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Vector operations, tiled operations, distributed execution, task graphs, ... What next ?

Samuel Thibault

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Vector operations, tiled operations,
distributed execution, task graphs, ...

What next ?

Samuel Thibault, University of Bordeaux
Inria STORM Team

High-Performance Computing

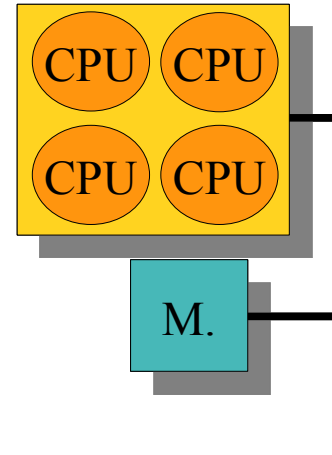
- Frontier supercomputer
- #1 on top500.org LINPACK benchmark
- 1.102 EFlop/s
- 9472 nodes
 - 1 AMD Epyc CPU
 - 4 AMD Instinct 250X GPUs
 - 4TB flash memory
 - Infinity Fabric interconnect
- Slingshot 100GB/s network
- 21.1 MW
- Also #1 Green 500



High-Performance Computing

Classical parallel programming

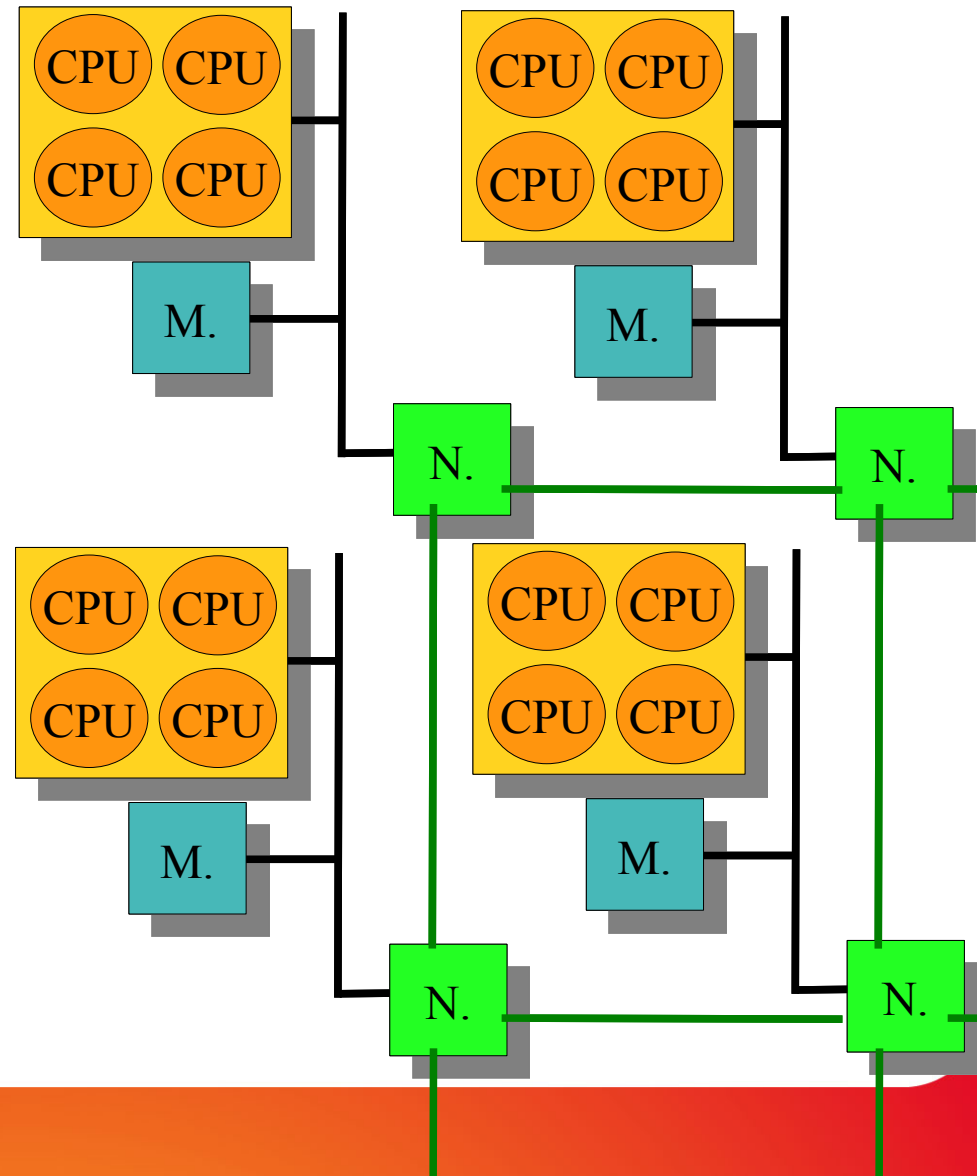
- threads



High-Performance Computing

Classical parallel programming

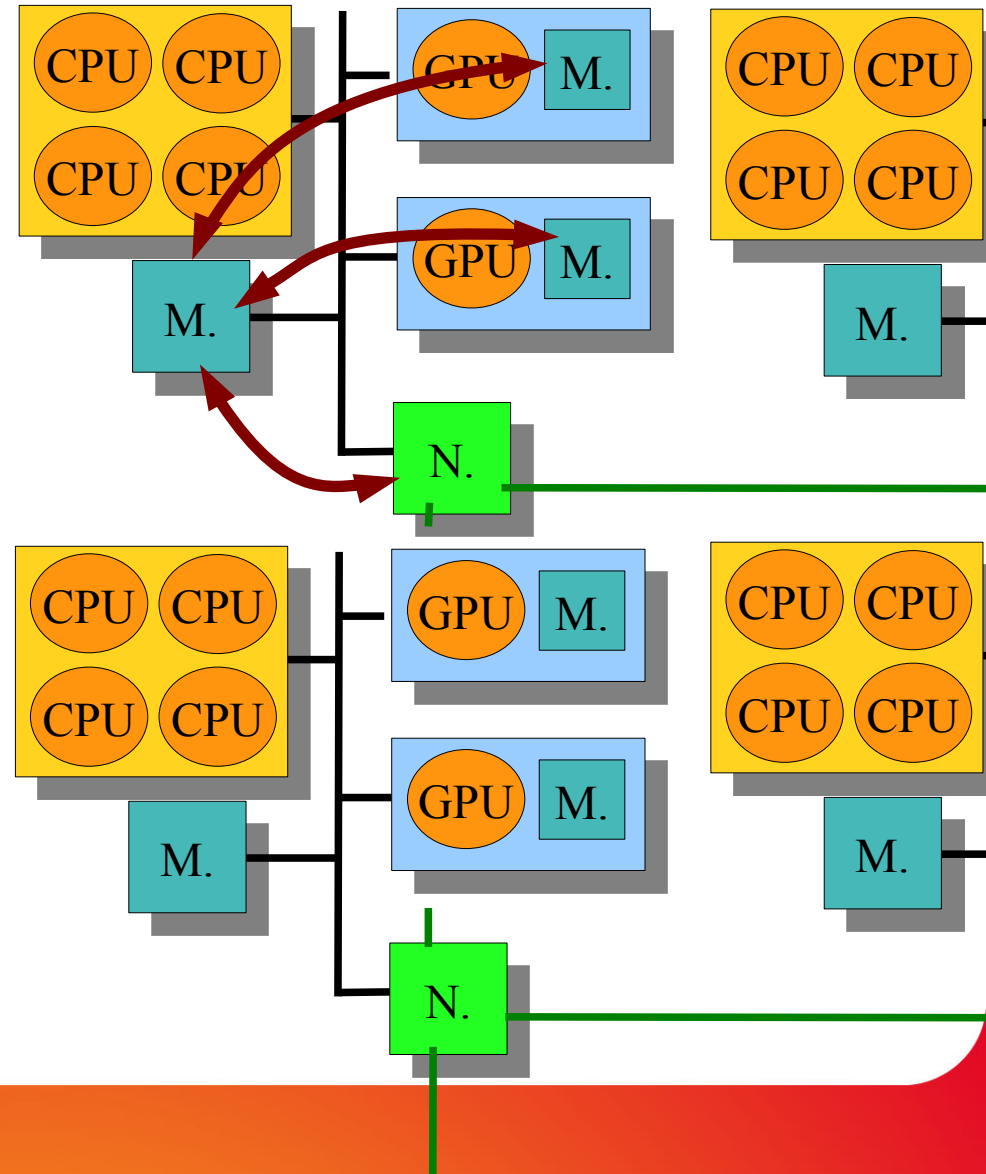
- threads
- MPI+threads



High-Performance Computing

Classical parallel programming

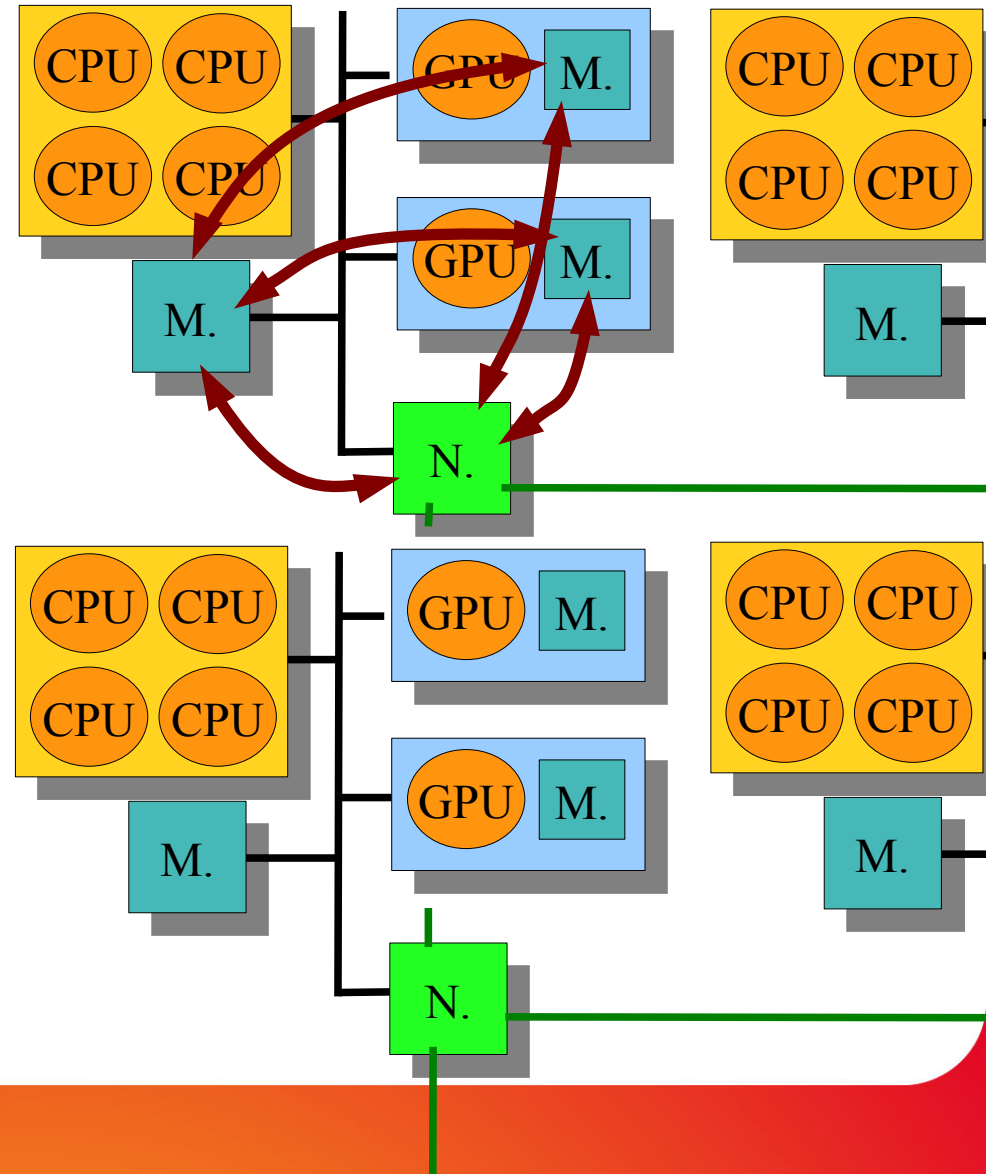
- threads
- MPI+threads
- MPI+threads+GPU
- Data transfers



High-Performance Computing

Classical parallel programming

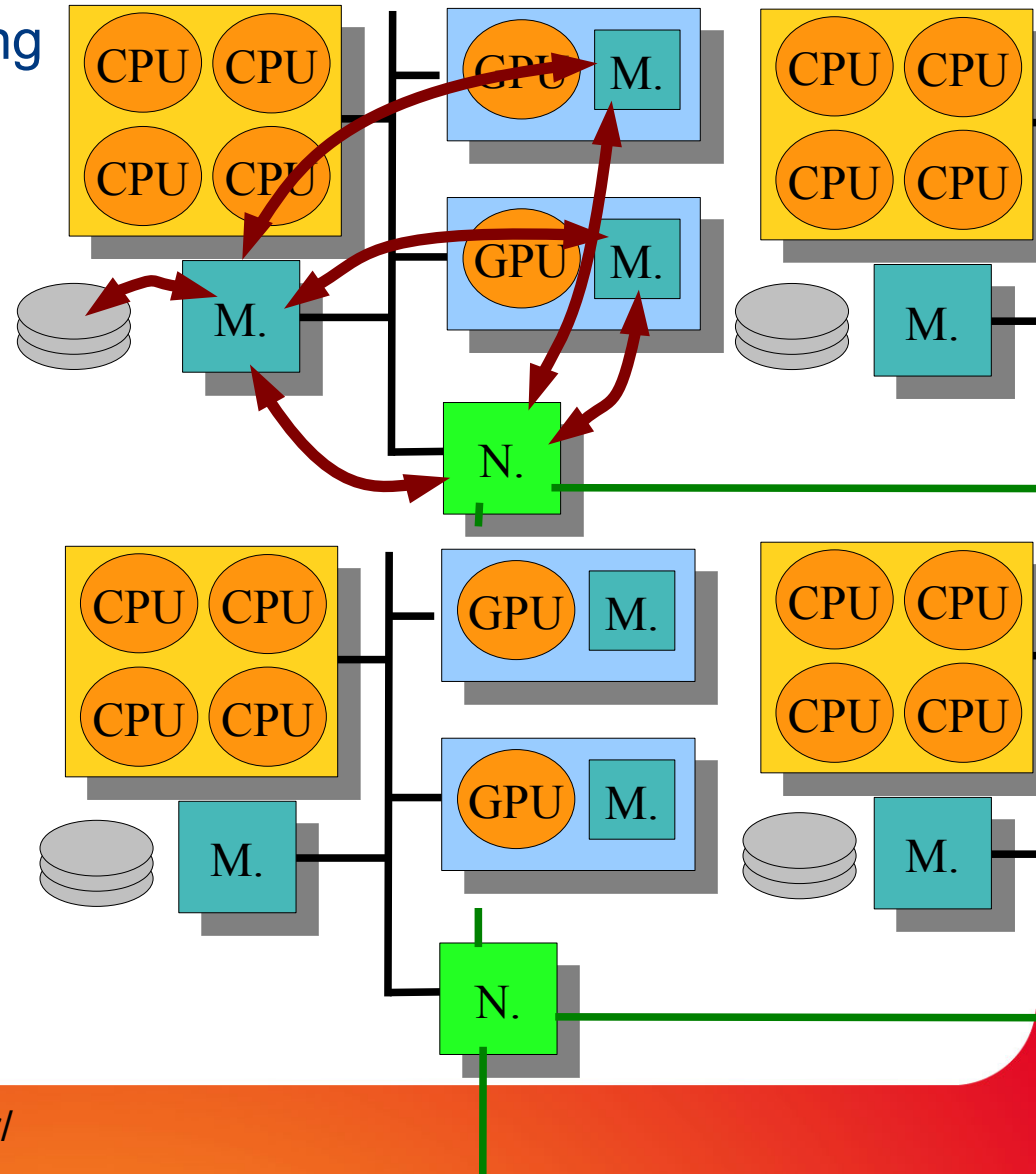
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High-Performance Computing

Classical parallel programming

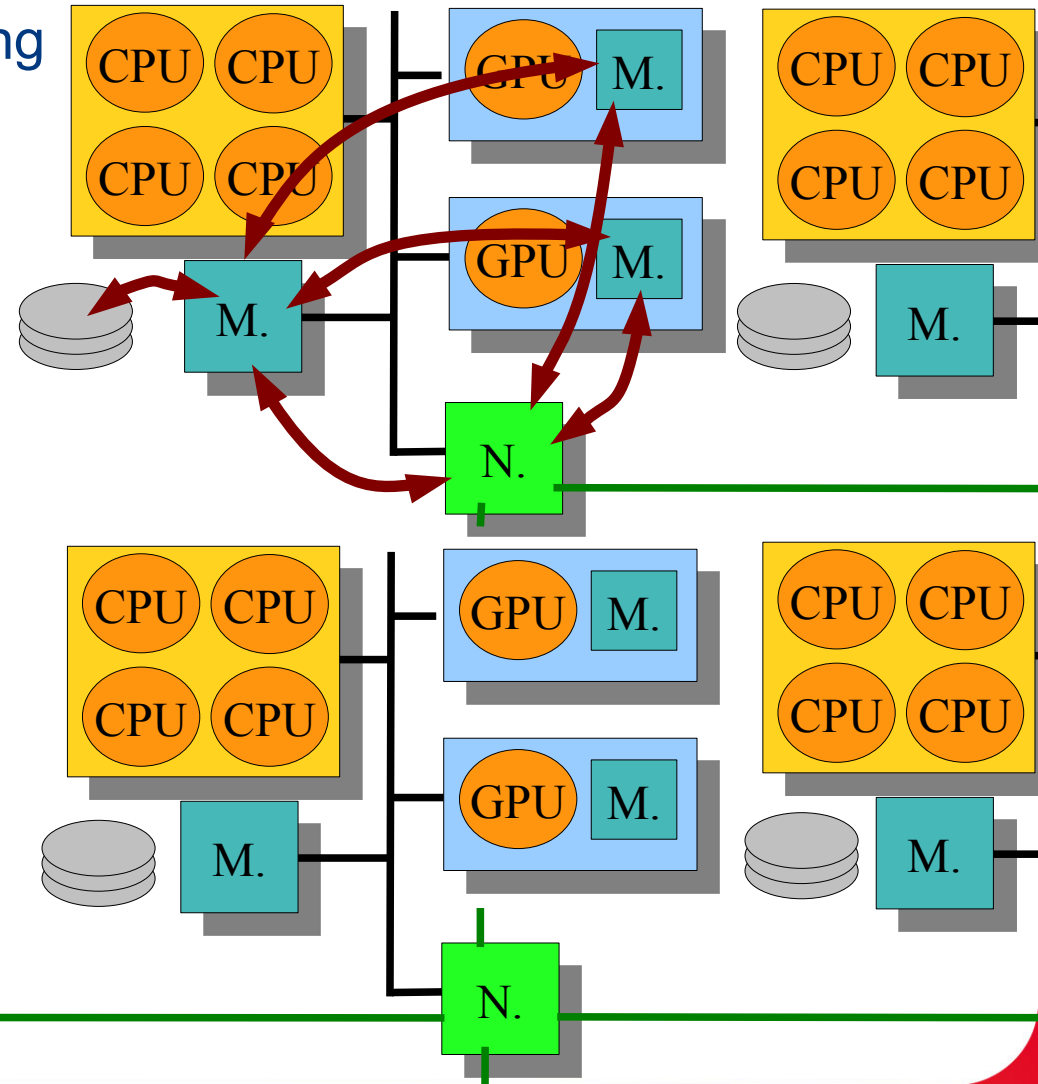
- threads
- MPI+threads
- MPI+threads+GPU
- Data transfers
- Disk storage



High-Performance Computing

Classical parallel programming

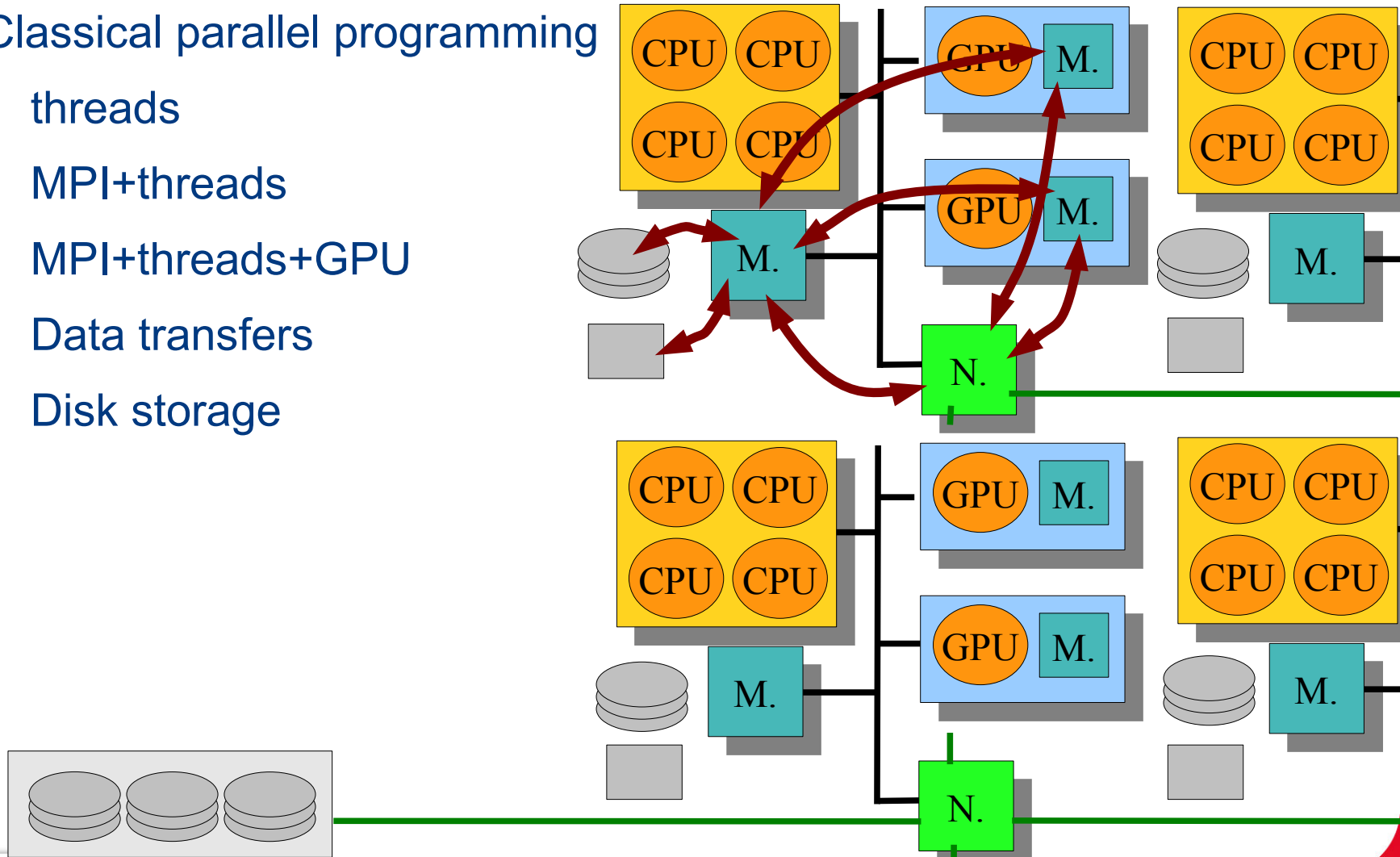
- threads
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High-Performance Computing

Classical parallel programming

- threads
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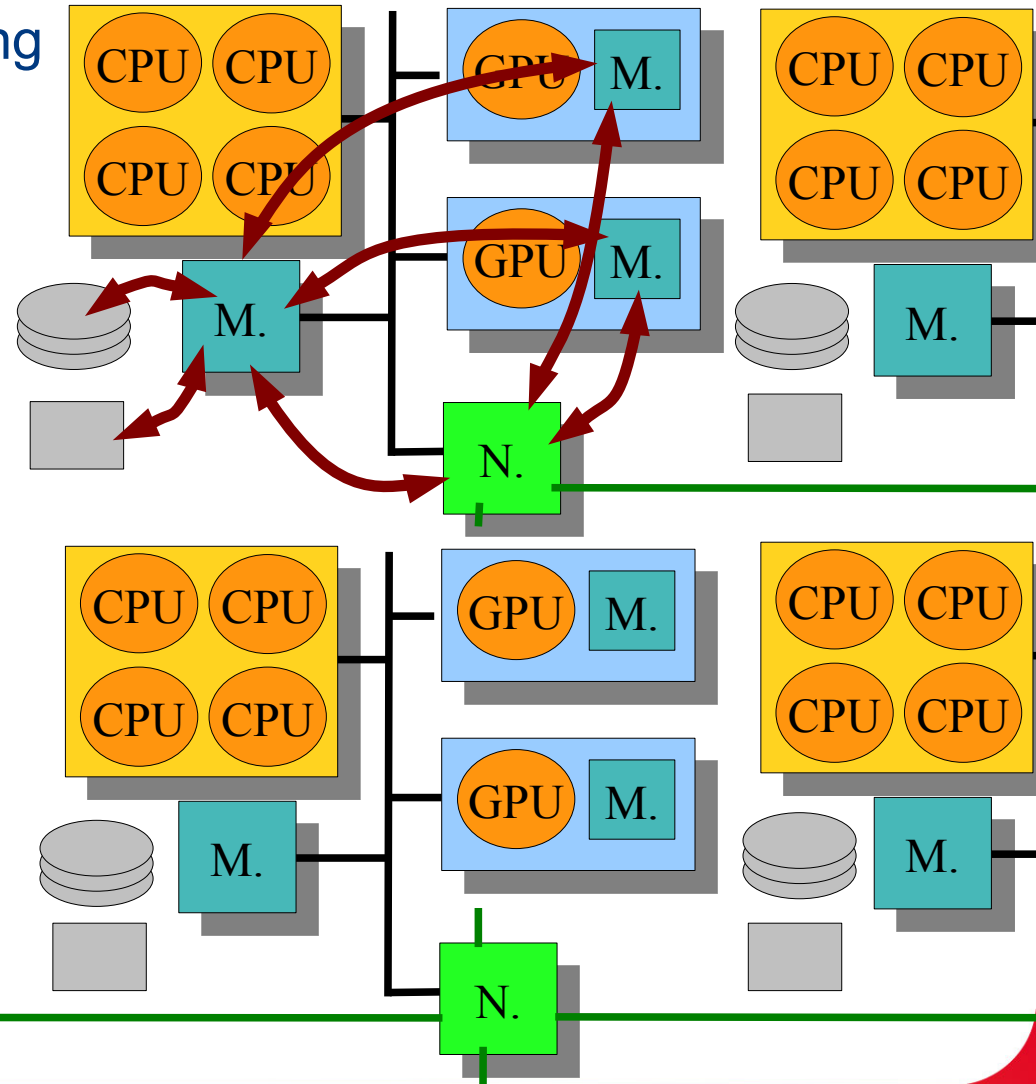


High-Performance Computing

Classical parallel programming

- threads
- MPI+threads
- MPI+threads+GPU
- Data transfers
- Disk storage

Manage it all by hand?!



