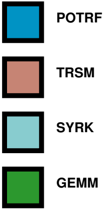

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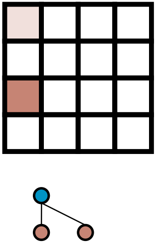

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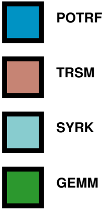

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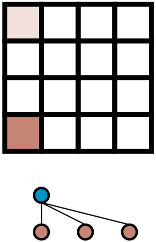

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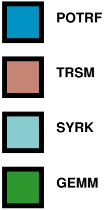

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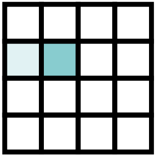

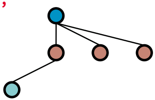

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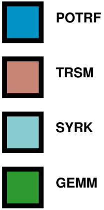

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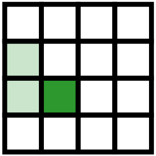

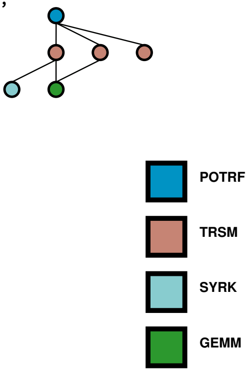

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Sequential Task Flow Graph Building

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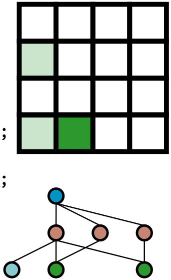

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```
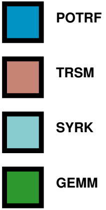

- Tasks are submitted asynchronously
- StarPU infers data dependences...
- ... and build a graph of tasks



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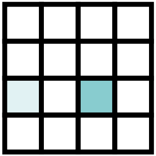

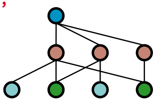

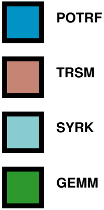

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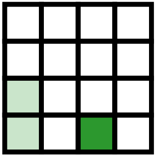

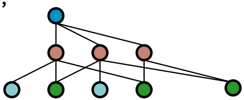

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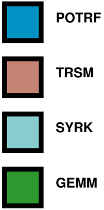

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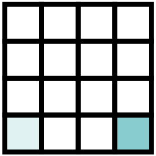

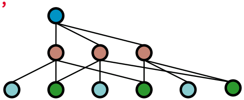

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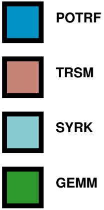

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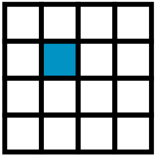

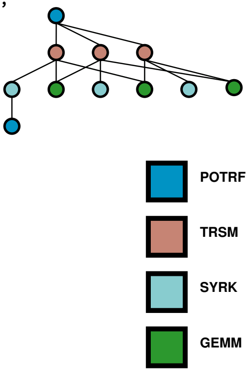

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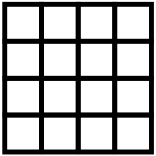
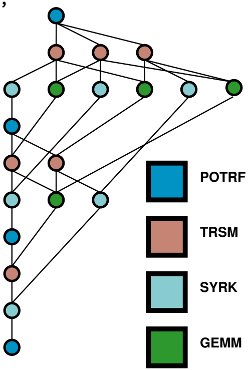




- Tasks are submitted asynchronously
- StarPU infers data dependences...
- ... and build a graph of tasks
- The graph of tasks is executed

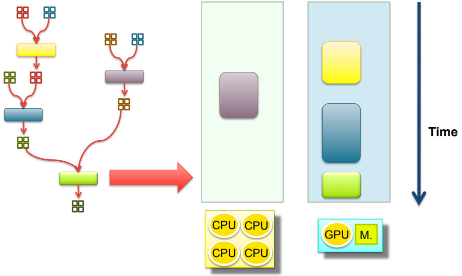
StarPU Execution Model: Task Scheduling

Mapping the graph of tasks (DAG) on the hardware

- Allocating computing resources
- Enforcing dependency constraints
- Handling data transfers

Adaptiveness

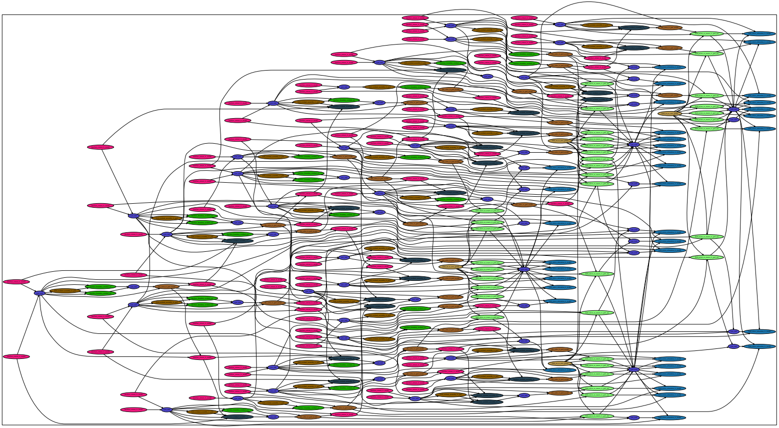
- A single DAG enables multiple schedulings
- A single DAG can be mapped on multiple platforms



Example: SCHNAPS, Implicit kinetic schemes

SCHNAPS Solver (Inria TONUS)

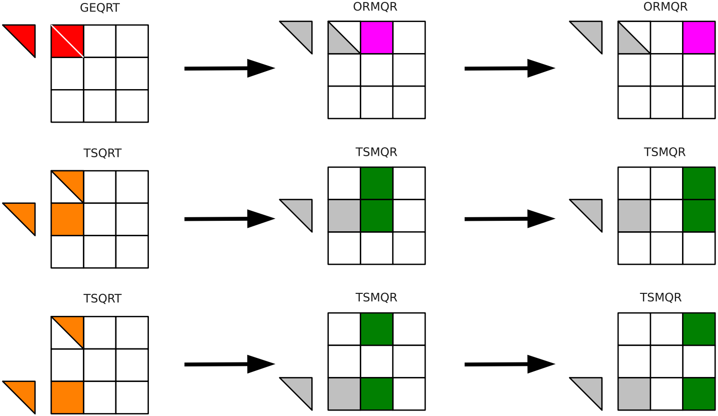
- Example of a task graph submitted to StarPU



Heterogeneous Showcase with Chameleon + StarPU

UTK, Inria HIEPACS, Inria RUNTIME

- QR decomp. on 16 CPUs (AMD) + 4 GPUs (C1060) using MAGMA GPU kernels



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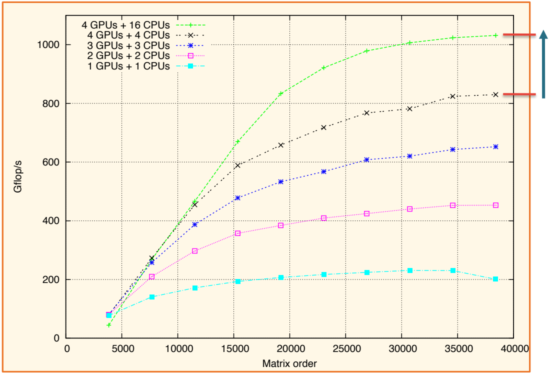

Measured increase:
+12 CPUs
~200 GFlops

Expected increase:
+12 CPUs
~150 Gflops

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Heterogeneous Showcase with Chameleon + StarPU

QR kernel properties

Kernel SGEQRT						
CPU:	9 GFlop/s	GPU:	30 GFlop/s	Speed-up:	3
Kernel STSQRT						
CPU:	12 GFlop/s	GPU:	37 GFlop/s	Speed-up:	3
Kernel SOMQRT						
CPU:	8.5 GFlop/s	GPU:	227 GFlop/s	Speed-up:	27
Kernel SSSMQ						
CPU:	10 GFlop/s	GPU:	285 GFlop/s	Speed-up:	28

Consequences

- Task distribution
  - SGEQRT: 20% Tasks on GPU
  - SSSMQ: 92% tasks on GPU
- Taking advantage of heterogeneity!
  - Only do what you are good for
  - Don't do what you are not good for

3

Programming with StarPU

Terminology

- Codelet
- Task
- Data handle

Definition: A Codelet

A **Codelet**. . .

- . . . relates an abstract computation kernel to its implementation(s)
- . . . can be instantiated into one or more **tasks**
- . . . defines characteristics common to a set of **task**s

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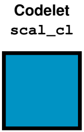

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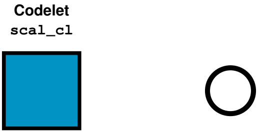

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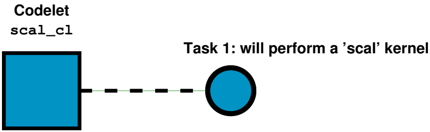

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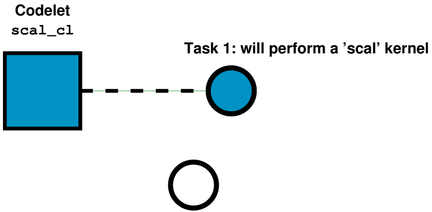

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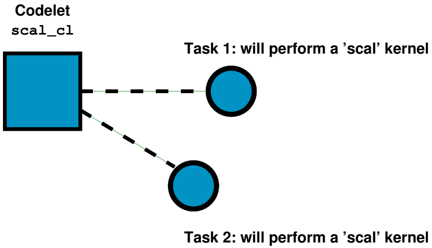

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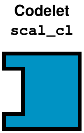

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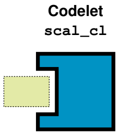

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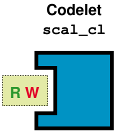

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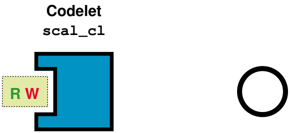

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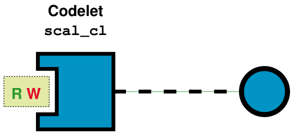

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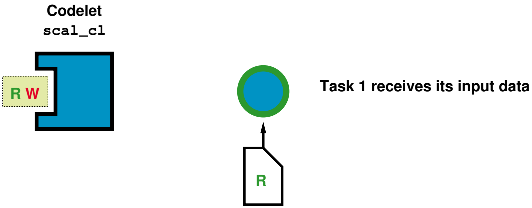

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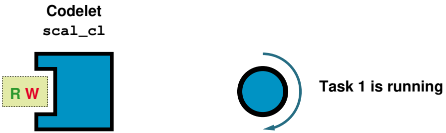

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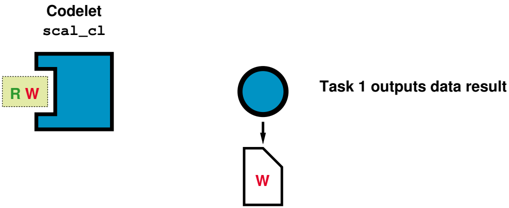

Definition: A Data Handle

A **Data Handle**. . .

- . . . designates a piece of data managed by StarPU
- . . . is typed (vector, matrix, etc.)
- . . . can be passed as input/output for a **Task**

Elementary API

- Declaring a codelet
- Declaring and Managing Data
- Writing a Kernel Function
- Submitting a task
- Waiting for submitted tasks

Declaring a Codelet

Define a **struct** starpu_codelet

```
struct starpu_codelet scal_cl = {
    ...
};
```

Declaring a Codelet

Define a **struct** **starpu_codelet**

- Plug the kernel function
  - Here: scal_cpu_func

```
struct starpu_codelet scal_cl = {
    .cpu_func  = { scal_cpu_func, NULL },
    ...
};
```

Declaring a Codelet

Define a **struct starpu_codelet**

- Plug the kernel function
  - Here: scal_cpu_func
- Declare the number of data pieces used by the kernel
  - Here: A single vector

```
struct starpu_codelet scal_cl = {
    .cpu_func  = { scal_cpu_func, NULL },
    .nbuffers = 1,
    ...
};
```

Declaring a Codelet

Define a **struct** **starpu_codelet**

- Plug the kernel function
  - Here: scal_cpu_func
- Declare the number of data pieces used by the kernel
  - Here: A single vector
- Declare how the kernel accesses the piece of data
  - Here: The vector is scaled in-place, thus R/W

```
struct starpu_codelet scal_cl = {
    .cpu_func  = { scal_cpu_func, NULL },
    .nbuffers = 1,
    .modes = { STARPU_RW },
};
```

Declaring and Managing Data

Put data under StarPU control

Declaring and Managing Data

Put data under StarPU control

- Initialize a piece of data

```
float vector[NX];
/* ... fill data ... */
```

Declaring and Managing Data

Put data under StarPU control

- Initialize a piece of data
- Register the piece of data and get a handle
  - The vector is now under StarPU control

```
float vector[NX];
/* ... fill data ... */

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

Declaring and Managing Data

Put data under StarPU control

- Initialize a piece of data
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  - The vector is now under StarPU control
- Use data through the handle

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/* ... use the vector through the handle ... */
```

Declaring and Managing Data

Put data under StarPU control

- Initialize a piece of data
- Register the piece of data and get a handle
  - The vector is now under StarPU control
- Use data through the handle
- Unregister the piece of data
  - The handle is destroyed
  - The vector is now back under user control

```
float vector[NX];
/* ... fill data ... */

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

/* ... use the vector through the handle ... */

starpu_data_unregister(vector_handle);
```

Writing a Kernel Function

- Every kernel function has the same C prototype

```
void scal_cpu_func(void *buffers[], void *cl_arg) {
    ...
}
```

Writing a Kernel Function

- Every kernel function has the same C prototype
- Retrieve the vector's handle

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

    ...
}
```

Writing a Kernel Function

- Every kernel function has the same C prototype
- Retrieve the vector's handle
- Get vector's number of elements and base pointer

```
void scal_cpu_func(void *buffers[], void *cl_arg) {
    struct starpu_vector_interface *vector_handle = buffers
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    unsigned n     = STARPU_VECTOR_GET_NX(vector_handle);
    float *vector = STARPU_VECTOR_GET_PTR(vector_handle);

    ...
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Writing a Kernel Function

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    float *ptr_factor = cl_arg;

    ...
}
```

Writing a Kernel Function

- Every kernel function has the same C prototype
- Retrieve the vector's handle
- Get vector's number of elements and base pointer
- Get the scaling factor as inline argument
- Compute the vector scaling

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

    unsigned n      = STARPU_VECTOR_GET_NX(vector_handle);
    float *vector = STARPU_VECTOR_GET_PTR(vector_handle);

    float *ptr_factor = cl_arg;

    unsigned i;
    for (i = 0; i < n; i++)
        vector[i] *= *ptr_factor;
}
```

Submitting a task

The **starpu_task_insert** call

- **Inserts** a task in the StarPU DAG

Submitting a task

The **starpu_task_insert** call

- **Inserts** a task in the StarPU DAG

Arguments

- The codelet structure

```
starpu_task_insert(&scal_cl
                   ...);
```

Submitting a task

The **starpu_task_insert** call

- **Inserts** a task in the StarPU DAG

Arguments

- The codelet structure
- The StarPU-managed data

```
starpu_task_insert(&scal_cl,
                   STARPU_RW, vector_handle,
                   ...);
```

Submitting a task

The **starpu_task_insert** call

- **Inserts** a task in the StarPU DAG

Arguments

- The codelet structure
- The StarPU-managed data
- The small-size inline data

```
starpu_task_insert(&scal_cl,
                   STARPU_RW, vector_handle,
                   STARPU_VALUE, &factor, sizeof(factor),
                   ...);
```

Submitting a task

The **starpu_task_insert** call

- **Inserts** a task in the StarPU DAG

Arguments

- The codelet structure
- The StarPU-managed data
- The small-size inline data
- 0 to mark the end of arguments

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

Submitting a task

The **starpu_task_insert** call

- **Inserts** a task in the StarPU DAG

Arguments

- The codelet structure
- The StarPU-managed data
- The small-size inline data
- 0 to mark the end of arguments

Notes

- The task is submitted non-blockingly

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- Dependencies are enforced with previously submitted tasks' data...

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- The codelet structure
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- The small-size inline data
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- ... following the natural order of the program

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- The codelet structure
- The StarPU-managed data
- The small-size inline data
- 0 to mark the end of arguments

Notes

- The task is submitted non-blockingly
- Dependencies are enforced with previously submitted tasks' data. . .
- . . . following the natural order of the program
- This is the **Sequential Task Flow Paradigm**

Waiting for Submitted Task Completion

- Tasks are submitted non-blockingly

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```
/* non-blocking task submits */
starpu_task_insert(...);
...
```

Waiting for Submitted Task Completion

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- Wait for all submitted tasks to complete their work

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/* non-blocking task submits */
starpu_task_insert(...);
...
```

Waiting for Submitted Task Completion

- Tasks are submitted non-blockingly
- Wait for all submitted tasks to complete their work

```
/* non-blocking task submits */
starpu_task_insert(...);
...

/* wait for all task submitted so far */
starpu_task_wait_for_all();
```

Basic Example: Scaling a Vector (main prog.)

```
float factor = 3.14;
float vector[NX];
```

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```
float factor = 3.14;
float vector[NX];
starpu_data_handle_t vector_handle;
```

Basic Example: Scaling a Vector (main prog.)

```
float factor = 3.14;
float vector[NX];
starpu_data_handle_t vector_handle;

/* ... fill vector ... */

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

Basic Example: Scaling a Vector (main prog.)

```
float factor = 3.14;
float vector[NX];
starpu_data_handle_t vector_handle;

/* ... fill vector ... */

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

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

Basic Example: Scaling a Vector (main prog.)

