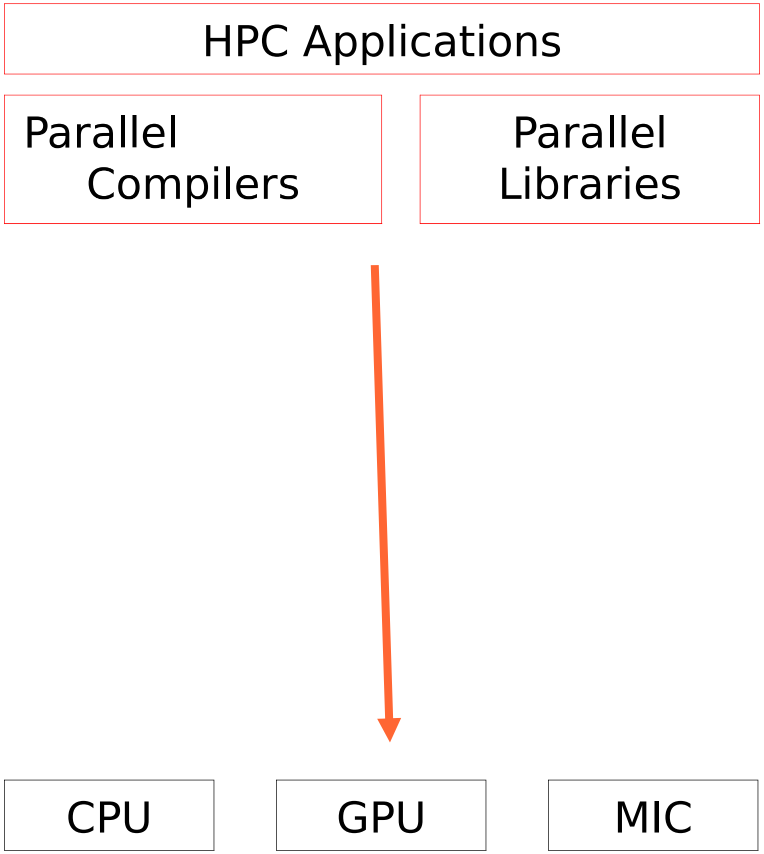
A runtime approach to dynamic resource allocation for sparse direct solvers

Andra Hugo, Abdou Guermouche Pierre-André Wacrenier, Raymond Namyst
Inria, LaBRI, University of Bordeaux

INRIA Bordeaux Sud-Ouest

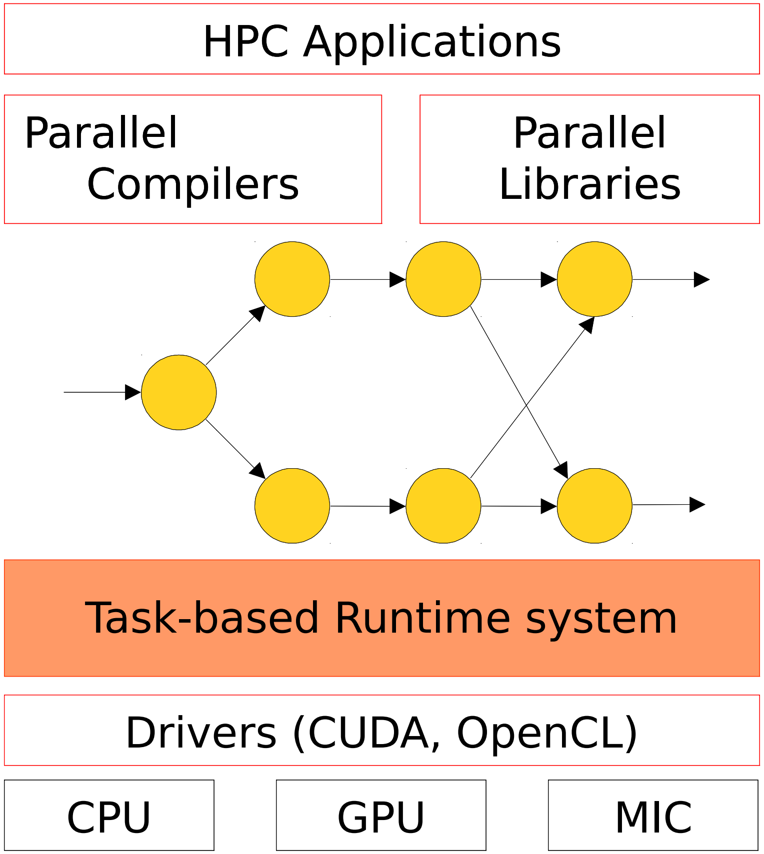
General context

- The classical approach is based on a mixture of technologies (e.g., MPI+OpenMP+CUDA) which
  - requires a big programming effort
  - is difficult to maintain and update
  - is prone to (performance) portability issues



General context

- Runtimes systems provide an abstraction layer that hides the architecture details
- The workload is expressed as a DAG of tasks where the dependencies are
  - defined explicitly
  - defined through rules
  - automatically inferred
- The scheduler decides when/where to execute a task
- The drivers deploy the code on the devices
- The memory manager does the memory transfers and guarantees the consistency

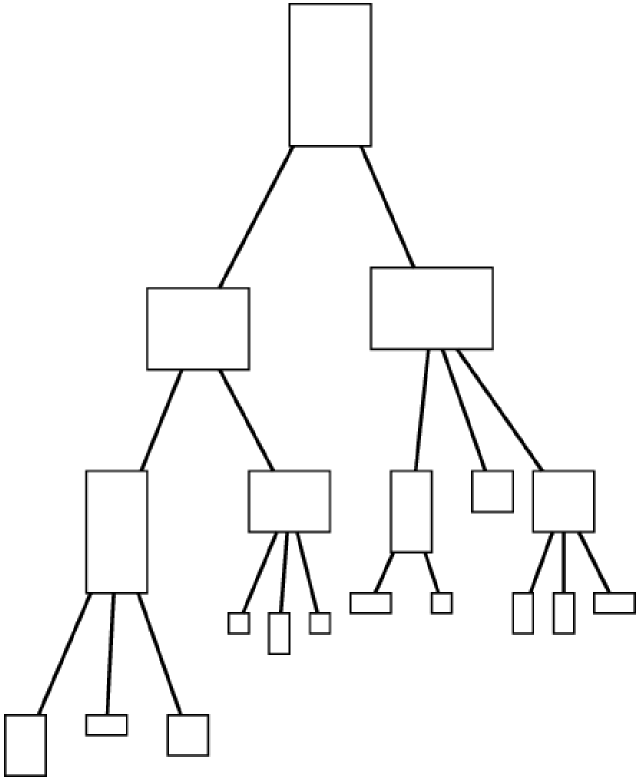


Motivation application

The qr_mumps sparse solver

The multifrontal QR factorization is guided by a graph called elimination tree

- Five elementary operations:
  - Activate
  - Panel
  - Update
  - Assembel
  - Clean