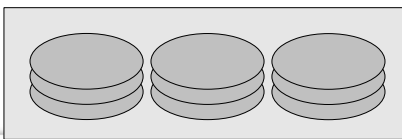
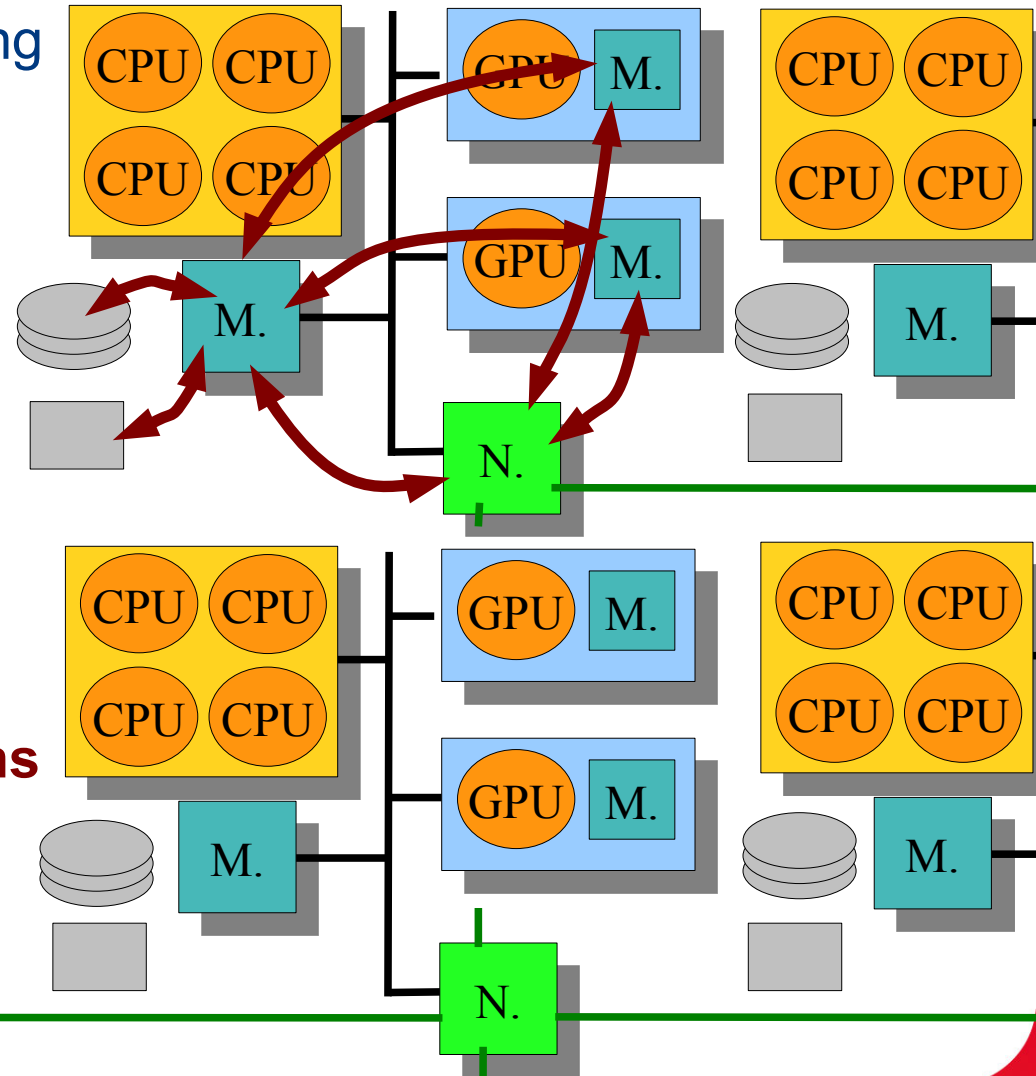
High-Performance Computing

Classical parallel programming

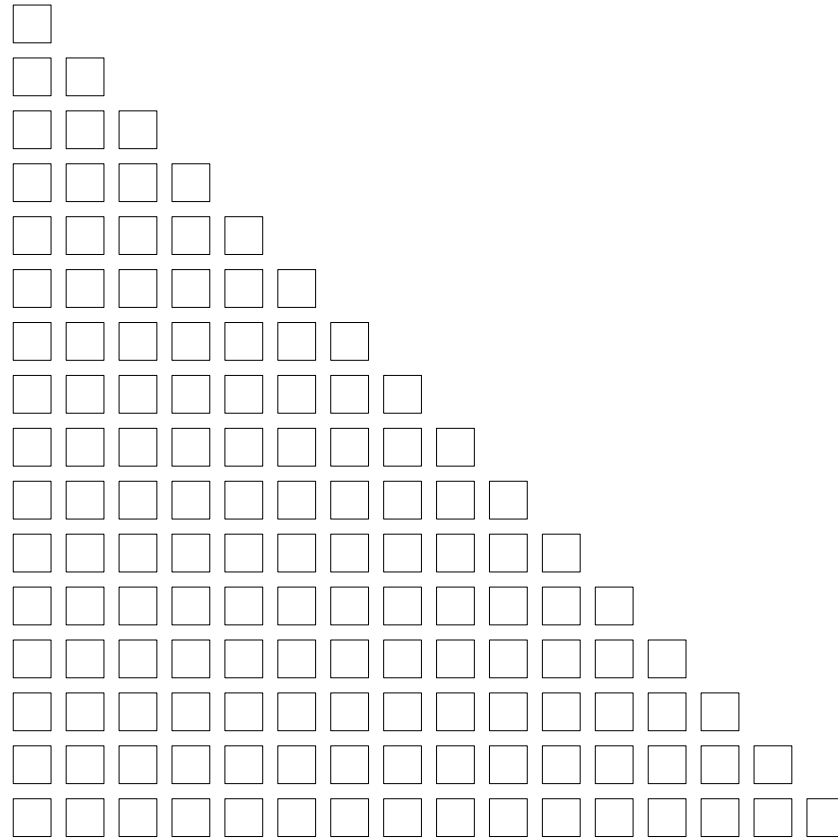
- threads
- MPI+threads
- MPI+threads+GPU
- Data transfers
- Disk storage

Manage it all by hand?!

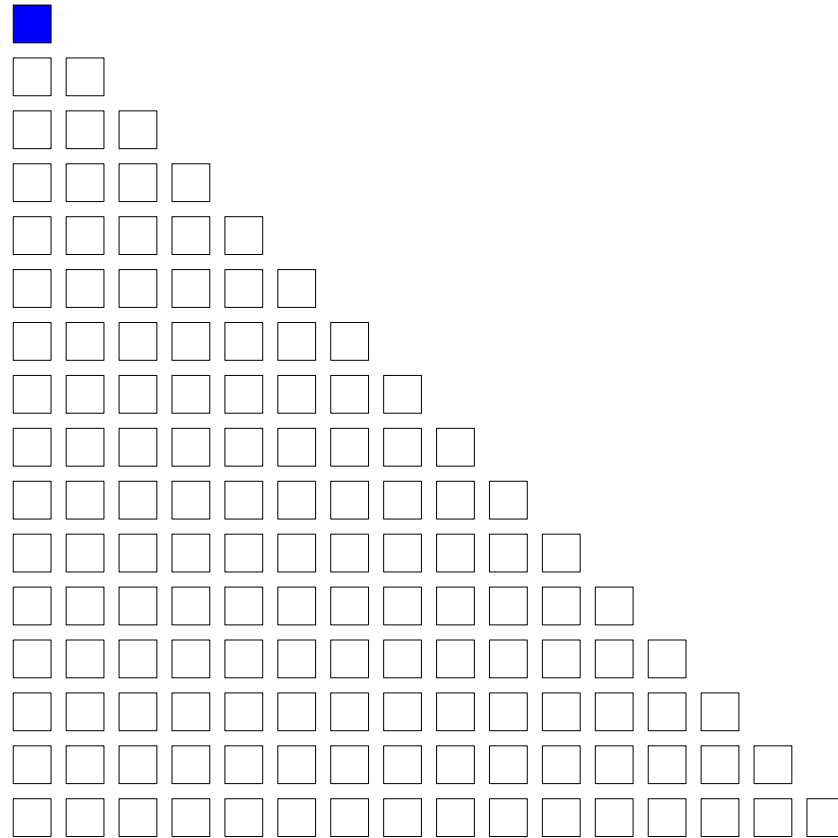
Need high-level abstractions



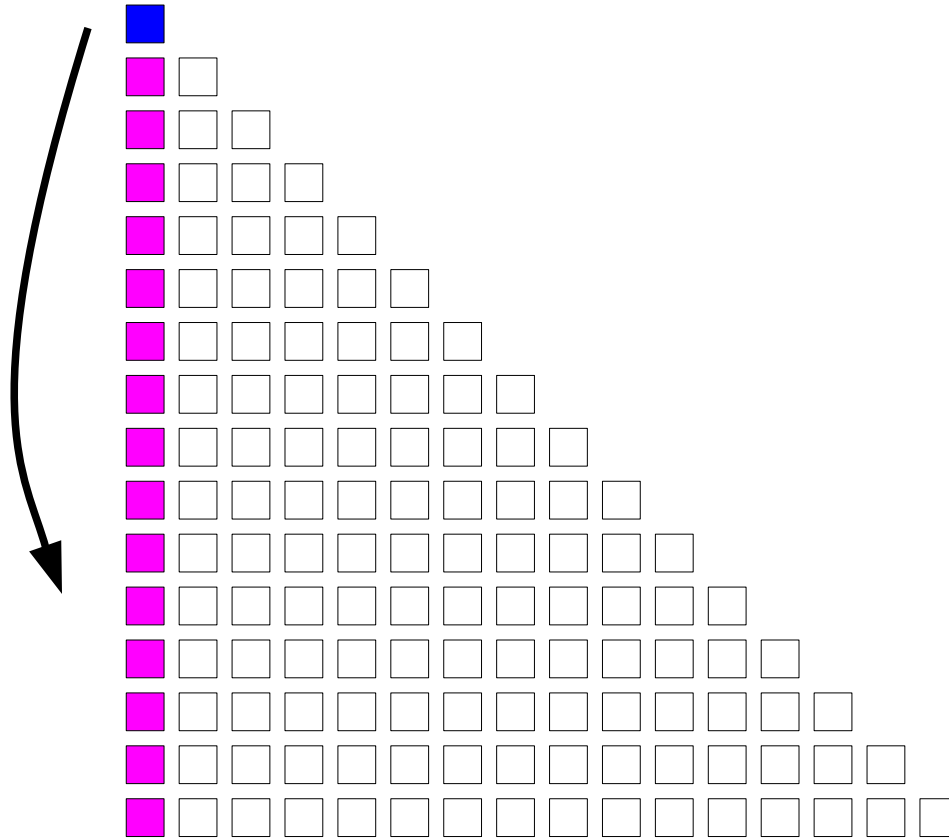
Cholesky ($A = L.L^T$)



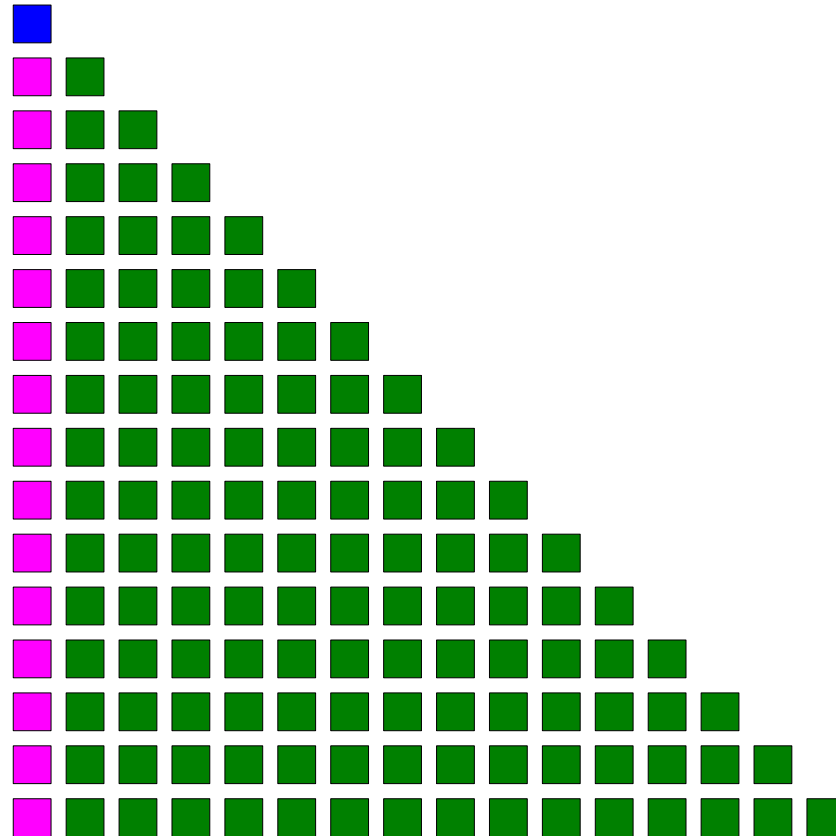
Cholesky ($A = L.L^T$)



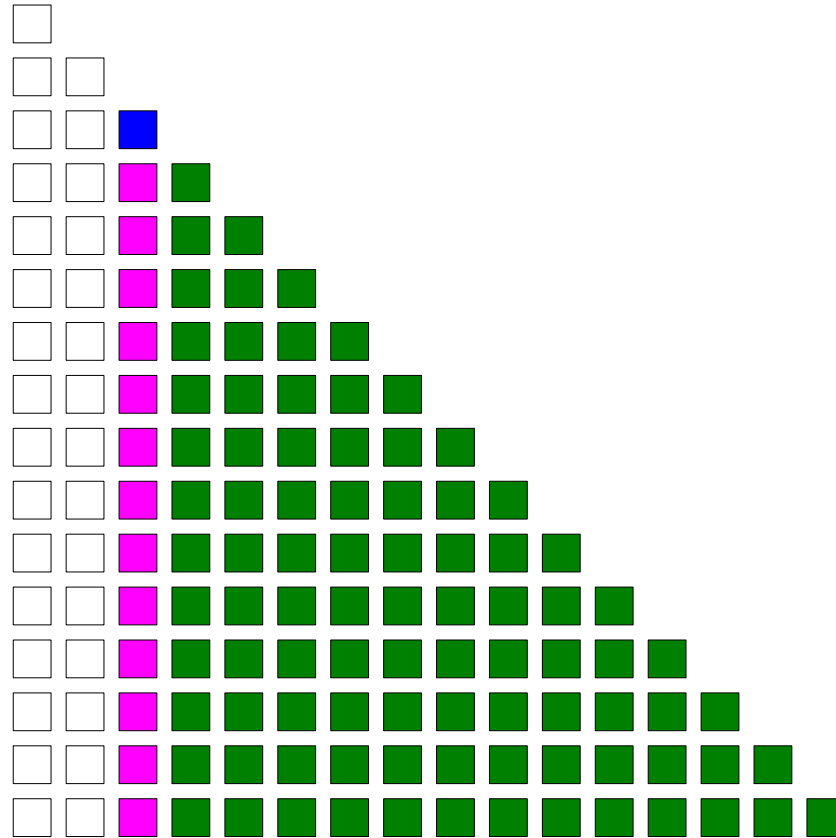
Cholesky ($A = L.L^T$)



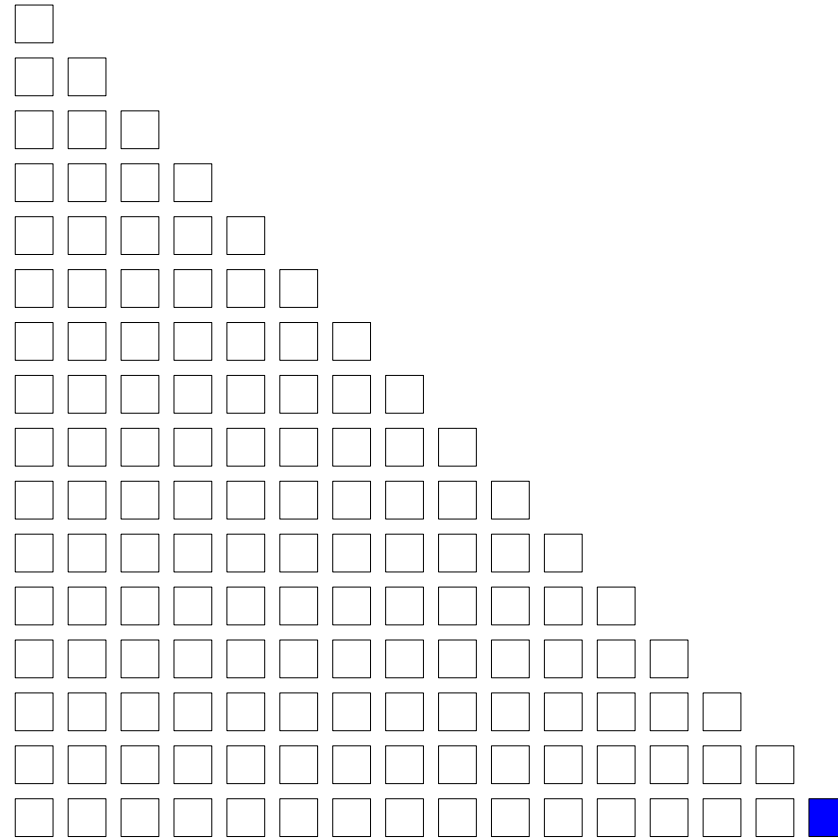
Cholesky ($A = L.L^T$)



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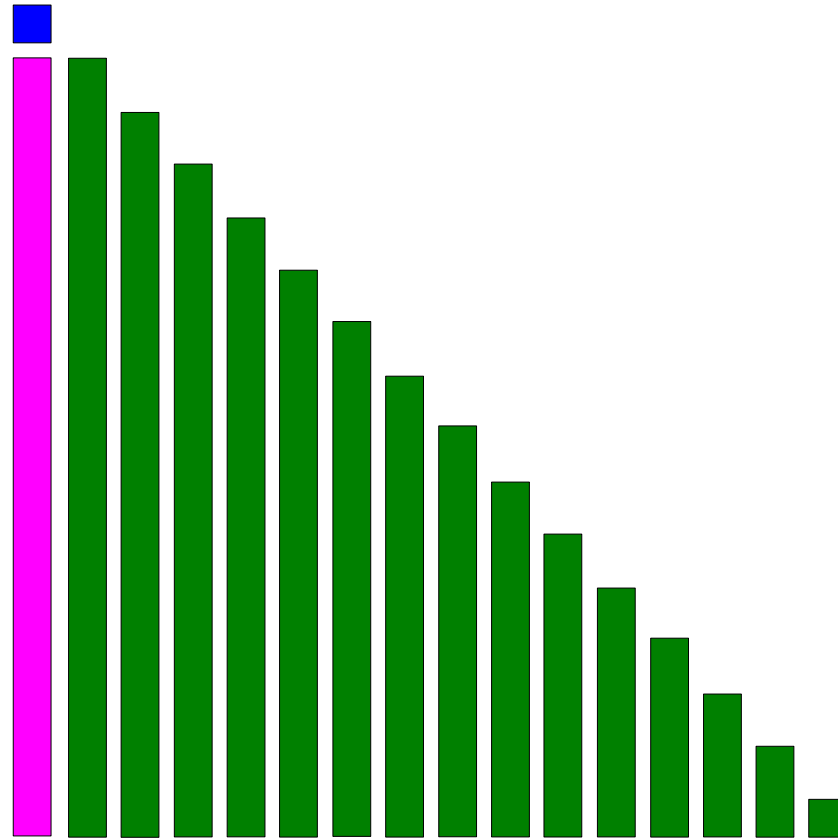


Cholesky ($A = L.L^T$)



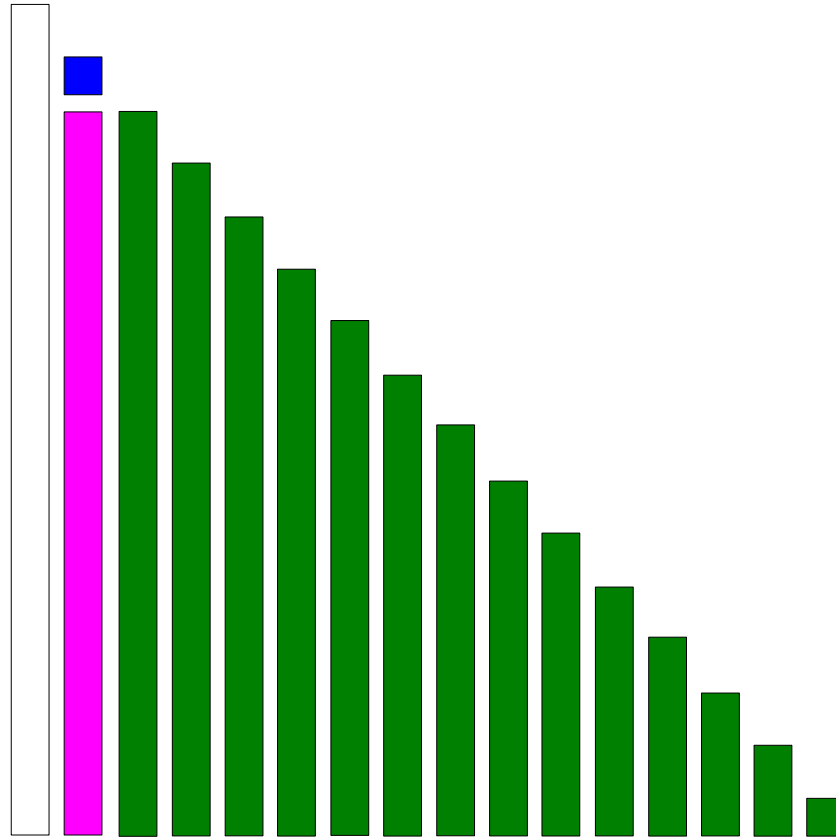
Cholesky, LINPACK

Vector computers (end '70s, '80s)



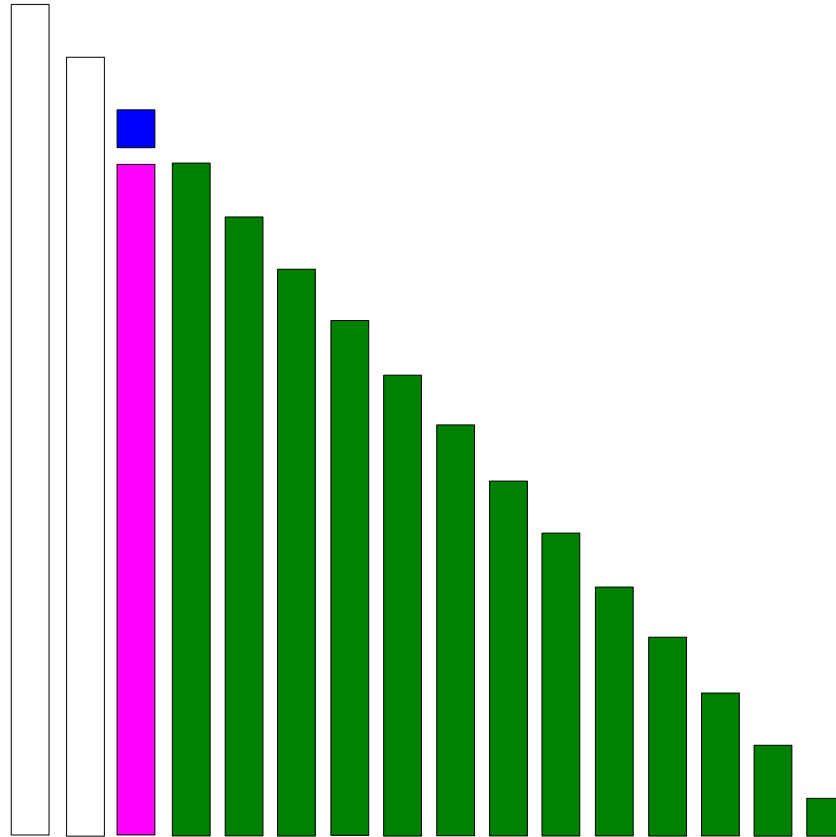
Cholesky, LINPACK

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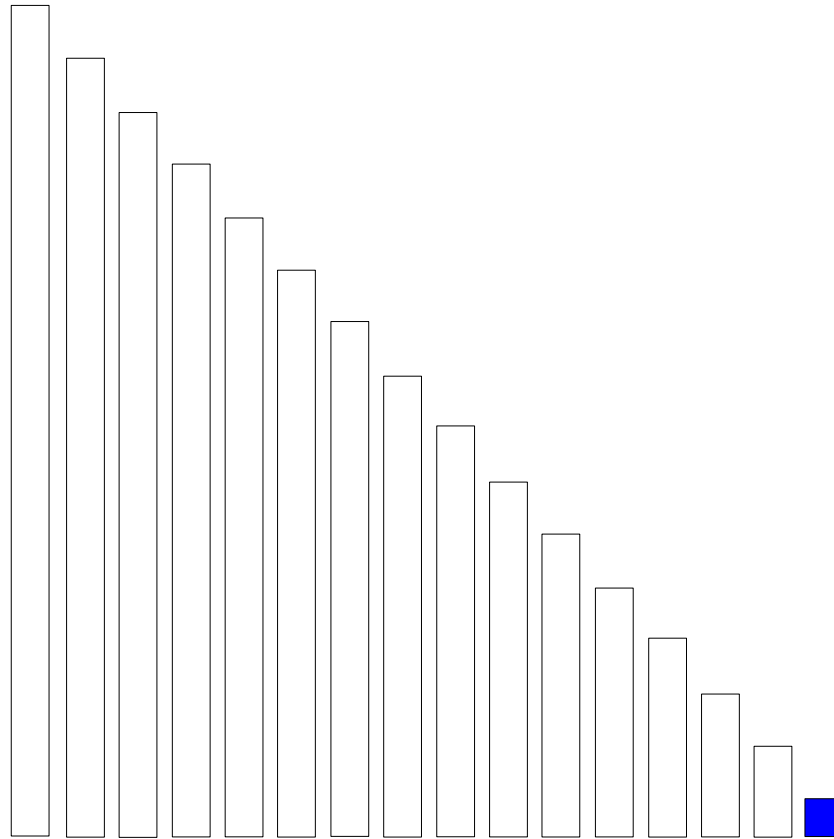
Cholesky, LINPACK

Vector computers (end '70s, '80s)