```c
float factor = 3.14;
float vector[NX];
starpu_data_handle_t vector_handle;

/* ... fill vector ... */

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

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

starpu_task_wait_for_all();
```

Basic Example: Scaling a Vector (main prog.)

```c
float factor = 3.14;
float vector[NX];
starpu_data_handle_t vector_handle;

/* ... fill vector ... */

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

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

starpu_task_wait_for_all();
starpu_data_unregister(vector_handle);

/* ... display vector ... */
```

Heterogeneity: Device Kernels

Extending a codelet to handle heterogeneous platforms

Heterogeneity: Device Kernels

Extending a codelet to handle heterogeneous platforms

- Multiple kernel implementations for a CPU
  - SSE, AVX, ... optimized kernels

```
struct starpu_codelet scal_cl = {
    .cpu_func = { scal_cpu_func,
            scal_sse_cpu_func, scal_avx_cpu_func, NULL },
    .nbuffers = 1,
    .modes = { STARPU_RW },
};
```

Heterogeneity: Device Kernels

Extending a codelet to handle heterogeneous platforms

- Multiple kernel implementations for a CPU
  - SSE, AVX, ... optimized kernels
- Kernels implementations for accelerator devices
  - OpenCL, NVidia Cuda kernels

```
struct starpu_codelet scal_cl = {
    .cpu_func  = { scal_cpu_func,
                   scal_sse_cpu_func, scal_avx_cpu_func, NULL },
    .opencl_func  = { scal_cpu_opencl, NULL },
    .cuda_func  = { scal_cpu_cuda, NULL },
    .nbuffers = 1,
    .modes = { STARPU_RW },
};
```

Writing a Kernel Function for CUDA

Writing a Kernel Function for CUDA

```
extern "C" void scal_cuda_func(void *buffers[], void *cl_arg)
{
    struct starpu_vector_interface *vector_handle = buffers[0];
    unsigned n    = STARPU_VECTOR_GET_NX(vector_handle);
    float *vector = STARPU_VECTOR_GET_PTR(vector_handle);
    float *ptr_factor = cl_arg;

    ...




}
```

Writing a Kernel Function for CUDA

```
extern "C" void scal_cuda_func(void *buffers[], void *cl_arg)
    {
    struct starpu_vector_interface *vector_handle = buffers
        [0];
    unsigned n     = STARPU_VECTOR_GET_NX(vector_handle);
    float *vector = STARPU_VECTOR_GET_PTR(vector_handle);
    float *ptr_factor = cl_arg;

    unsigned threads_per_block = 64;
    unsigned nblocks = (n+threads_per_block-1)/
        threads_per_block;

    ...

}
```

Writing a Kernel Function for CUDA

```
extern "C" void scal_cuda_func(void *buffers[], void *cl_arg)
    {
    struct starpu_vector_interface *vector_handle = buffers
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    unsigned n    = STARPU_VECTOR_GET_NX(vector_handle);
    float *vector = STARPU_VECTOR_GET_PTR(vector_handle);
    float *ptr_factor = cl_arg;

    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()>>>(n,vector,*
            ptr_factor);
}
```

Writing a Kernel Function for CUDA

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

    ...
}

extern "C" void scal_cuda_func(void *buffers[], void *cl_arg)
    {
    struct starpu_vector_interface *vector_handle = buffers
        [0];
    unsigned n     = STARPU_VECTOR_GET_NX(vector_handle);
    float *vector = STARPU_VECTOR_GET_PTR(vector_handle);
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}
```

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

extern "C" void scal_cuda_func(void *buffers[], void *cl_arg)
    {
    struct starpu_vector_interface *vector_handle = buffers
        [0];
    unsigned n     = STARPU_VECTOR_GET_NX(vector_handle);
    float *vector = STARPU_VECTOR_GET_PTR(vector_handle);
    float *ptr_factor = cl_arg;

    unsigned threads_per_block = 64;
    unsigned nblocks = (n+threads_per_block-1)/
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    vector_mult_cuda<<<nblocks,threads_per_block,0,
        starpu_cuda_get_local_stream()>>>(n,vector,*
            ptr_factor);
}
```
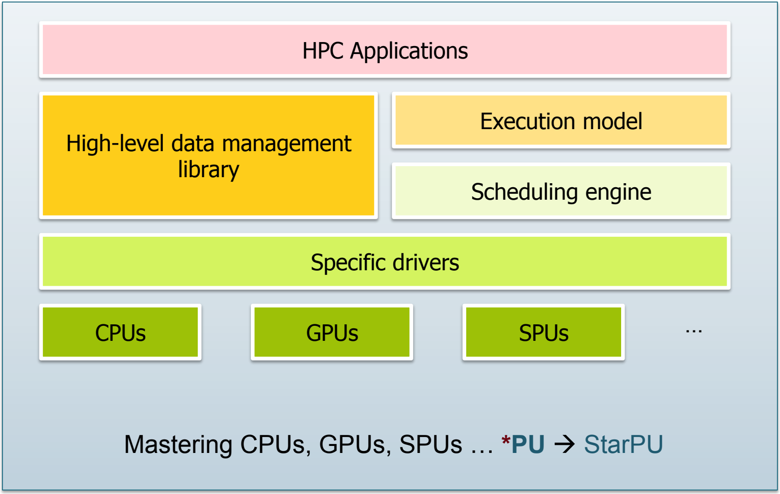
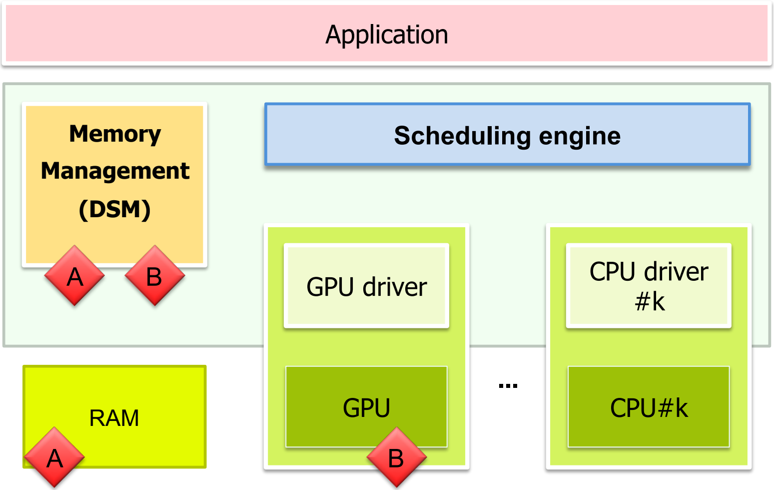

4

StarPU Internals

StarPU Internal Structure

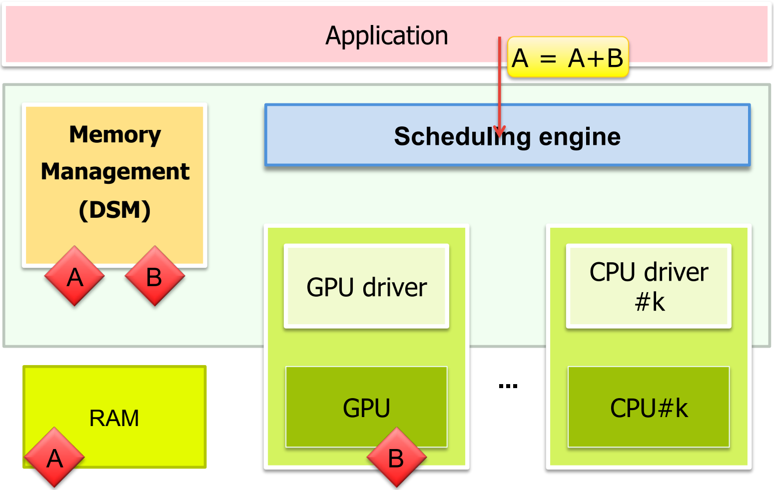


StarPU Internal Functioning



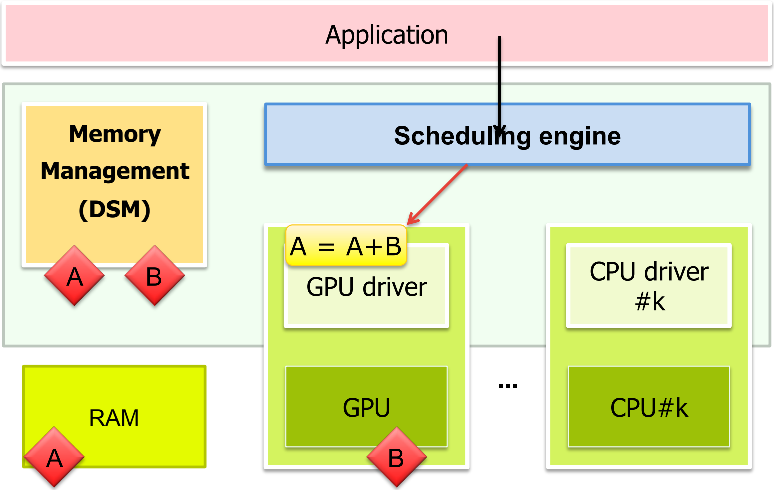
Submit task « A+=B »

StarPU Internal Functioning



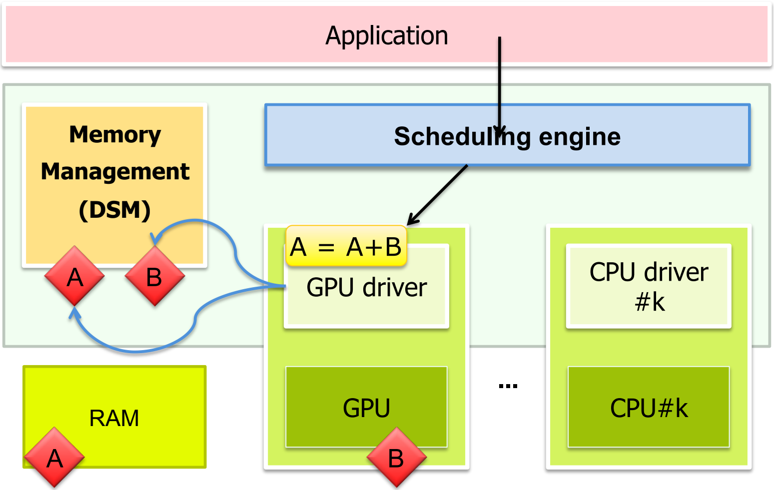
Submit task « A+=B »

StarPU Internal Functioning



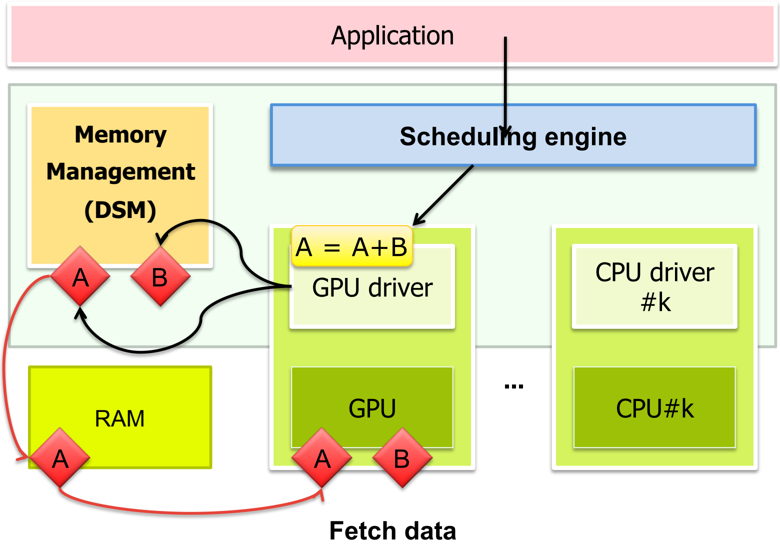
Schedule task

StarPU Internal Functioning

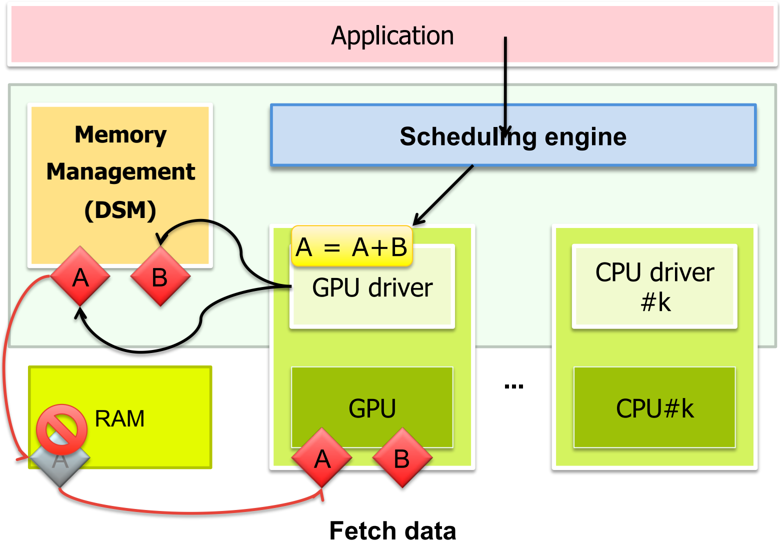


Fetch data

StarPU Internal Functioning



StarPU Internal Functioning



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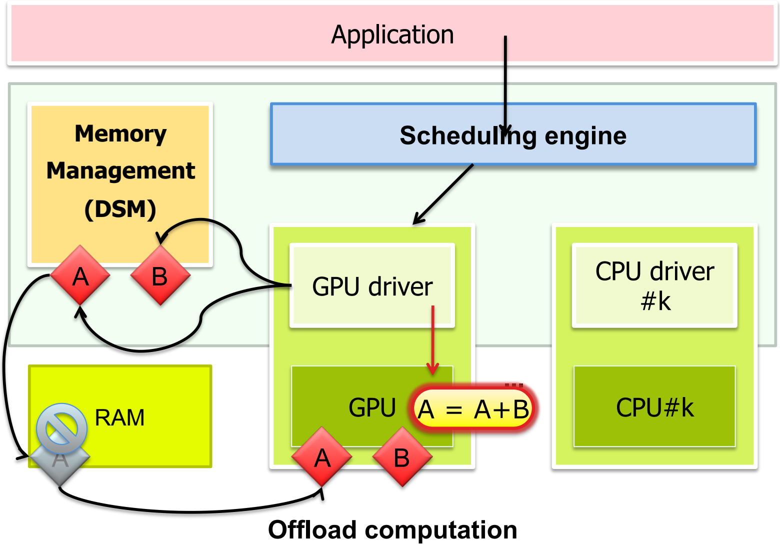
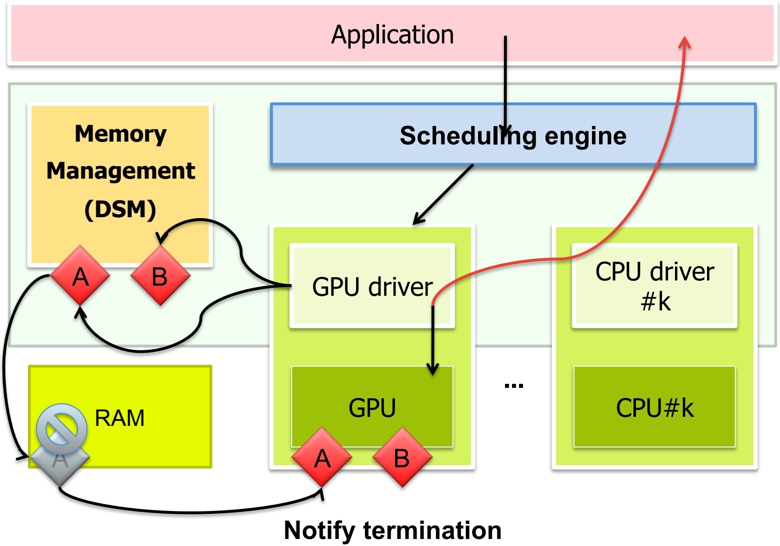


StarPU Internal Functioning



5

Scheduling Policies

StarPU Scheduling Policies

- No *one size fits all* policy
- Selectable scheduling policy
  - Predefined set of popular policies: eager, work-stealing, etc.

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Going beyond?

StarPU Scheduling Policies

- No *one size fits all* policy
- Selectable scheduling policy
  - Predefined set of popular policies: eager, work-stealing, etc.

Going beyond?

Scheduling is a decision process:

- Providing more input to the scheduler...
- ... can lead to better scheduling decisions

What kind of information?

- Relative importance of tasks
  - Priorities
- Cost of tasks
  - Codelet models
- Cost of transferring data
  - Bus calibration

Selecting a Scheduling Policy

- Use the STARPU_SCHED environment variable

Selecting a Scheduling Policy

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- Example 1: selecting the prio scheduler

```
$ export STARPU_SCHED=prio
$ my_program
...
```

Selecting a Scheduling Policy

- Use the STARPU_SCHED environment variable
- Example 1: selecting the prio scheduler
- Example 2: selecting the dm scheduler

```
$ export STARPU_SCHED=prio
$ my_program
...
```

```
$ export STARPU_SCHED=dm
$ my_program
...
```

Selecting a Scheduling Policy

- Use the STARPU_SCHED environment variable
- Example 1: selecting the prio scheduler
- Example 2: selecting the dm scheduler
- Example 3: resetting to default scheduler eager