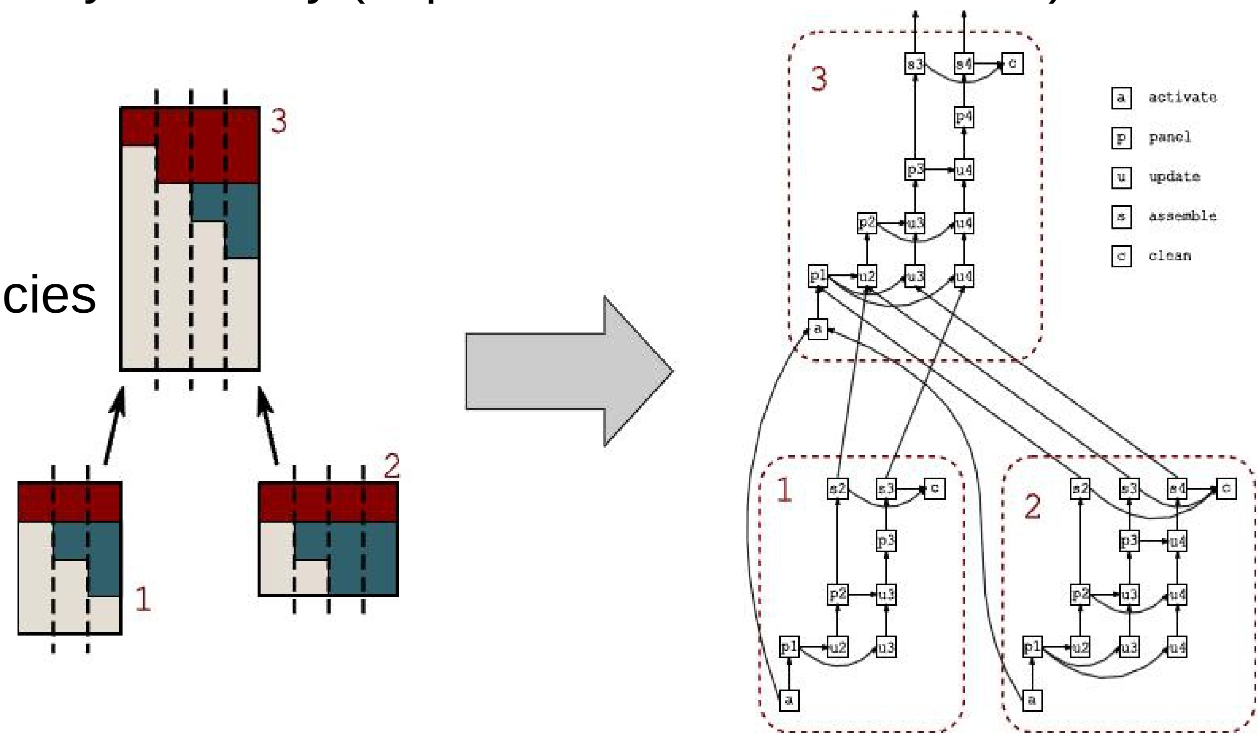
Motivation application

The qr_mumps sparse solver

The multifrontal QR factorization is guided by a graph called elimination tree

- Data-flow parallel approach
  - Tasks are operations on portion of fronts (1-D partitioning)
  - Tasks are scheduled dynamically (dependencies between them)

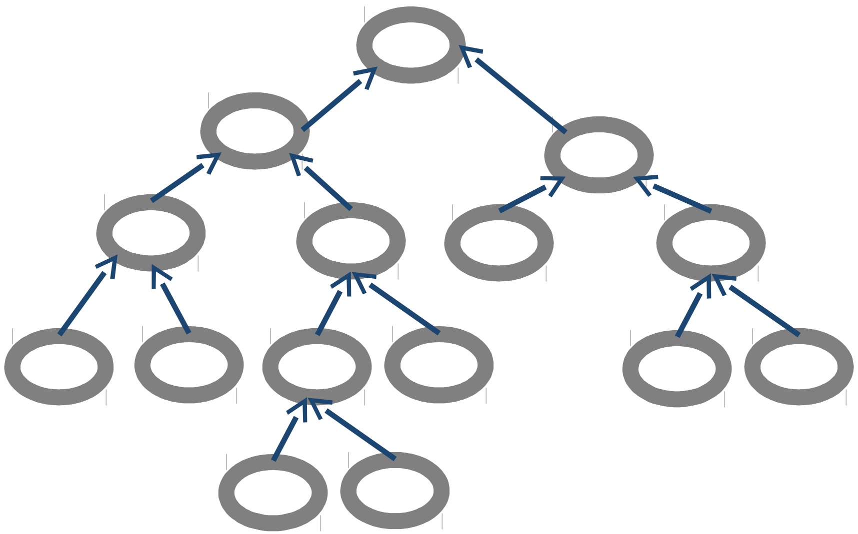
- Tree of DAGs :
  - Nodes = DAG
  - Edges = dependencies

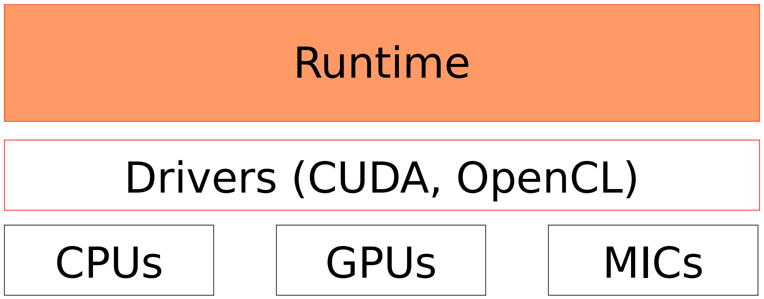


DAG structure of the parallel applications:

Submitted to the runtime

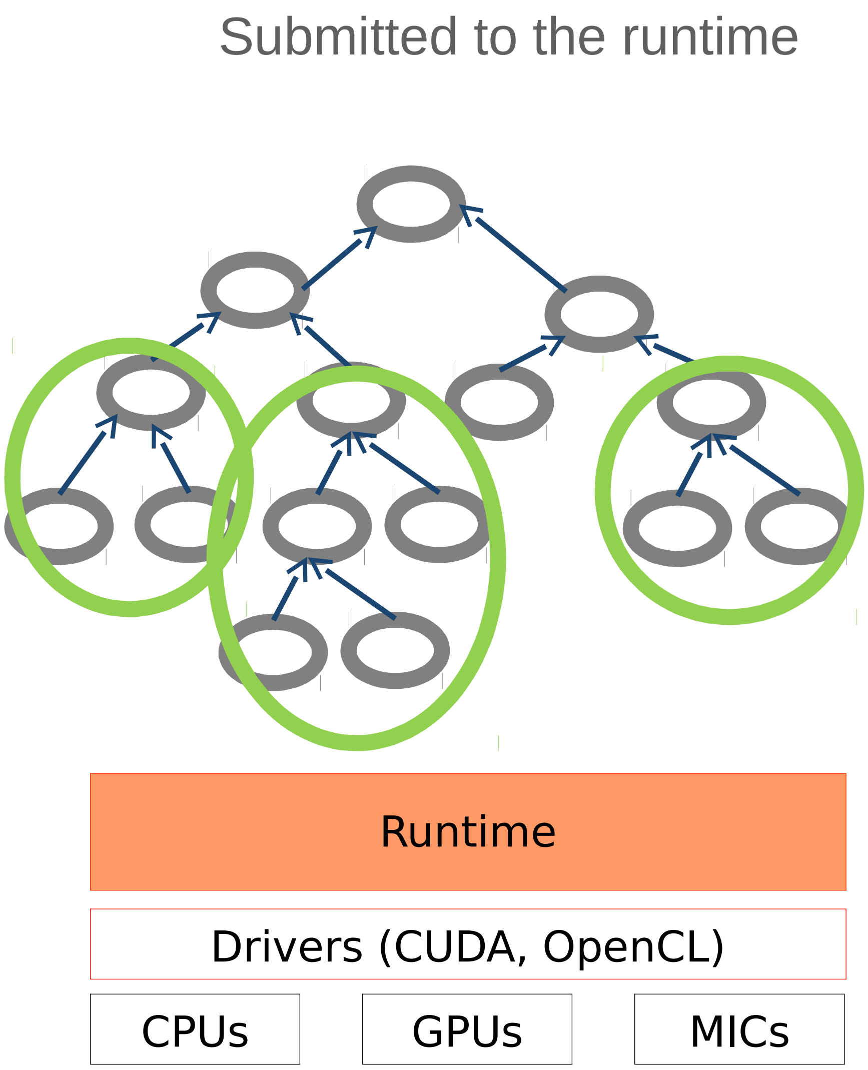
- Use data-flow approach:
  - DAG of sequential tasks
- Advantages:
  - Fine granularity
  - Increased parallelism
- Drawbacks for big DAGs:
  - Overhead of the runtime
  - Complexity of the scheduling





DAG structure of the parallel applications:

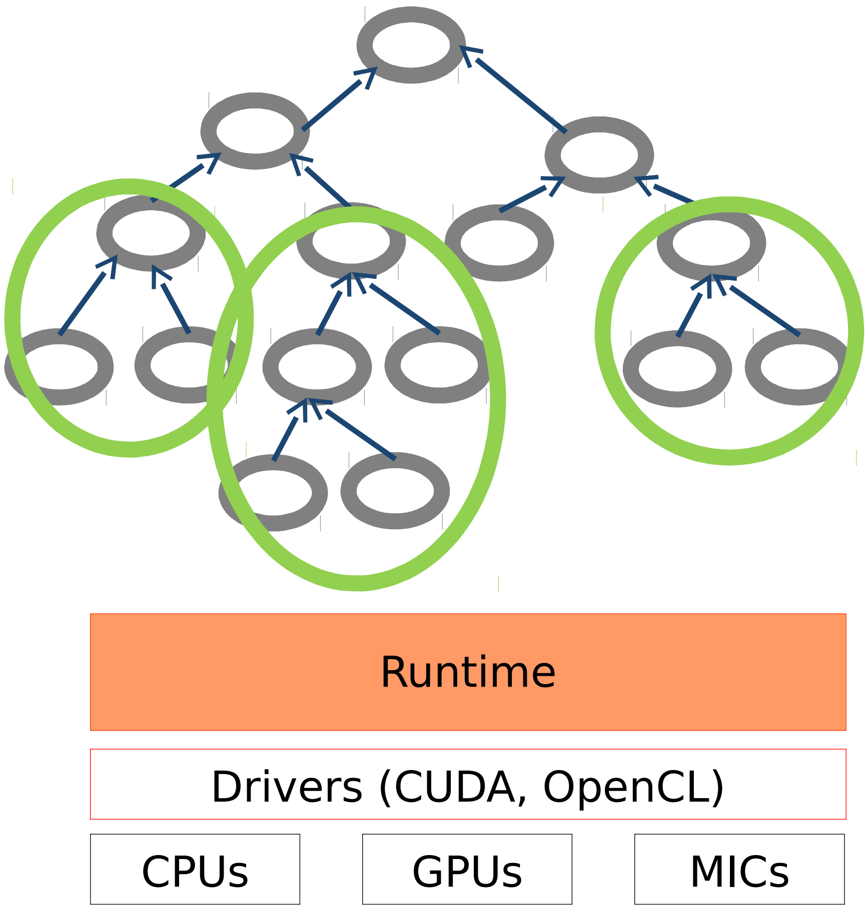
- Use data-flow approach:
  - DAG of sequential tasks
- Advantages:
  - Fine granularity
  - Increased parallelism
- Drawbacks for big DAGs:
  - Overhead of the runtime
  - Complexity of the scheduling
- Possible solution:
  - Pack sub-DAGs into bigger tasks : malleable tasks
  - Use high-level scheduling algorithm



Interraction between the application & the runtime

The runtime doesn't "automatically" ...

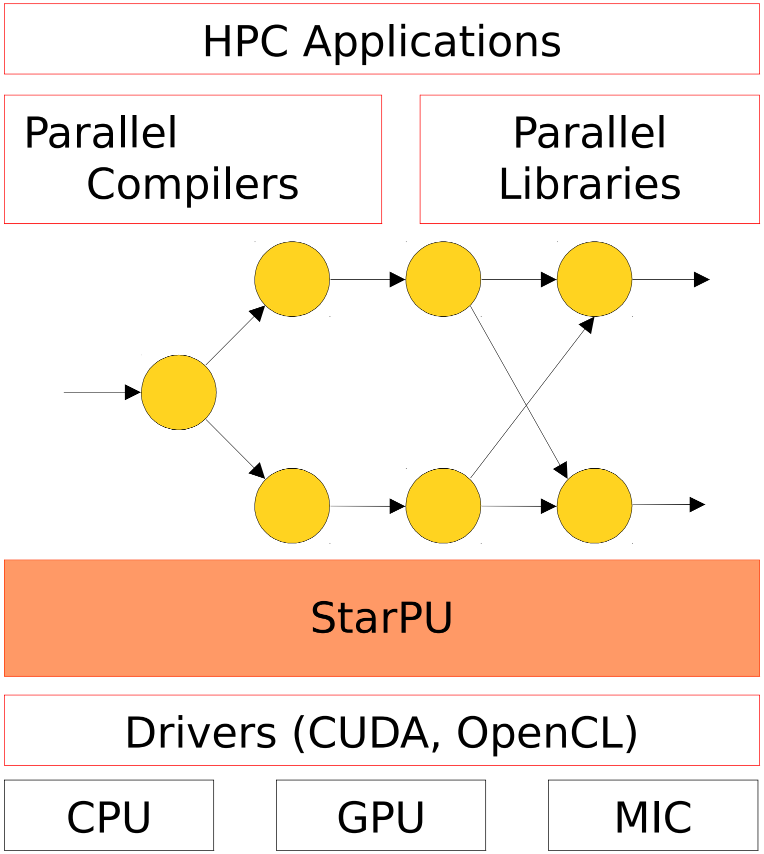
- Improve the performance of the application:
  - Structure the DAG (application)
  - Map it to the topology (runtime)
    - ⇒ Enhance locality
    - ⇒ Respect the critical path
- Difficulties:
  - What branches of the DAG to merge
  - Allocate resources for them



Using StarPU as an experimental platform

to study resource negociation

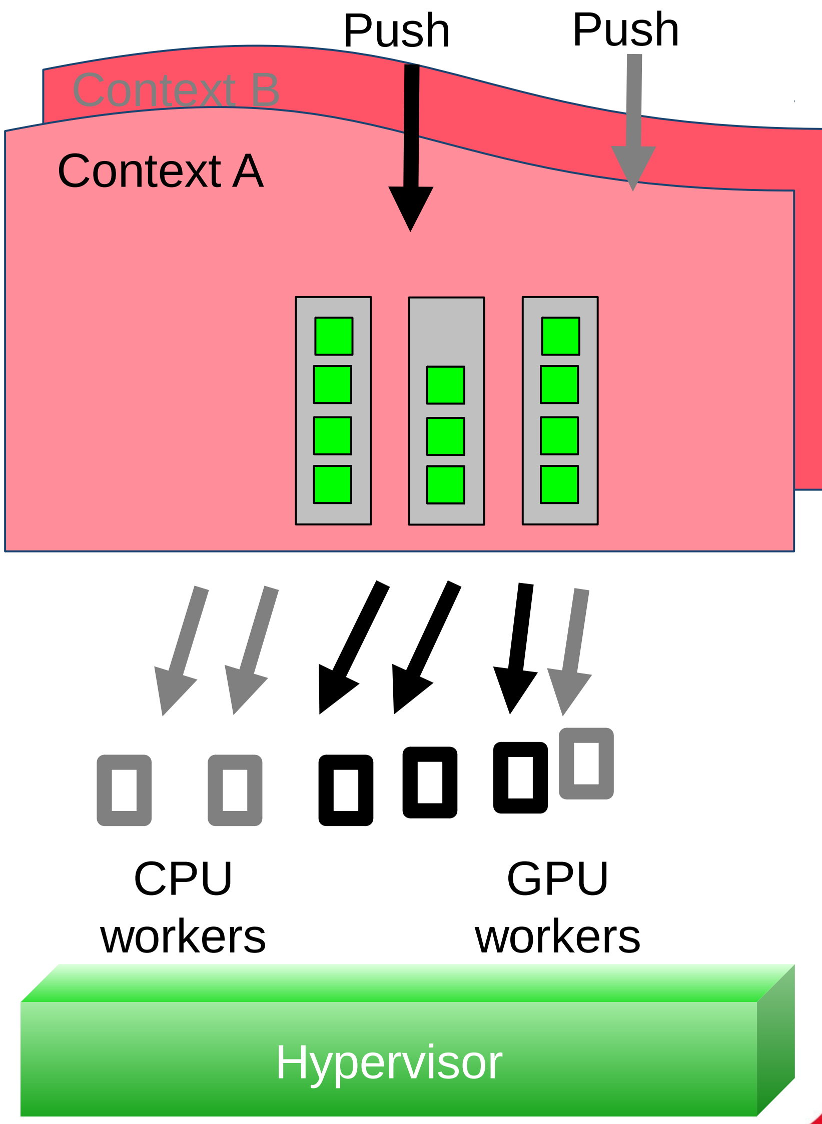
- The StarPU runtime system
  - Dynamically schedule tasks on all processing units
    - See a pool of heterogeneous processing units
  - Avoid unnecessary data transfers between accelerators
    - Software VSM for heterogeneous machines
  - Open scheduling platform
    - Different schedulers to meet different needs