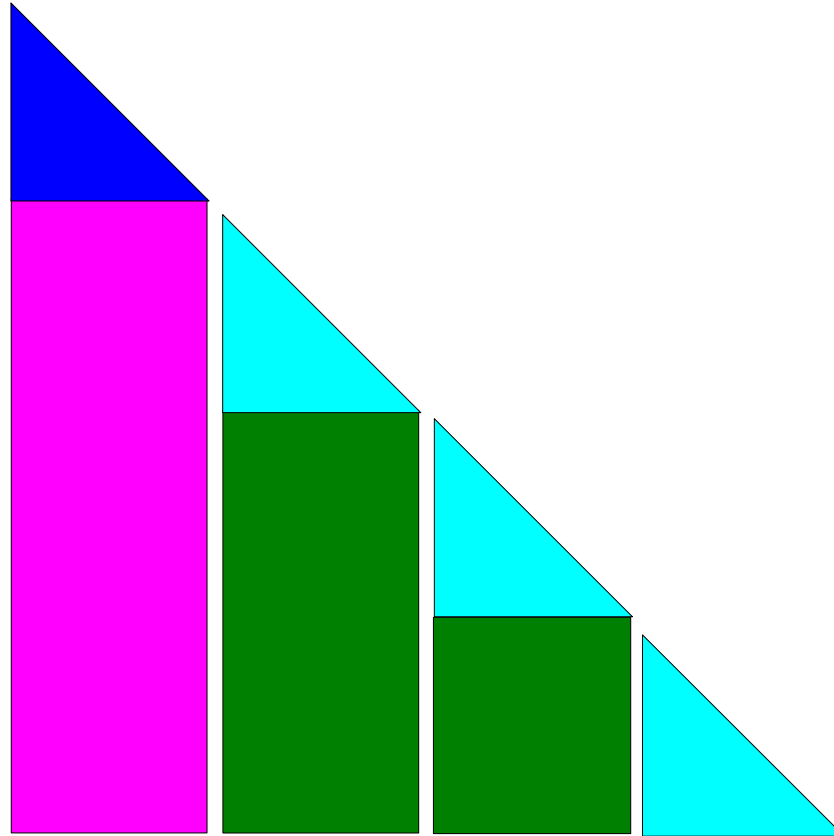
Cholesky, LINPACK

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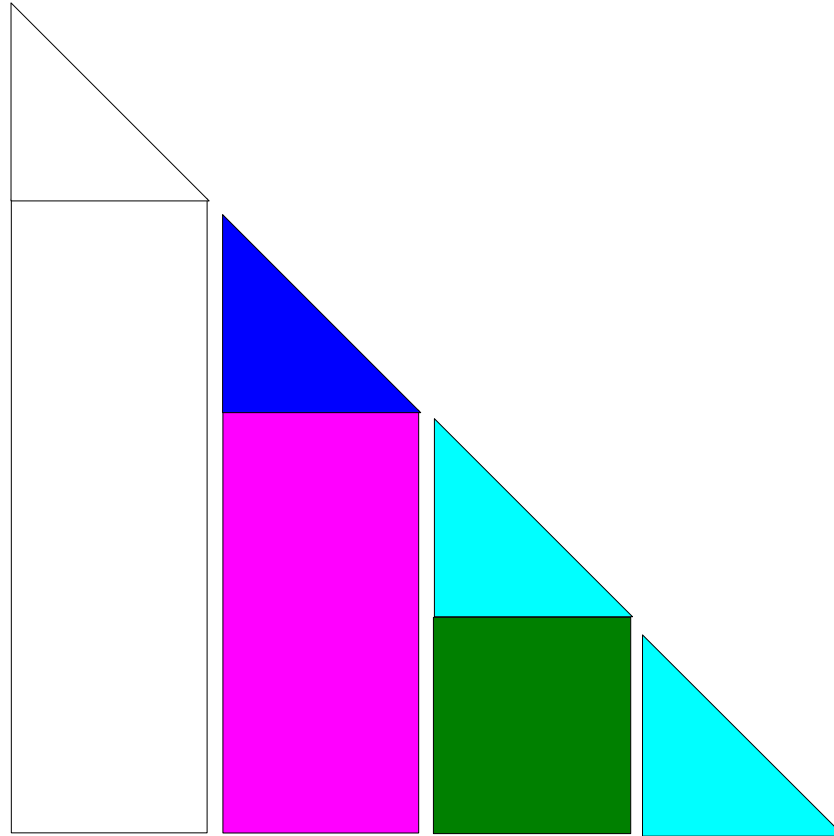
Cholesky, LAPACK

Computers with cache (early '90s-today), blocked operations : BLAS



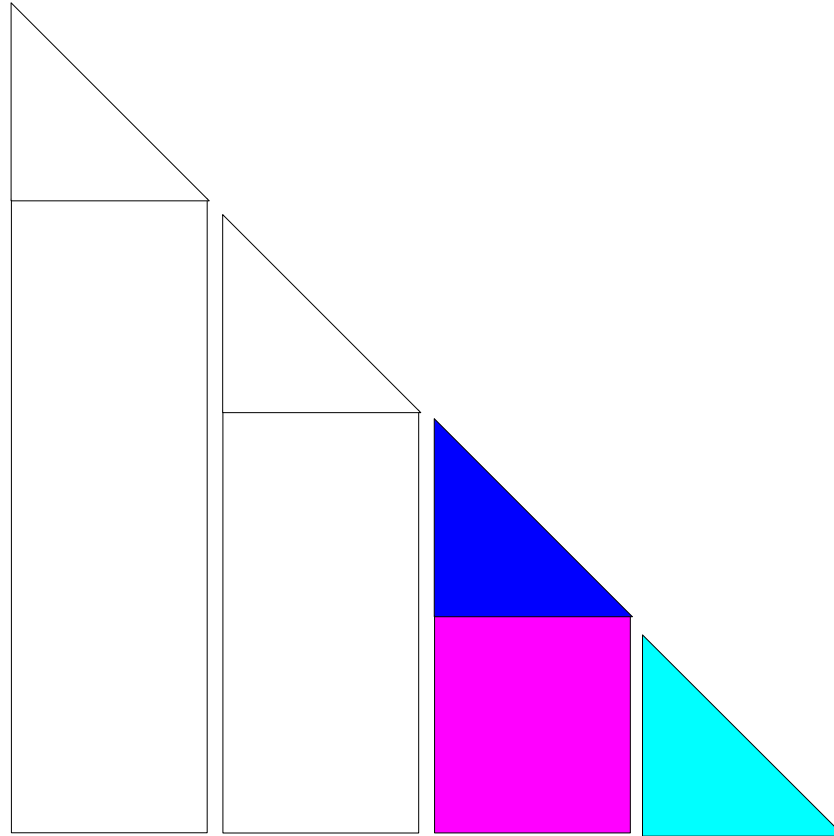
Cholesky, LAPACK

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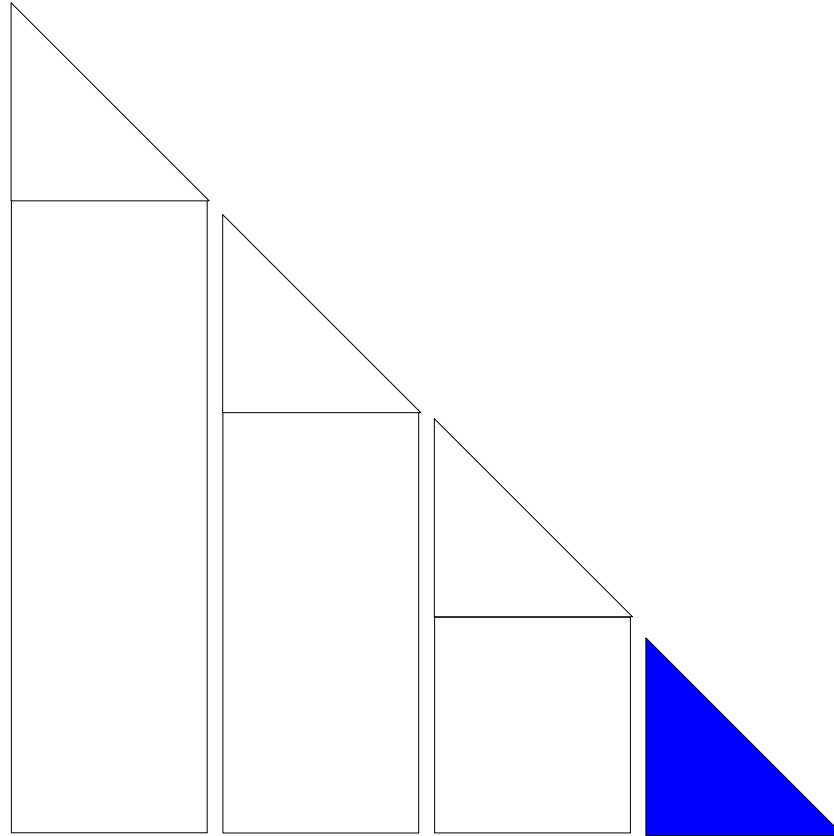
Cholesky, LAPACK

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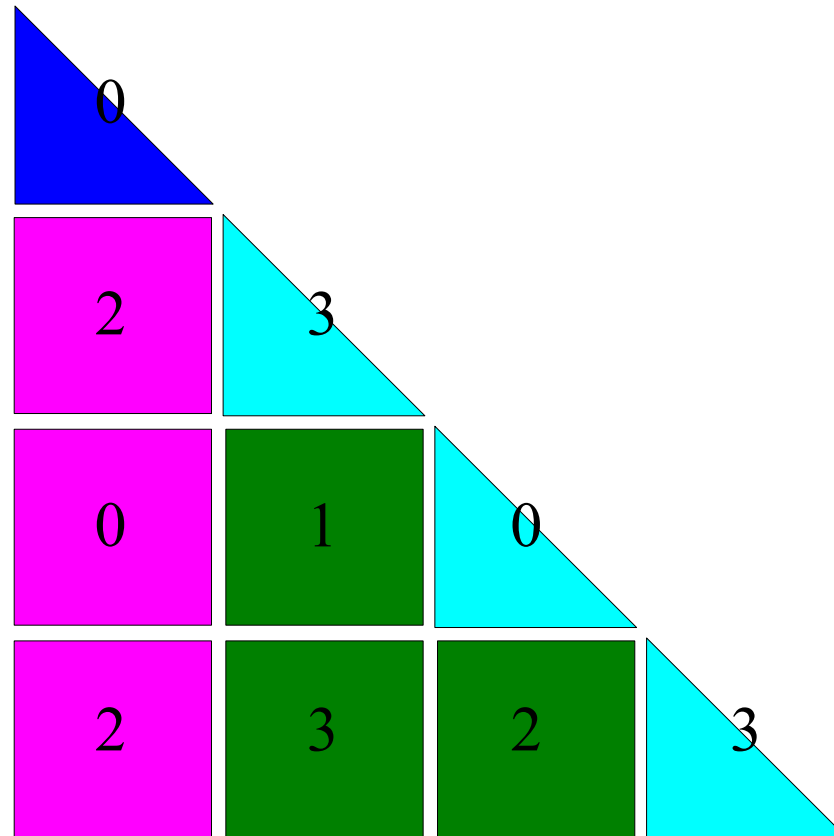
Cholesky, LAPACK

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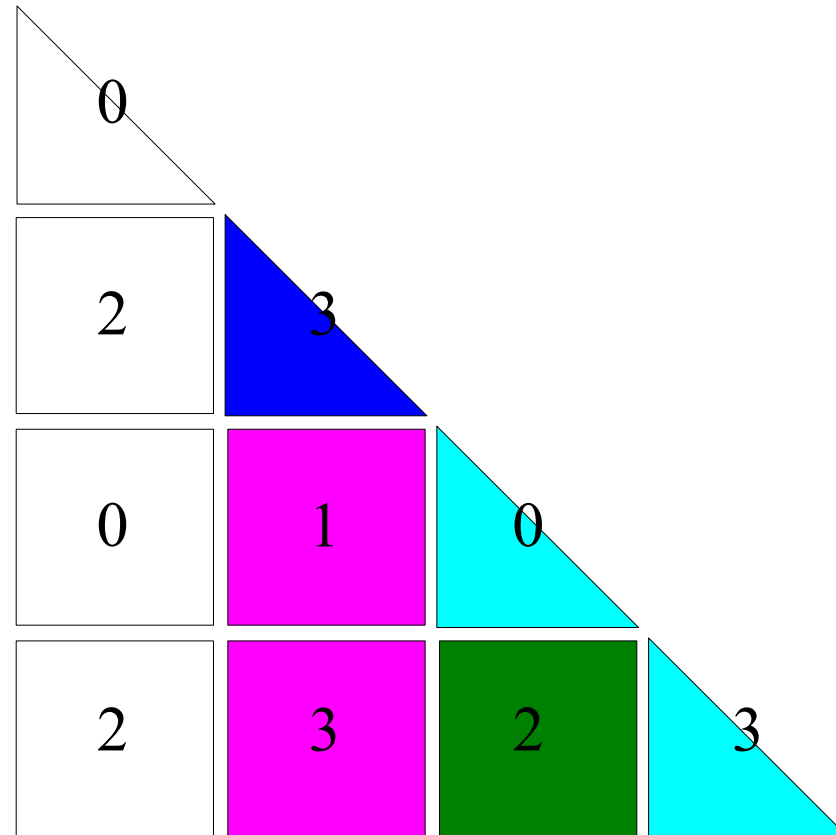
Cholesky, ScaLAPACK

Distributed Computers (late '90s-today), 2D-block-cyclic distribution



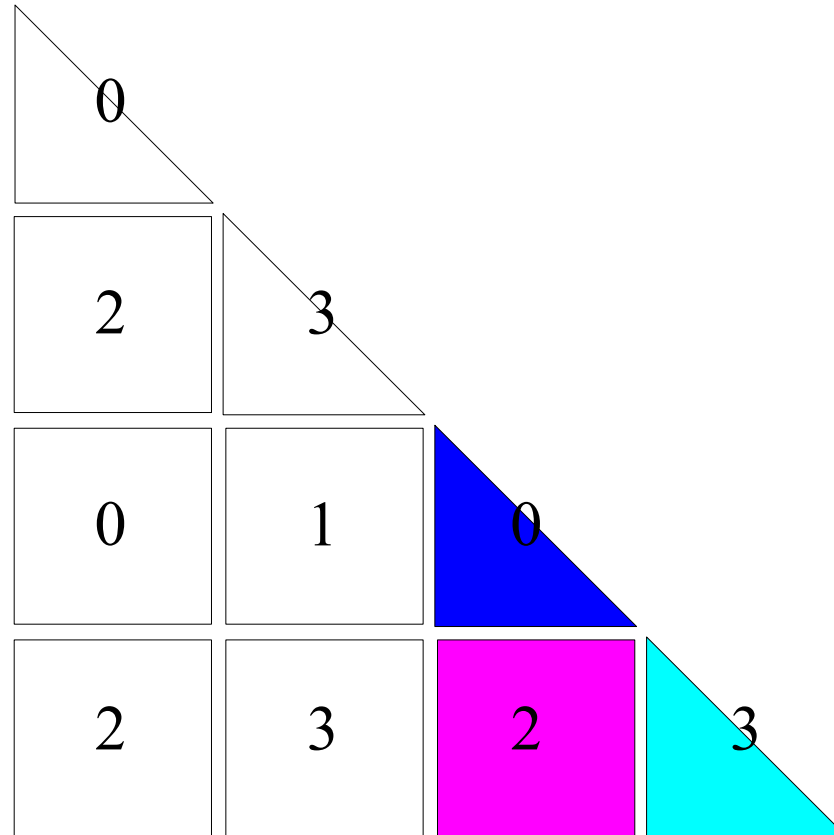
Cholesky, ScaLAPACK

Distributed Computers (late '90s-today), 2D-block-cyclic distribution



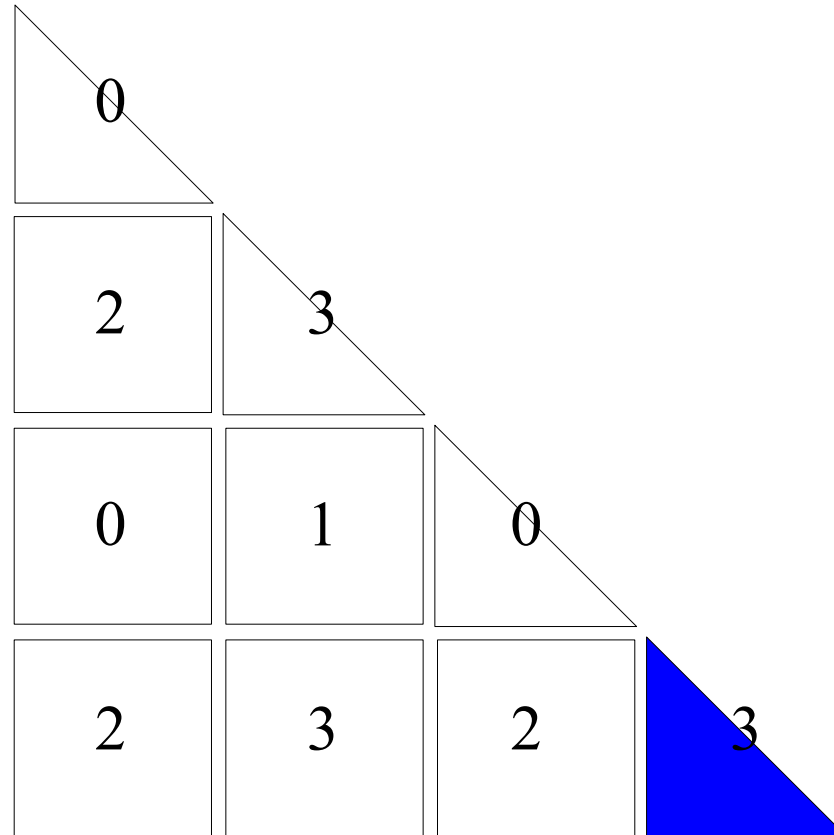
Cholesky, ScaLAPACK

Distributed Computers (late '90s-today), 2D-block-cyclic distribution



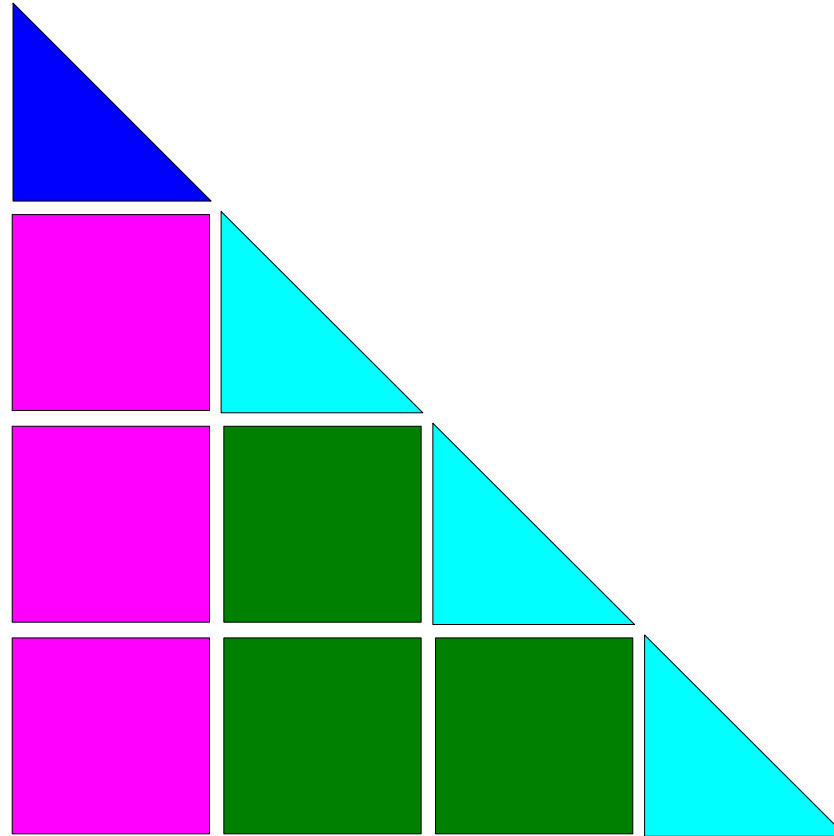
Cholesky, ScaLAPACK

Distributed Computers (late '90s-today), 2D-block-cyclic distribution



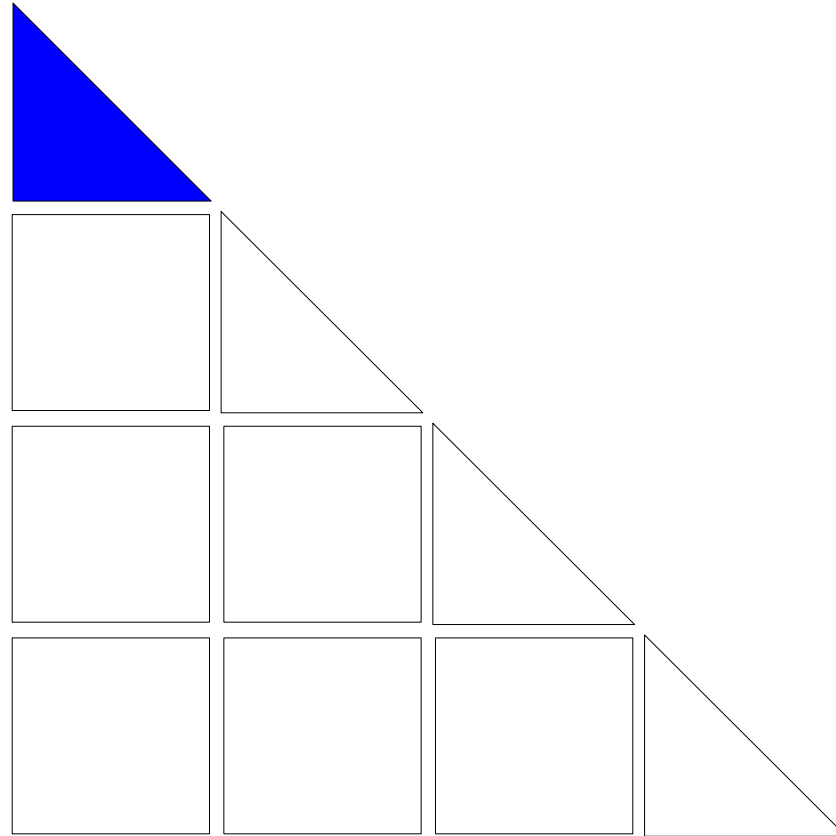
Cholesky, PLASMA

Task graph (~'08-today)



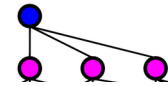
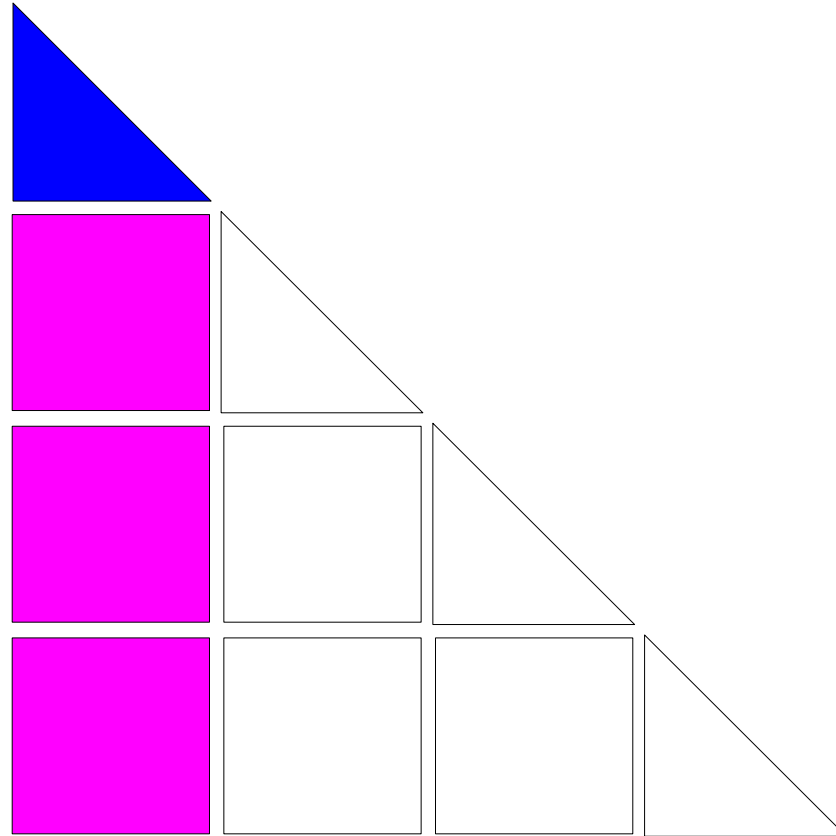
Cholesky, PLASMA

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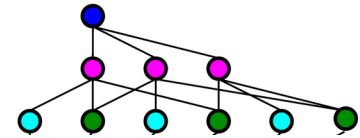
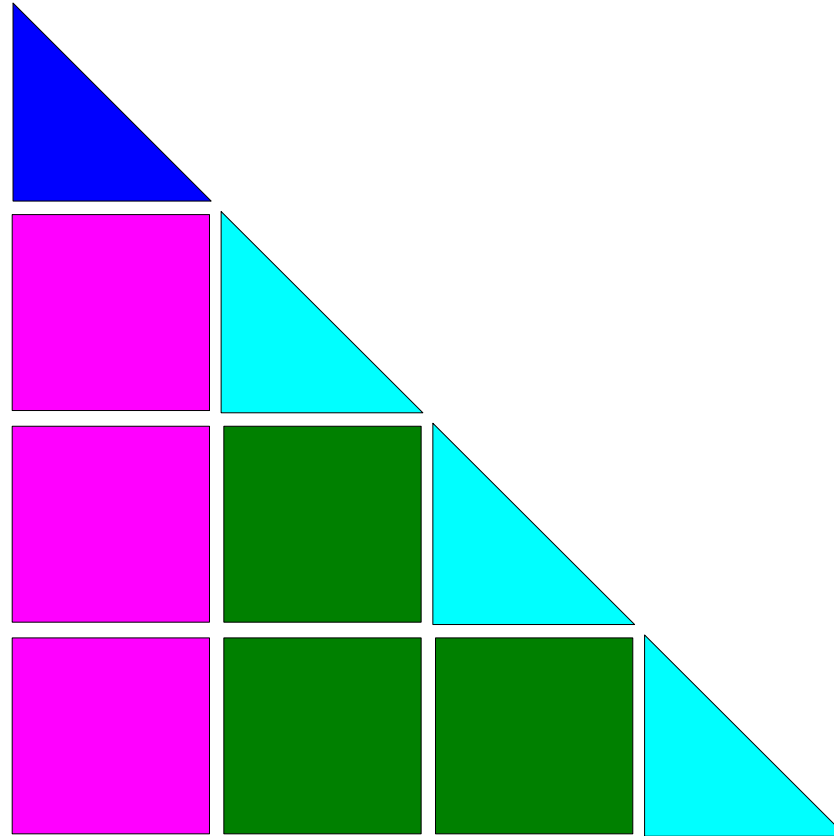
Cholesky, PLASMA

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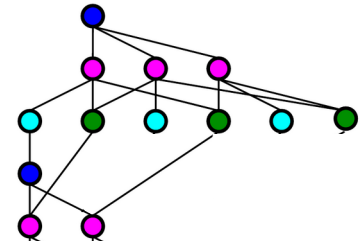
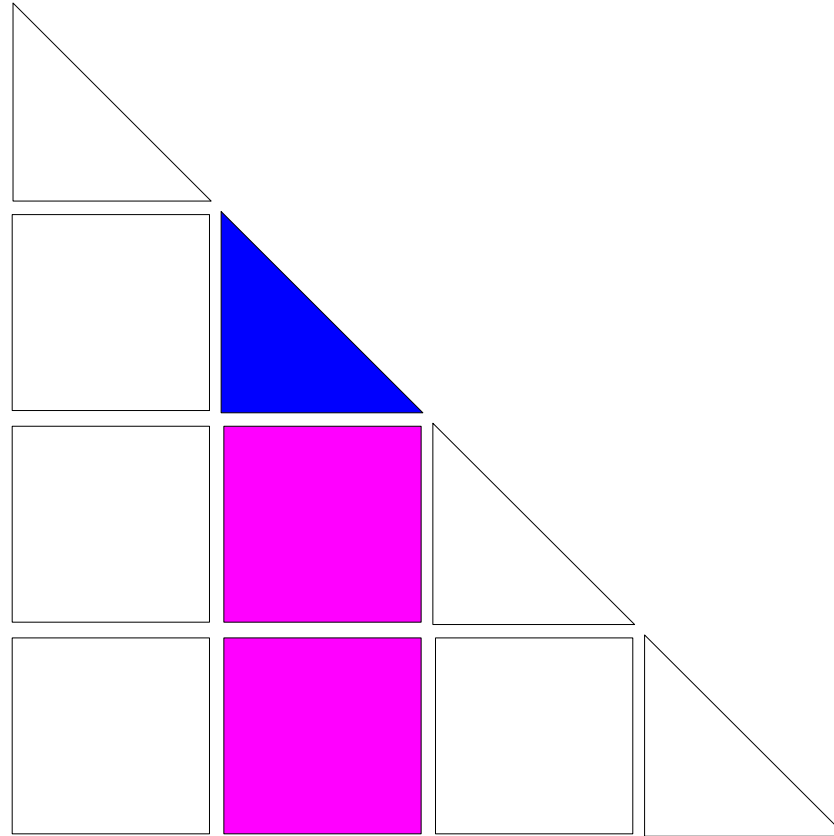
Cholesky, PLASMA