```
$ export STARPU_SCHED=prio
$ my_program
...
```

```
$ export STARPU_SCHED=dm
$ my_program
...
```

```
$ unset STARPU_SCHED
$ my_program
...
```

Selecting a Scheduling Policy

- Use the STARPU_SCHED environment variable
- Example 1: selecting the prio scheduler
- Example 2: selecting the dm scheduler
- Example 3: resetting to default scheduler eager
- No need to recompile the application

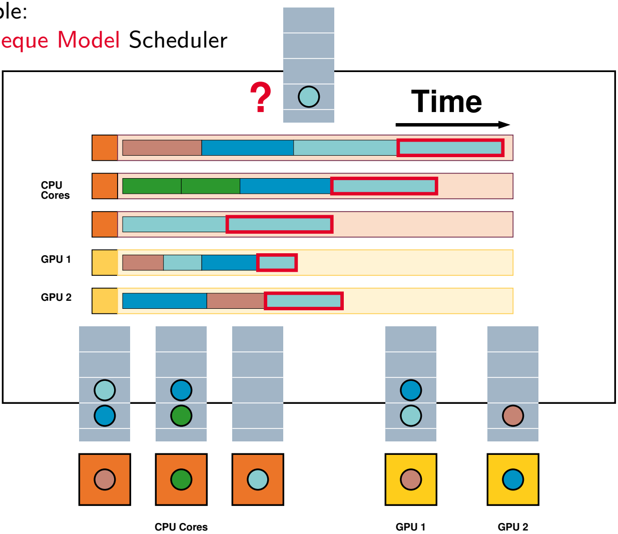
```
$ export STARPU_SCHED=prio
$ my_program
...
```

```
$ export STARPU_SCHED=dm
$ my_program
...
```

```
$ unset STARPU_SCHED
$ my_program
...
```

Task Mapping using a Performance Model

- Example:
  The Deque Model Scheduler



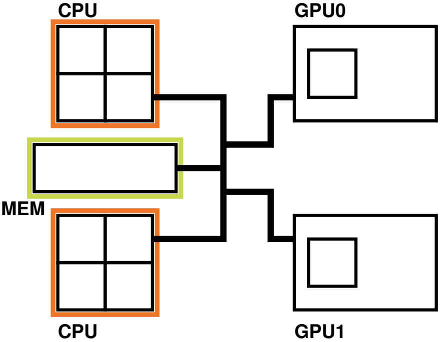
Task Mapping using a Performance Model

- Using codelet performance models
  - Kernel calibration on each available computing device
  - **Raw** history model of kernels' past execution times
  - **Refined** models using regression on kernels' execution times history
- Model parameter(s)
  - **Data size**
  - **User-defined** parameters

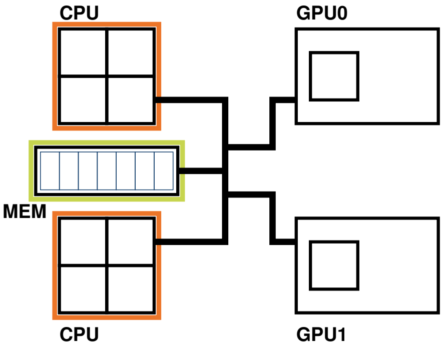
6

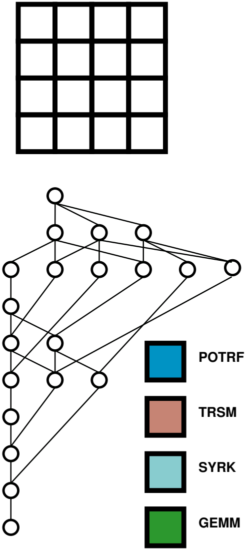
Data Management

StarPU Heterogeneous Execution Model / Data Management

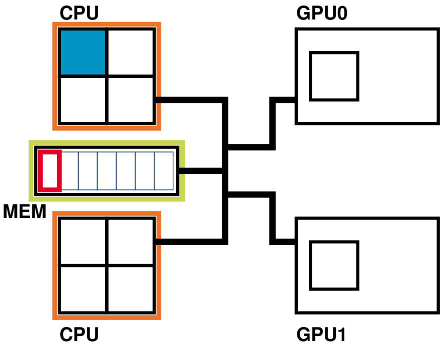


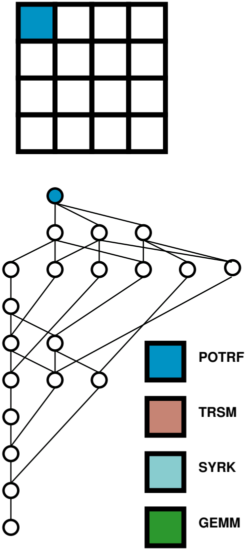
StarPU Heterogeneous Execution Model / Data Management



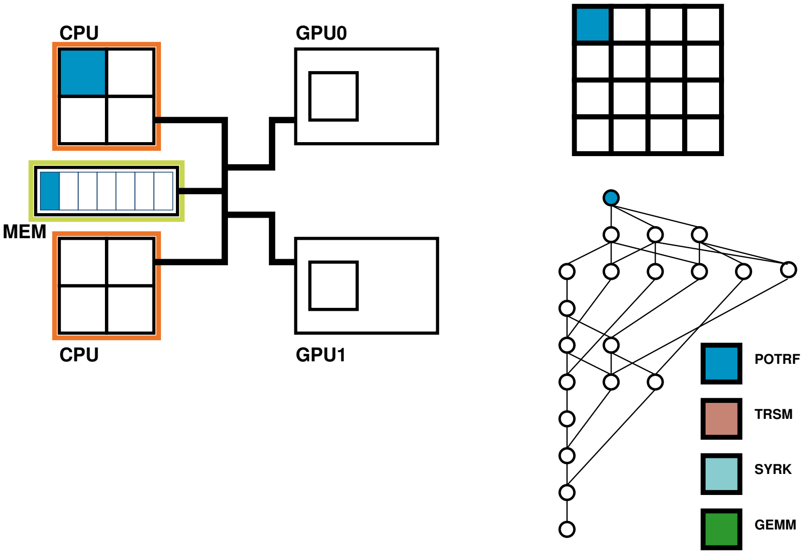


StarPU Heterogeneous Execution Model / Data Management

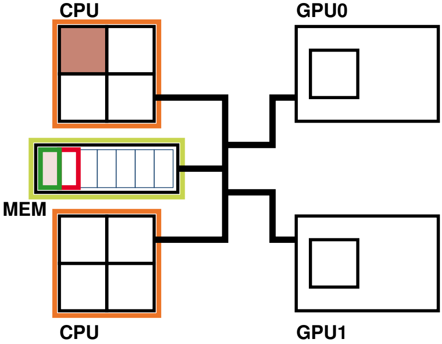


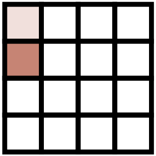


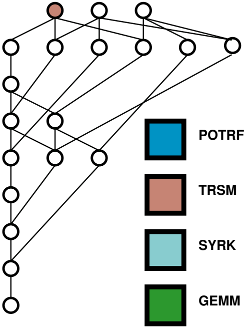
StarPU Heterogeneous Execution Model / Data Management



StarPU Heterogeneous Execution Model / Data Management

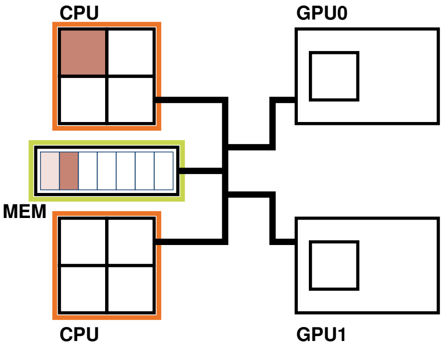


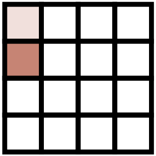


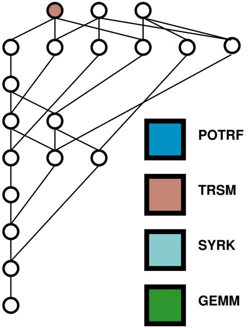


- Handles dependencies

StarPU Heterogeneous Execution Model / Data Management







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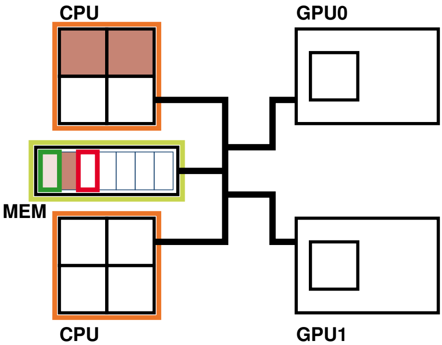
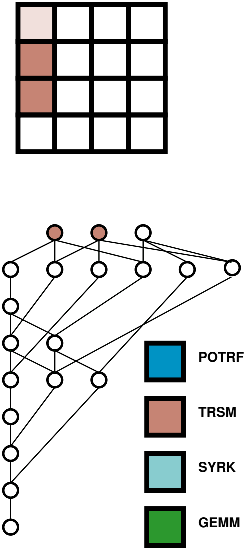
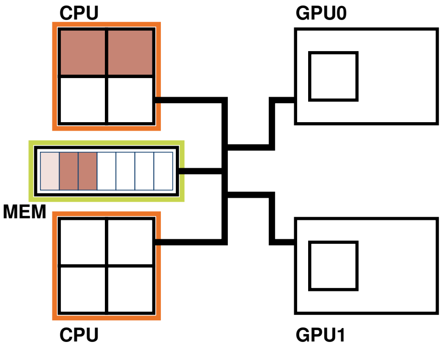
StarPU Heterogeneous Execution Model / Data Management

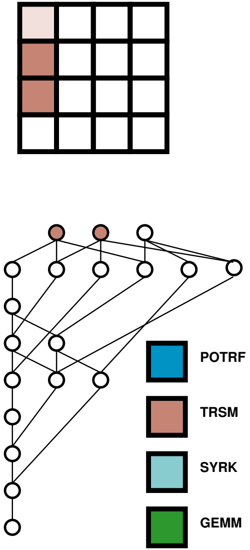




- Handles dependencies

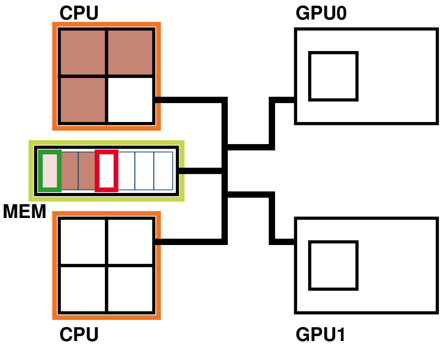
StarPU Heterogeneous Execution Model / Data Management

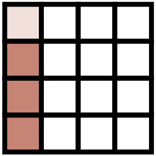


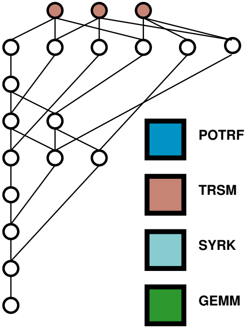


- Handles dependencies

StarPU Heterogeneous Execution Model / Data Management







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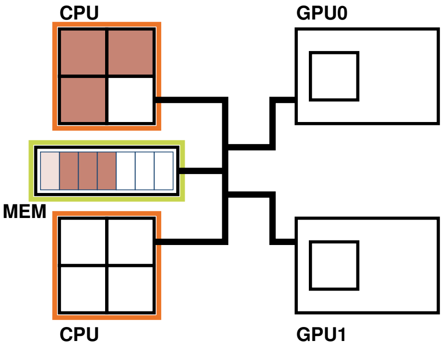
StarPU Heterogeneous Execution Model / Data Management



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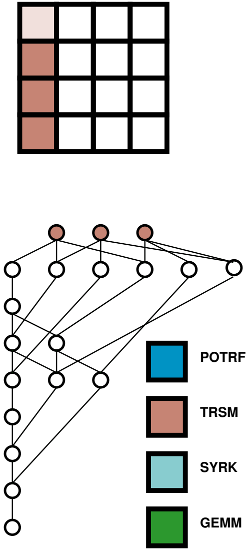
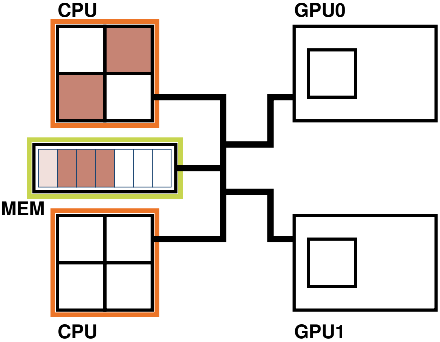
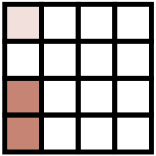
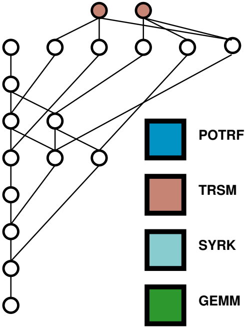


StarPU Heterogeneous Execution Model / Data Management







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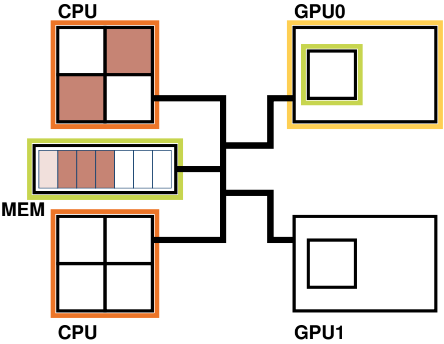
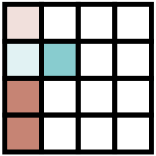
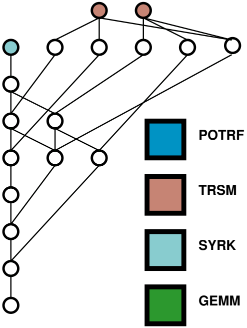
StarPU Heterogeneous Execution Model / Data Management

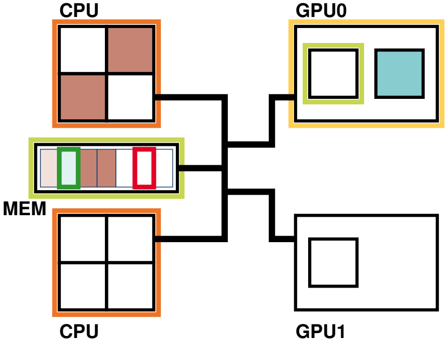


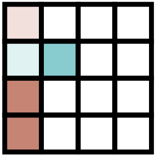


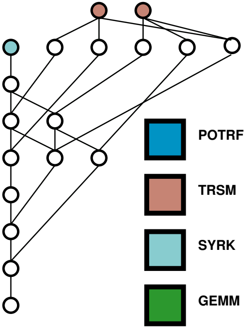


- Handles dependencies
- Handles scheduling (policy)

StarPU Heterogeneous Execution Model / Data Management







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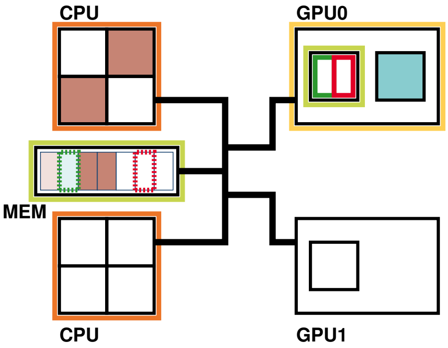

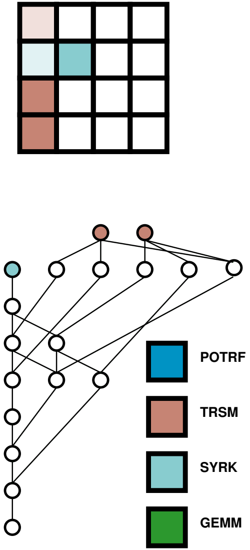

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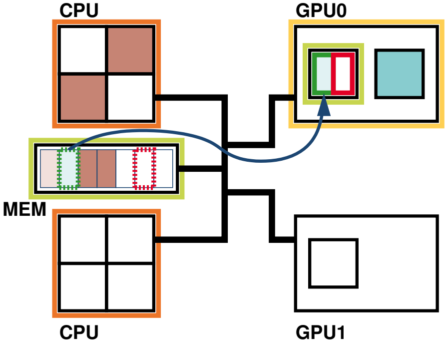

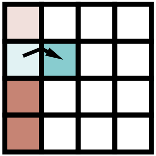

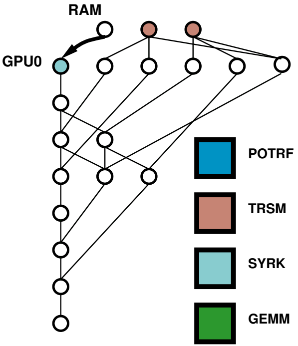

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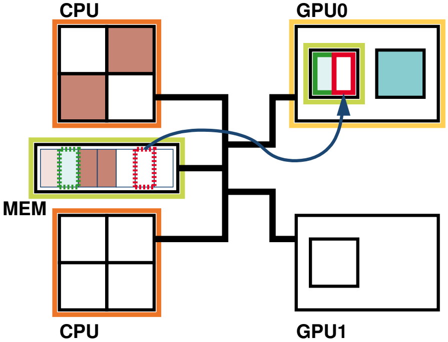

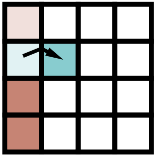

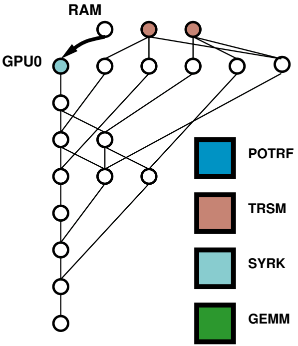

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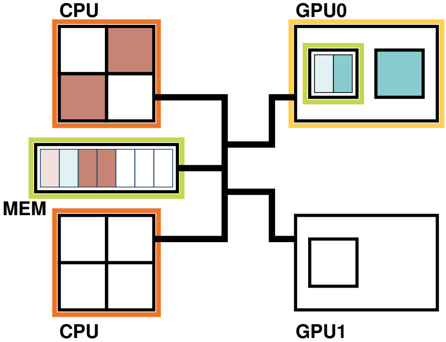

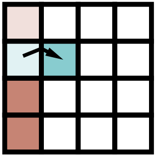

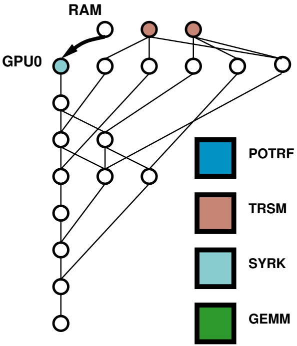

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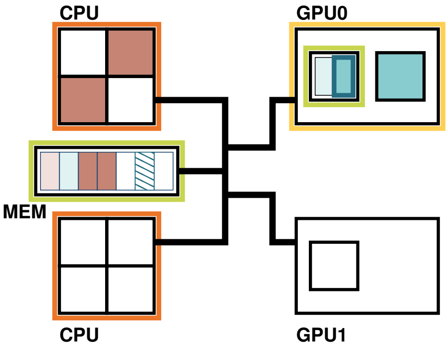
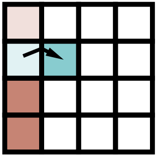
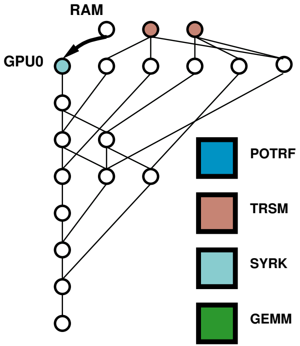
StarPU Heterogeneous Execution Model / Data Management







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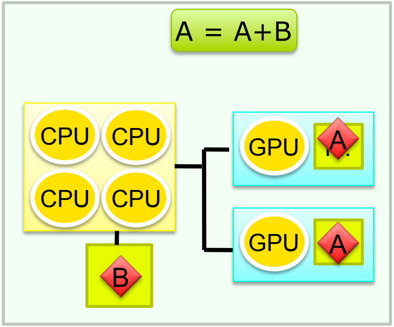
Distributed Shared Memory Consistency

MSI Protocol

- M: Modified
- S: Shared
- I: Invalid



Data A

I	S	S

Data B

M	I	I

Distributed Shared Memory Consistency

MSI Protocol

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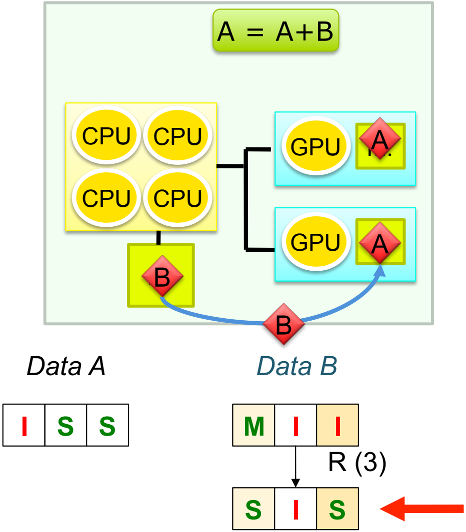

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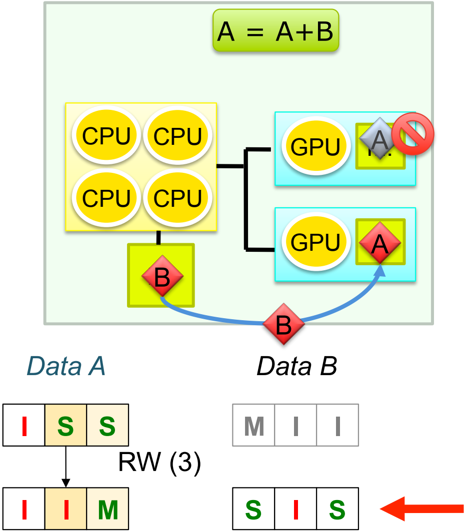

Data Transfer Cost Modelling for Improved Scheduling

Discrete accelerators

- CPU $\leftrightarrow$ GPU transfers
- Data transfer cost vs kernel offload benefit

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Transfer cost modelling

- Bus calibration
  - Can differ even for identical devices
  - Platform's topology

Data Transfer Cost Modelling for Improved Scheduling

Discrete accelerators

- CPU $\leftrightarrow$ GPU transfers
- Data transfer cost vs kernel offload benefit

Transfer cost modelling

- Bus calibration
  - Can differ even for identical devices
  - Platform's topology

Data-transfer aware scheduling

- Deque Model Data Aware (dmda) scheduling policy variants
- Tunable data transfer cost bias
  - locality
  - vs load balancing

Data Prefetching

Task states

- Submitted
  - Task inserted by the application
- Ready
  - Task's dependencies resolved
- Scheduled
  - Task queued on a computing unit
- Executing
  - Task running on a computing unit

Data Prefetching

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Anticipate on the **Scheduled** → **Executing** transition

- Prefetch triggered ASAP after **Scheduled** state

Data Prefetching

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  - Task running on a computing unit

Anticipate on the **Scheduled** → **Executing** transition

- Prefetch triggered ASAP after **Scheduled** state
- Prefetch may also be triggered by the application

Data Interfaces

Multiple data types supported

- Vector
- Matrix
- BCSR sparse matrix

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

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

Data Interfaces

Multiple data types supported

- Vector
- Matrix
- BCSR sparse matrix