Scheduling Contexts: to manage parallel tasks

- Isolate concurrent parallel codes
  - "lightweight virtual machines"

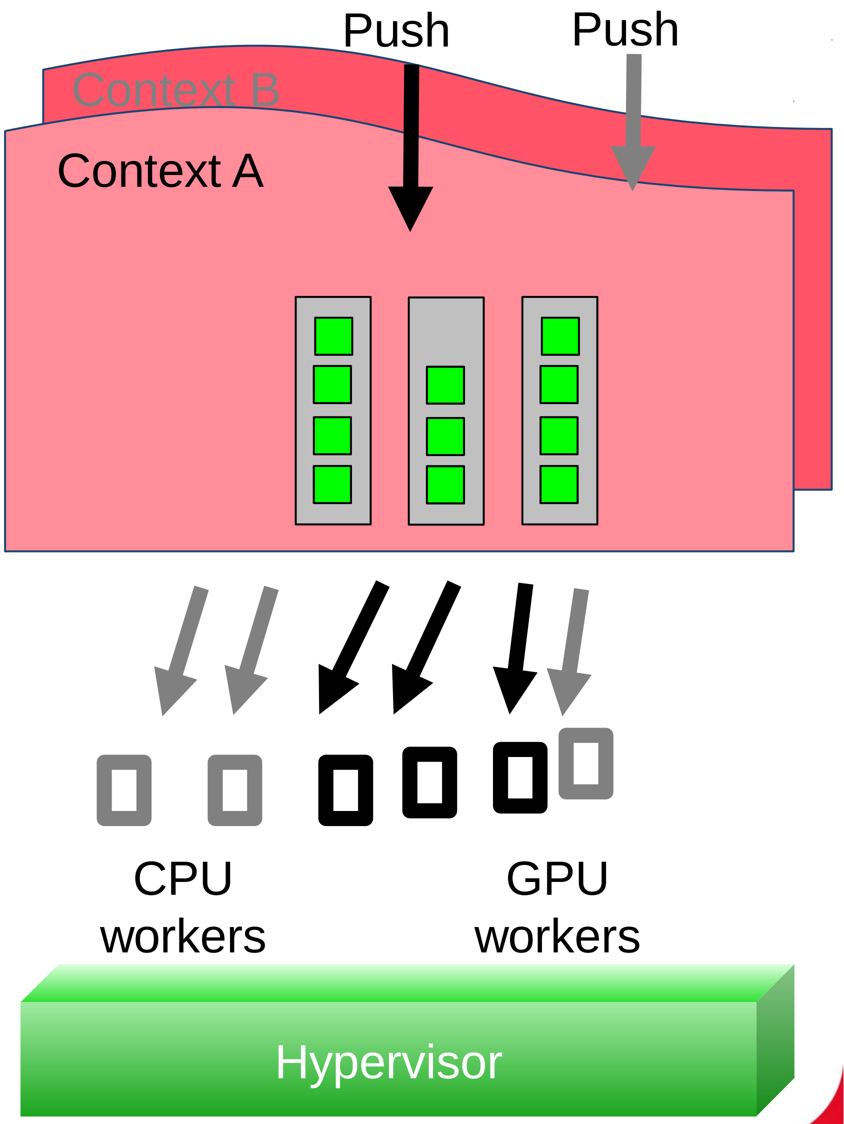
Toward code composability



Scheduling Contexts: to manage parallel tasks

- Isolate concurrent parallel codes
  - "lightweight virtual machines"
- Contexts may *expand* and *shrink*
  - **Hypervised approach**
    - Resize contexts
    - Share resources
  - Maximize overall throughput
  - Use dynamic feedback both from application and runtime
    - Monitor the PUs
    - Monitor the application

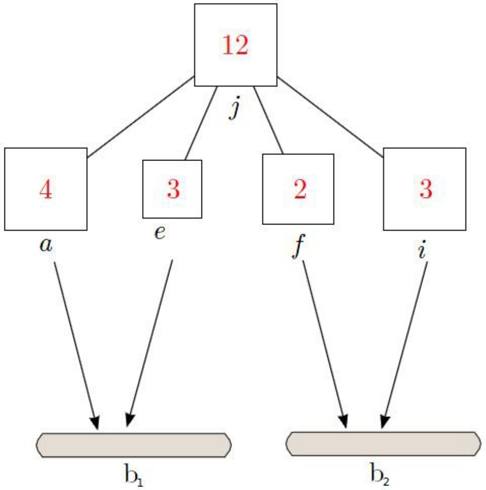
Toward code composability



Hierarchical parallelism in qr_mumps

- Idea:
  - Split the set of PUs among the branches
  - Consider their workload
  - Assign all PUs to at least one subtree

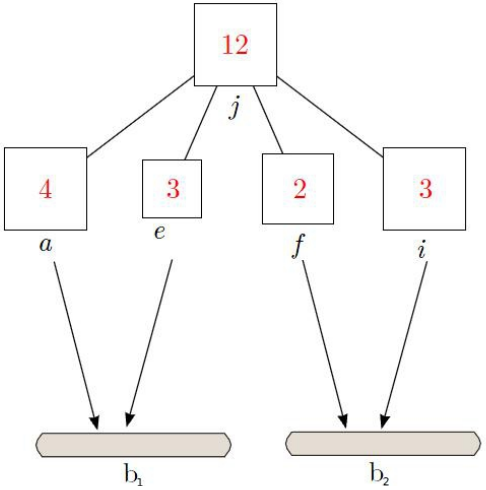
Proportional mapping

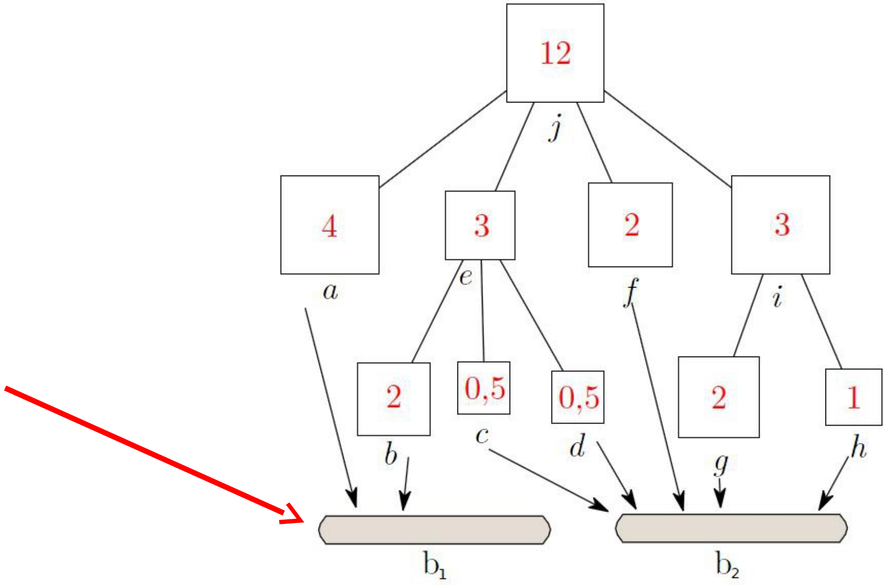


Hierarchical parallelism in qr_mumps

- Idea:
  - Split the set of PUs among the branches
  - Consider their workload
  - Assign all PUs to at least one subtree
- Extension of the algorithm:
  - Stopping criterion for the top-down process
  - Bundles: set of PUs sharing a level of memory