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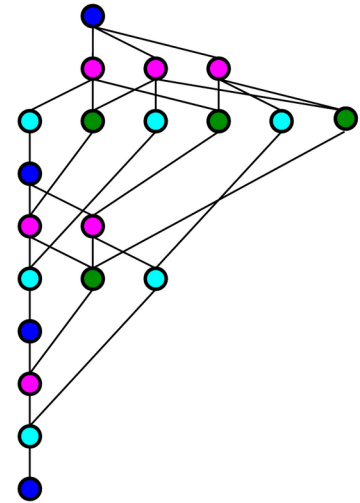
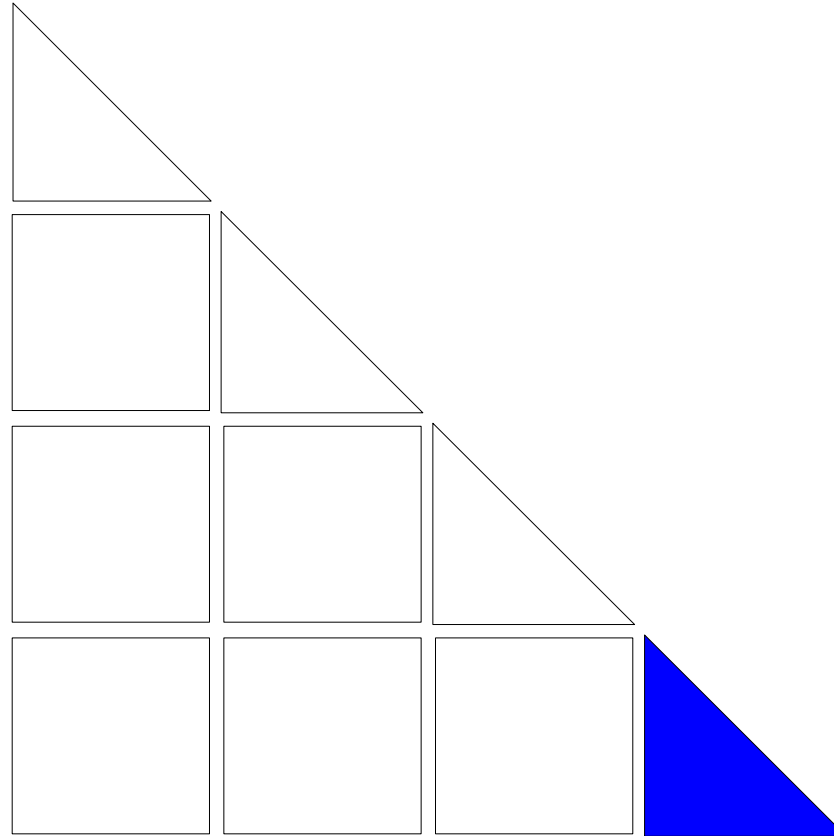
Cholesky, PLASMA

Task graph (~'08-today)



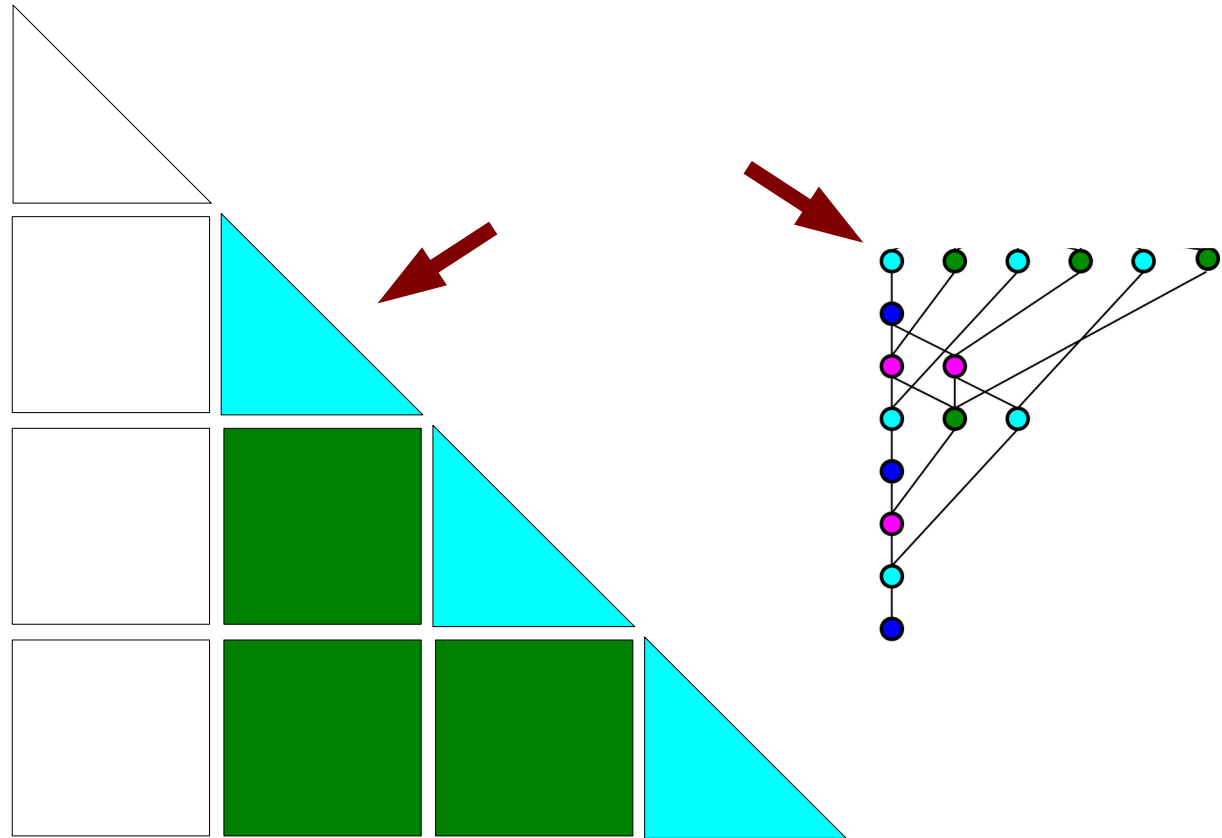
Cholesky, PLASMA

Task graph (~'08-today)



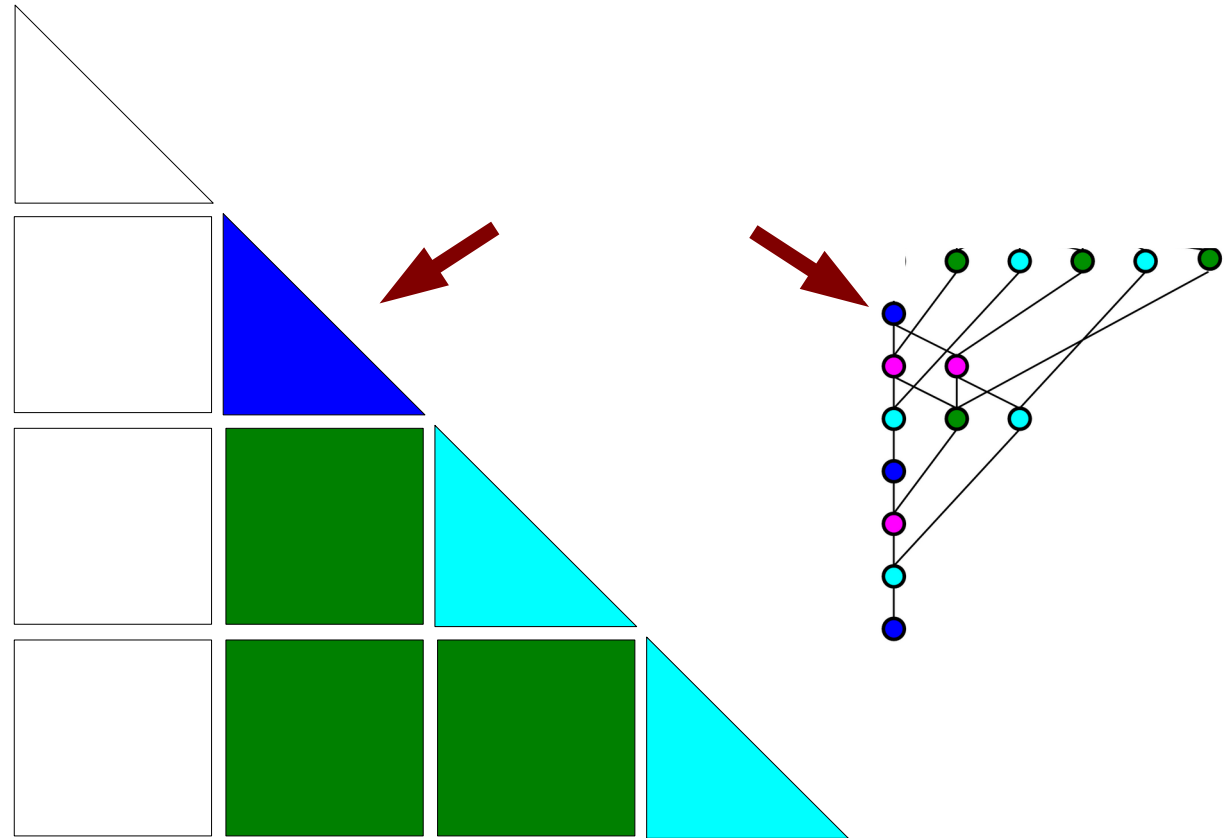
Cholesky, PLASMA

Task graph (~'08-today), **priorities**



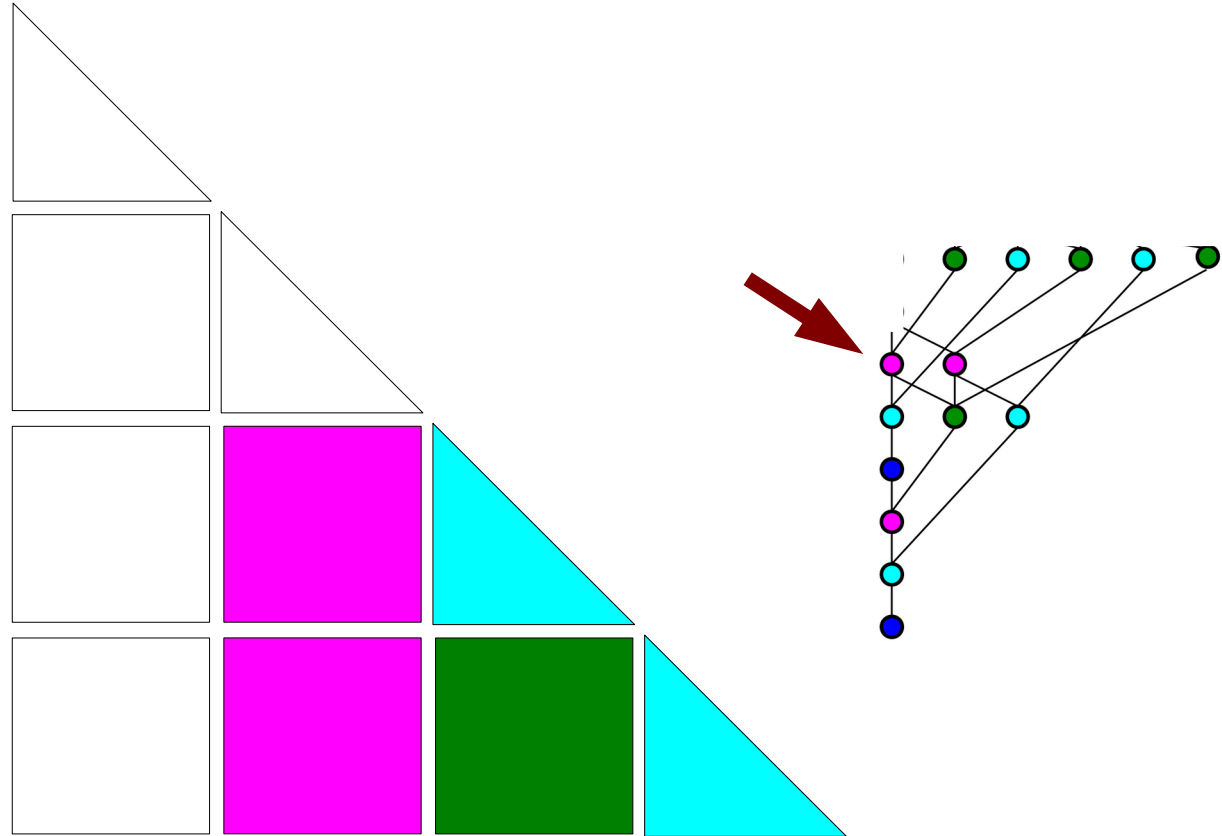
Cholesky, PLASMA

Task graph (~'08-today), **priorities**



Cholesky, PLASMA

Task graph (~'08-today), **priorities**



Task graphs in HPC

Runtime systems

- OmpSs, PARSEC, StarPU, SuperGlue/DuctTeip, XKaapi...

Standards

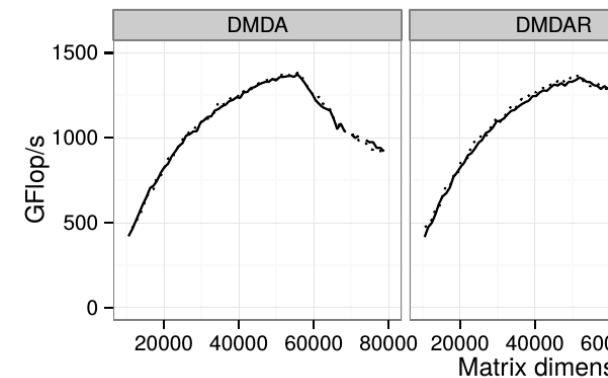
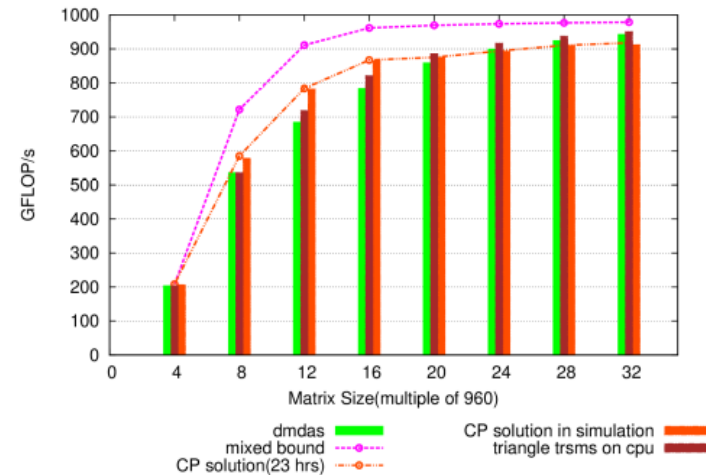
- OpenMP4.0 introduced task dependencies

Applications

- Chameleon, DPLASMA, SLATE for dense linear algebra
- qr_mumps, PaStiX for sparse linear algebra
- ScalFMM for FMM
- ...

Task-based support

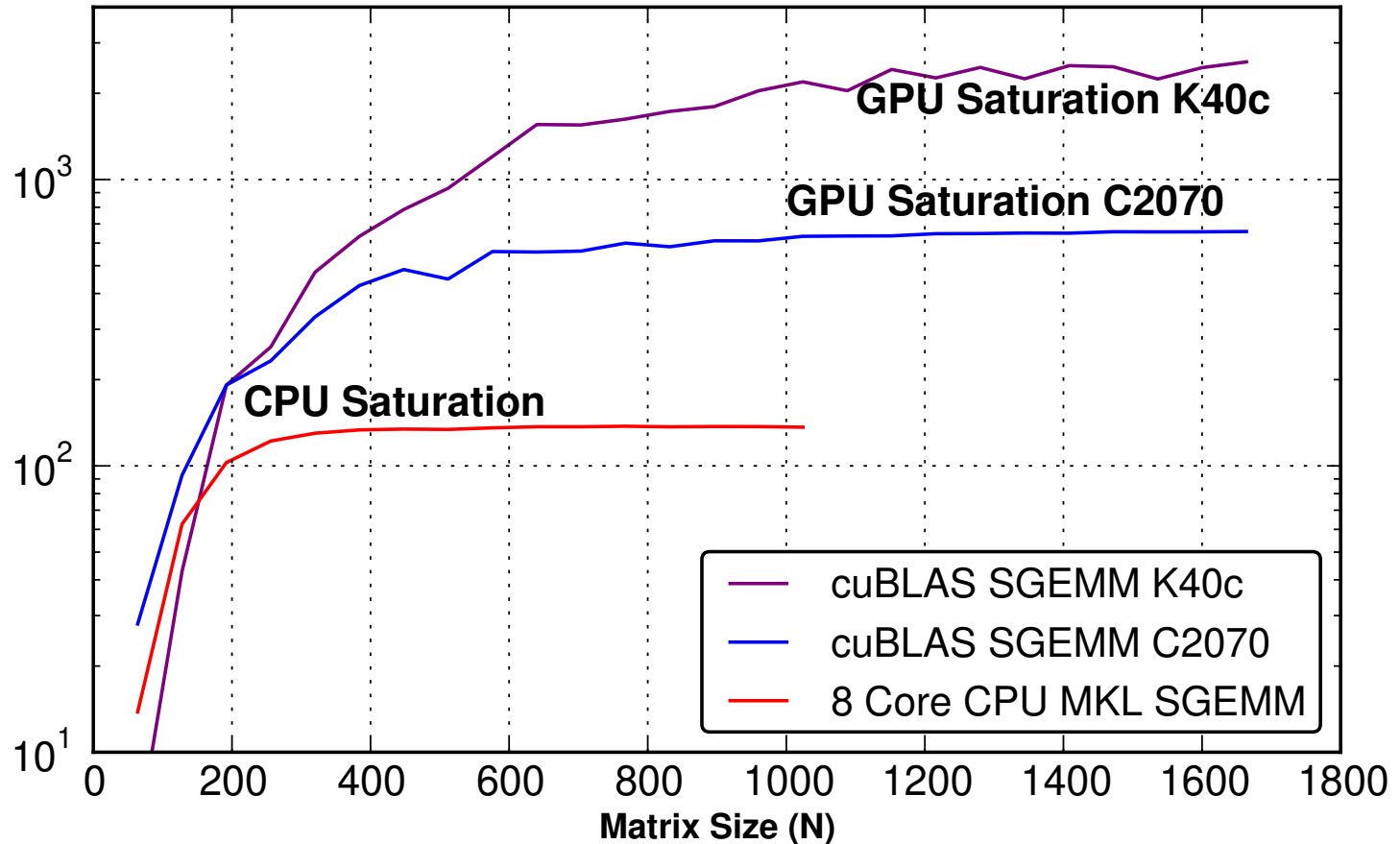
- Task/data scheduling
 - Load balancing
 - Data prefetching
 - Pipelining
 - GPU memory limitation management
- Distributed execution through MPI
- Out-of-core: optimized swapping to disk
- High-level performance analysis
- Performance bounds
- Debugging sequential execution
- Reproducible performance simulation



How big should a task be?

- Small enough to get parallelism to **feed** all processing units
- Large enough to **efficiently** use the processing units

How big should a task be?



From PARSEC : « Hierarchical DAG Scheduling for Hybrid Distributed Systems »,
Wu, Bouteiller, Bosilca, Faverge, Dongarra

How big should a task be?

GPUs

- Efficient only with large tile sizes

CPUs

- Need many tasks

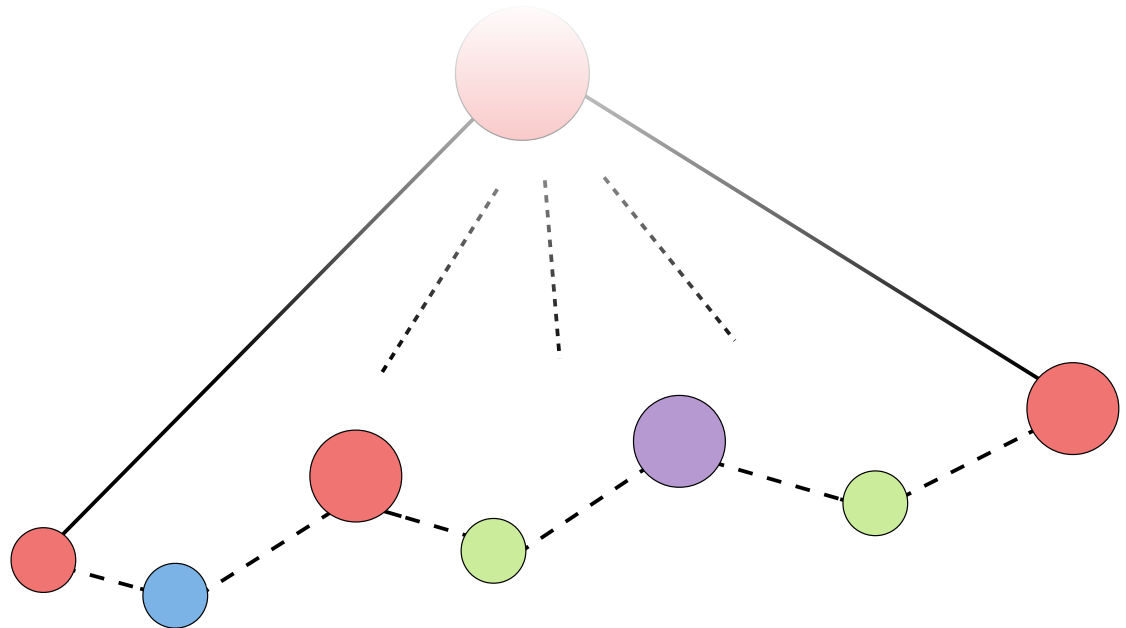
→ **Hybrid** task size

More generally, **hierarchical** task graphs

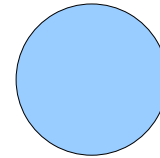
- Seen in CEA, OmpSs, PaRSEC, StarPU

Outline

- How big should a task be?
- Hierarchical task graphs
- Opportunities

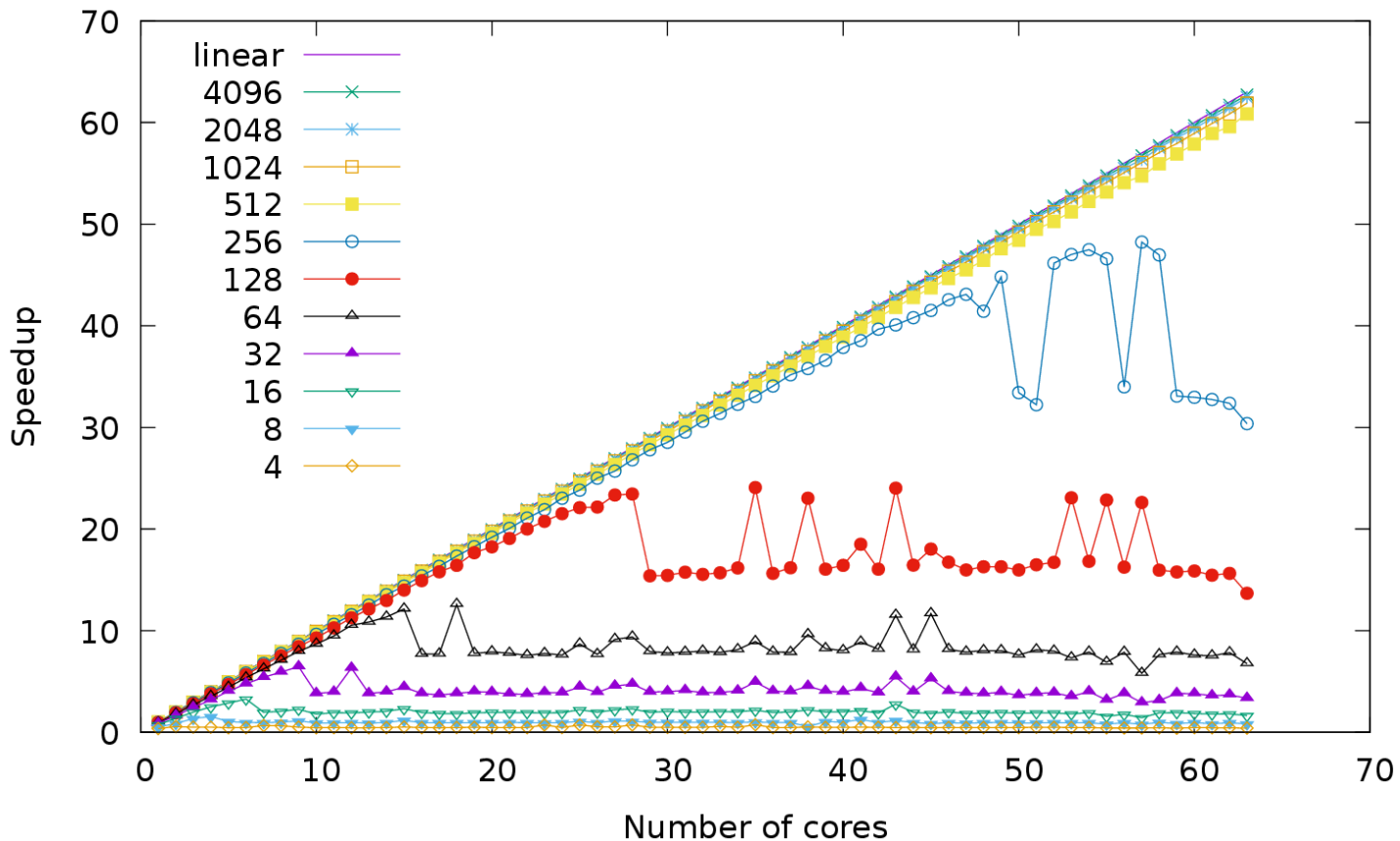


How big should a task be?