```
float matrix[NX*NY];
starpu_data_handle_t handle;

starpu_matrix_data_register(&handle, 0, (uintptr_t)matrix,
                            NX, NX, NY, sizeof(matrix[0]));
```

Data Interfaces

Multiple data types supported

- Vector
- Matrix
- BCSR sparse matrix

```
...
starpu_data_handle_t handle;

starpu_bcsr_data_register(&handle, 0, NNZ, NROW,
            (uintptr_t)bcsr_matrix_data,
            bcsr_matrix_indices, bcsr_matrix_rowptr,
                first_entry,
            BLOCK_NROW, BLOCK_NCOL, sizeof(double));
```

Data Interfaces

Multiple data types supported

- Vector
- Matrix
- BCSR sparse matrix
- Extensible data type set
  - You can write your own, specifically tailored data type

Data Interfaces

Multiple data types supported

- Vector
- Matrix
- BCSR sparse matrix
- Extensible data type set
  - You can write your own, specifically tailored data type
- Only the byte size and the shape of data matter, not the actual element type (integer, float, double precision float, ...)

Partitioning

Splitting a piece of managed data into several handles

- Granularity adjustment
- Notion of **filter**

Partitioning

Splitting a piece of managed data into several handles

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Partition

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

/* Partition the vector in NB_PARTS sub-vectors */
struct starpu_data_filter filter = {
    .filter_func = starpu_vector_filter_block,
    .nchildren = NB_PARTS
};
starpu_data_partition(handle, &filter);

/* Data can only be accessed through sub-handles now */
```

Partitioning

Splitting a piece of managed data into several handles

- Granularity adjustment
- Notion of **filter**

Partition → Use

```
for (i=0; i<starpu_data_get_nb_children(handle); i++) {
    /* Get subdata number i */
    starpu_data_handle_t sub_handle =
        starpu_data_get_sub_data(handle, 1, i);

    starpu_task_insert(
        &scal_cl,
        STARPU_RW, sub_handle,
        STARPU_VALUE, &factor, sizeof(factor),
        0);
}
```

Partitioning

Splitting a piece of managed data into several handles

- Granularity adjustment
- Notion of **filter**

Partition → Use → Unpartition

```
/* Wait for submitted tasks to complete */
starpu_task_wait_for_all();

/* Unpartition data */
starpu_data_unpartition(handle, 0);

/* Data can now be accessed through 'handle' only */
```

Asynchronous Partitioning

Inserting a partitioning request in the submission flow

Two steps

Asynchronous Partitioning

Inserting a partitioning request in the submission flow

Two steps

- Partition planning

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

/* Partition the vector in NB_PARTS sub-vectors */
struct starpu_data_filter filter = {
    .filter_func = starpu_vector_filter_block,
    .nchildren = NB_PARTS
};
starpu_data_handle_t children[NB_PARTS];
starpu_data_partition_plan(handle, &filter, children);

/* Data can only be accessed through sub-handles now */
```

Asynchronous Partitioning

Inserting a partitioning request in the submission flow

Two steps

- Partition planning
- Asynchronous partition inforcement

```
starpu_task_insert(&scal_cl,
     STARPU_RW, handle,
     STARPU_VALUE, &factor1, sizeof(factor1), 0);
starpu_data_partition_submit(handle, NB_PARTS, children);
for (i=0; i<NB_PARTS; i++) {
    starpu_task_insert(&scal_cl,
         STARPU_RW, children[i],
         STARPU_VALUE, &factor2, sizeof(factor2),
         0);
}
starpu_data_unpartition_submit(handle, NB_PARTS, children,
    node);
starpu_task_insert(&scal_cl,
     STARPU_RW, handle,
     STARPU_VALUE, &factor3, sizeof(factor3), 0);
```

Reduction

Merge contributions from a set of tasks into a single buffer

- Define neutral element initializer
- Define reduction operator

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- Define reduction operator

Define zero

```
void bzero_cpu(void *descr[], void *cl_arg) {
    double *v_zero = (double *)STARPU_VARIABLE_GET_PTR(descr[0]);
    *v_zero = 0.0;
}

struct starpu_codelet bzero_cl = {
    .cpu_funcs = { bzero_cpu, NULL },
    .nbuffers = 1
};
```

Reduction

Merge contributions from a set of tasks into a single buffer

- Define neutral element initializer
- Define reduction operator

Define zero → Define op

```
void accumulate_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;
}

struct starpu_codelet accumulate_cl = {
    .cpu_funcs = { accumulate_cpu, NULL },
    .nbuffers = 1
};
```

Reduction

Merge contributions from a set of tasks into a single buffer

- Define neutral element initializer
- Define reduction operator

Define zero → Define op → Reduce task contributions

```
starpu_variable_data_register(&accum_handle, -1,
                               NULL, sizeof(type));
starpu_data_set_reduction_methods(accum_handle,
                                  &accumulate_cl, &bzero_cl);

for (b = 0; b < nblocks; b++)
    starpu_task_insert(&dot_kernel_cl,
        STARPU_REDUX, accum_handle,
        STARPU_R, starpu_data_get_sub_data(v1, 1, b),
        STARPU_R, starpu_data_get_sub_data(v2, 1, b),
        0);
```

Commutative Write Accesses

- Write accesses enforce sequential consistency by default
  - To strong for some kind of workloads
  - N-body, unstructured meshes

Commutative Write Accesses

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  - To strong for some kind of workloads
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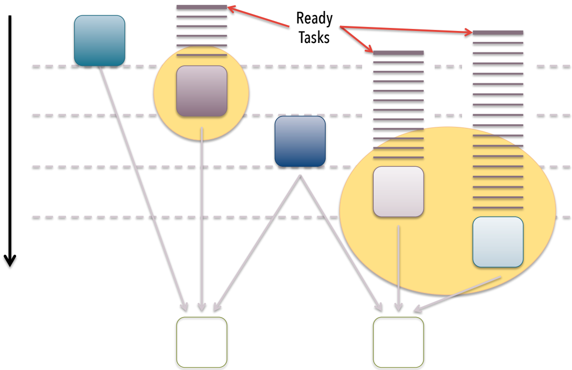


Commutative Write Accesses

- Write accesses enforce sequential consistency by default
  - To strong for some kind of workloads
  - N-body, unstructured meshes
- **Commute**: allows a set of tasks to modify a buffer in any order

```
starpu_task_insert(&cl1,
     STARPU_R, handle0,
     STARPU_RW, handle,
     0);
starpu_task_insert(&cl2,
     STARPU_R, handle1,
     STARPU_RW|STARPU_COMMUTE, handle,
     0);
starpu_task_insert(&cl2,
     STARPU_R, handle2,
     STARPU_RW|STARPU_COMMUTE, handle,
     0);
starpu_task_insert(&cl3,
     STARPU_R, handle3,
     STARPU_RW, handle,
     0);
```

7

Analysis and Monitoring

Feedback mechanisms

Online Tools

- Statistics
- Visual debugging

Offline Tools

- Trace-based analysis

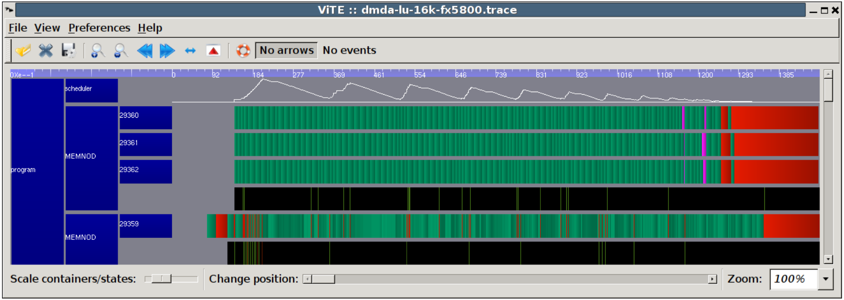
Offline Trace-Based Feedback

- FxT trace collection
- Trace analysis and display
  - ViTE Gantt
  - Graphviz DAG
  - R plots

Offline Feedback – Trace Analysis

Automatically generated

- Dependency graph (DAG)
- Activity diagramm (GANTT)
  – Visualize with ViTE



Offline Feedback – Kernel Model

Display the codelet performance models recorded by StarPU

- Command-line tool starpu_perfmodel_display
- History-based models
- Regression-based models

Offline Feedback – Kernel Model

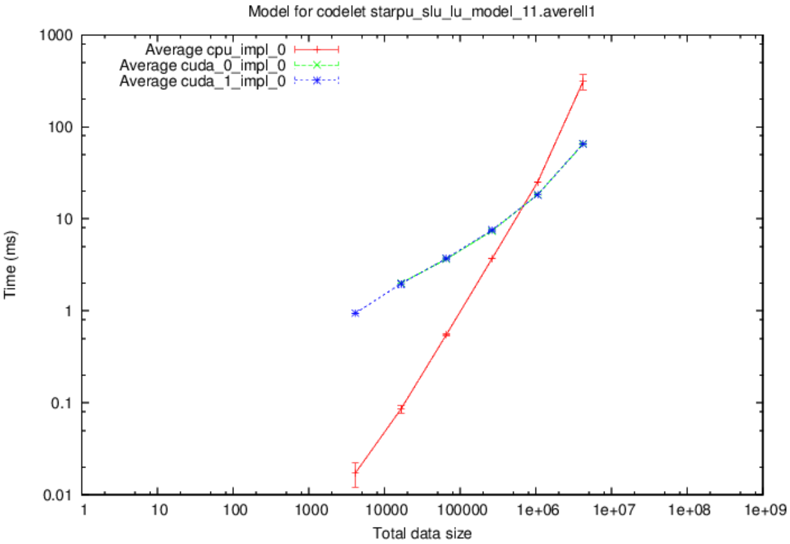
Display the codelet performance models recorded by StarPU

- Command-line tool starpu_perfmodel_display
- History-based models
- Regression-based models

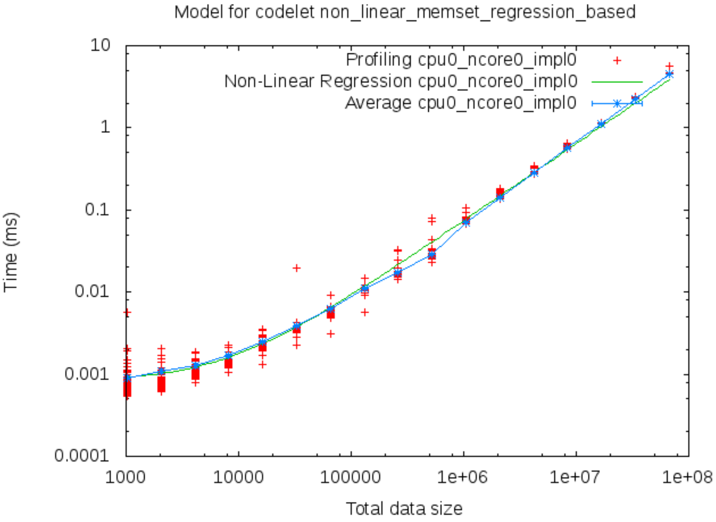
```
$ starpu_perfmodel_display -s starpu_slu_lu_model_11