Proportional mapping

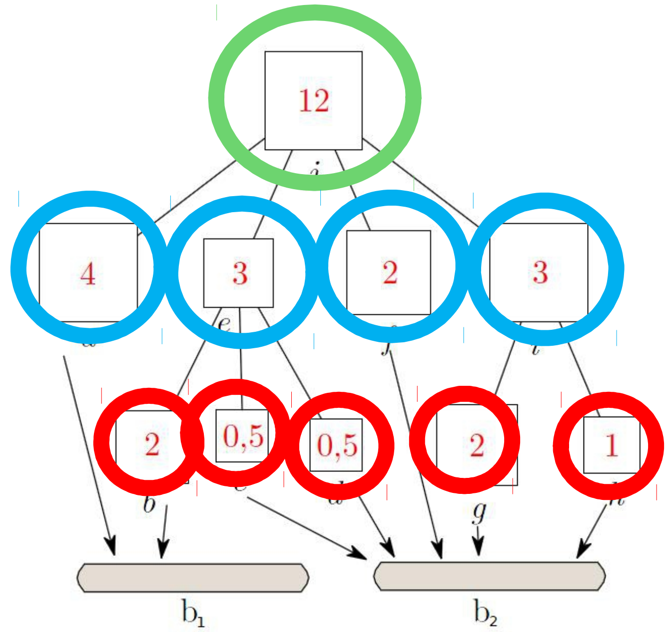


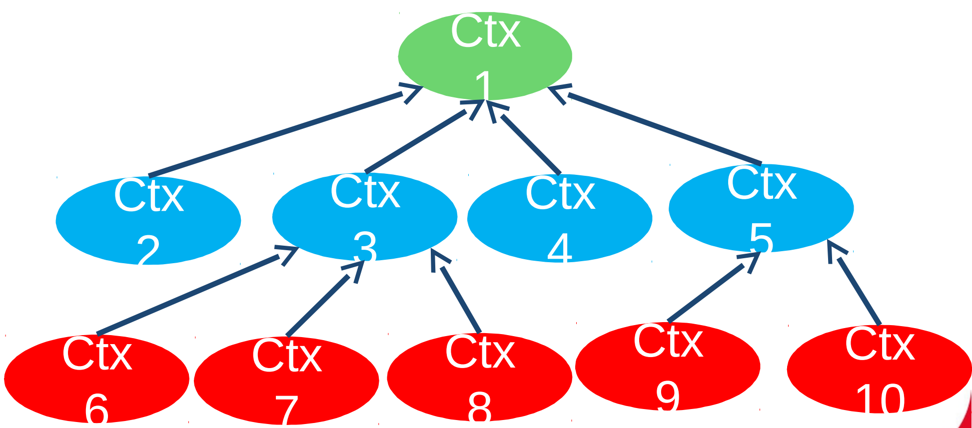


Hierarchical parallelism in qr_mumps

- Balance the workload of the tasks
- DAG of malleable tasks
- Provide to the runtime:
  - The hierarchy of parallel tasks
  - The workload of the parallel tasks
    - Estimates built during analysis
    - Dynamic updates during factorization

Proportional mapping



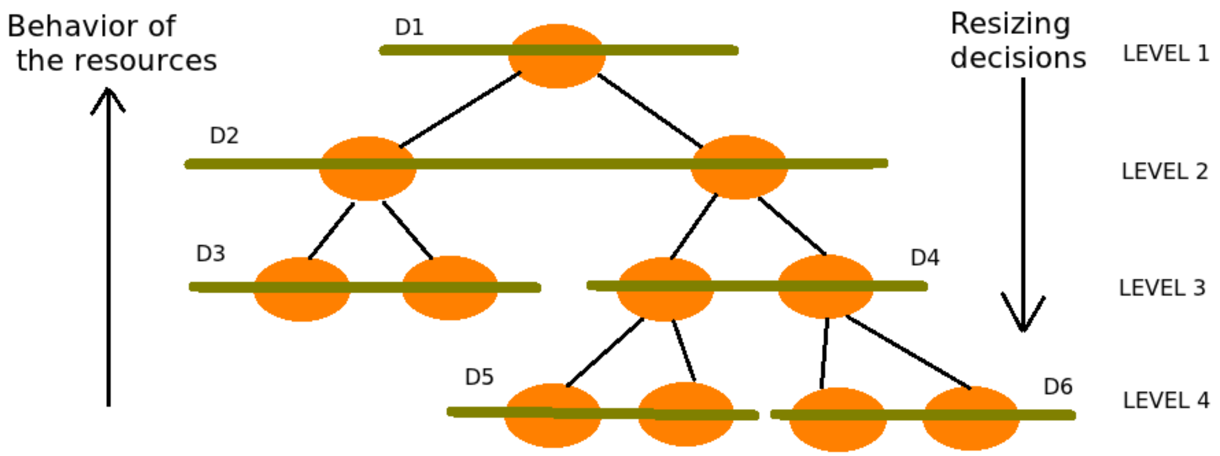


Resize hierarchally the scheduling contexts

The role of the Hypervisor

- Monitors the PUs
- Information coming from the leaves towards the root:
  - Efficiency of the PUs
  - Speed of the scheduling contexts

- Resizes the contexts locally
  - Resizing decisions at each level
  - Deadlines per children sharing the same parent



Allocate processing units to the contexts

By predicting the future

- ***Input***: the workload (number of flops) of each context
- Rough computation of the number of resources needed by each context
  - How many CPUs allocated to each context?

$$\max\left(\frac{1}{t_{max}}\right) \text{subject to} \left(\begin{array}{l} \left(\forall c \in C, n_{\alpha,c} v_{\alpha,c} \geq \dfrac{W_c}{t_{max}}\right) \\ \wedge \left(\displaystyle\sum_{c \in C} n_{\alpha,c} = n_\alpha\right) \\ \wedge \left(\forall c \in C, n_{\alpha,c} < max_{\alpha,c}\right) \end{array}\right)$$

Allocate processing units to the contexts

By predicting the future

- ***Input***: the workload (number of flops) of each context
- Rough computation of the number of resources needed by each context
  - How many CPUs allocated to each context?

nCPUs in Context c

Workload of Context c

$$\max\left(\frac{1}{t_{max}}\right) \text{subject to} \left(\begin{array}{l} \left(\forall c \in C, n_{\alpha,c} v_{\alpha,c} \geq \frac{W_c}{t_{max}}\right) \\ \wedge \left(\sum_{c \in C} n_{\alpha,c} = n_\alpha\right) \\ \wedge \left(\forall c \in C, n_{\alpha,c} < max_{\alpha,c}\right) \end{array} \right)$$

Allocate processing units the tree

By predicting the future

- ***Input***: the workload (number of flops) of each context
- Rough computation of the number of resources needed by each context
  - How many CPUs allocated to each context?

nCPUs in Context c

Workload of Context c

$$\max\left(\frac{1}{t_{max}}\right) \text{ subject to } \left(\begin{array}{l} \left(\forall c \in C, n_{\alpha,c} v_{\alpha,c} \geq \frac{W_c}{t_{max}}\right) \\ \wedge \left(\sum_{c \in C} n_{\alpha,c} = n_\alpha\right) \\ \wedge \left(\forall c \in C, n_{\alpha,c} < max_{\alpha,c}\right) \end{array} \right)$$