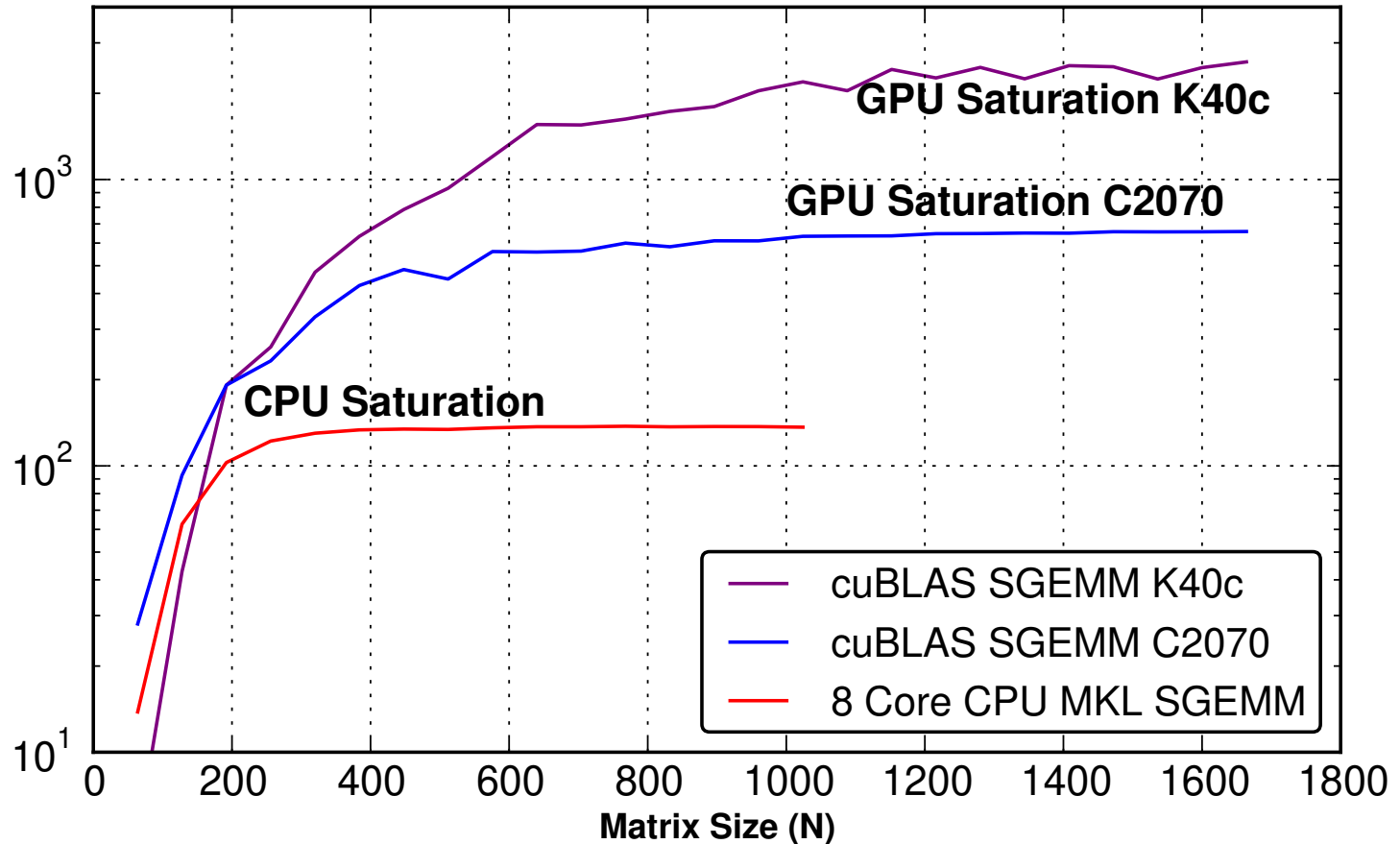


How big should a task be?

- Lower bound due to runtime overhead
 - Proposed by Martin Tillenius for DuctTeip (U. Uppsala)



How big should a task be?



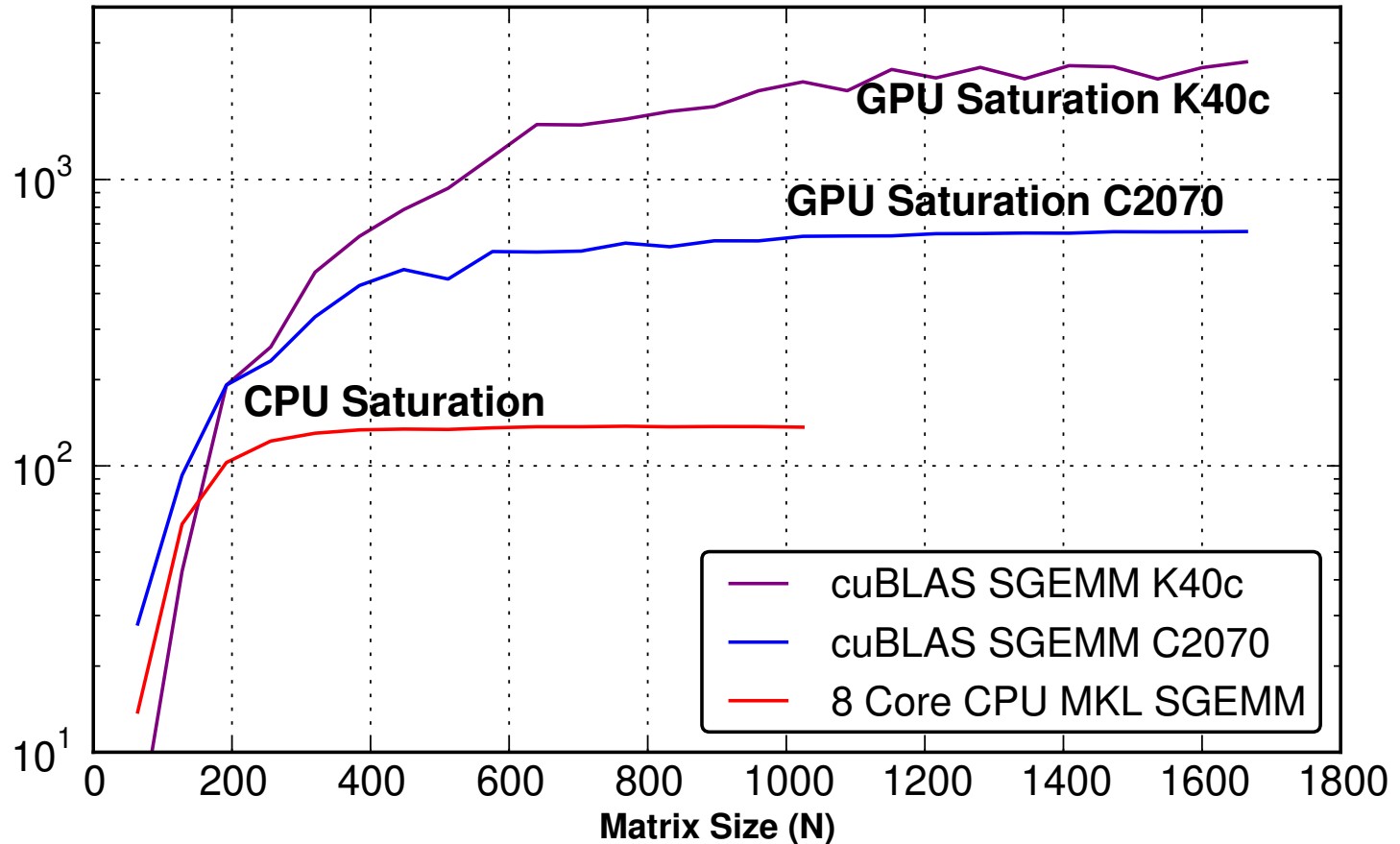
From PARSEC : « Hierarchical DAG Scheduling for Hybrid Distributed Systems »,
Wu, Bouteiller, Bosilca, Faverge, Dongarra

How big should a task be?

GPUs

- Have **thousands** for cores to feed
- Newer generations require yet larger sizes
- Can run several kernels at the same time
 - Still limited

How big should a task be?



From PARSEC : « Hierarchical DAG Scheduling for Hybrid Distributed Systems »,
Wu, Bouteiller, Bosilca, Faverge, Dongarra

How big should a task be?

CPUs

- Have many independent cores
 - Need many tasks
- Can use parallel implementations (e.g. from MKL)
 - But better have subtasks to interleave them

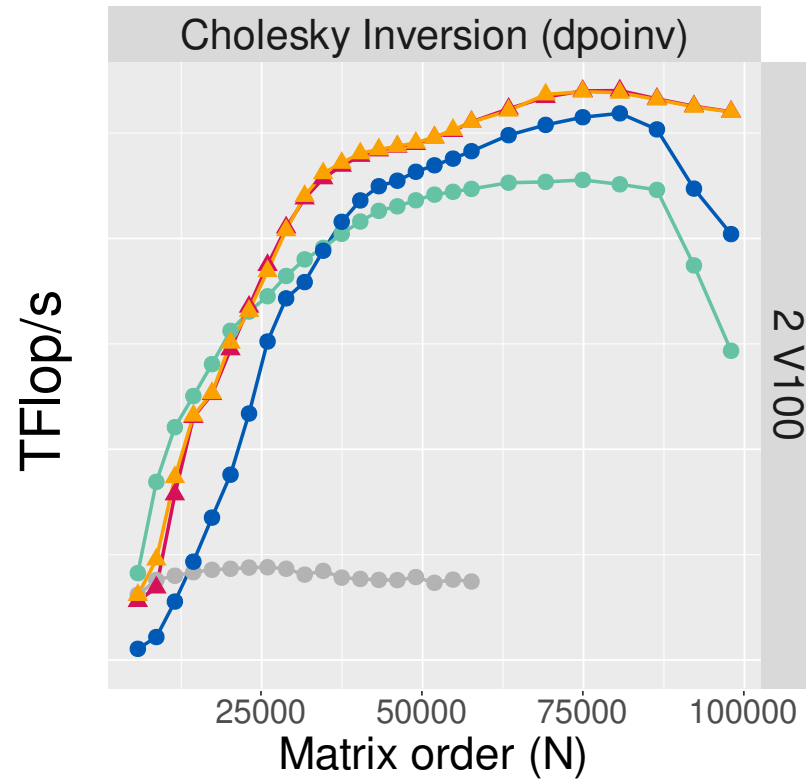
How big should a task be?

How size does not fit all

Gwenolé Lucas experimented with Chameleon

- Cholesky inversion
- 2 NVIDIA V100
- 2 Xeon Gold 6142
- Different matrix tile sizes : 2880 / 960 / 320

Hybrid tile sizes



Version: Tile sizes

● Non-Hierarchical: 2880
● Non-Hierarchical: 960
● Non-Hierarchical: 320

▲ Hierarchical: 2880 / 960
▲ Hierarchical: 2880 / 960 / 320

How big should a task be?

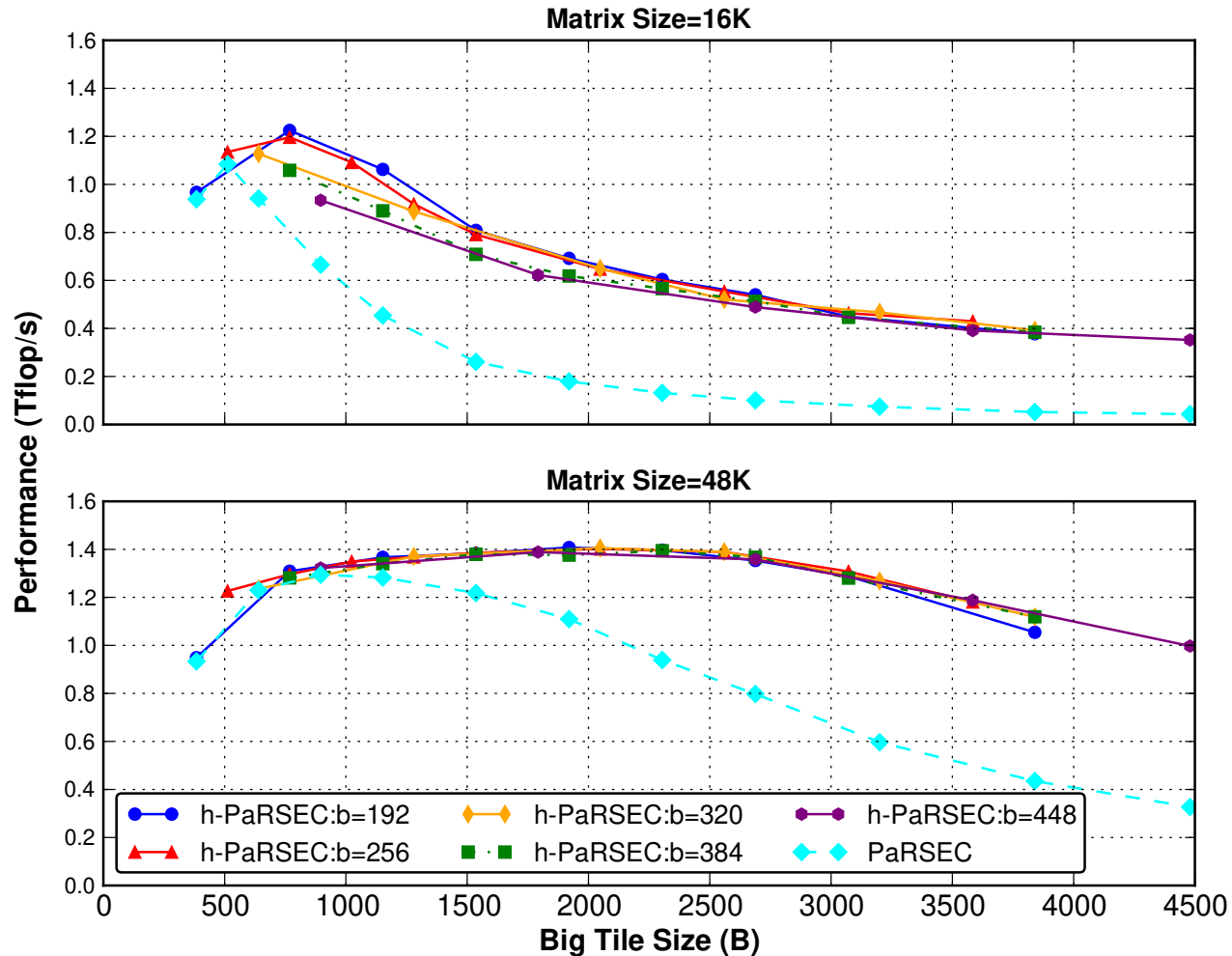
Tuning the tile size?

- B = “big” tile size, for GPUs
 - Large enough for GPUs
 - Not too large for parallelism

- b = “small” tile size, for CPUs
 - Large enough for CPUs
 - Not too large for parallelism

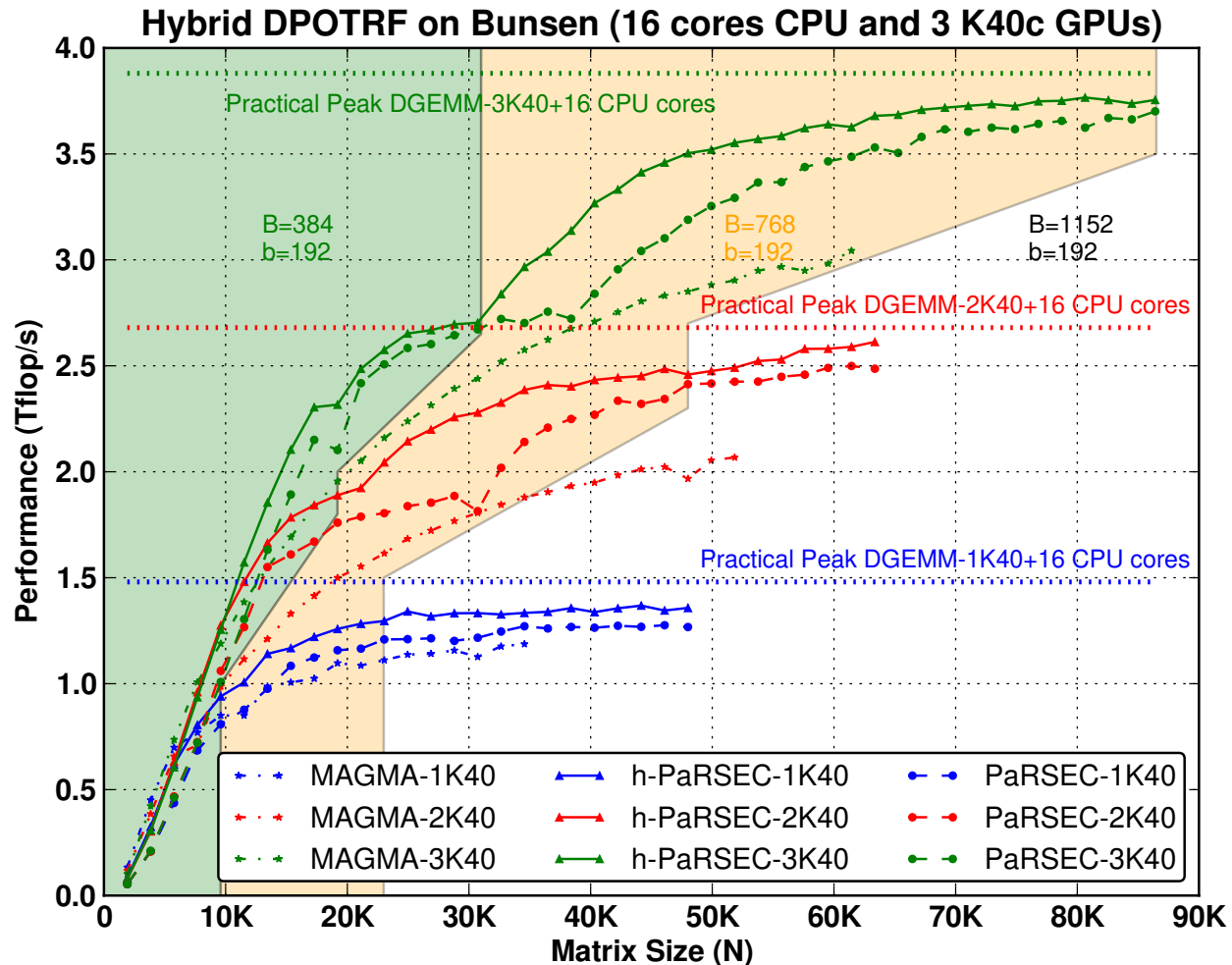
With Parsec, Wu, Bouteiller, Bosilca, Faverge and Dongarra experimented tuning

How big should a task be?



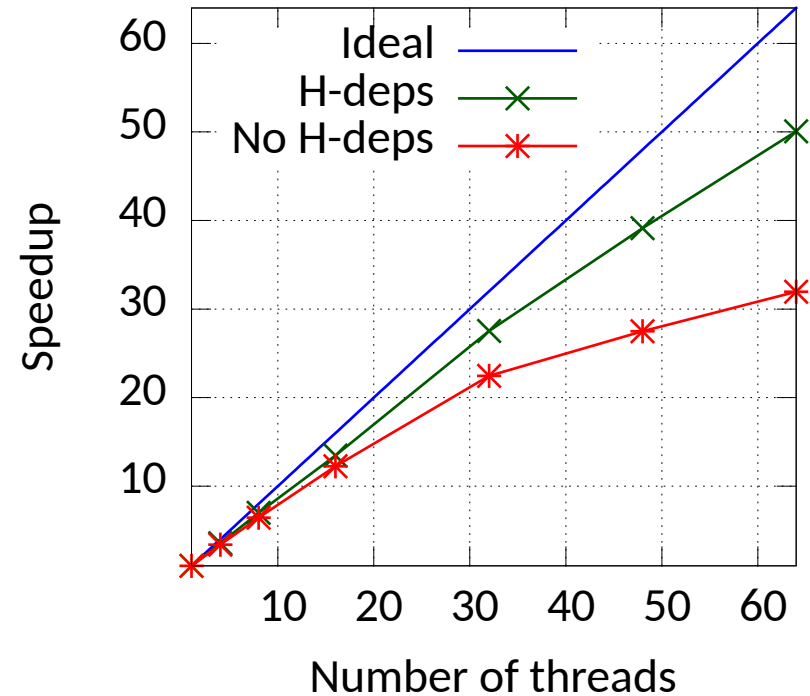
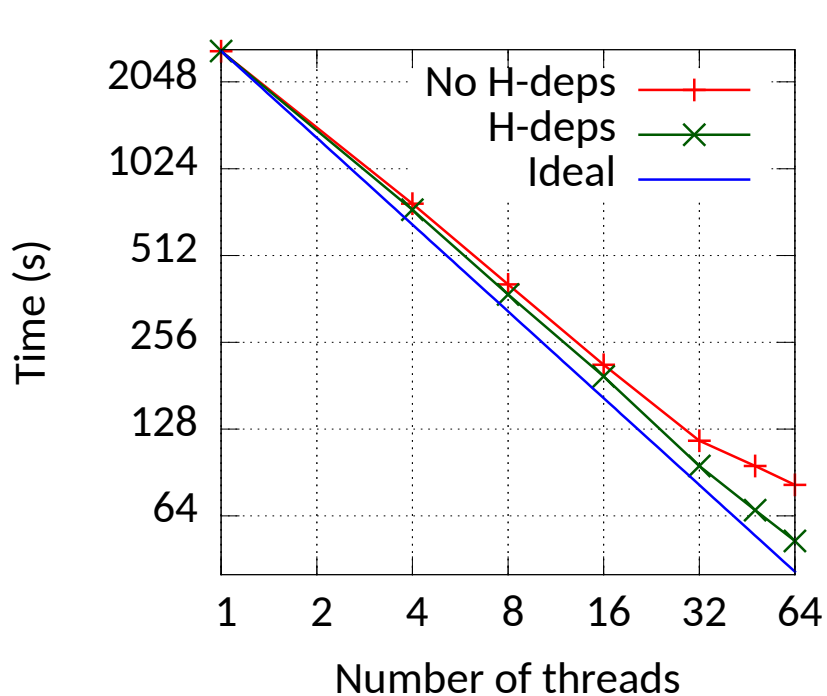
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How big should a task be?



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How big should a task be?



From CEA : « A hierarchical fast direct solver for distributed memory machines with manycore nodes », Augonnet, Goudin, Kuhn, Lacoste, Namyst, Ramet

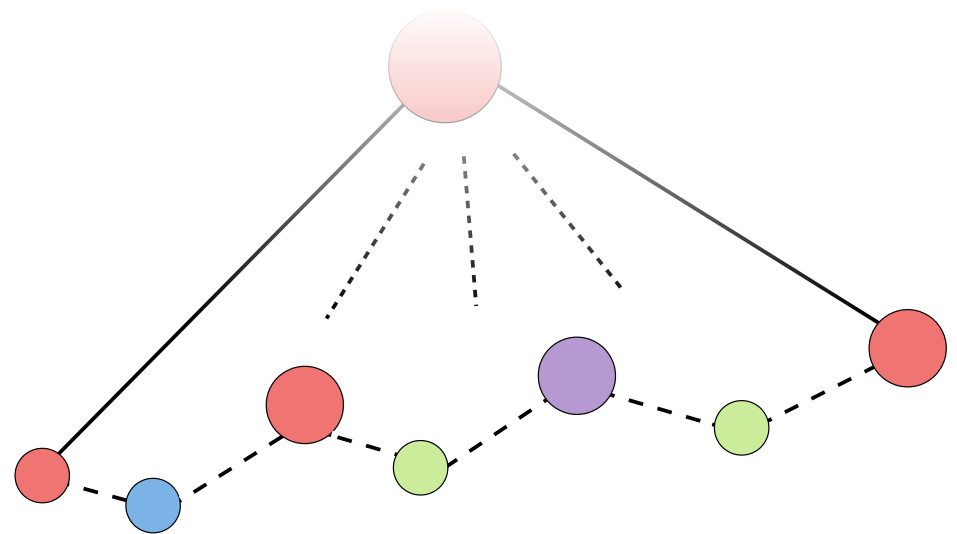
How big should a task be?

Multiple answers

- Depends on available platform parallelism
- Depends on available application parallelism
- Depends on application phases

Automatically adapt?

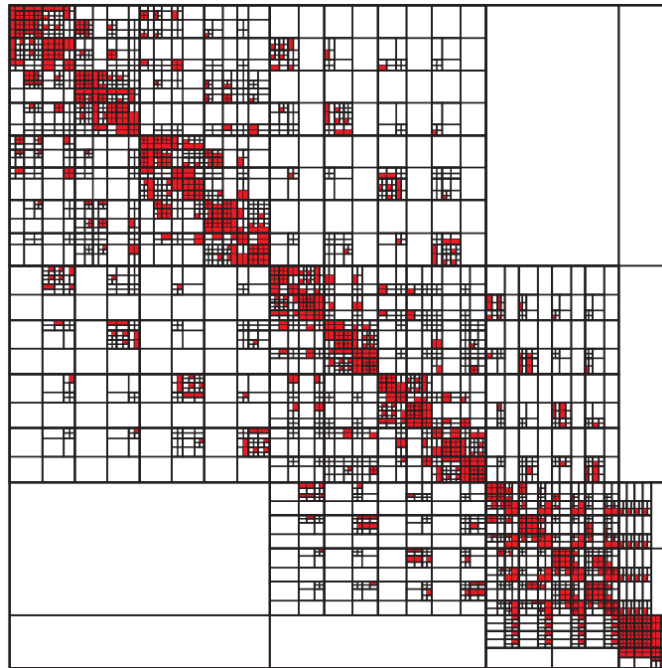
Hierarchical task graphs



Hierarchical task graphs

Applications themselves are recursive

- e.g. h-matrices

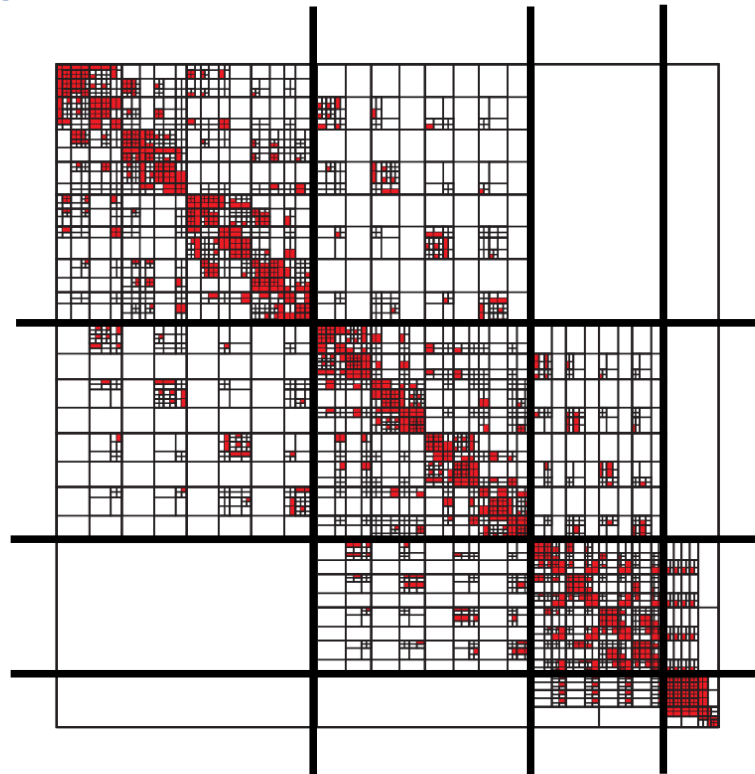


From Airbus Group

Hierarchical task graphs

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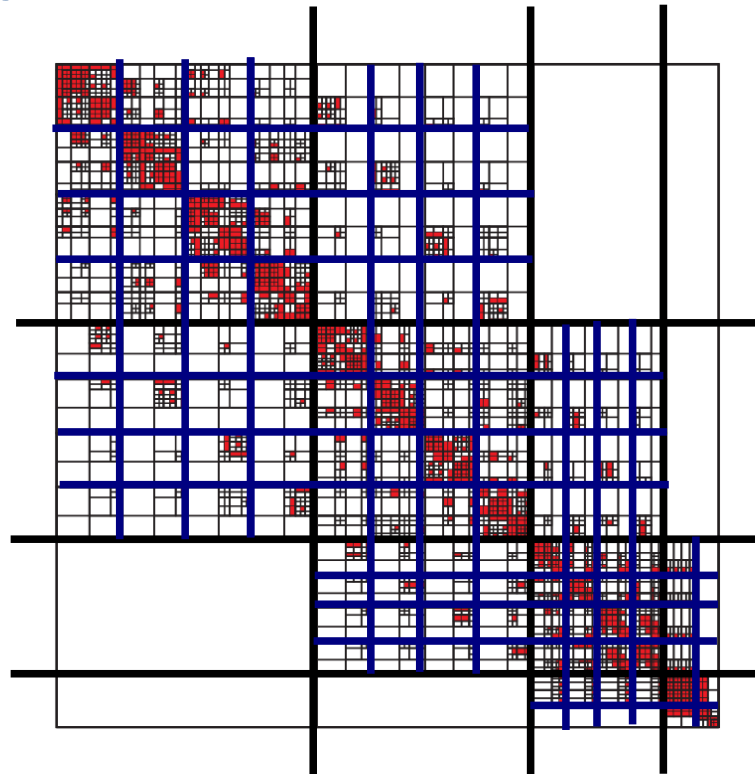