performance model for cpu0_parallel1_impl0
# hash      size        mean (us)        stddev (us)     n
aa6d4ef7    4194304     3.055501e+05     5.804822e+04    48
```

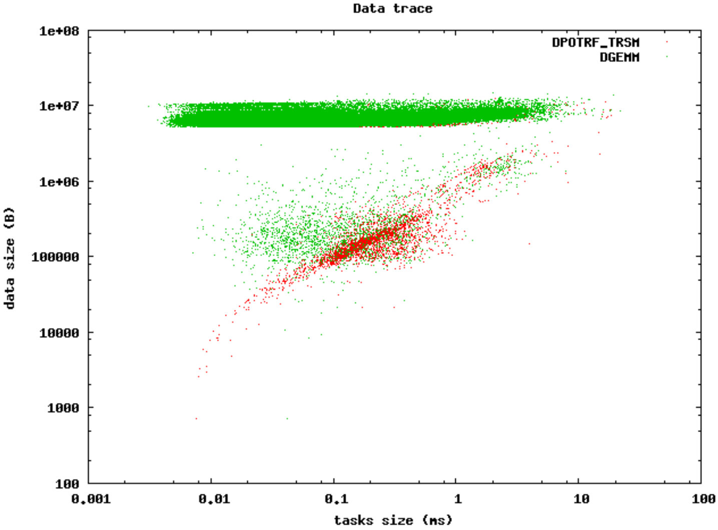
Offline Feedback – Kernel Model Characteristics



Offline Feedback – Kernel Model Regression Fitness



Offline Feedback – Synthetic Kernels' Behaviour



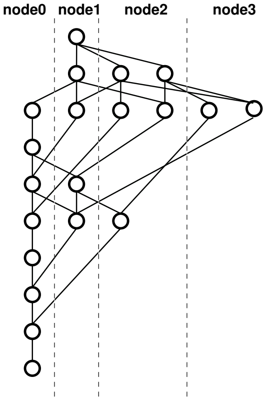
8

Distributed Computing

Distributed Support

Sequential Task Flow Paradigm on Clusters

Each node unrolls the sequential task flow



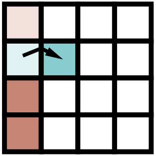
Data↔Node Mapping

- Provided by the application
- Can be altered dynamically

Distributed Support

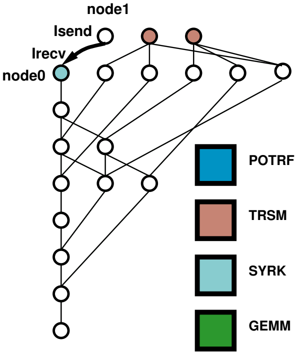
Sequential Task Flow Paradigm on Clusters

Each node unrolls the sequential task flow



Inter-node dependence management

- Inferred from the task graph edges
- Automatic **Isend** and **Irecv** calls



Distributed Support

Sequential Task Flow Paradigm on Clusters

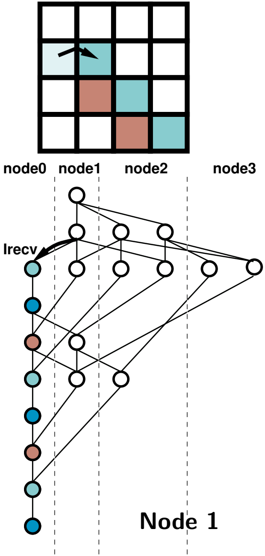
Each node unrolls the sequential task flow

Task↔Node Mapping

- Inferred from data location:
  - *Tasks move to data they modify*
- No global scheduling
- No synchronizations

Optimization

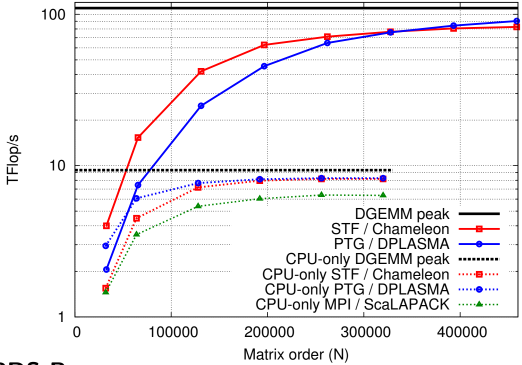
- Local DAG pruning



Distributed Scalability Study Results

Chameleon linear algebra library (Inria Team HiePACS)

- Heterogeneous cluster: 1152 CPU cores+288 GPUs



IEEE TPDS Paper:

DOI: 10.1109/TPDS.2017.2766064 — https://hal.inria.fr/hal-01618526

9

Interoperability and Composition

Composing Multiple Codes

Rationale

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- Sharing computing resources. . .

Composing Multiple Codes

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- Sharing computing resources...
- ... among multiple DAGs

Composing Multiple Codes

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- ... simultaneously

Composing Multiple Codes

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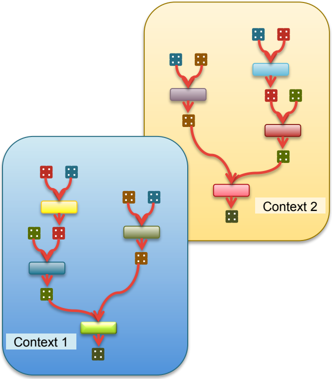
Scheduling Contexts



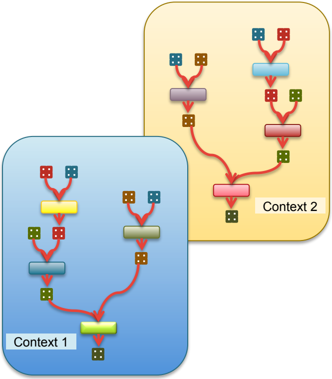
Composing Multiple Codes

Rationale

- Sharing computing resources. . .
- . . . among multiple DAGs
- . . . simultaneously

Scheduling Contexts

- Map DAGs on subsets of computing units



Composing Multiple Codes

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- Sharing computing resources. . .
- . . . among multiple DAGs
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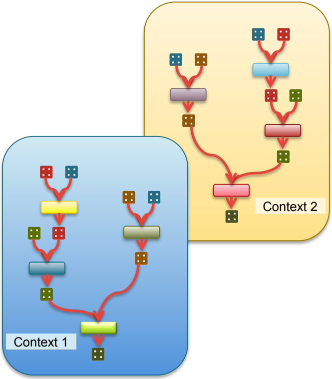
Scheduling Contexts

- Map DAGs on subsets of computing units
- Isolate competing kernels or library calls
  - OpenMP kernel, Intel MKL, etc.



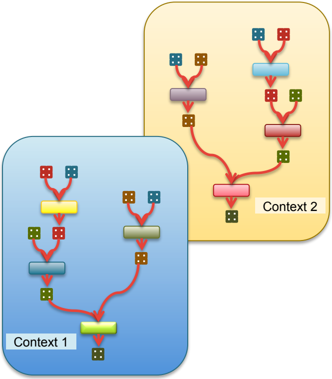
Composing Multiple Codes

Rationale

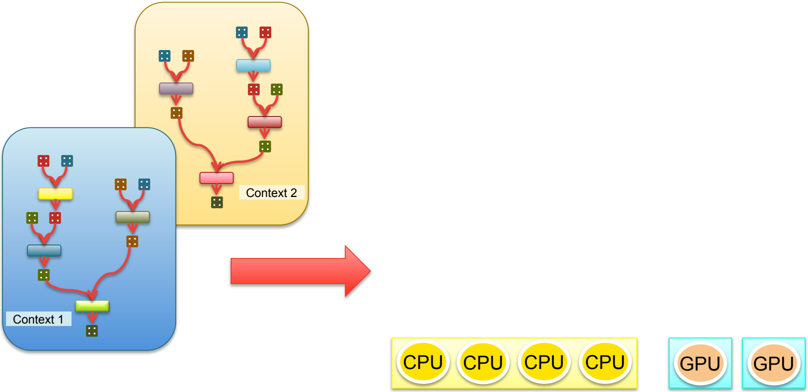
- Sharing computing resources. . .
- . . . among multiple DAGs
- . . . simultaneously

Scheduling Contexts

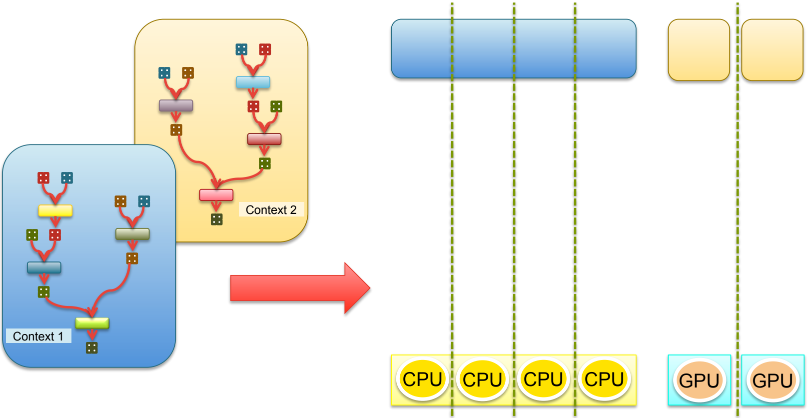
- Map DAGs on subsets of computing units
- Isolate competing kernels or library calls
  - OpenMP kernel, Intel MKL, etc.
- Select scheduling policy per context



Contexts: Dynamic Resource Management



Contexts: Dynamic Resource Management



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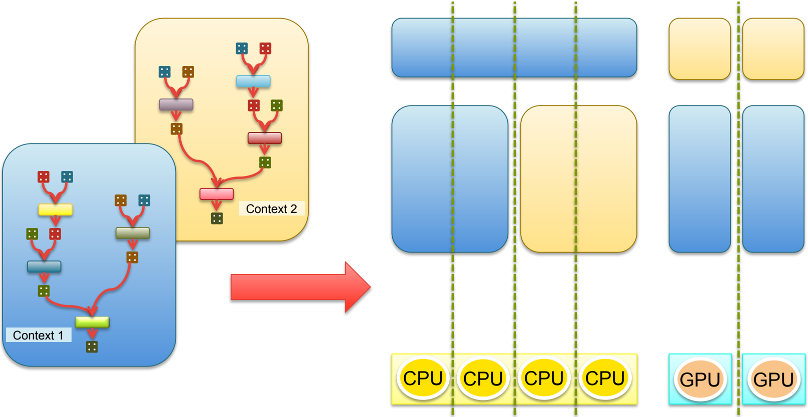

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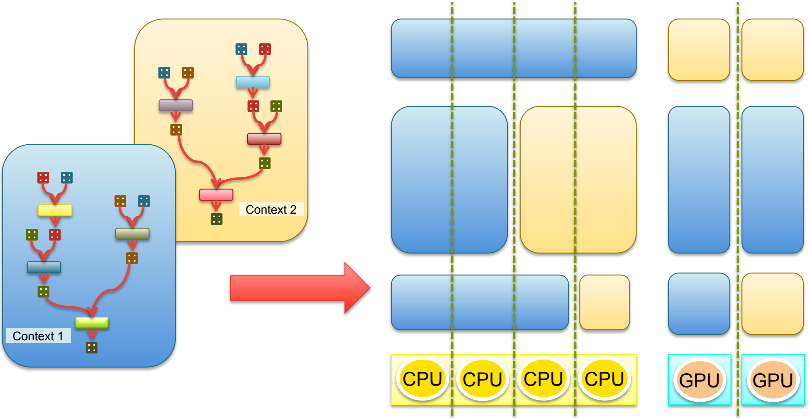

Interoperability

How to Make Runtimes, Libs Cooperate?

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- Project INTERTWinE (EU H2020, 3-years, 2015-2018)
  - Task-based runtimes: StarPU, OmpSs, PaRSEC, OpenMP
  - Networking APIs: MPI, GASPI
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  - Applications
- Cooperative resource allocation and management
  - Cores