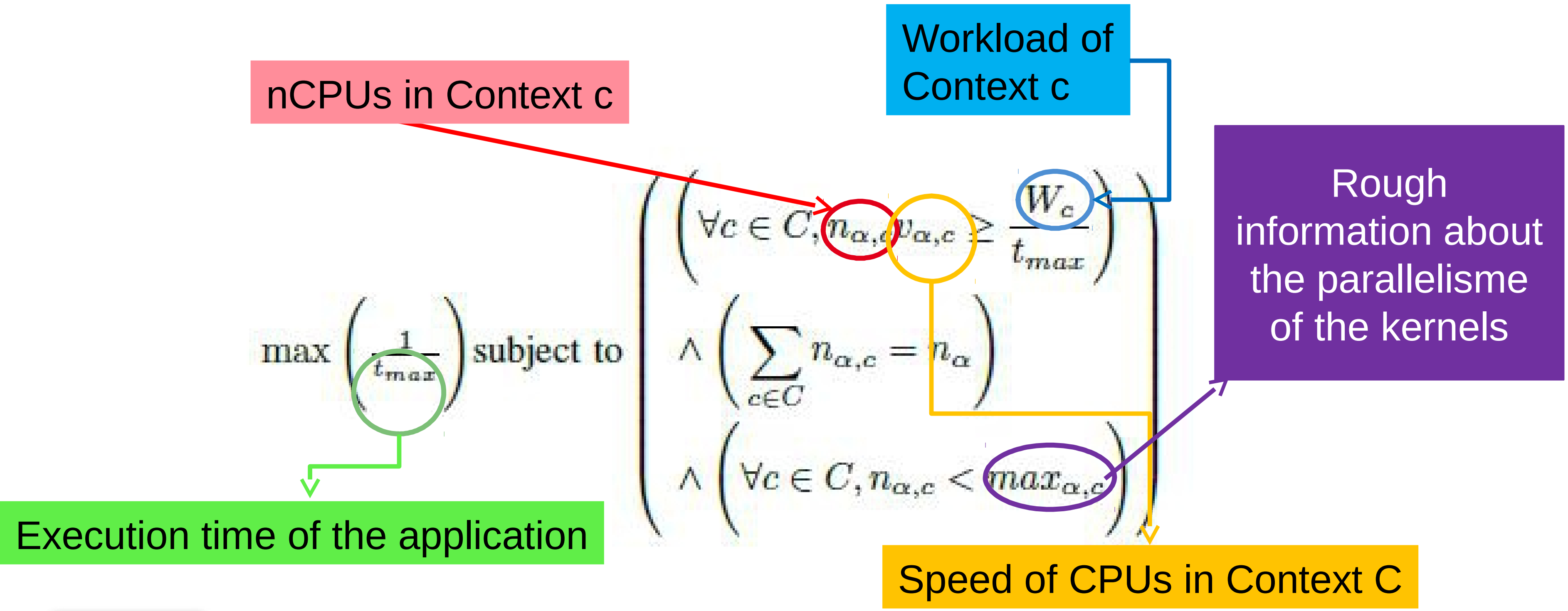
Execution time of the application

Speed of CPUs in Context C

Allocate processing units to the contexts

By predicting the future

- ***Input***: the workload (number of flops) of each context
- Rough computation of the number of resources needed by each context
  - How many CPUs allocated to each context?



Triggering the reallocation of resources

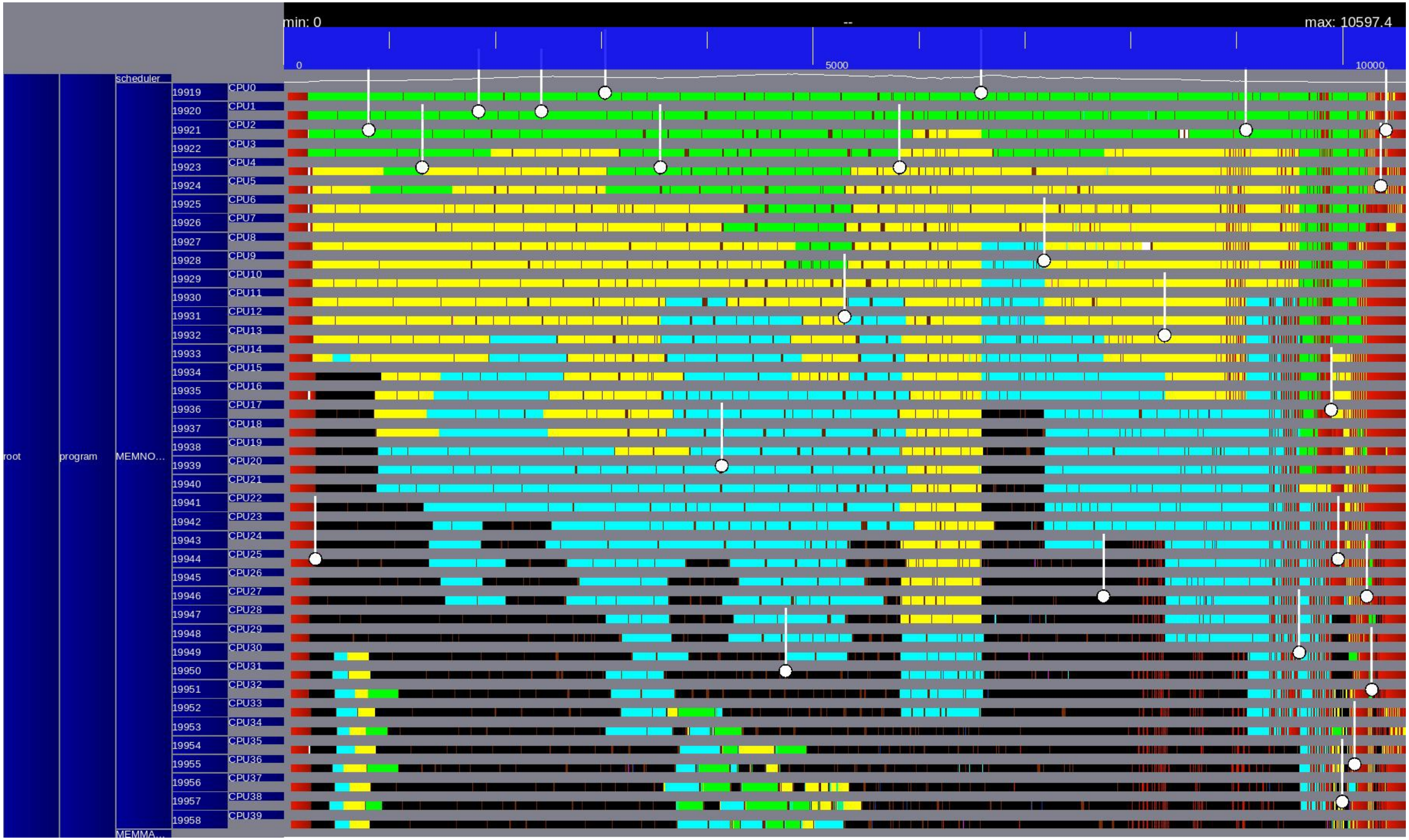
When static dimensioning is not enough

- The hypervisor monitors:
  - Idle PUs
  - Execution speed of the contexts
    - Execution time of the application cut in intervals
    - Observed Speed = executed_flops / time
    - Target speed = #PUs * average speed of PU

- The hypervisor:
  - Iterates hierarchically the tree of contexts (root -> leaves)
  - Searches for idle PUs or slow contexts
  - Stops at the level where the application doesn't behave "well"
  - Triggers resizing hierarchically starting from that level