From Airbus Group

Hierarchical task graphs

Applications themselves are recursive

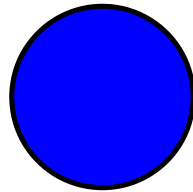
- e.g. h-matrices



From Airbus Group

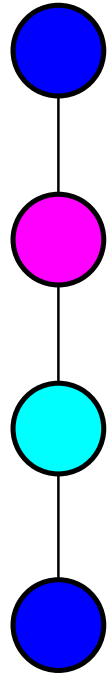
Hierarchical task graphs

Ideally, should just start with one huge task, and split



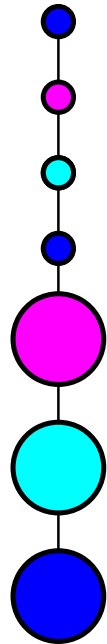
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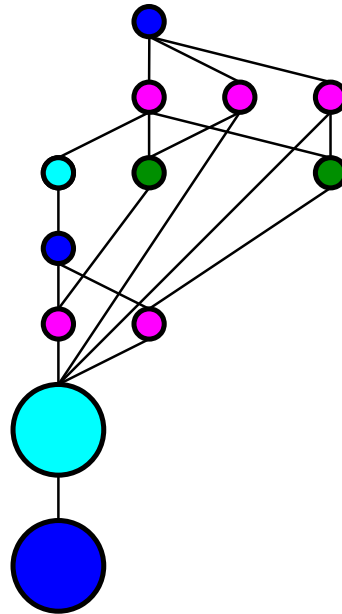
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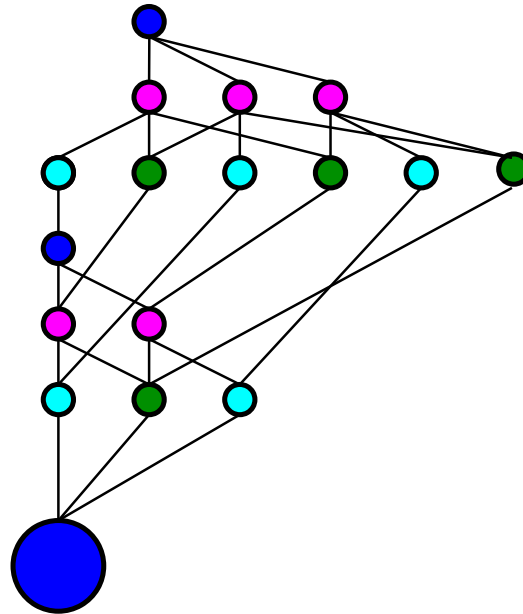
Hierarchical task graphs

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Hierarchical task graphs

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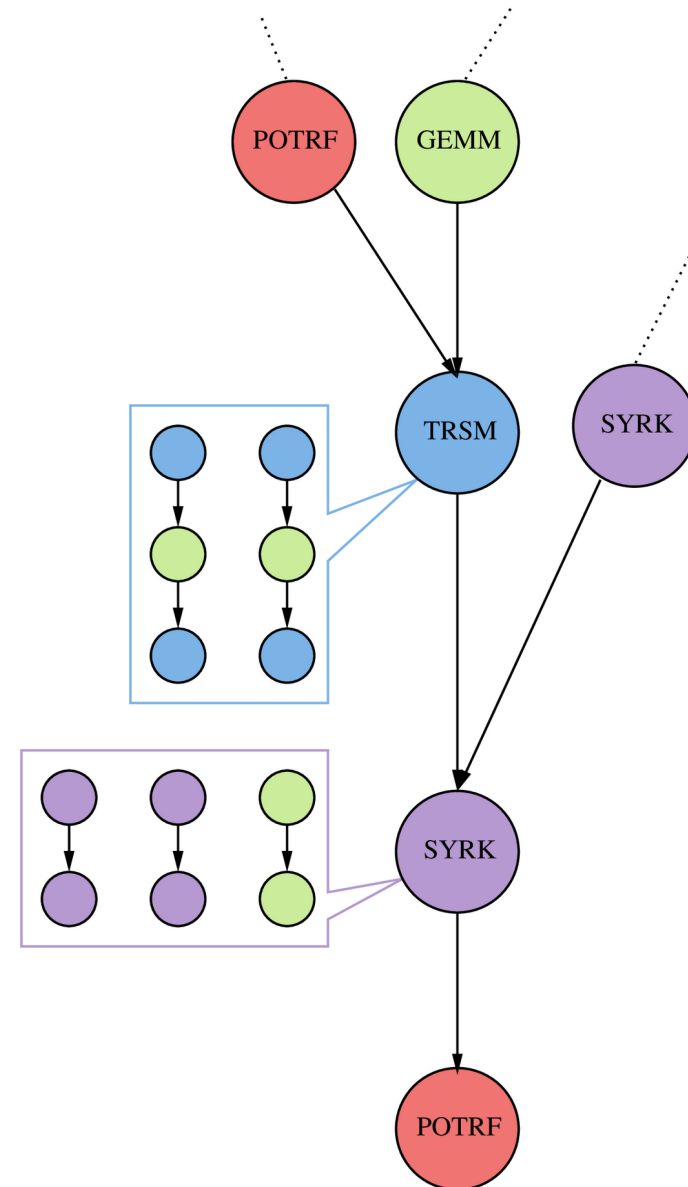
Hierarchical task graphs

- In OpenMP?

```

TRSM(A, B) {
#pragma omp task depend(in:A, inout:B) wait
{
#pragma omp task \
    depend(in:A[0][0], inout:B[0][0])
    TRSM(A[0][0], B[0][0])
#pragma omp task \
    depend(in:A[0][0], inout:B[1][0])
    TRSM(A[0][0], B[1][0])
#pragma omp task \
    depend(in:A[1][0], in:B[0][0], inout:B[0][1])
    GEMM(A[1][0], B[0][0], B[0][1])
...

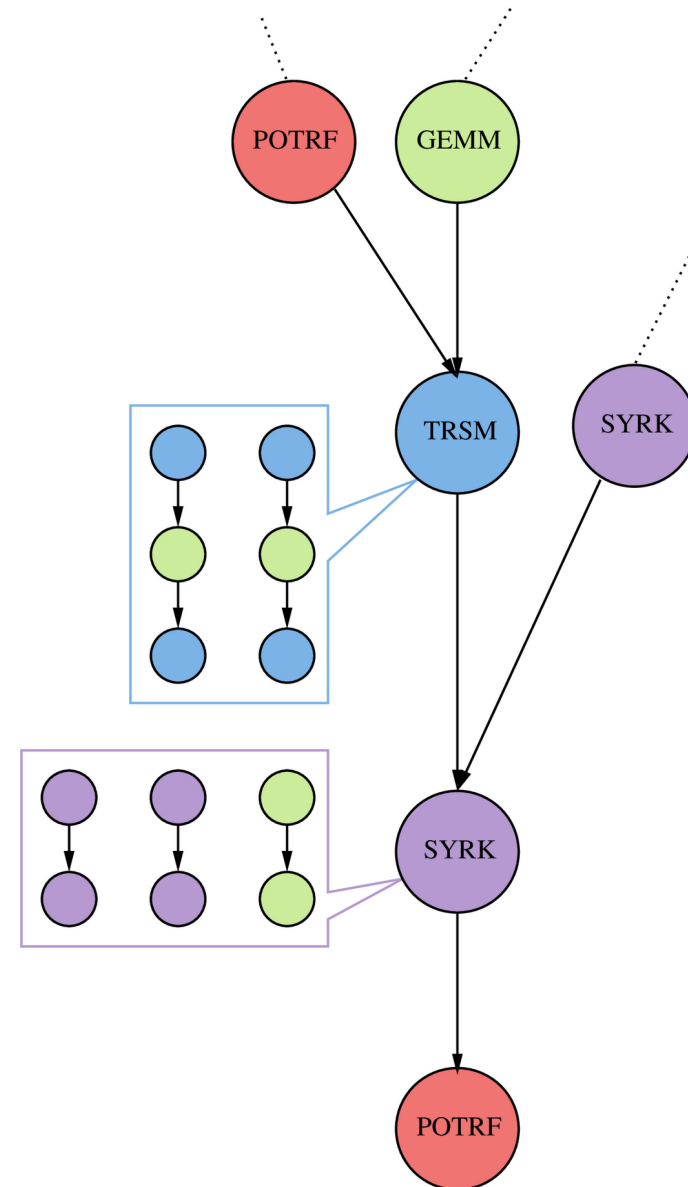
```



Hierarchical task graphs

Synchronization concerns

- Fork-join parallelism
- Hindered by synchronization induced by task graph



Hierarchical task graphs

- OmpSs introduced weak dependencies

```
TRSM(A, B) {
```

```
#pragma omp task depend(weakin:A, weakinout:B) \
```

```
    weakwait
```

```
{
```

```
#pragma omp task \
```

```
    depend(in:A[0][0], inout:B[0][0])
```

```
    TRSM(A[0][0], B[0][0])
```

```
#pragma omp task \
```

```
    depend(in:A[0][0], inout:B[1][0])
```

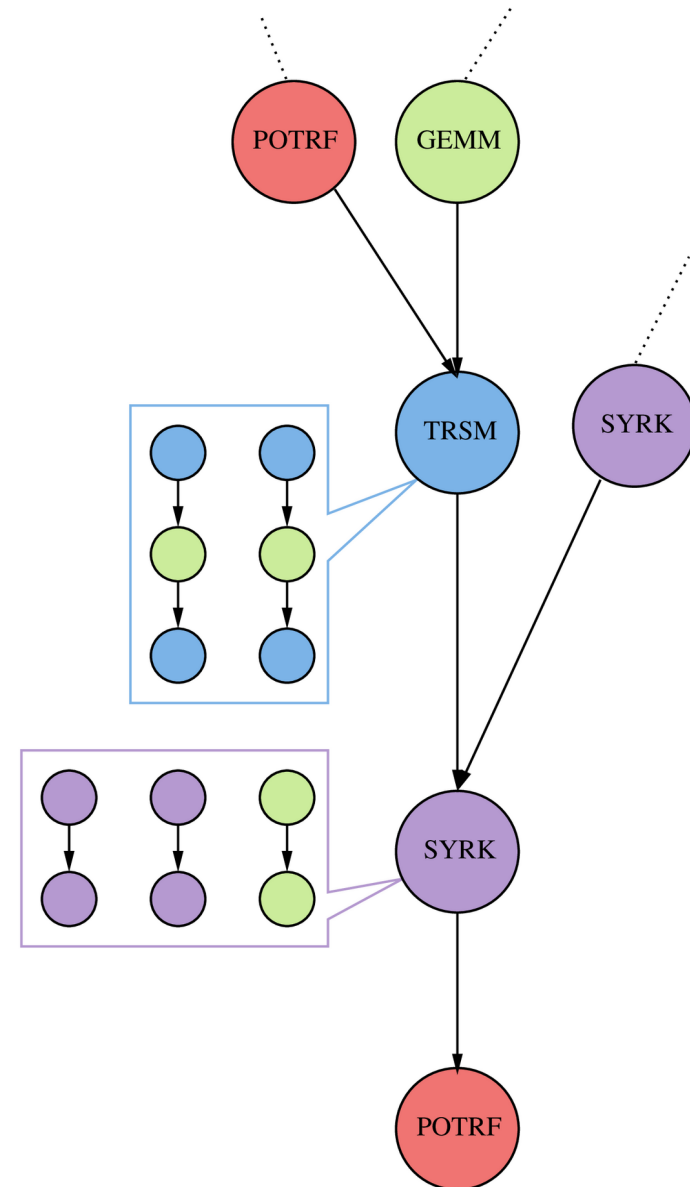
```
    TRSM(A[0][0], B[1][0])
```

```
#pragma omp task \
```

```
    depend(in:A[1][0], in:B[0][0], inout:B[0][1])
```

```
    GEMM(A[1][0], B[0][0], B[0][1])
```

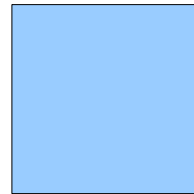
```
...
```



Hierarchical task graphs

In StarPU

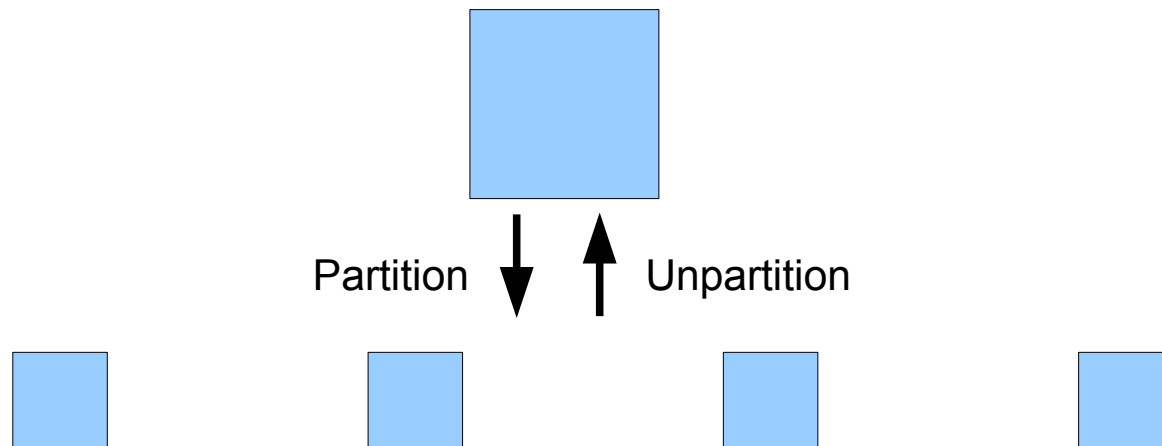
- Explicit data registration
- Recursive partitioning



Hierarchical task graphs

In StarPU

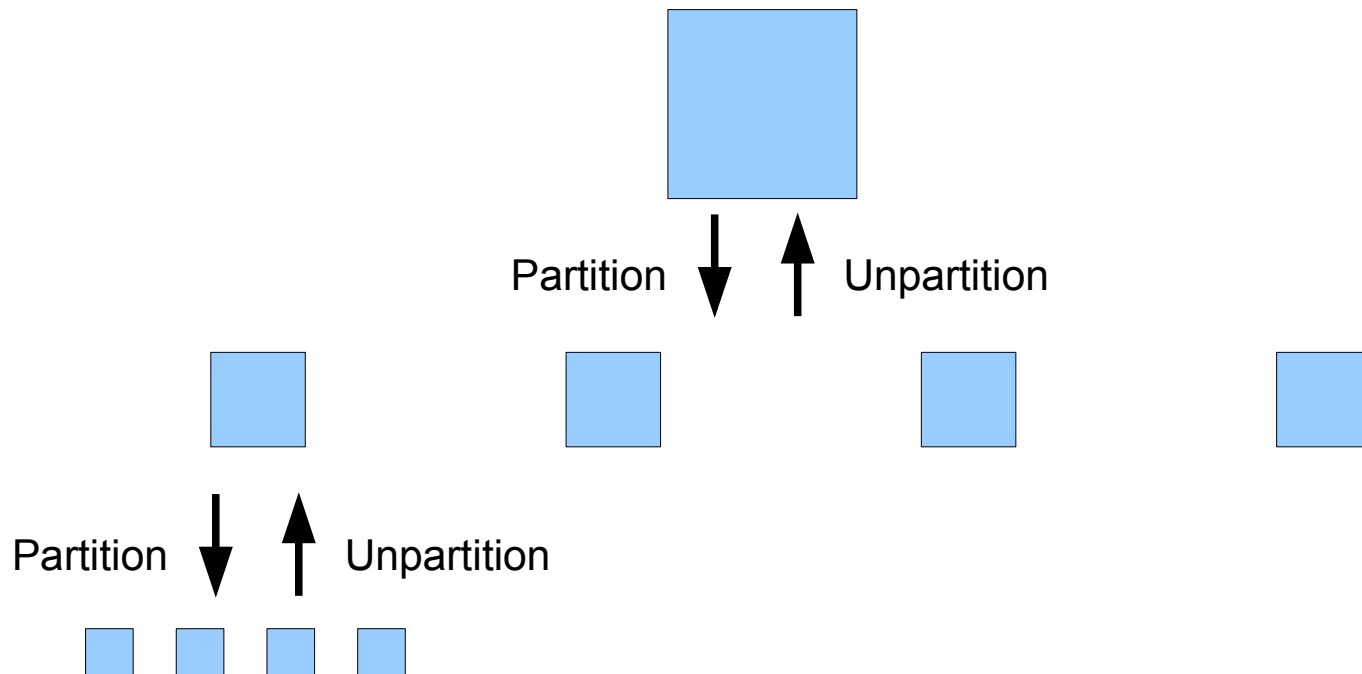
- Explicit data registration
- Recursive partitioning



Hierarchical task graphs

In StarPU

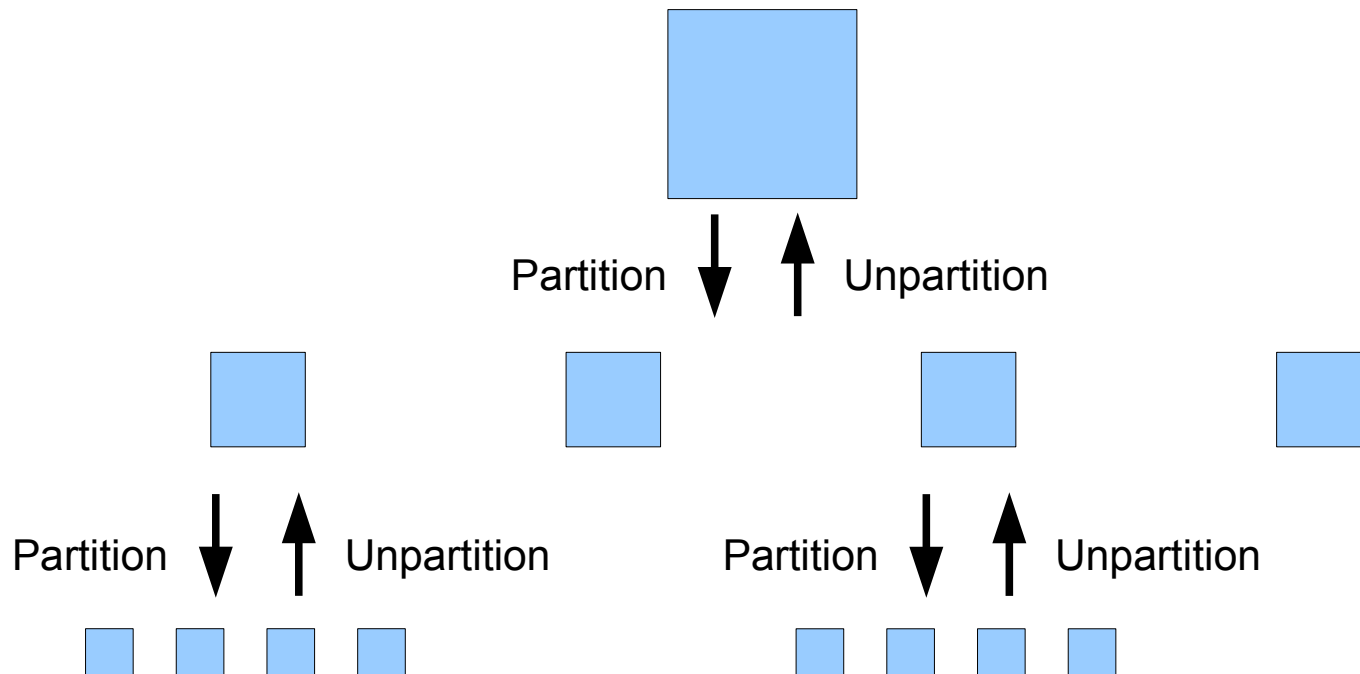
- Explicit data registration
- Recursive partitioning



Hierarchical task graphs

In StarPU

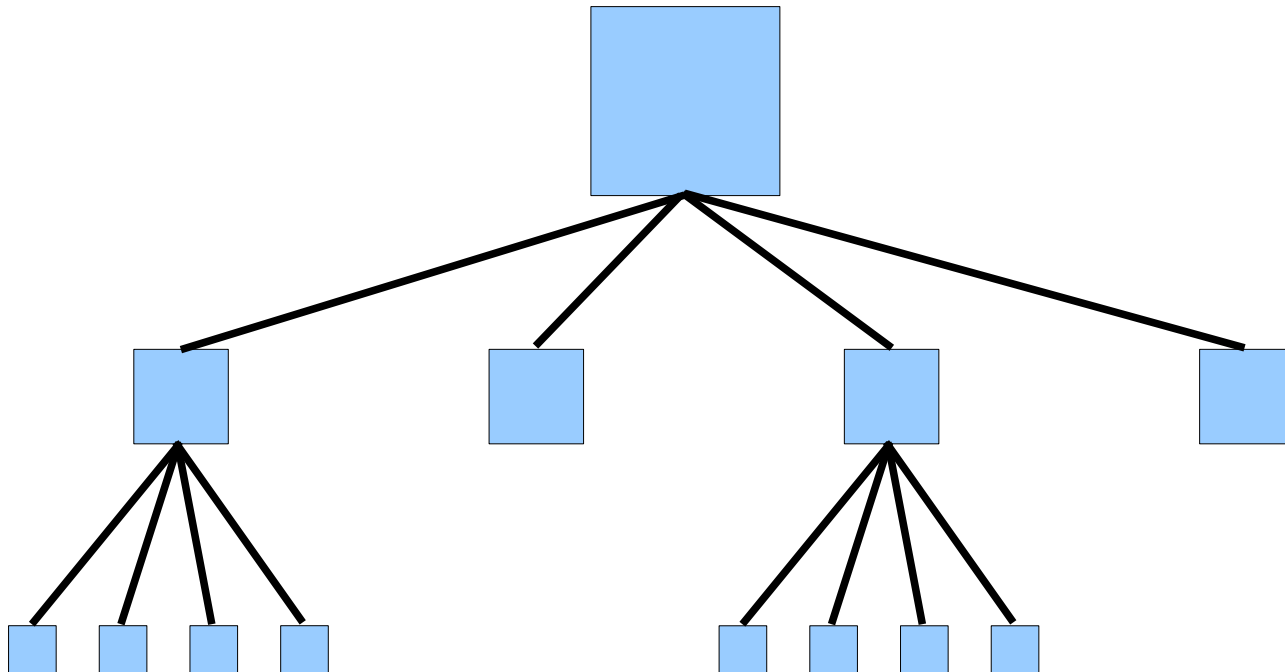
- Explicit data registration
- Recursive partitioning



Hierarchical task graphs

In StarPU

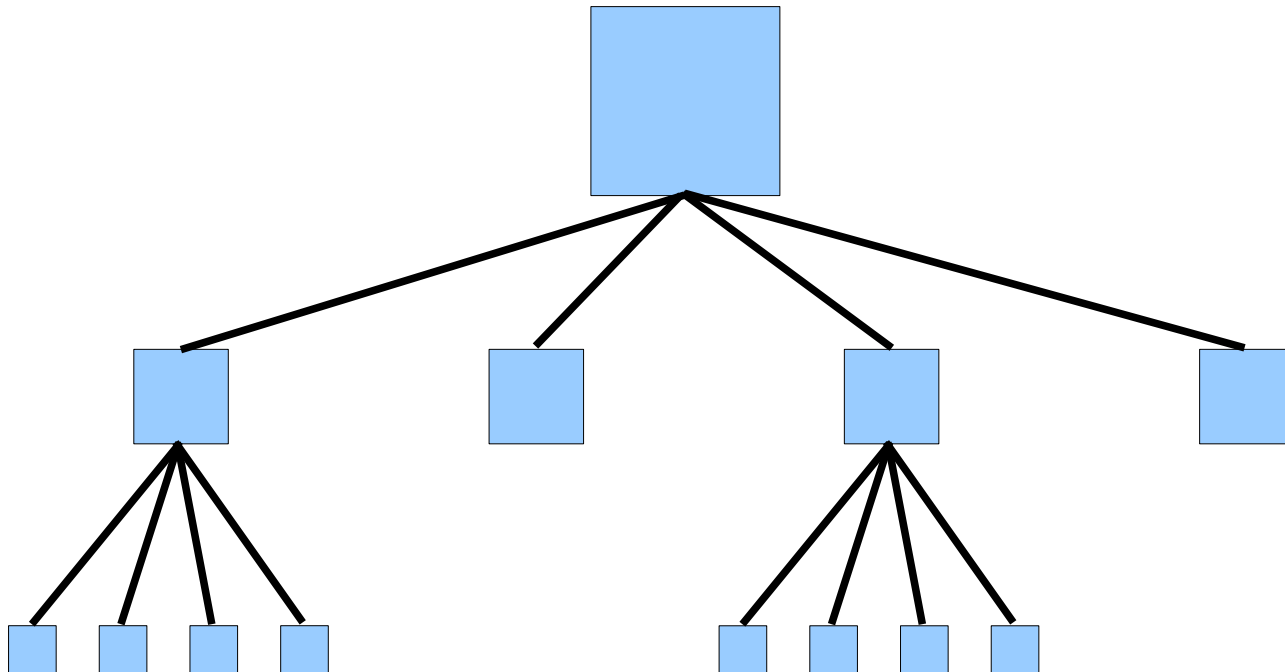
- Explicit data registration
- Recursive partitioning



Hierarchical task graphs

In StarPU

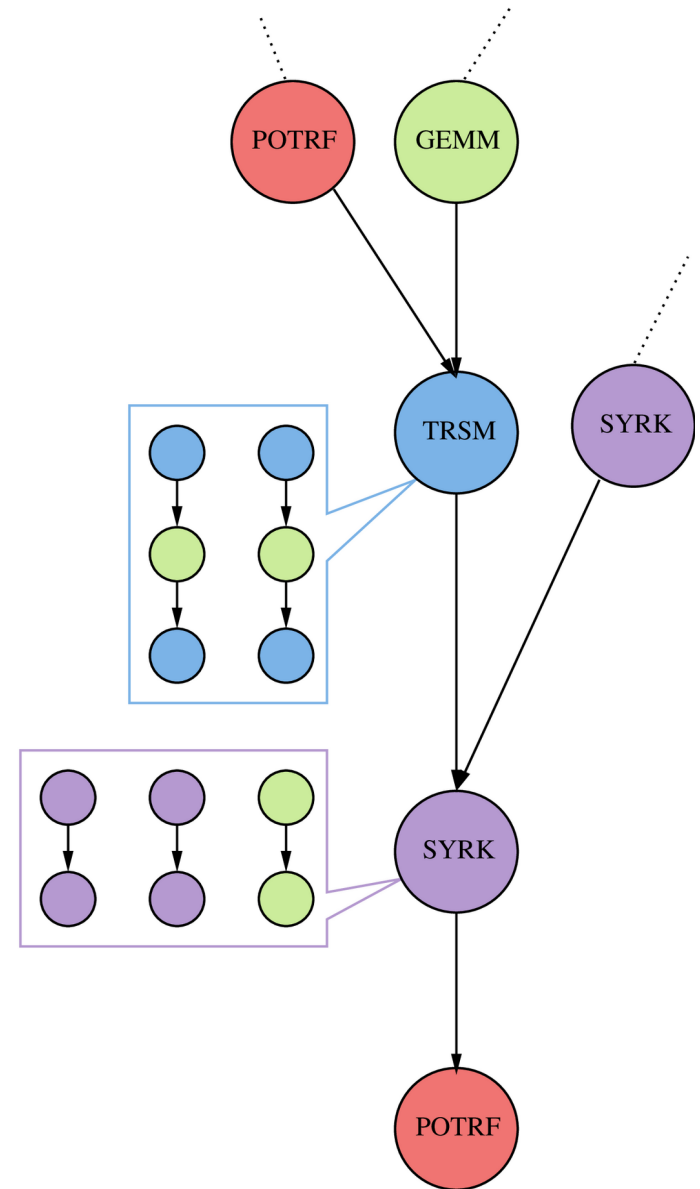
- Multi-level data coherency, among CPUs-GPUs-disk
- Enables seamless recursive tasks
- More details in Gwenolé Lucas' talk Thursday 14:40



Hierarchical task graphs

Multi-level data coherency

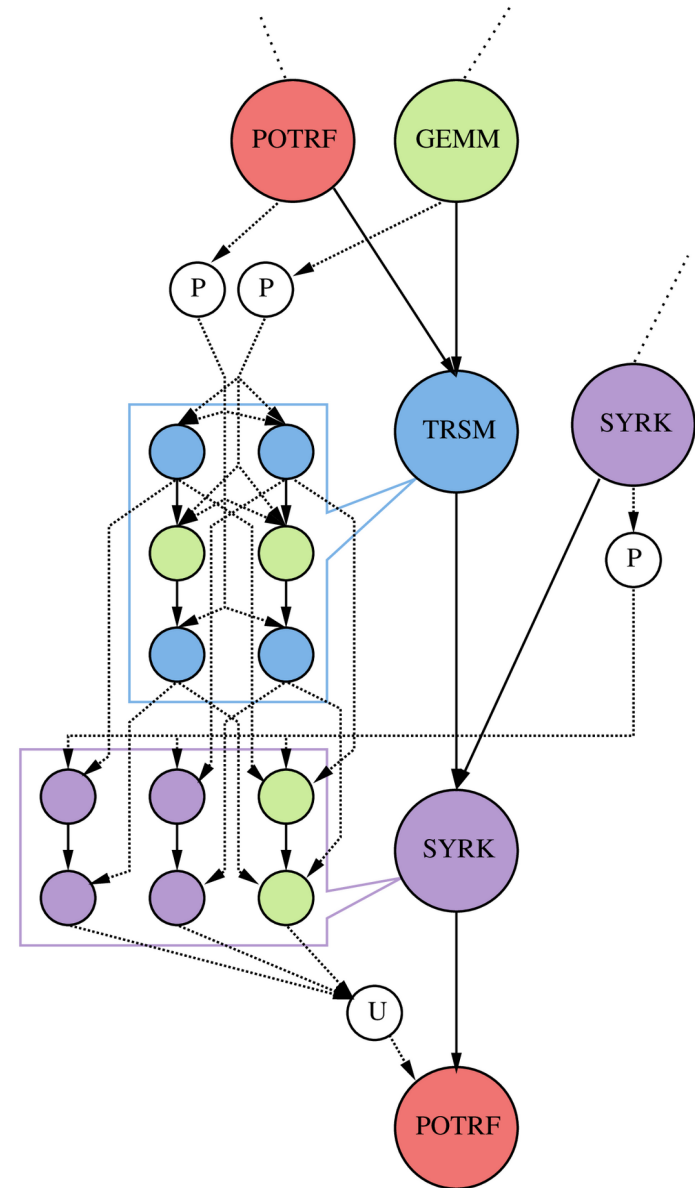
- Synchronization pseudo-tasks
 - Only when needed
- Result is exactly as appropriate
→ Just split at will!