  - Accelerators
  - Memory
  - Pinned memory segments
  - ...

www.intertwine-project.eu

Resource Management APIs

Olivier Aumage (Inria), Vicenç Beltran & Xavier Teruel (BSC)

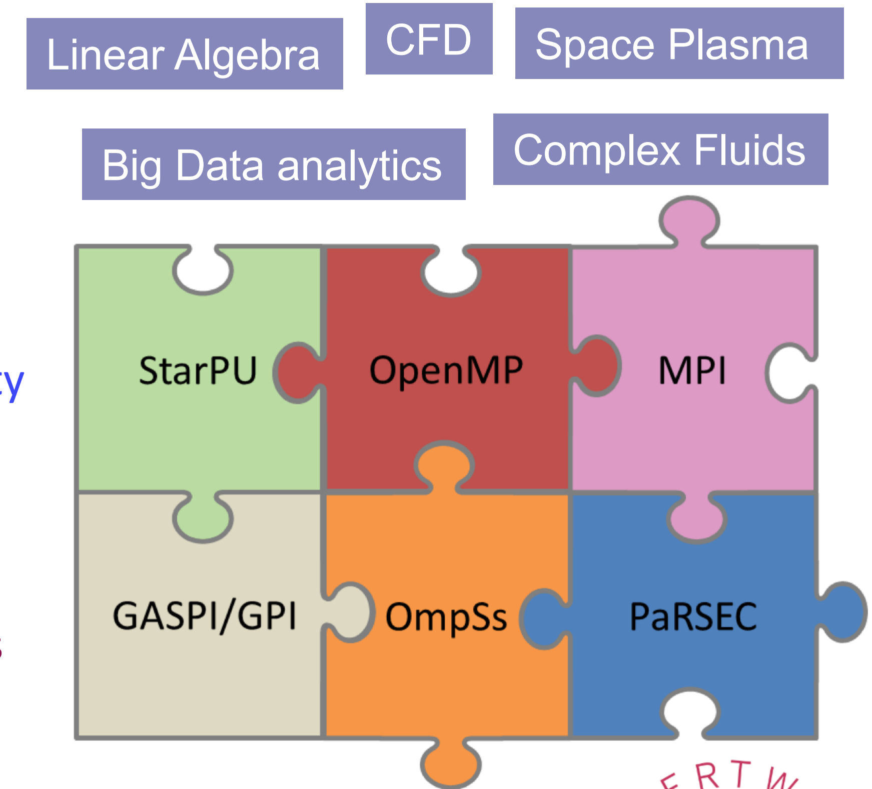
http://www.intertwine-project.eu

This project is funded from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement no. 671602.

INTERTWinE

Interoperability between programming models for scalable performance on extreme-scale supercomputers

- **Co-design methodology**
  - Define interoperability requirements, implement+evaluate, drive new requirements
  - Work with real applications
- **Computational Resource Management**
  - Coordinated resource sharing for interoperability between runtime systems, libraries
- **Distributed Data Management**
  - Scalable, transparent data sharing on heterogeneous, distributed memory hierarchies
- **Engagement with HPC community**
  - Standards bodies: OpenMP, MPI, GASPI
  - Courses, workshops and Best Practice Guides



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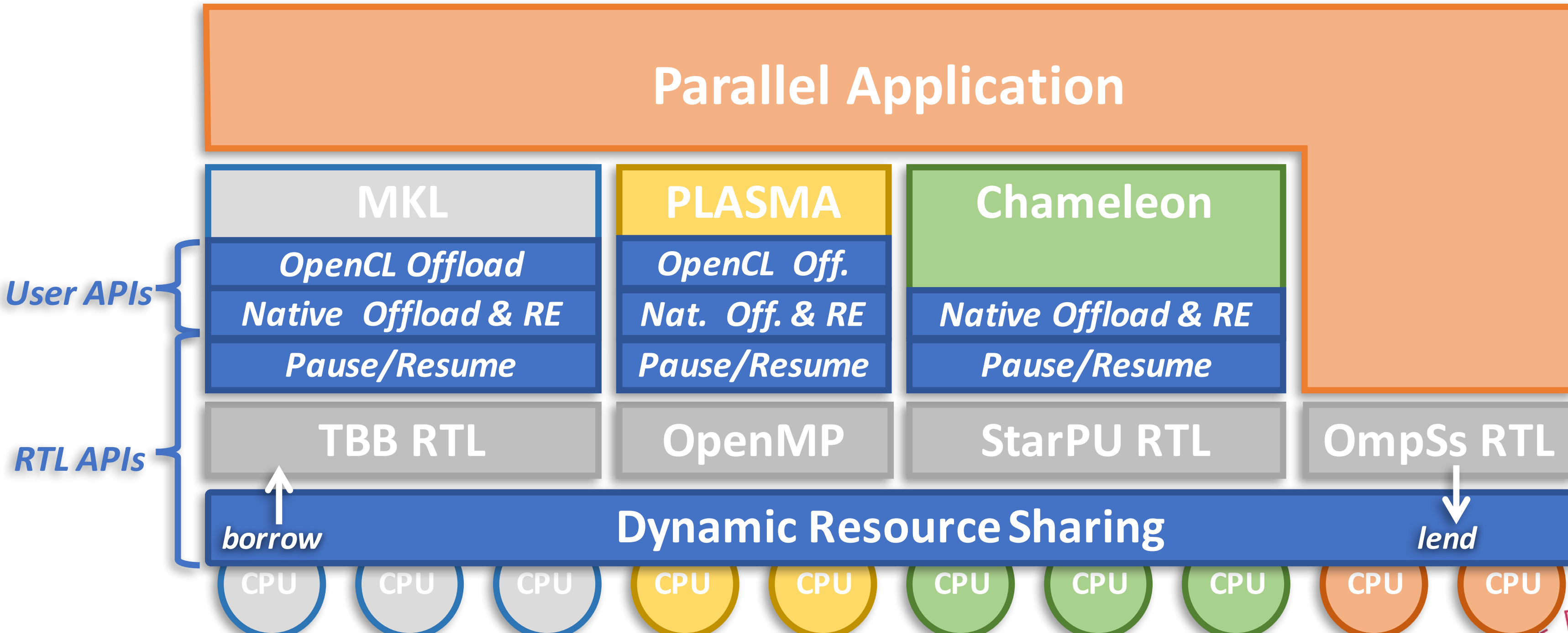
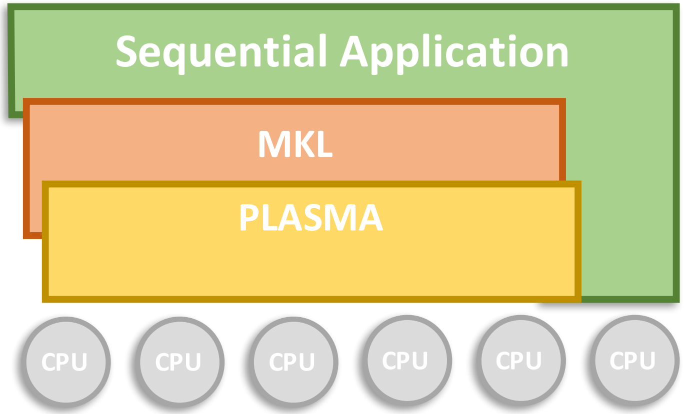
Computational Resource Management Objectives

- Implement a **Resource Management API** to share computing resources between parallel applications, libraries and runtime systems



Motivation
Sequential applications + parallel libraries

- Fork-join pattern



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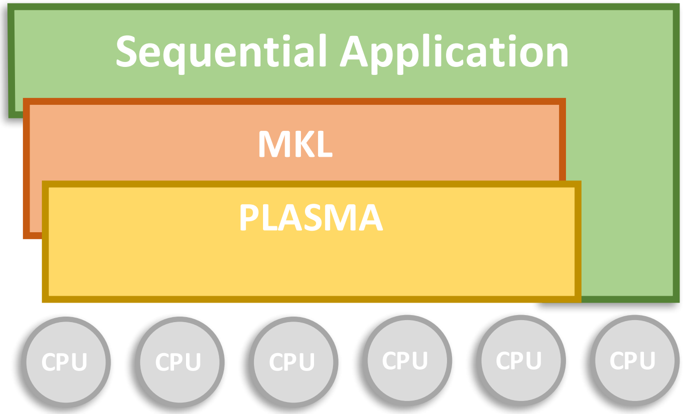
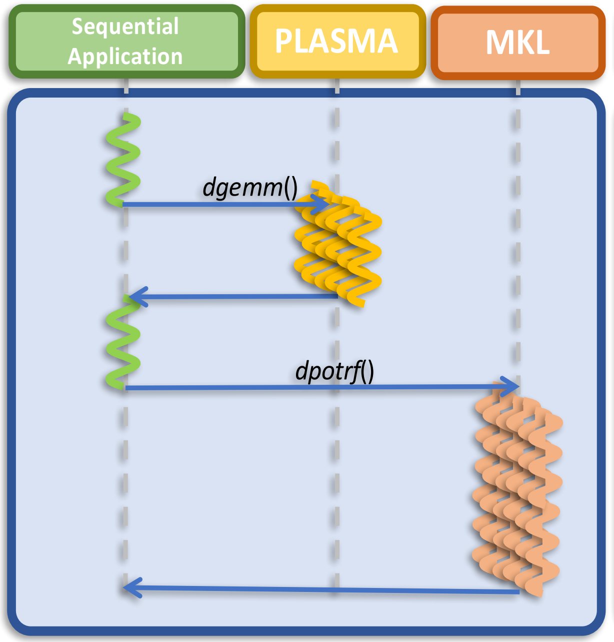
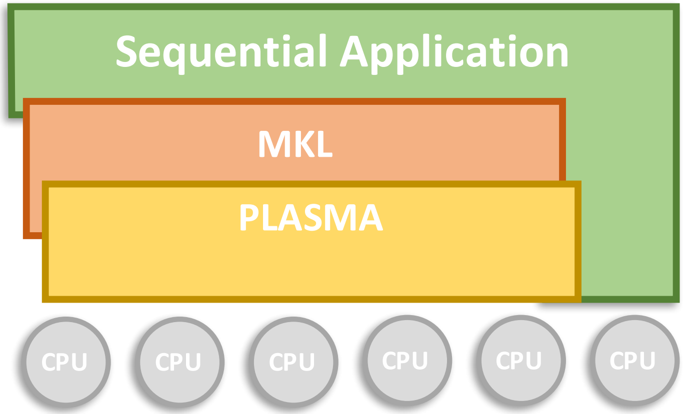
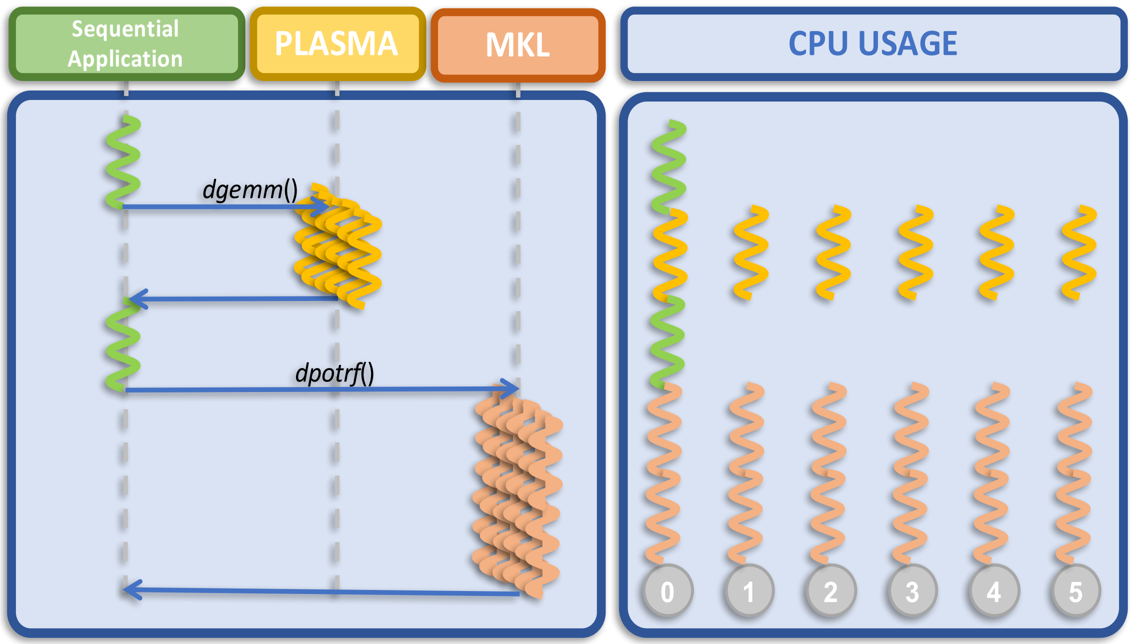




Motivation
Sequential applications + parallel libraries

- Fork-join pattern
- No over-subscription, but most **CPUs underutilized** on sequential parts





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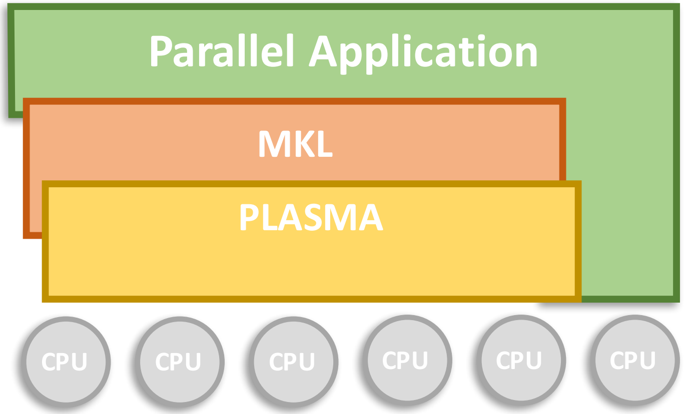
Parallel application + parallel libraries



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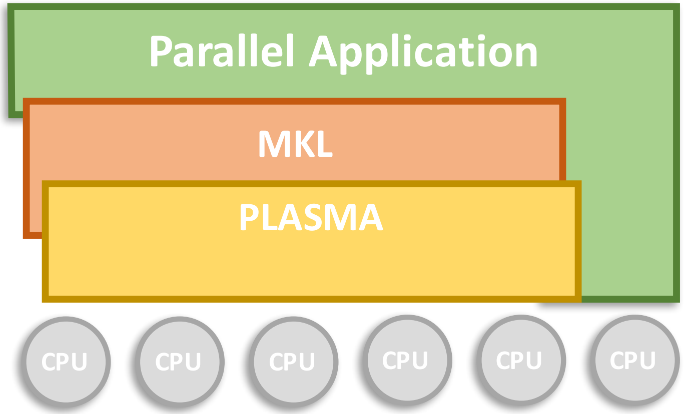
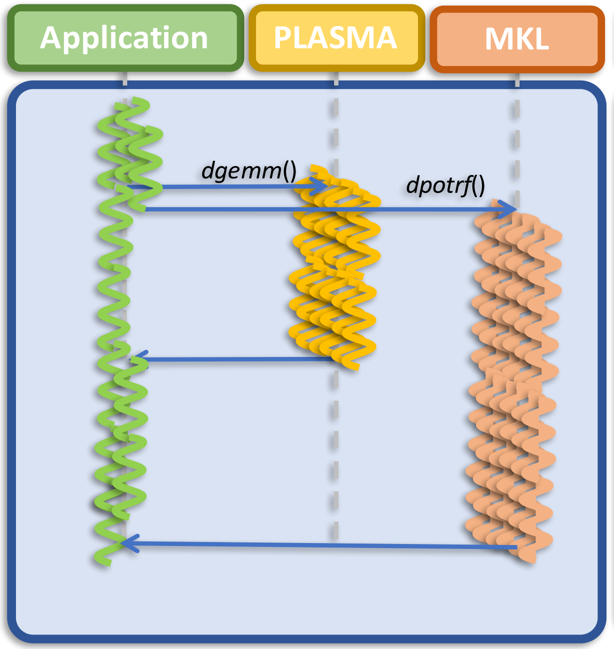
Parallel application + parallel libraries

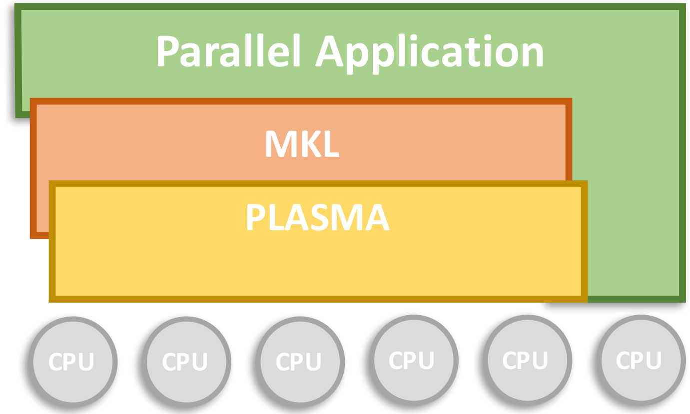
- **Uncoordinated access to CPU cores**

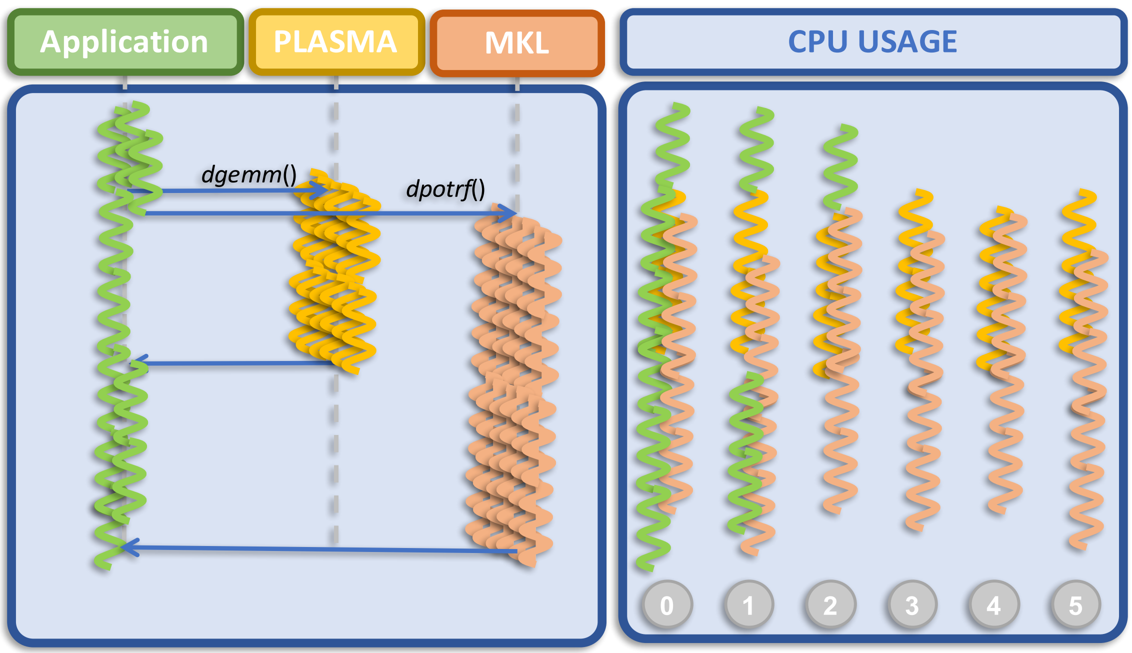




Motivation
Parallel application + parallel libraries

- Uncoordinated access to CPU cores
- **Oversubscription**
  - Cache pollution
  - Higher number of context switches





Interoperable node-level resource sharing

Computational Resource Sharing

- **Multiple codes compete for CPU cores, accelerator devices on cluster nodes**
  - Application threads
  - Numerical libraries threads
  - Runtime systems threads
  - Communication library threads

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  - Ability to express dynamic resource requirements:
    - computational-heavy periods, idleness periods

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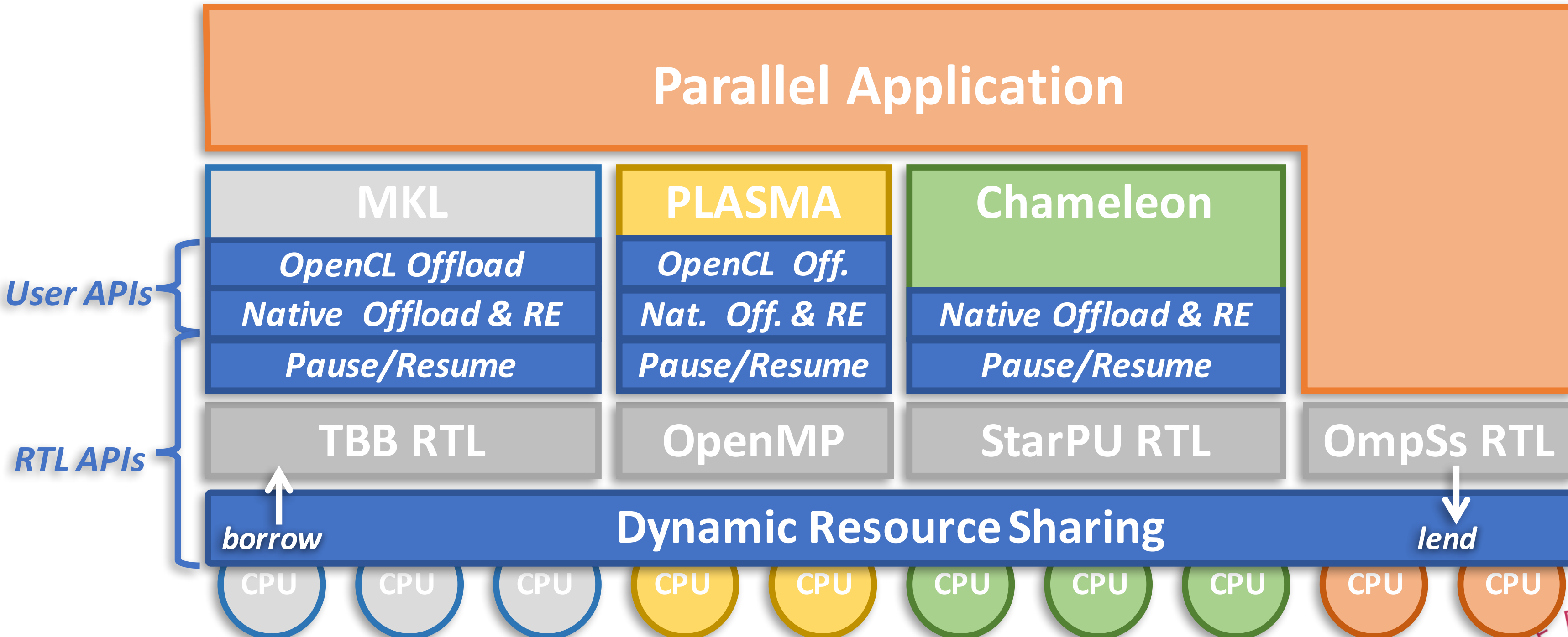
→ **INTERTWinE Resource Management APIs**

Resource Manager Overview

- Implement a **Resource Manager** to share CPU resources between parallel application, libraries and runtime systems



Resource Manager APIs
Native offload and resource enforcement API

Coordinated execution of a parallel library kernel from a parallel application

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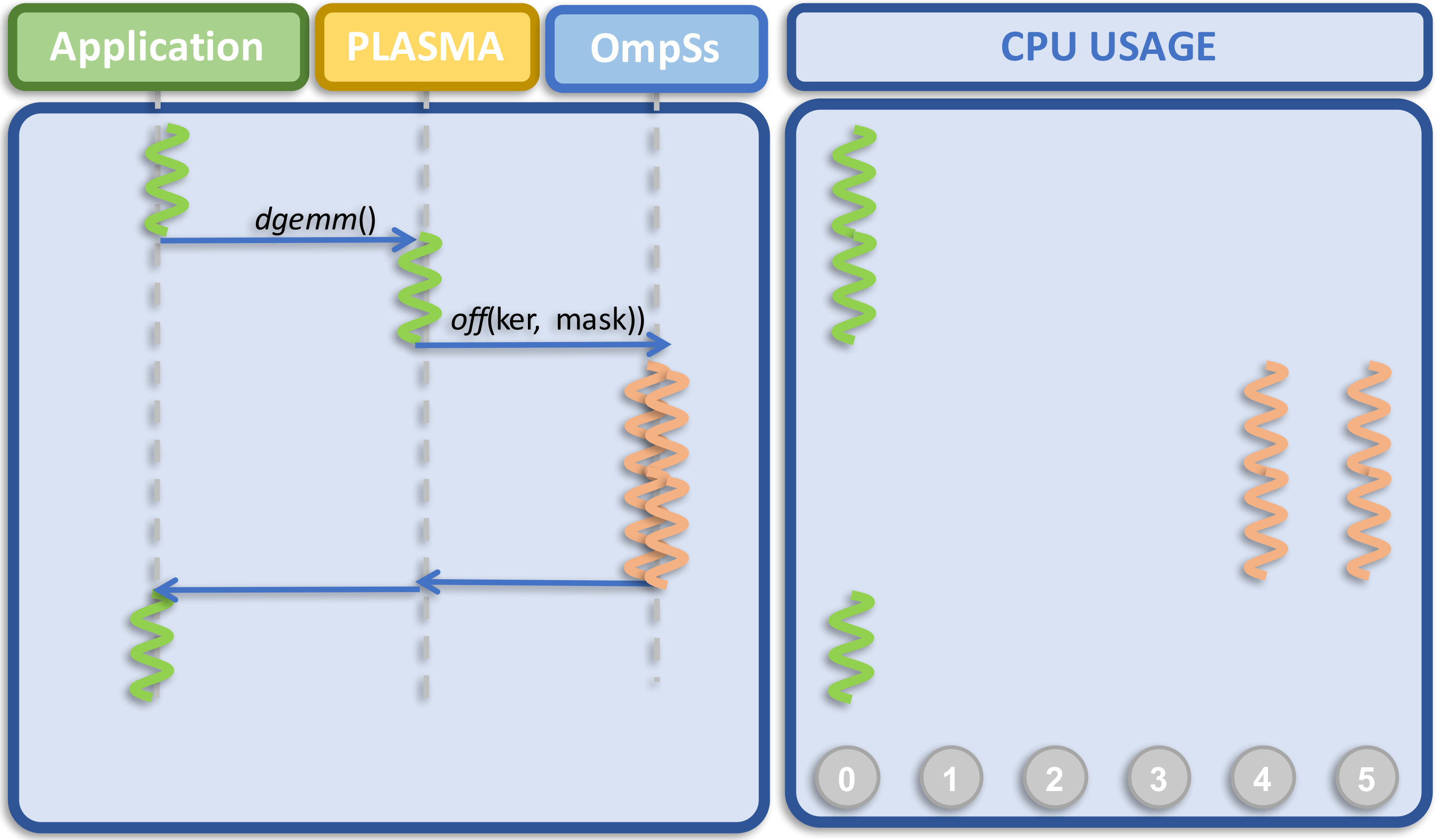


Resource Manager APIs
Native offload and resource enforcement API

- **Each runtime has its own (similar) asynchronous API:**
  - Nanos6

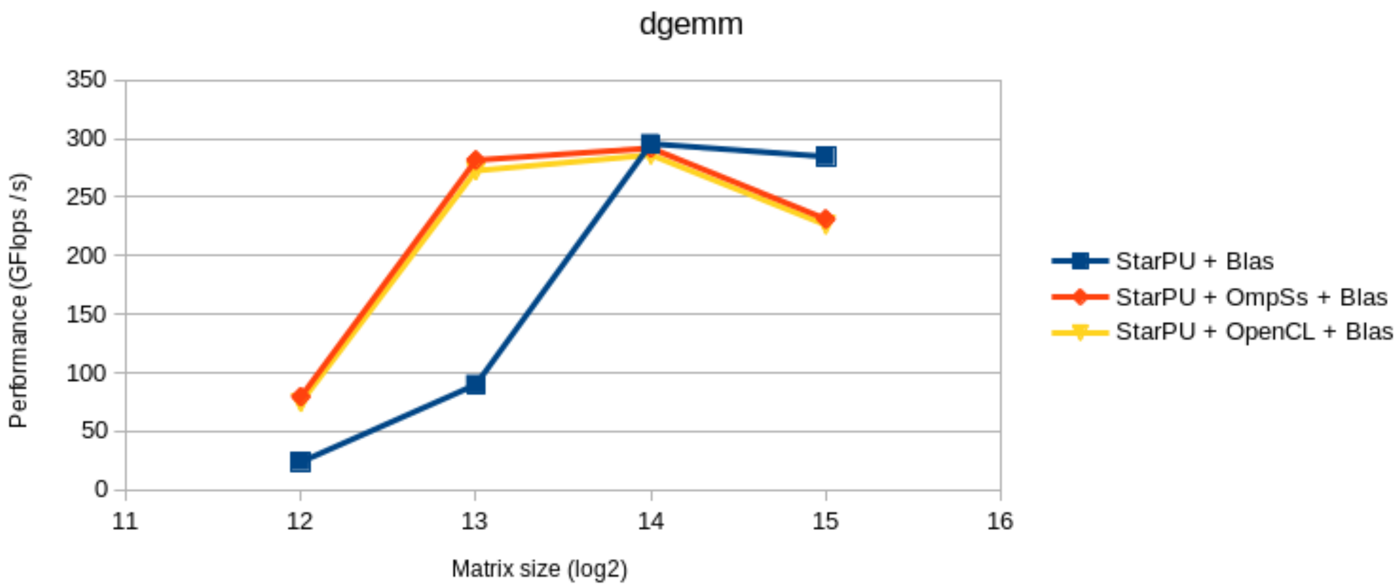
```
void nanos_spawn_function(
        void (*function)(void *),
        void *args,
        void (*completion_callback)(void *),
        void *completion_args,
        char const *label,
        cpu_set_t *cpu_mask)
```

  - StarPU