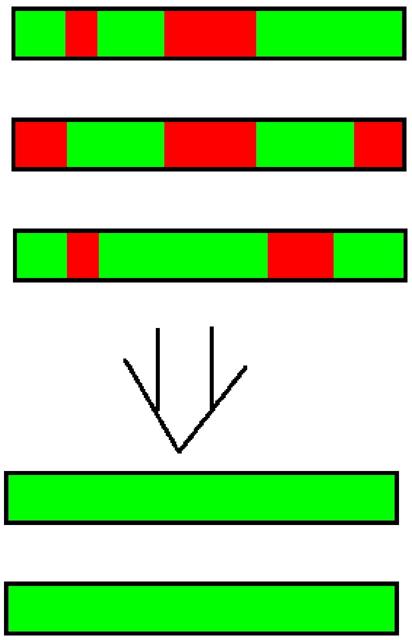
Using contexts to guide scheduling

Dynamically assigning PUs to the parallel nodes of the tree



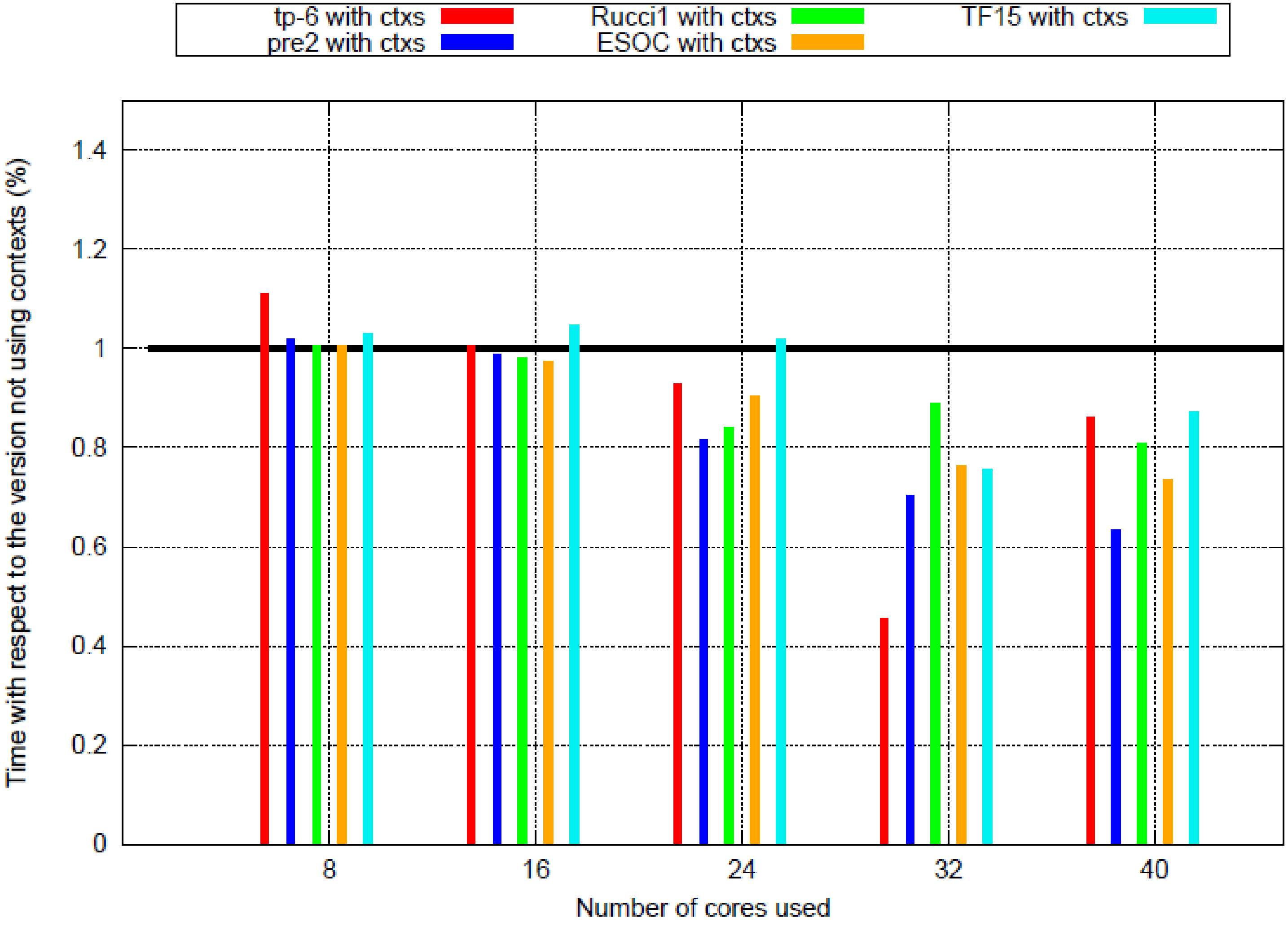
Scalability of the parallel tasks

- Idleness problem:
  - Sequential elementary tasks
  - Correct nCPUs but not enough tasks
- Possible solution:
  - Use the idle time to compute a ***max***
  - Drawback:
    - When to increase it?
    - What to do with the unused PUs?
- Intuition:
  - Use parallel/moldable elementary tasks to approximate malleable tasks
  - Need to find a *good* tradeoff between inner and outer parallelism