Hierarchical task graphs

Multi-level data coherency

- Synchronization pseudo-tasks
 - Only when needed
 - Result is exactly as appropriate
- Just split at will!



Dividing tasks

No extra synchronization

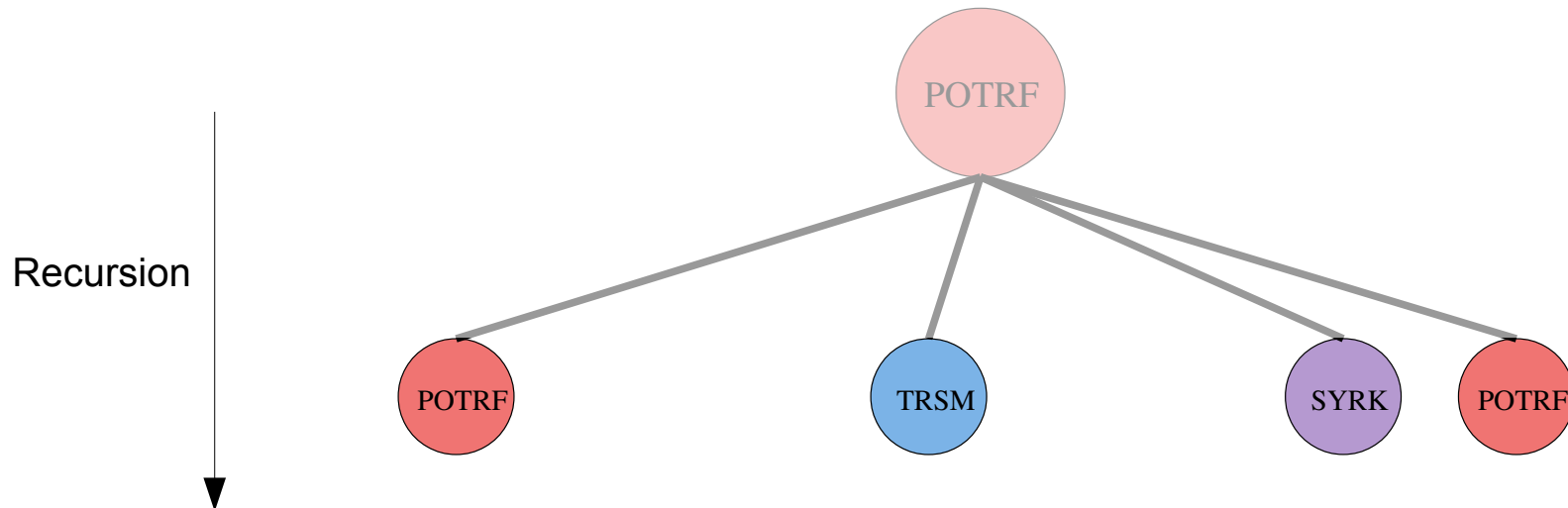
→ Can consider task graph subdivision as a tree



Dividing tasks

No extra synchronization

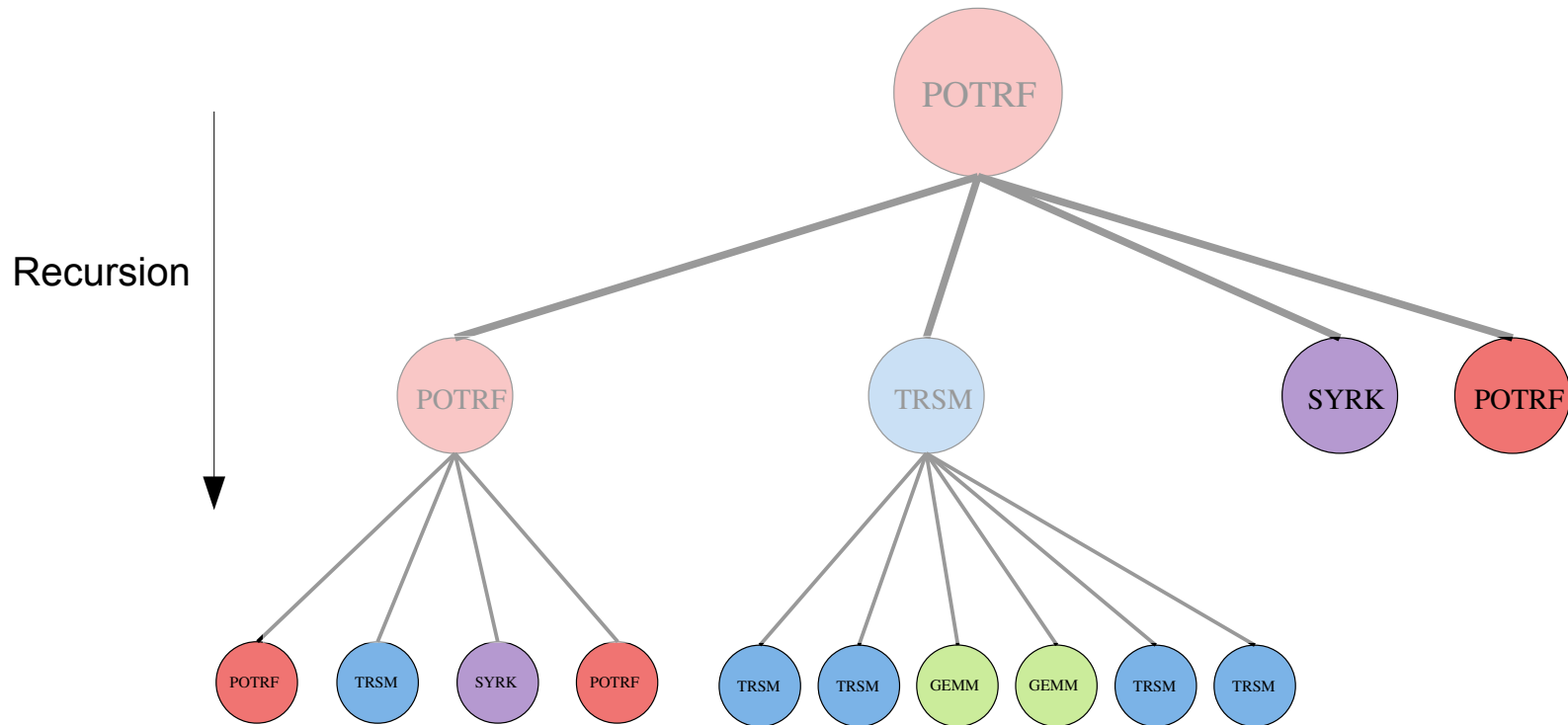
→ Can consider task graph subdivision as a tree



Dividing tasks

No extra synchronization

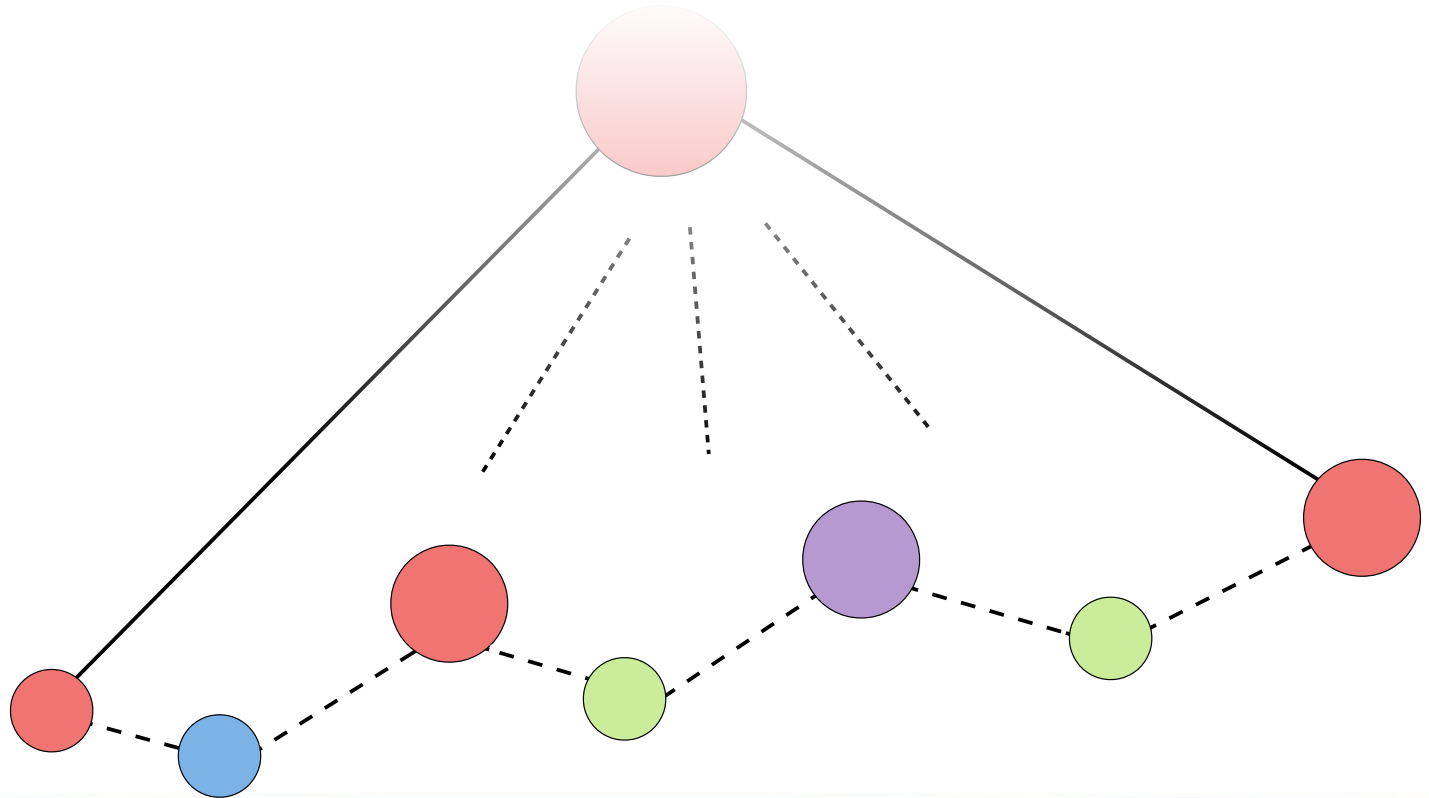
→ Can consider task graph subdivision as a tree



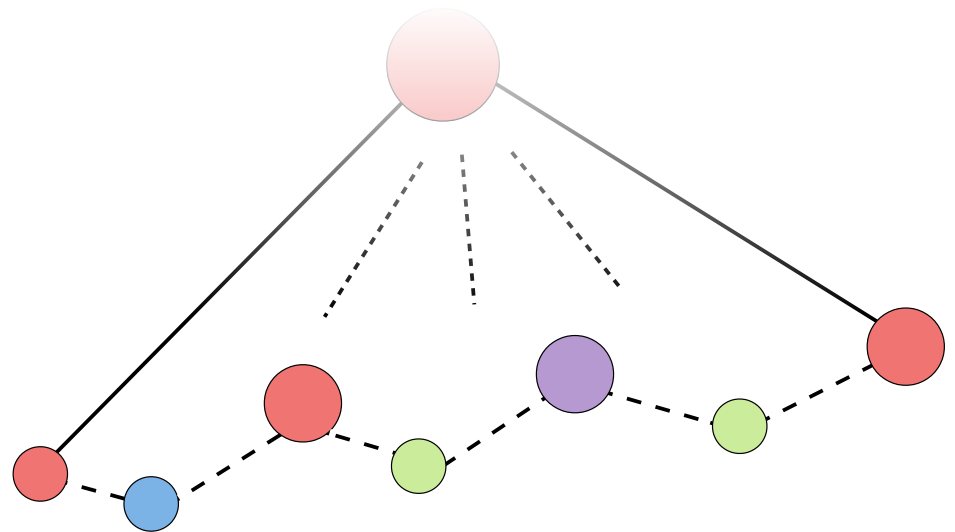
Dividing tasks

No extra synchronization

- Can consider task graph subdivision as a tree
- Decide at will where and when to stop recursing



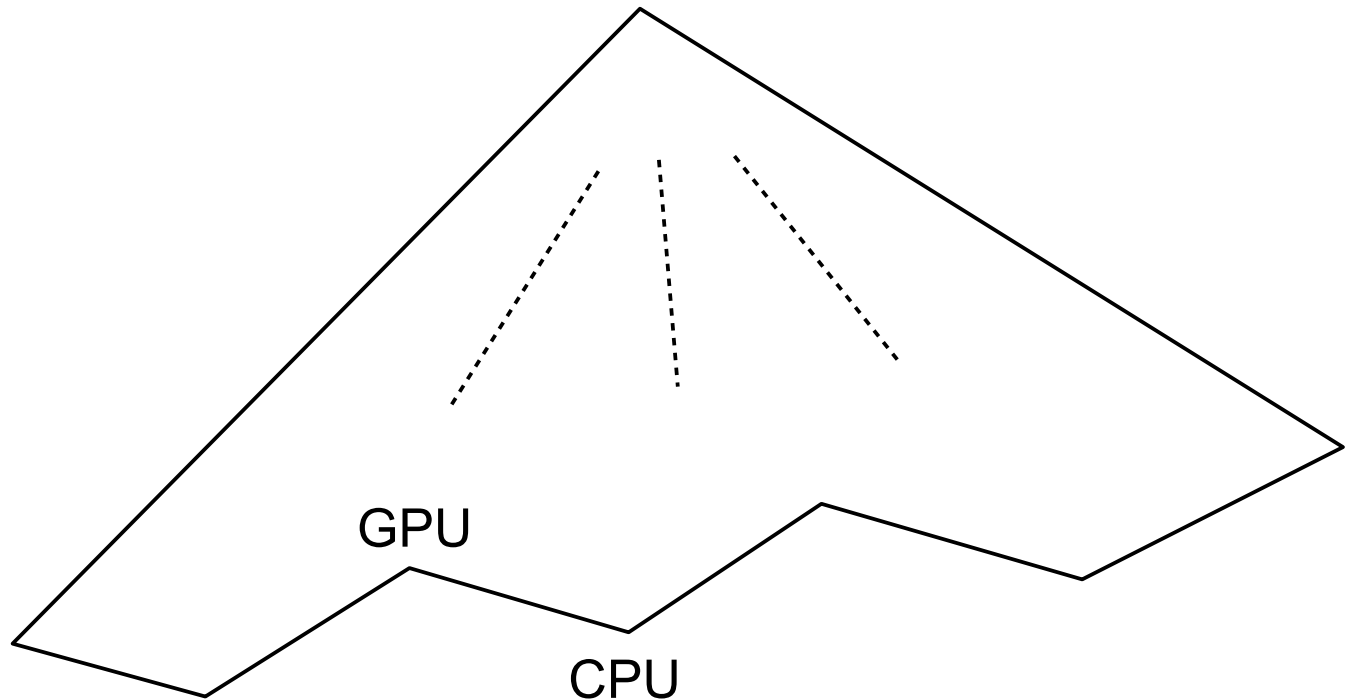
Opportunities



Opportunities

GPU / CPU efficiency management

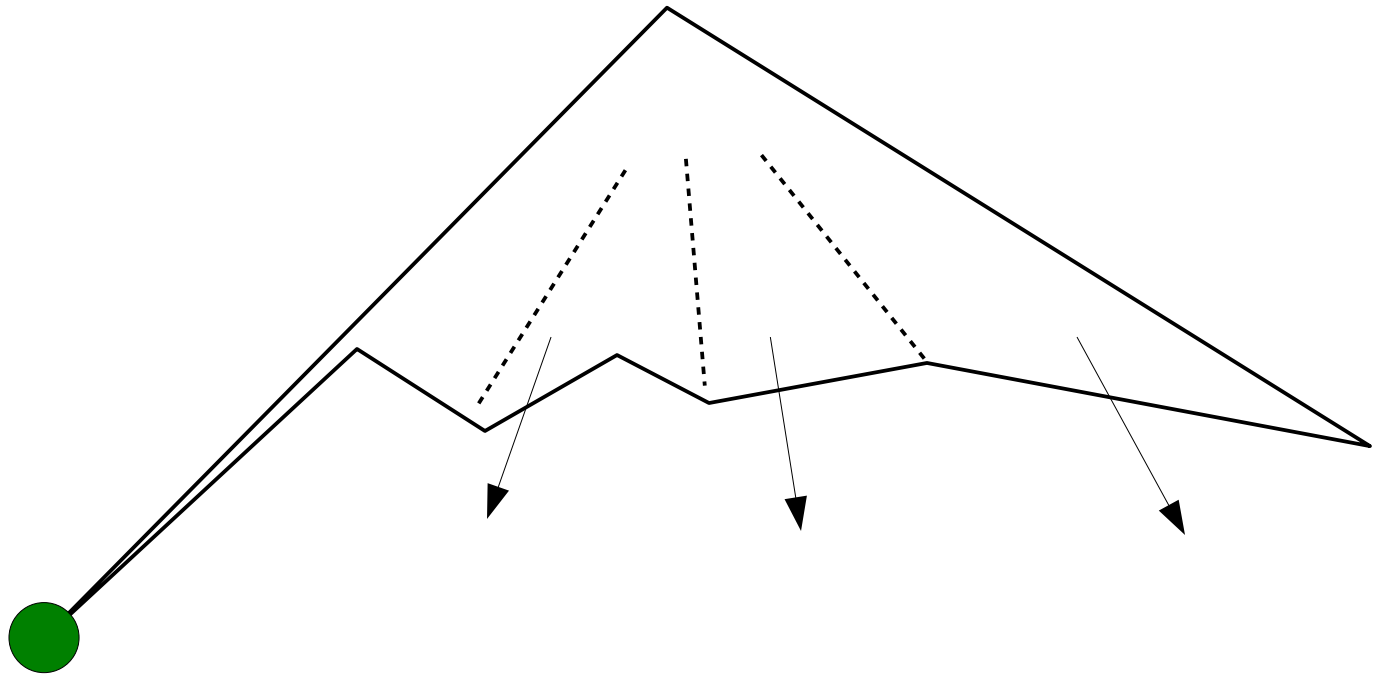
- Stop recursing at desired tile size
- Care for latency of the task graph critical path



Opportunities

Parallel submission

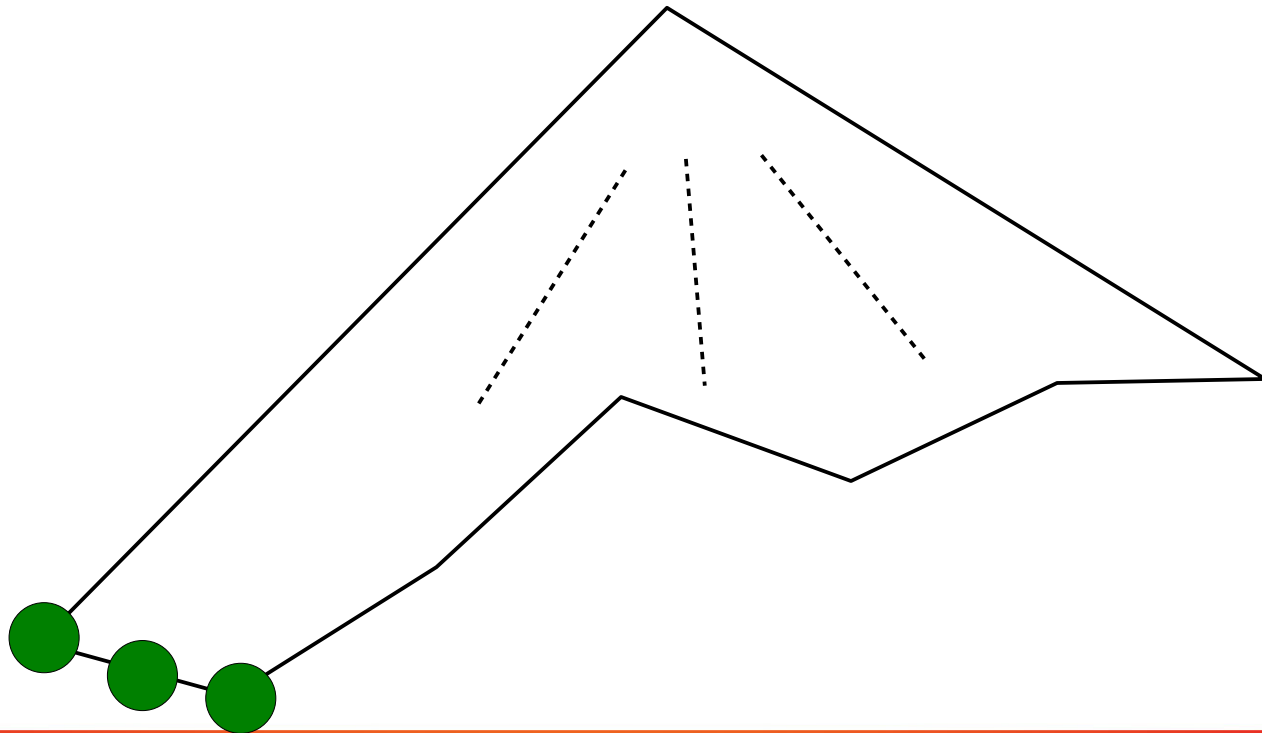
- Unroll the graph in parallel
- While one PU is computing the first task



Opportunities

Delay unrolling

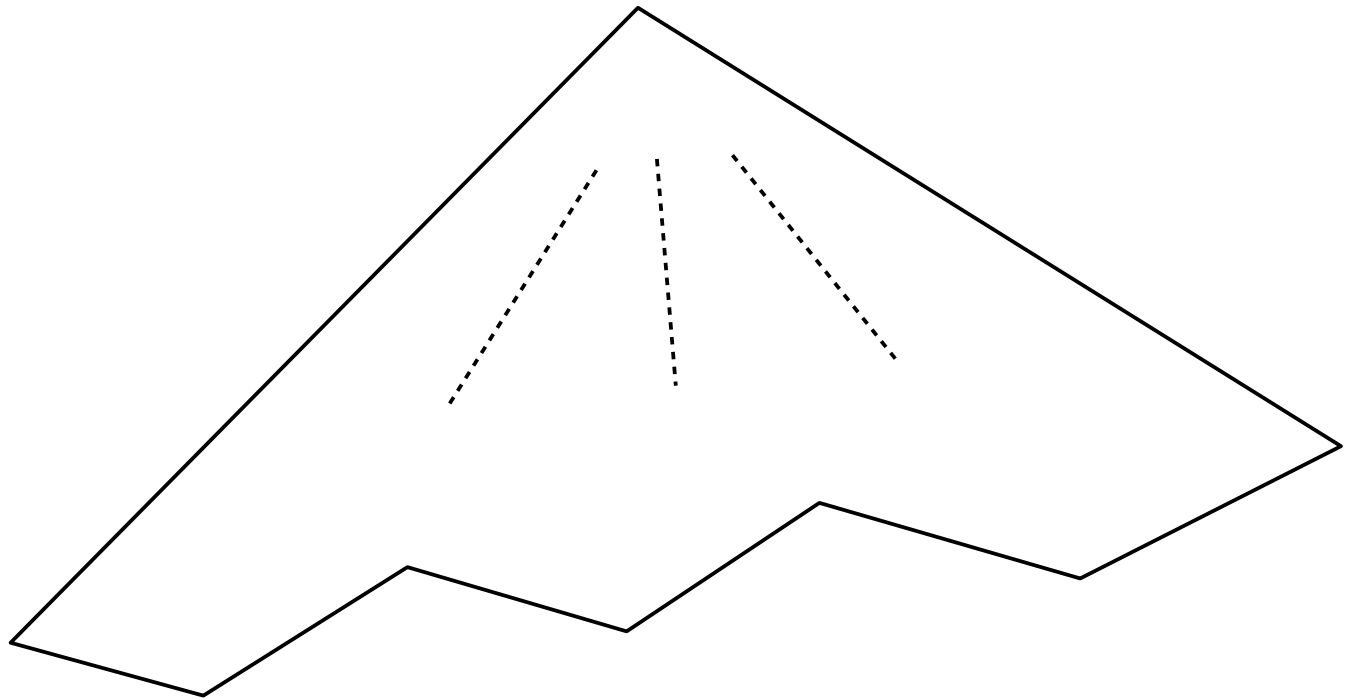
- Observe behavior before unrolling the rest accordingly
- Decorrelate submission and execution