```
void starpurm_spawn_kernel_on_cpus_callback(
        void *data,
        void(*f)(void *),
        void *args,
        hwloc_cpuset_t cpuset,
        void(*cb_f)(void *),
        void *cb_args)
```

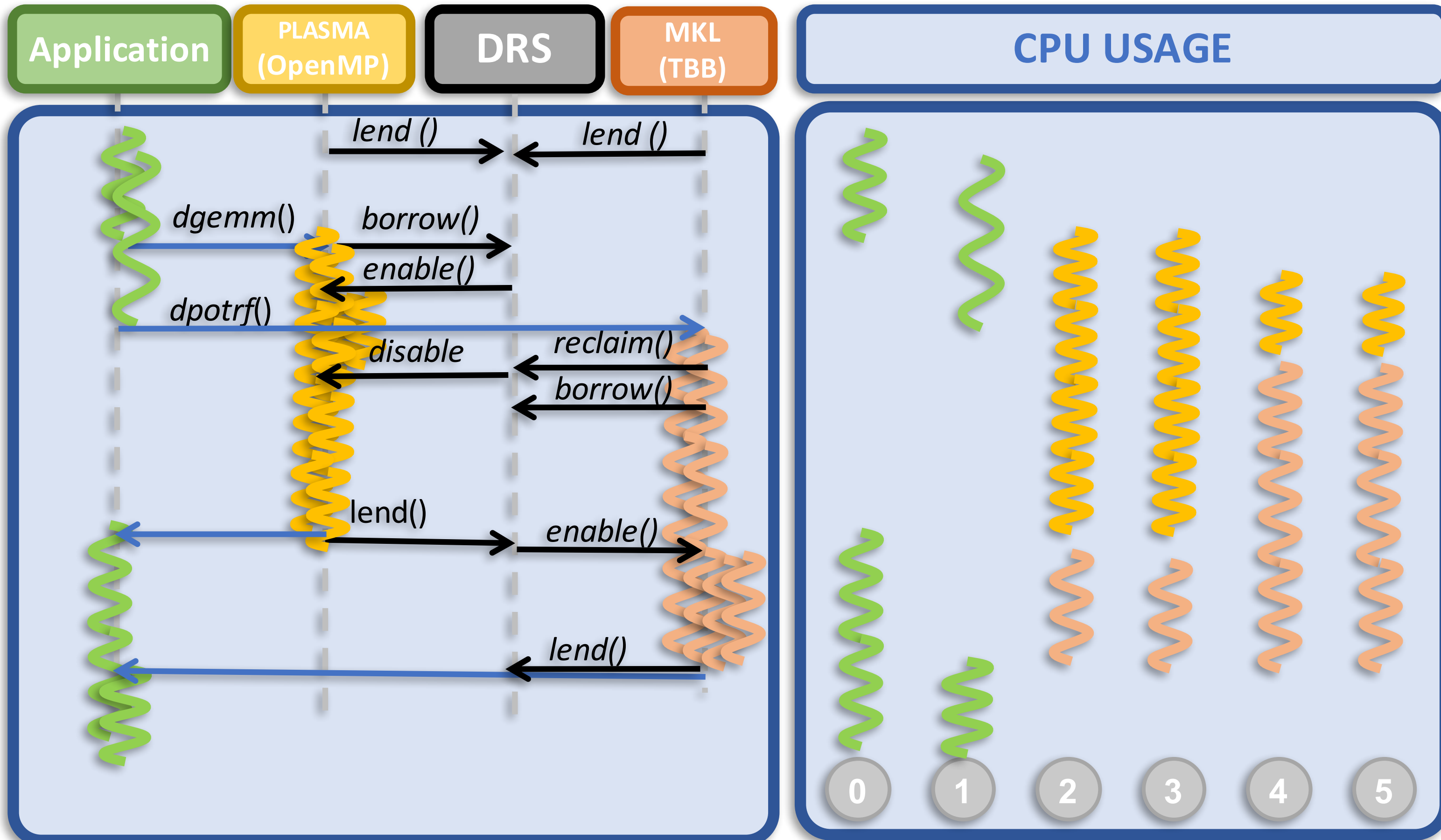
Resource Manager APIs
Performance evaluation of Native (and OpenCL) offloading API

- **MatMul: 16 CPUs**
  - Outermost task: block size 4K, 4 CPUs assigned to each task
  - Innermost task: block size 512 bytes



  - When there is only one level of tasks, high performance is not achieved until matrix is very big

Resource Manager APIs
Dynamic Resource Sharing (DRS)



Resource Manager APIs
Dynamic Resource Sharing (DRS)

- **See StarPU dynamic resource management animation**

Accelerator Resource Management

- **Dynamic Resource Sharing API extended for devices**
  - Device sharing routines
    - **Lend/Reclaim device**
    - **Acquire/Return device**

Accelerator Resource Management

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  - Device types supported
    - CUDA devices
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  - Device types supported
    - CUDA devices
    - OpenCL devices
    - (Xeon Phi KNC accelerator devices, …)
  - Dynamic notifications
    - Device becoming idle, from the runtime point of view
    - Device becoming needed, from the runtime point of view
    - Could be interfaced with DLB as for the CPU support.

INTERTWinE – Resource Management APIs

- **Exascale Scheme**
  - Parallel application + Parallel libraries
- **Need for coordinated access to computing resources**
  - Avoid undersubscription, oversubscription, idleness
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INTERTWinE Resource Management APIs

- Kernel offload and resource enforcement APIs
  - Native & via OpenCL
- Dynamic resource sharing API
- (Pause/Resume API)

INTERTWinE:
Programming Model INTERoperability ToWards Exascale

Visit http://www.intertwine-project.eu to find out about our:

- **Best Practice Guides:**
  - Writing GASPI-MPI Interoperable Programs
  - MPI + OpenMP Programming
  - MPI + OmpSs Interoperable Programs
  - Open MP/OmpSs/StarPU + Multi-threaded Libraries Interoperable Programs
- **"Developer Hub" of resources for developers & application users**

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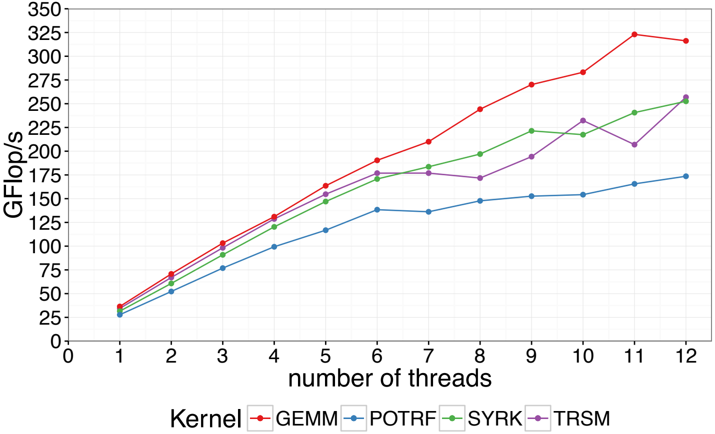
10

Advanced Scheduling Topics

Multicore CPUs: Parallel Tasks

Multicore CPUs: Parallel Tasks (T. Cojean)

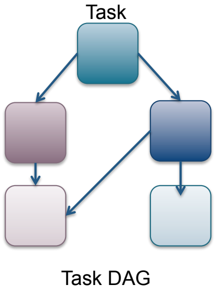
Kernel sweet spots: example with Cholesky factorization kernels
(1x Xeon E5-2680v3 2.5GHz 12 cores)

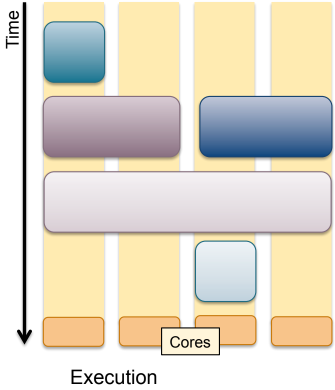


Multicore CPUs: Parallel Tasks

Rationale

- Run parallel kernels on multiple CPU cores
- Address CPU/GPU computing power imbalance
- Address nested-runtime interoperability





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- Big kernel for GPU
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Make use of existing parallel kernels/codes

- Interoperability
- Libraries: BLAS, FFT, . . .
- OpenMP code

Multicore CPUs – Technical details

Two flavors of **parallel tasks**

Multicore CPUs – Technical details

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Fork-mode

- StarPU provides threads on the participating cores

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SPMD-mode

- StarPU launches the task on a single core
- . . . and let the task create its own threads
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Locality enforcement in NUMA context

- Combined worker threads

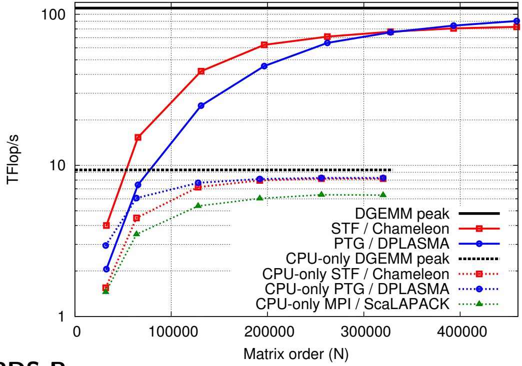
Submission-side Task Flow Optimizations

- Global task-graph pruning in distributed computing sessions
- Memory subscription control

Distributed Scalability Study Results

Chameleon linear algebra library (Inria Team HiePACS)

- Heterogeneous cluster: 1152 CPU cores+288 GPUs



IEEE TPDS Paper:

DOI: 10.1109/TPDS.2017.2766064 — https://hal.inria.fr/hal-01618526

Distributed Support

Sequential Task Flow Paradigm on Clusters

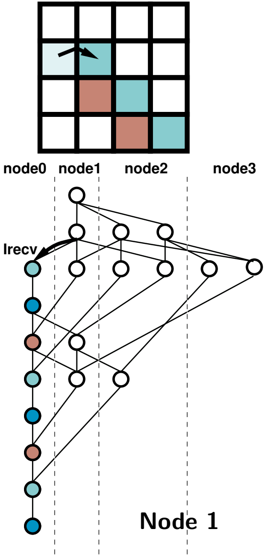
Each node unrolls the sequential task flow

Task↔Node Mapping

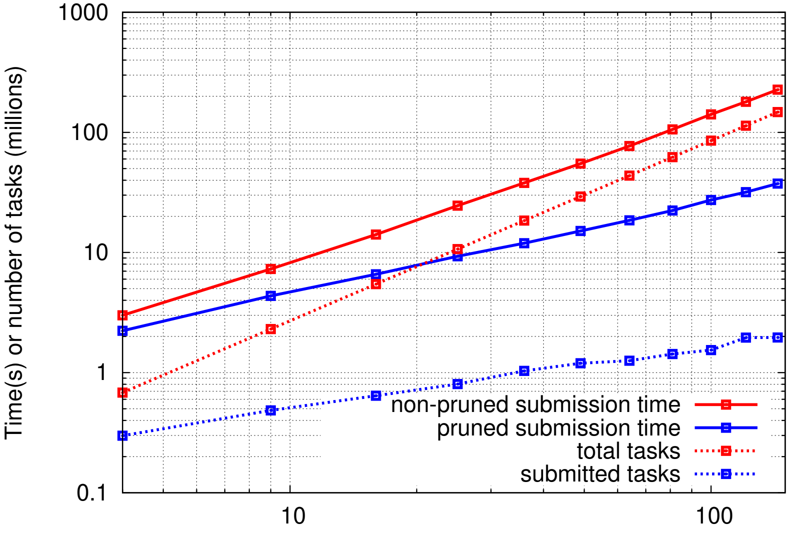
- Inferred from data location:
  - *Tasks move to data they modify*
- No global scheduling
- No synchronizations

Optimization

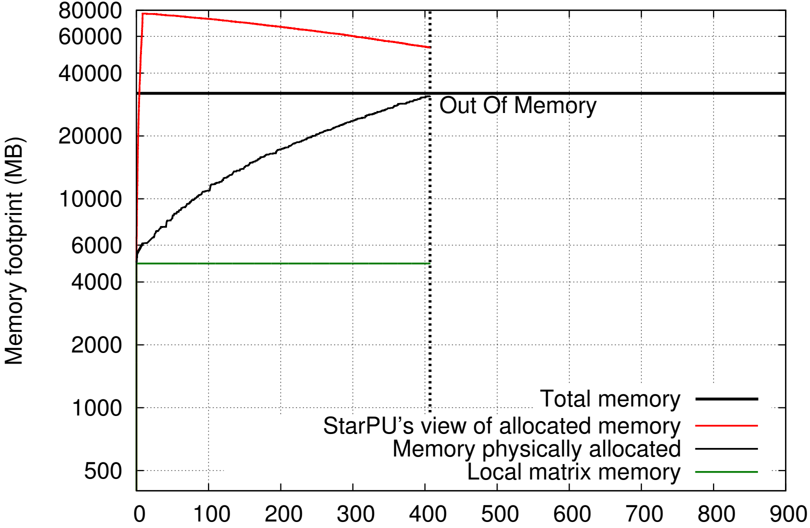
- **Local DAG pruning**



Global Task-Graph Pruning Issue



Unbounded Task Submission Issue

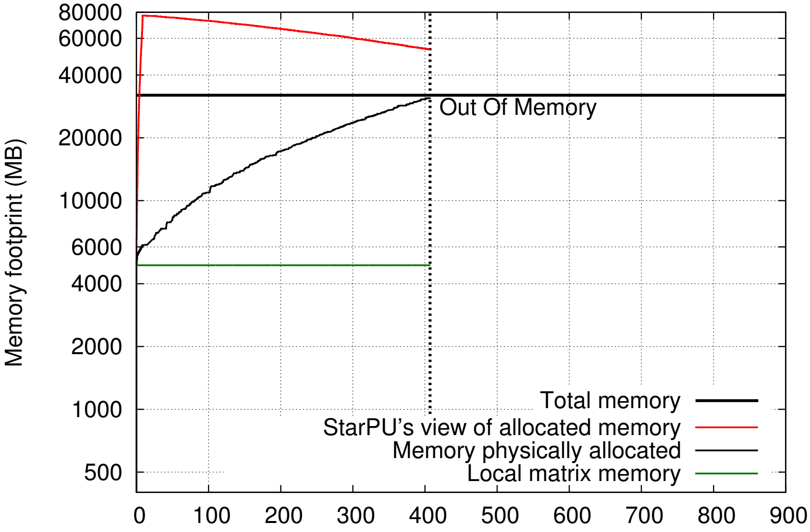


Implementing Some Scheduling Lookahead Window

Control of the task submission flow

- **Memory tracking**
  - Account the memory subscription
- **Task submission throttling**
  - Blocking mechanism of the task submission flow
  - Allows the task submission to be controlled by an external criteria
- A **control policy** which uses the **memory tracking** to **throttle the task submission flow**

Memory Behaviour Without Memory Control



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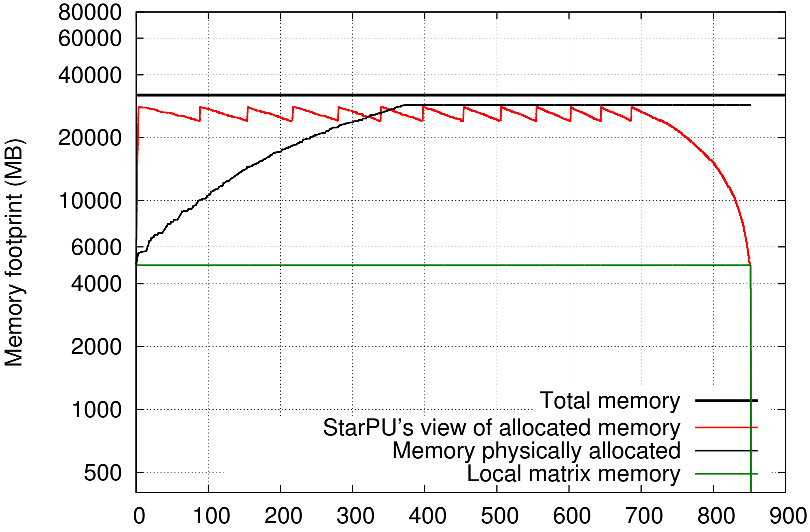

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Advanced Data Management Topics

Advanced Data Management

Advanced Data Management

Heterogeneous data layout

- Multiformat support

Advanced Data Management

Heterogeneous data layout

- Multiformat support

Large workloads

- Out-of-core support

Data Layout

Heterogeneous platforms

- Heterogeneous data layout requirements
- Example:
  - Arrays of Structures (AoS), for CPU cache locality
  - vs Structures of Arrays (SoA), for GPU coalesced memory accesses
  - vs Arrays of Structures of Arrays (AoSoA), for MIC/Xeon Phi
  - ... any other data layout

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StarPU enables Multiformat kernel implementations

- User-provided data layout conversion codelets...
- ... automatically called upon transfers between devices

Multiformat

Example

- Declare conversion codelets