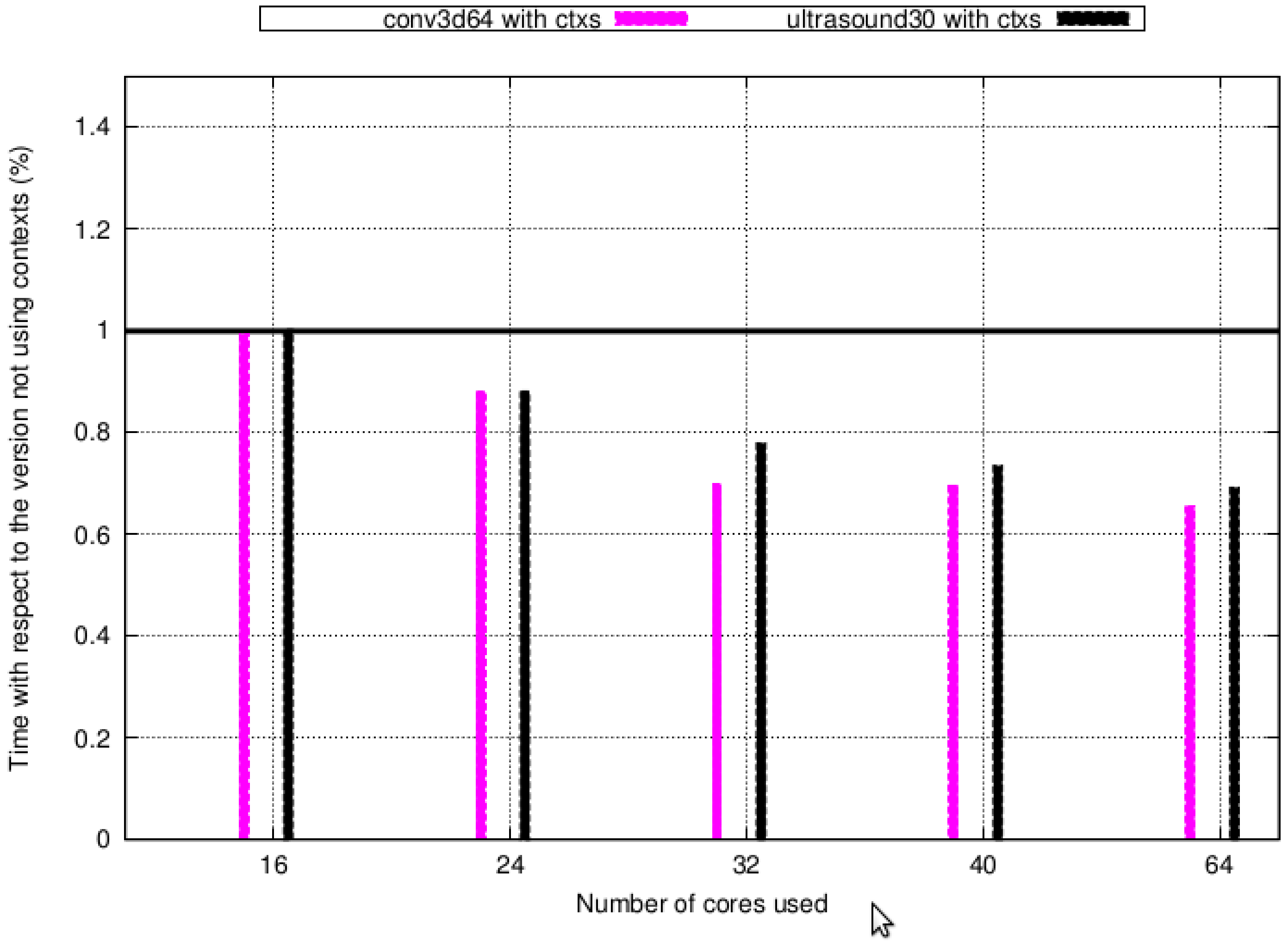
Using contexts to guide scheduling

Efficiency gain: on small problems



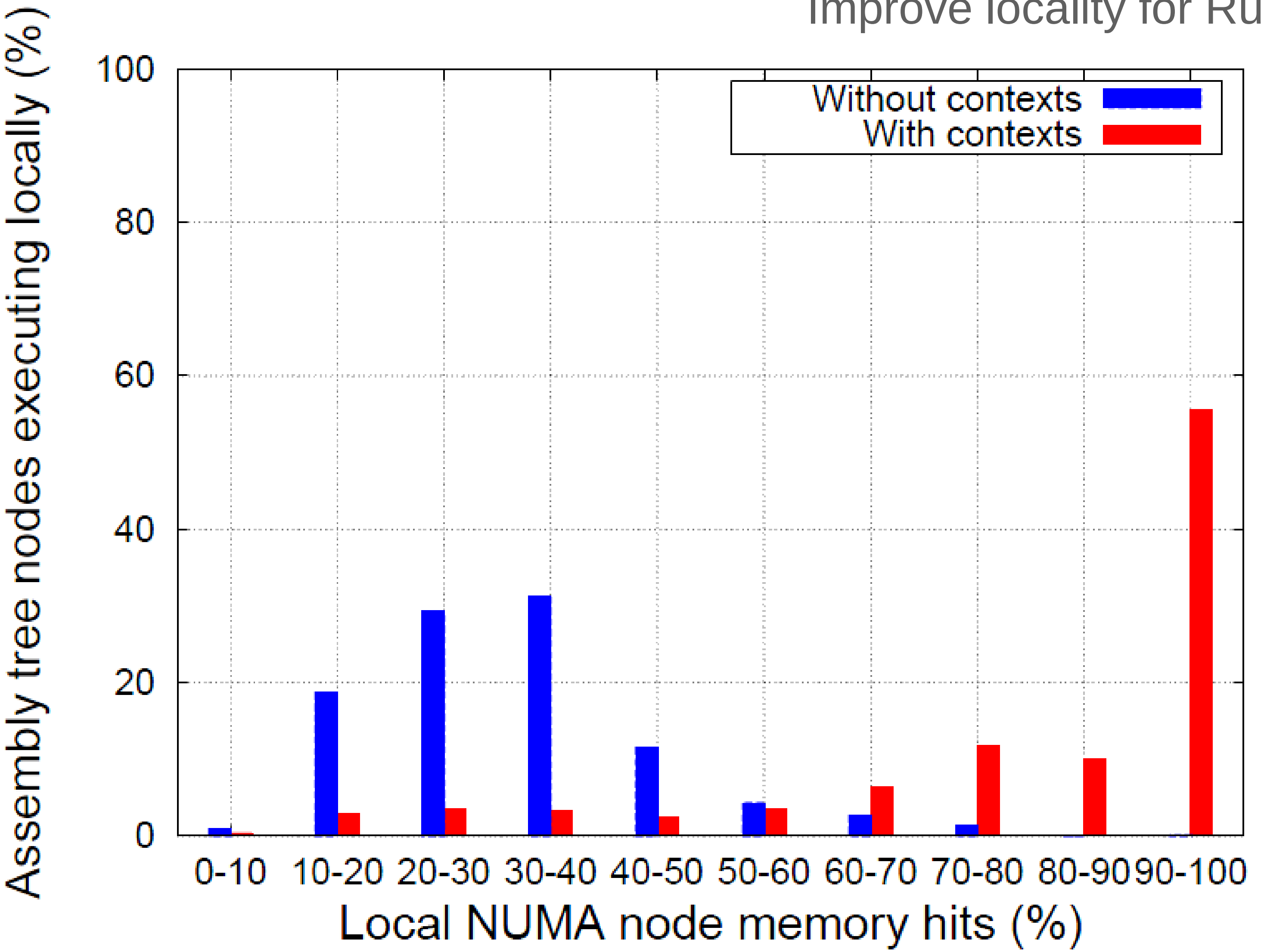
Using contexts to guide scheduling

Efficiency gain: on large problems



Using contexts to guide scheduling

Improve locality for Rucci1

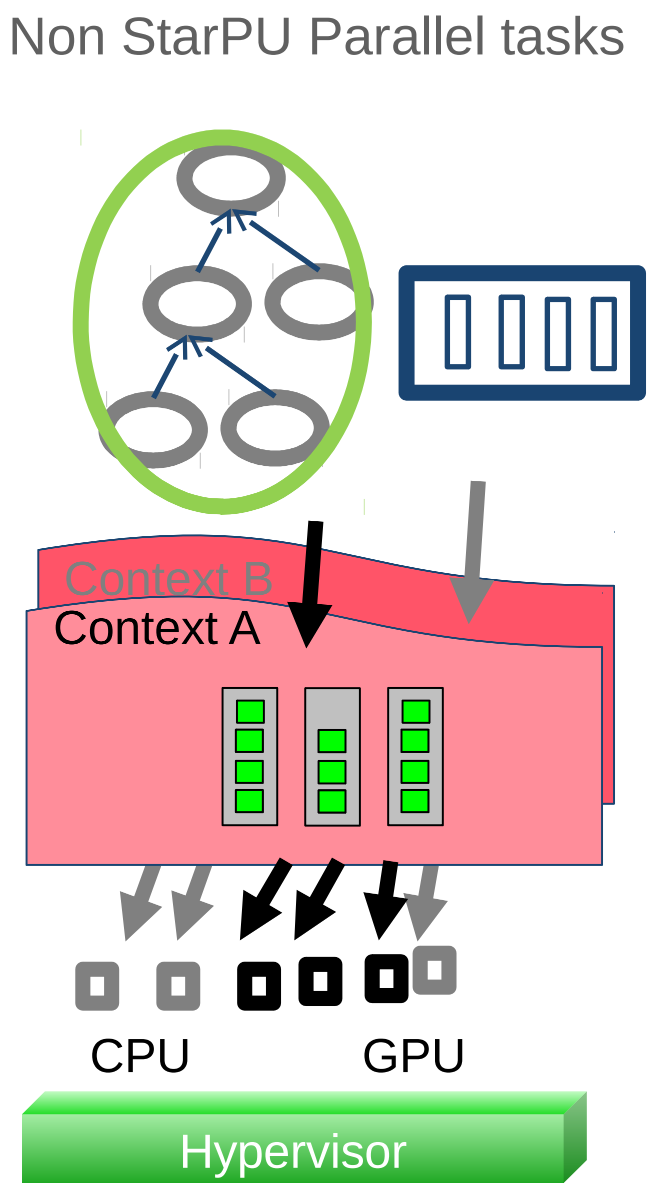


Conclusion

- Structure the parallelism of the application
  - By building a hierarchy of the scheduling contexts
- Use the hypervisor in order to:
  - Monitor the efficiency of the PUs
  - Monitor the speed of the scheduling contexts
  - Dynamically resize the scheduling contexts
- Improve the behavior of qr_mumps:
  - By enforcing the locality
  - By respecting the critical path
- Need a strong interaction between the solver and the hypervisor

On going work (1/2)

- Deal with non-StarPU tasks
  - Sub-DAGs of StarPU tasks
  - Parallel tasks (parallel mkl blas, …)
- Resizing StarPU/OpenMP/TBB contexts
  - Common metrics?
- Contexts as a way to better utilize Heterogeneous/Manycore Architectures
  - GPUs
  - Intel Xeon Phi accelerators



On going work (2/2)

- Increase the amount of parallelism
  - Move to 2D partitionning of frontal matrices when needed.
- Limit the memory usage of the factorization
  - Control task submission while avoiding deadlocks.
- Consider different paradigms (e.g. PTG model)
  - A ParSEC-based version of the solver is being developped.
- Exploit accelerator-based heterogeneous architectures
  - GPU, Intel Xeon-Phi, …
  - Still preliminary.
  - Need for scheduling algorithms for graphs of malleable/moldable tasks running on heterogeneous platforms.
- Study distributed memory architectures.