Opportunities

Delay unrolling

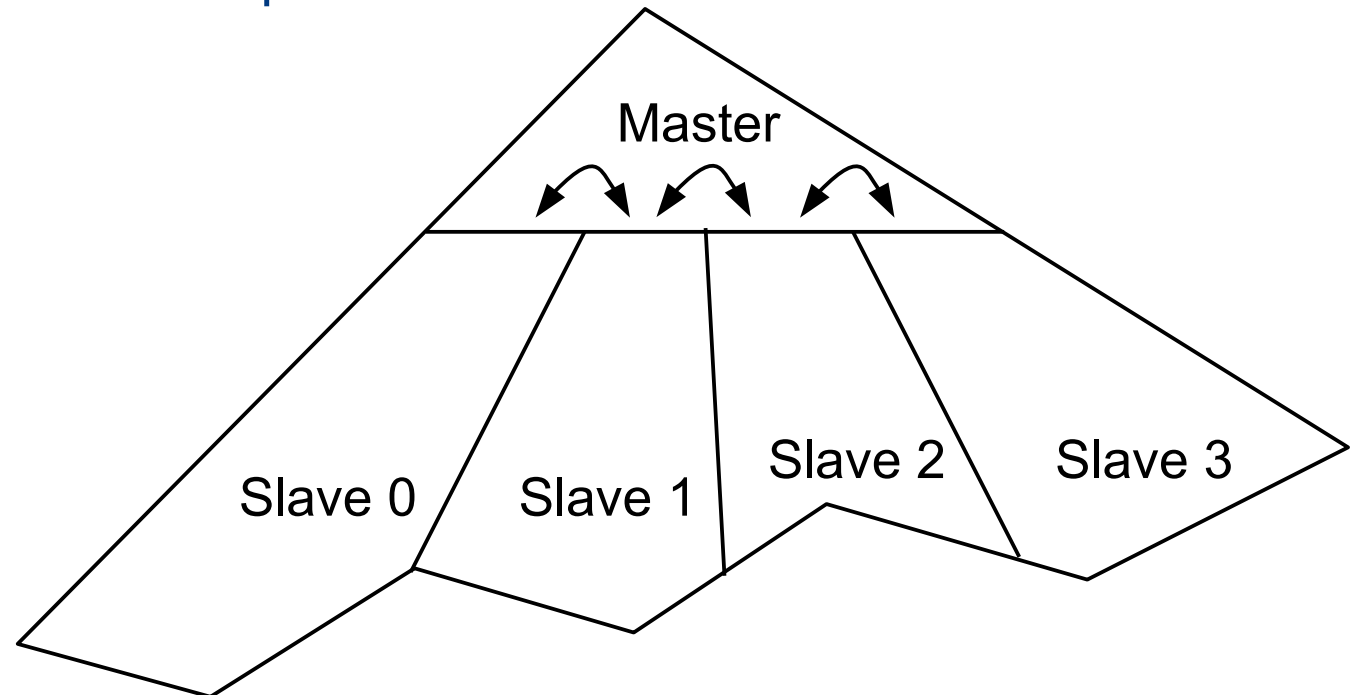
- Observe behavior before unrolling the rest accordingly
- Decorrelate submission and execution



Opportunities

Scaling at large

- Master unrolls higher recursion levels, schedules result
- Slaves unroll the rest
- Master still contention point

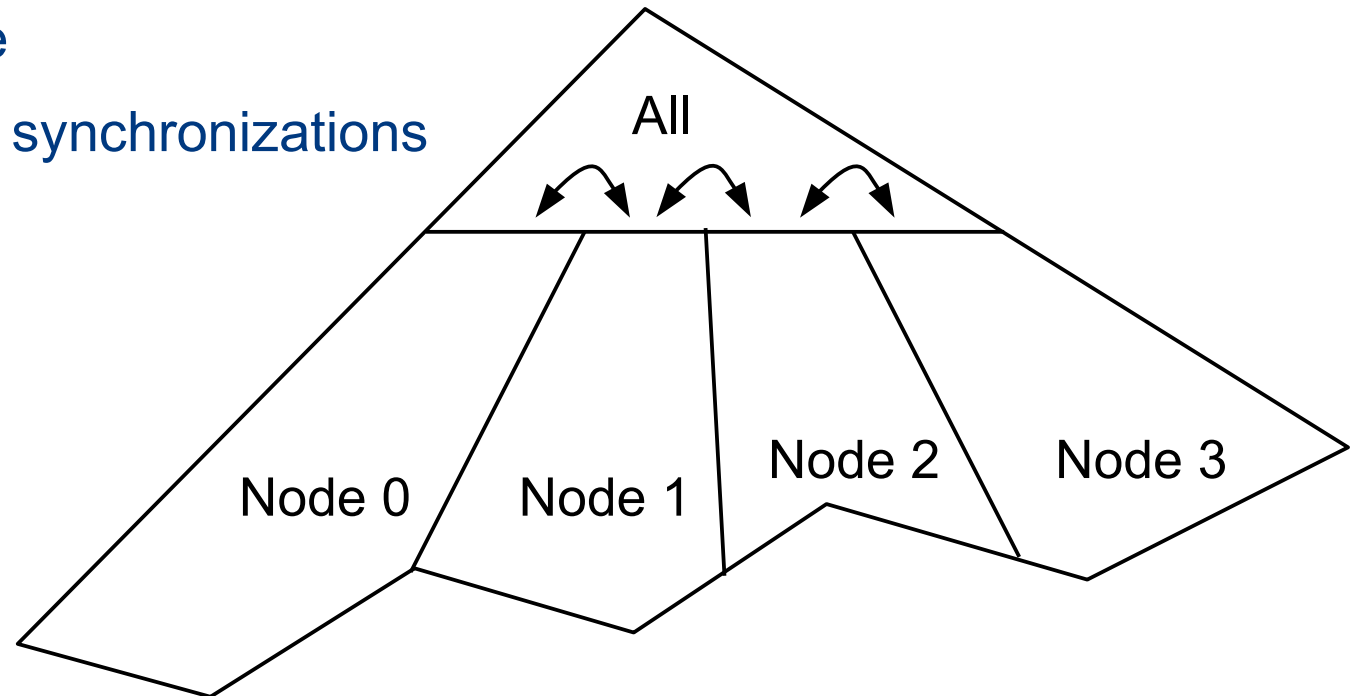


Opportunities

Scaling at large

- All nodes unroll higher recursion levels, determine task mapping
- Nodes unroll their own remaining recursion
- Network communication quite coarse

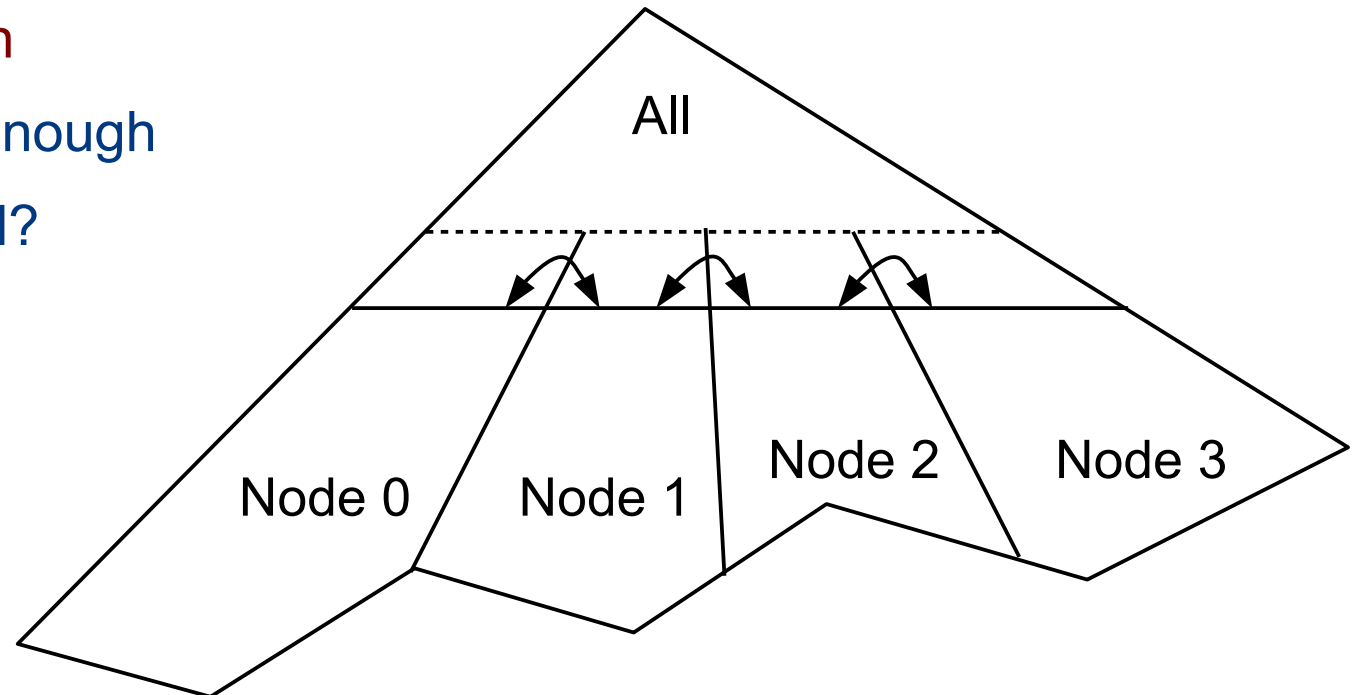
→ Spurious synchronizations



Opportunities

Scaling at large

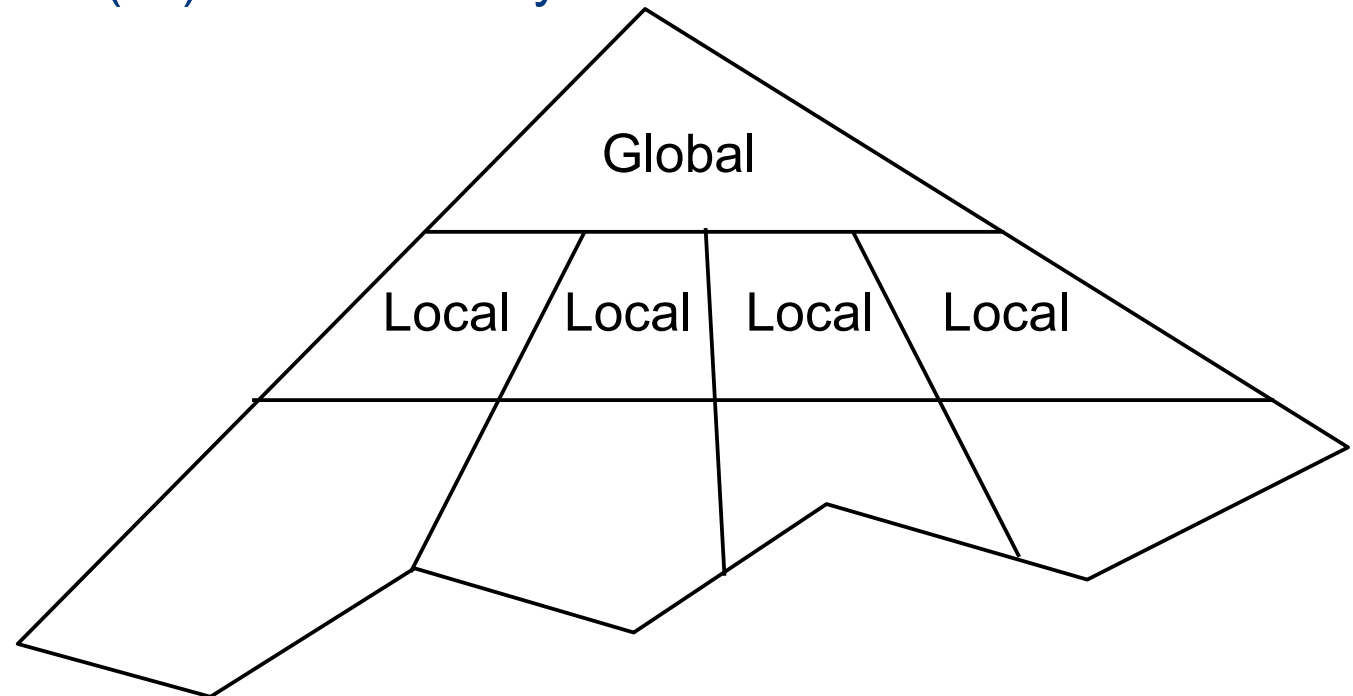
- All nodes unroll higher recursion levels, determine task mapping
- Nodes unroll their own remaining recursion
- Network communication at **finer grain**
- Fine-grain enough vs overhead?



Opportunities

Scheduling at large

- High-level global task graph scheduling, e.g. mapping, critical path
- High-level local task graph scheduling, e.g. memory-based ordering
- $O(N^2)$ or even $O(N^3)$ not that costly



Opportunities

- Computation efficiency
- Scaling at large
- Scheduling at large

NumPEX PEPR project

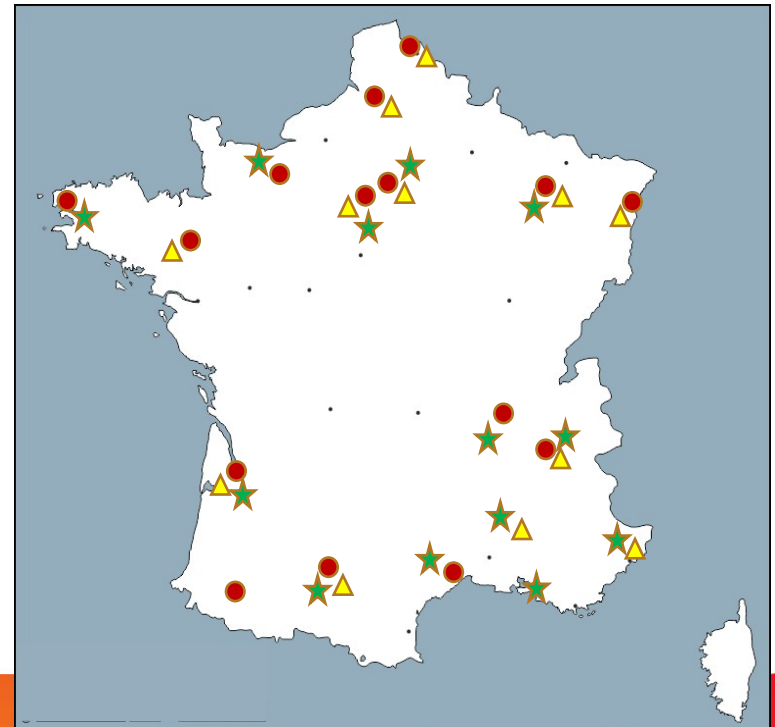
NumPEX project

Building a national ecosystem for the future exaflops machine hosted in France

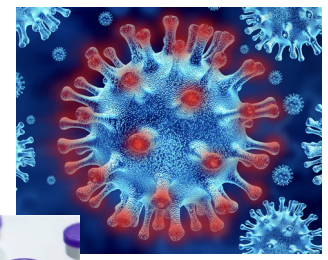
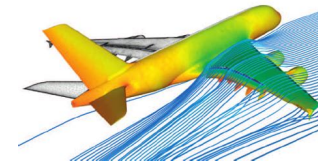
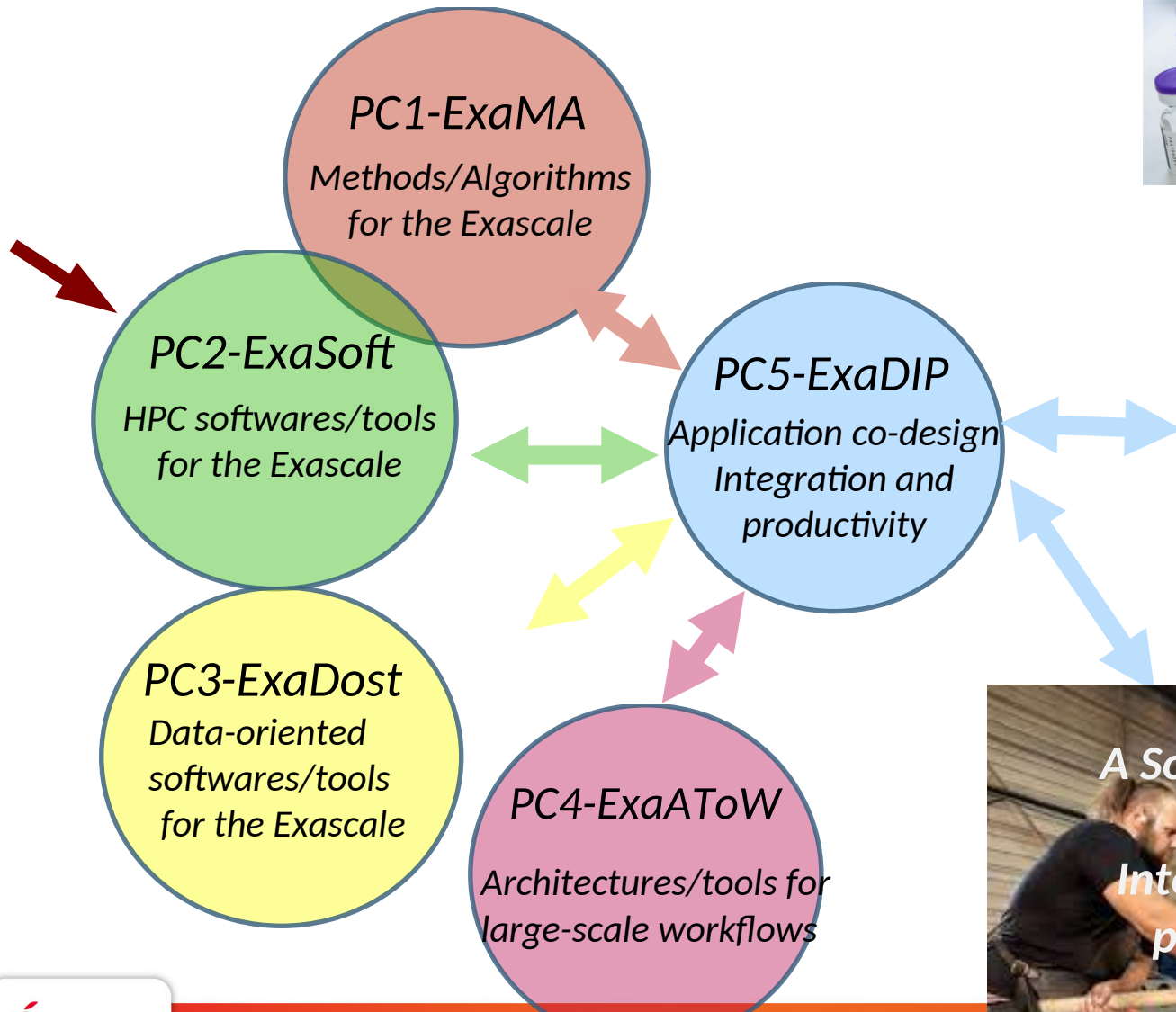
- Facilitate conception, deployment, and monitoring of composite applications at large scale
- Efficiently exploit a heterogeneous architecture with many accelerators
- Control the energy envelope

80 teams in France

- Maths/computation/data
- ★ Applications/demonstrators
- ▲ NumPEX contributors



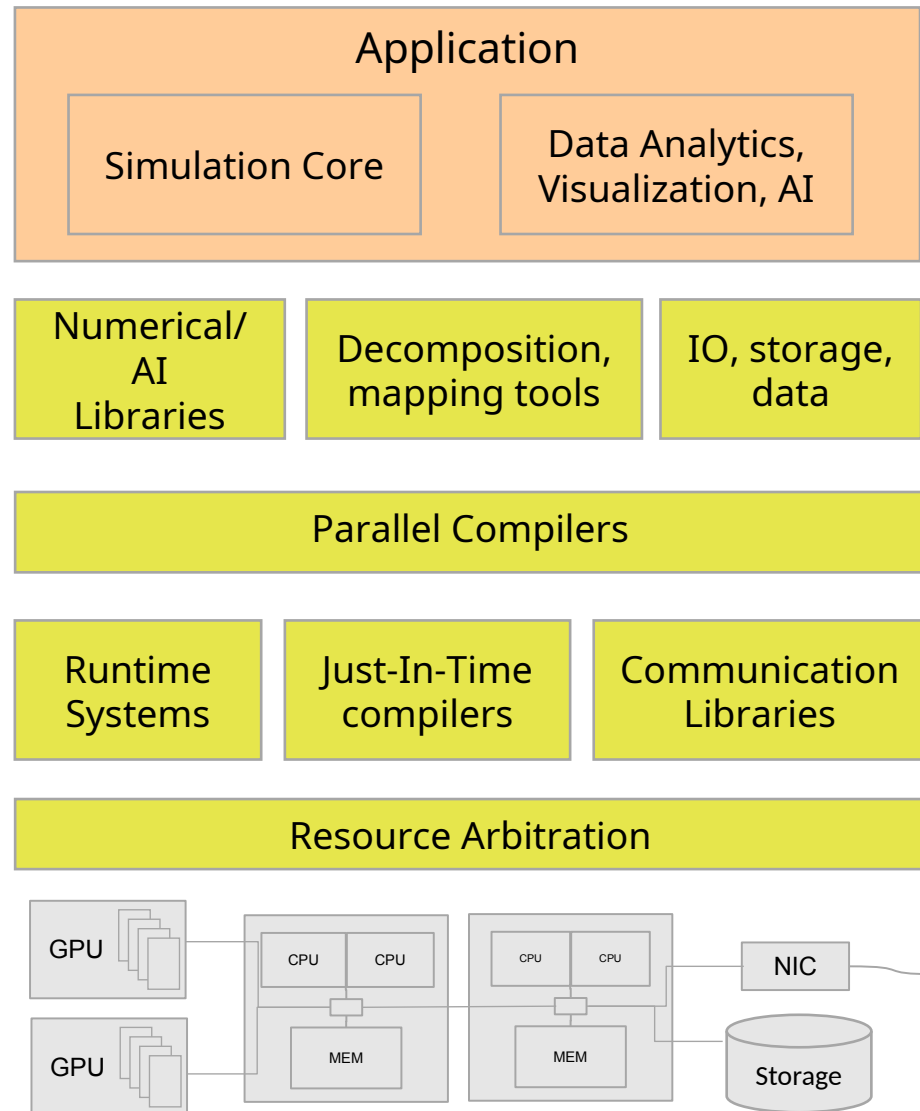
NumPEX project



NumPEX project

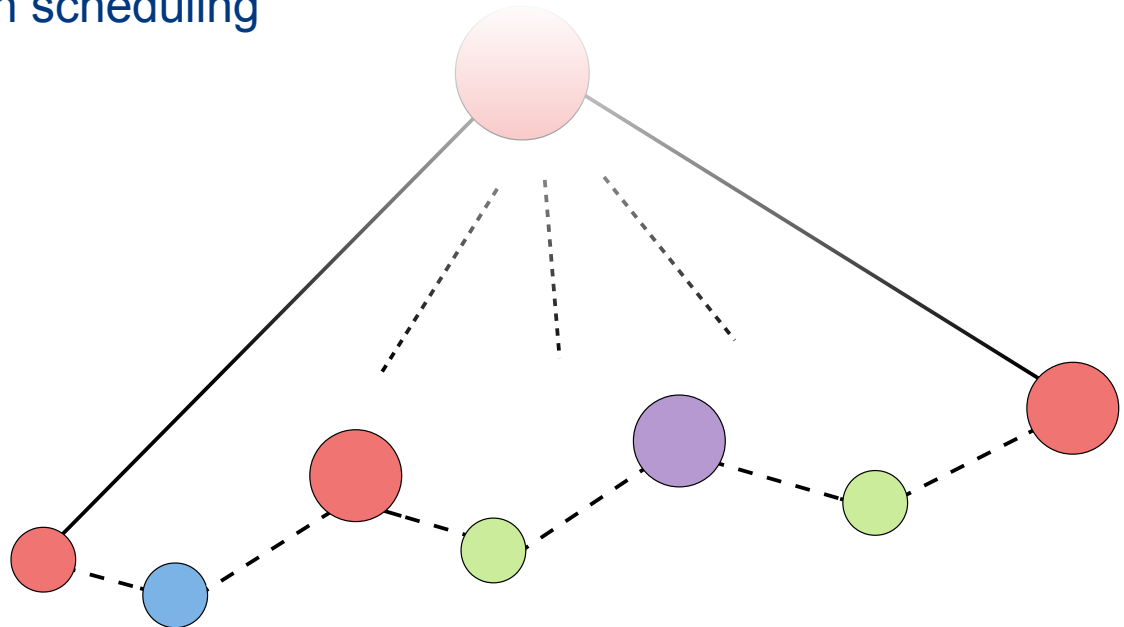
PC2-ExaSoft

- Holistic approach
 - Contribute to a sound, consistent software stack
 - Most components should fit together!
 - Bridge the gap between existing languages/software/tools
 - Integrate state-of-the-art research results
 - Demonstrate relevance on representative applications
- WP3 : Runtime Systems at Exascale



Conclusion

- Programming large systems requires abstraction
- Recursive applications are there
- Hierarchical task graphs seems an opportunity for
 - Controlling task size
 - Controlling task submission
 - High-level task graph scheduling



The StarPU runtime system

Development context

- History
 - Started in 2008
 - PhD Thesis of Cédric Augonnet
 - StarPU main core \approx 70k lines of code
 - Written in C
- Open Source
 - Released under LGPL
 - Sources freely available
 - git repository and nightly tarballs
 - See <https://starpu.gitlabpages.inria.fr/>
 - Open to external contributors
- [HPPC'08]
- [Europar'09] – [CCPE'11],... >1500 citations

Features

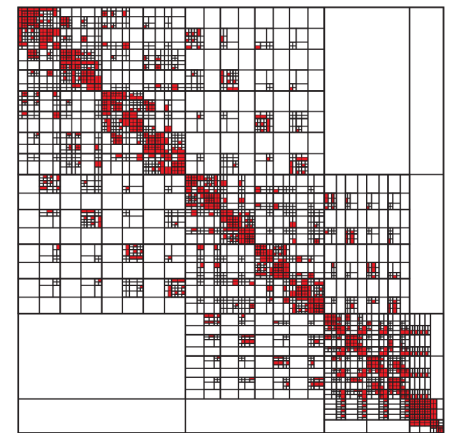
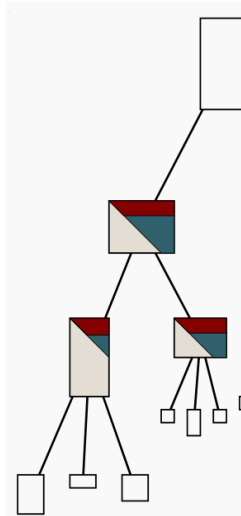
- C, OpenMP, OpenCL APIs
- CPUs, GPUs, Phi
- Advanced task mapping & scheduling
- Optimized data transfers
- Cluster Support through MPI
- Out-Of-Core support
- Simulation support
- Performance analysis tools

The StarPU runtime system

Success stories

Task-based programming actually makes things easier!

- QR-Mumps (sparse linear algebra)
 - Non-task version: only 1D decomposition
 - Task version: 2D decomposition, flurry of parallelism
 - With seamless memory control
- H-Matrices (compressed linear algebra, Airbus)
 - Out-of-core support
 - Could run cases unachievable before
 - e.g. 1600 GB matrix with 256 GB memory
 - Shipped to Airbus customers
- Implemented CFD, FMM, CG, stencils, ...



The StarPU runtime system

Supported platforms

- Supported architectures
 - Multicore CPUs (x86, PPC, ...)
 - NVIDIA GPUs
 - OpenCL devices (eg. AMD cards)
 - HIP
 - FPGA (ongoing)
 - Old Intel Xeon Phi (MIC), SCC, Kalray MPPA, Cell (decommissioned)
- Supported Operating Systems
 - Linux
 - Mac OS
 - Windows

Applications on top of StarPU

Using CPUs, GPUs, distributed, out of core, ...

- Dense linear algebra
 - Cholesky, QR, LU, ... : Chameleon (based on Plasma/Magma)
- Sparse linear algebra
 - QR_MUMPS
 - PaStiX
- Compressed linear algebra
 - BLR, h-matrices
- Fast Multipole Method
 - ScalFMM
- Conjugate Gradient
- Other programming models : Data flow, skeletons
 - SignalPU, SkePU
- ...