```
/* Conversion codelets */
struct starpu_multiformat_data_interface_ops format_ops = {
     .cuda_elemsize = 2 * sizeof(float),
     .cpu_to_cuda_cl = &cpu_to_cuda_cl,

     .cuda_to_cpu_cl = &cuda_to_cpu_cl,
     .cpu_elemsize = 2 * sizeof(float),
     ...
};

/* Multiformat handle registration */
starpu_multiformat_data_register(handle, 0,
                                 &array_of_structs, NX, &format_ops);
```

Multiformat

Example

- Declare conversion codelets
- Array of structures for CPU

```
/* CPU Computation Kernel */

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

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

Multiformat

Example

- Declare conversion codelets
- Array of structures for CPU
- Structure of arrays for NVidia CUDA GPU

```
/* GPU Computation Kernel */

extern "C" void
multiformat_scal_cuda_func(void *buffers[], void *cl_arg) {
    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]);

    ...
}
```

Large workloads

Using disks as StarPU memory nodes

- Out-of-Core

Large workloads

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- Out-of-Core
- Enable StarPU to evict temporarily unused data to disk

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Input/Output Support

Integration with general StarPU's memory management layer

- StarPU data handles
- Task dependencies
- Multiple I/O drivers supported

Many possible use scenarios

- **Out-of-core** / swap
- Mitigated startup load / solution output
- Building block for fault tolerance

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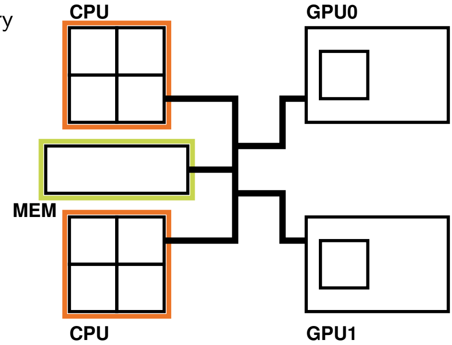

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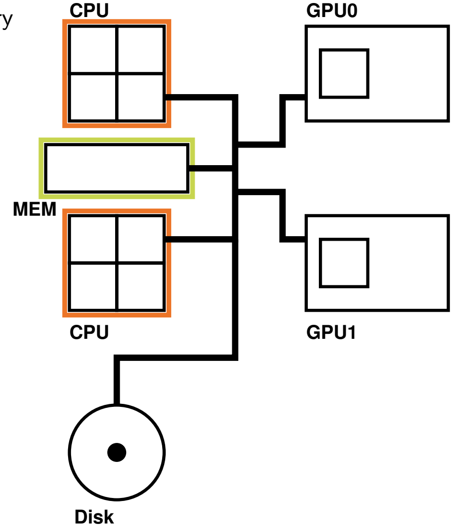

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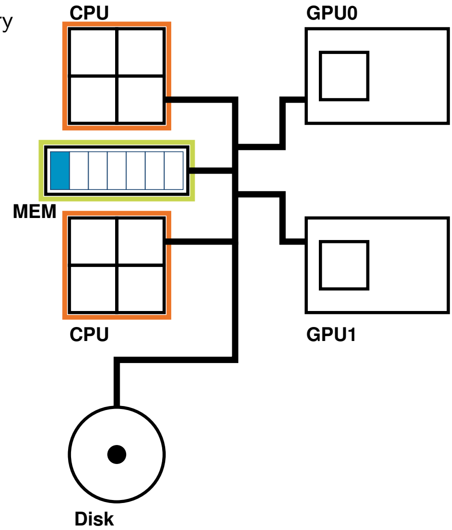

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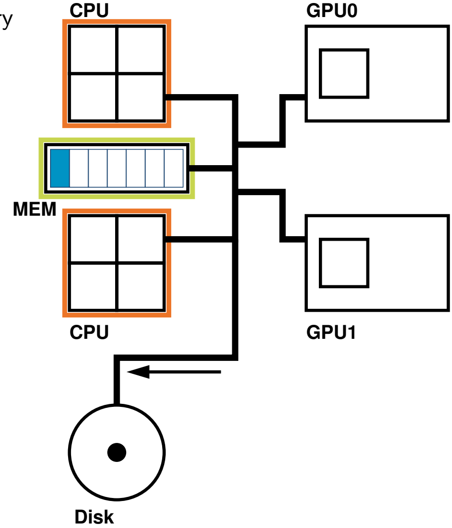

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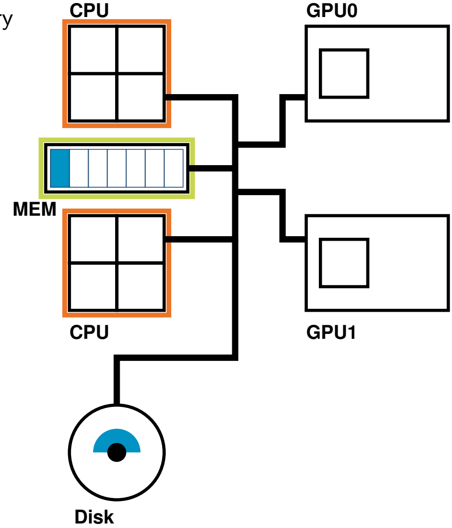

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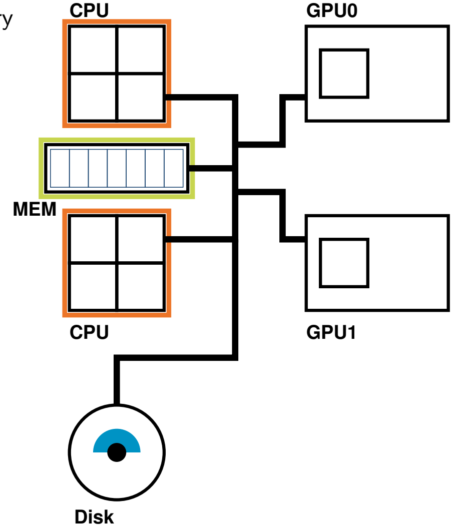

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- **Out-of-core** / swap
- Mitigated startup load / solution output
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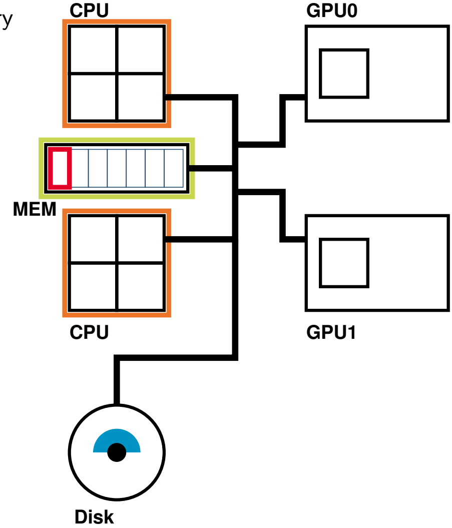

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Integration with general StarPU's memory management layer

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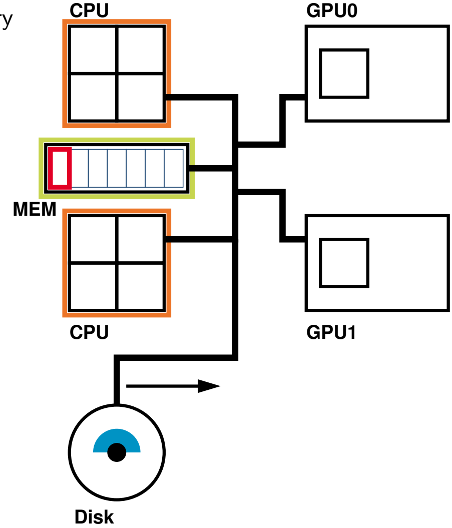

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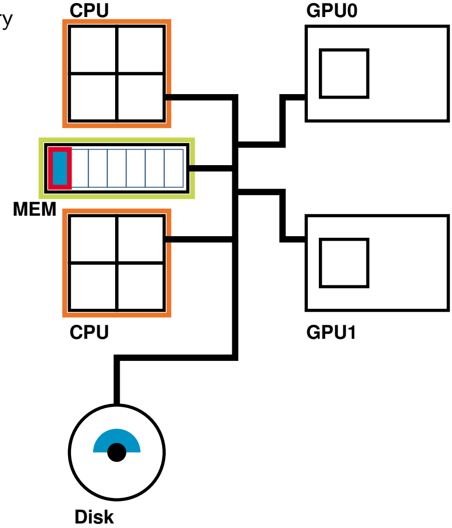

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Advanced Analysis and Monitoring Topics

Computing the Theoretical Lower Bound. . .

. . . on Execution Time

- Have realistic expectations from the scheduler
- Identify issues
  - Abnormal overhead
  - Bugs

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Scheduling without executing kernels

- Requires the SimGrid simulation environment
- Enables simulating large-scale scenarios
  - Large data sets
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- Relies on **real** performance models...
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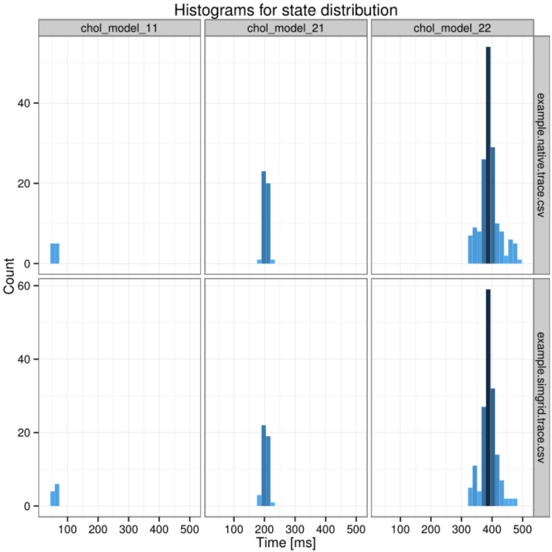
Simulation accuracy with SimGrid



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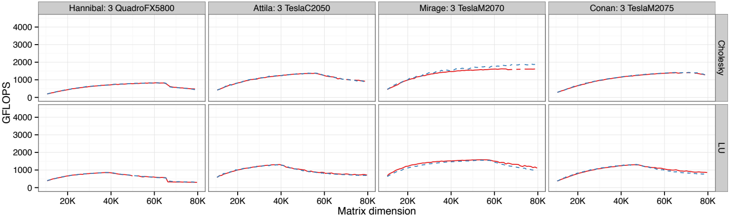

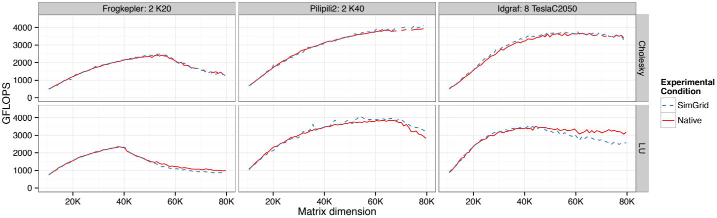

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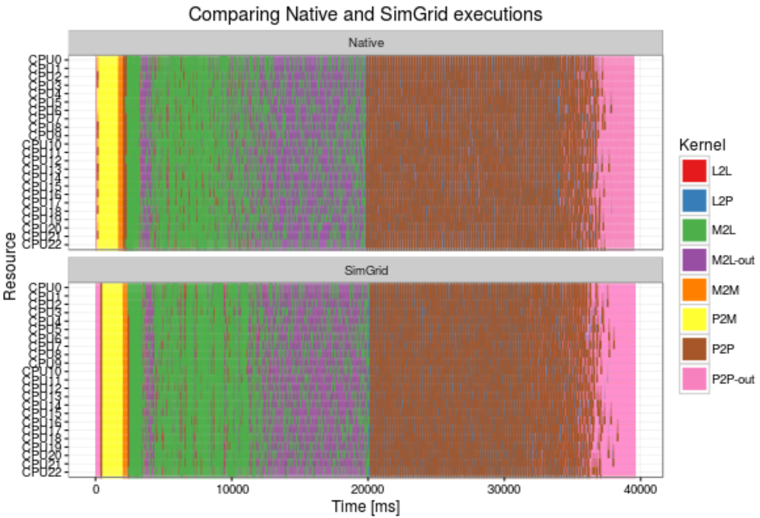

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Conclusion

StarPU

A Unified Runtime System for Heterogeneous Multicore Architectures

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Programming Model: **Async. Task Submission + Inferred Dependencies**

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Execution Model: **Scheduler + Distributed Shared Memory**

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Programming Model: **Async. Task Submission + Inferred Dependencies**
Execution Model: **Scheduler + Distributed Shared Memory**

The key combination for:

- Portability
- Control
- Adaptiveness
- Optimization

Portability of Performance

Thanks for your attention.

StarPU runtime system

Web Site: http://starpu.gforge.inria.fr/

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