703650 VO Parallel Systems WS2019/2020
Domain Decomposition and Load Balancing

Philipp Gschwandtner

Overview

- last week’s feedback results
- domain decomposition
- load (im)balance
- “Tales from the Proseminar”

Last Week’s Feedback Results

- 12 messages total
  - overall, you seem very happy
  - except for a few small complaints/requests/remarks
    - 6x fast speech…
    - 1x request for more code samples
    - 1x request for a break after 45 mins
    - 1x complaint regarding the time slot
    - 1x request for team presentations in the PS

- feel free to give further feedback anytime

Motivation (Load Balancing)

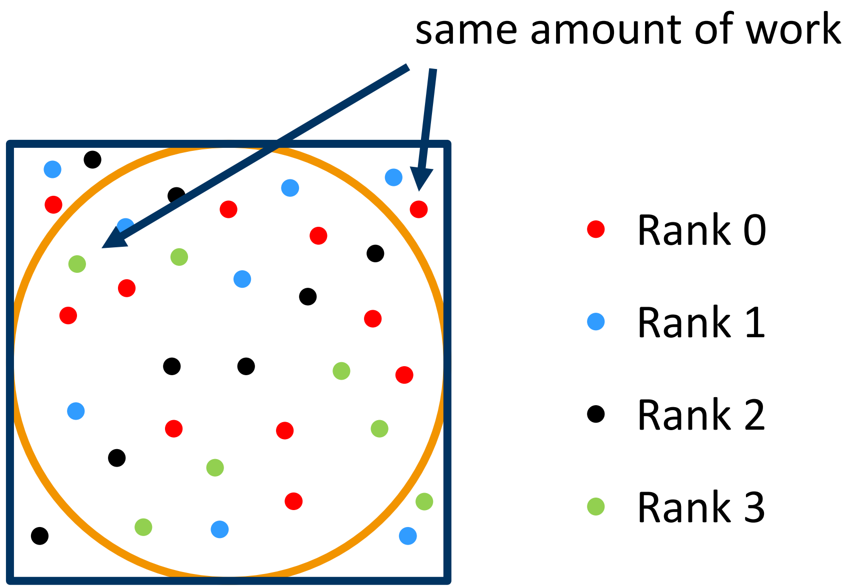
- Monte Carlo π
  - amount of work per rank depends only on number of samples
- 2D heat stencil
  - amount of work per rank depends only on number of elements

```
...
int localSamples = samples/numRanks
...
```

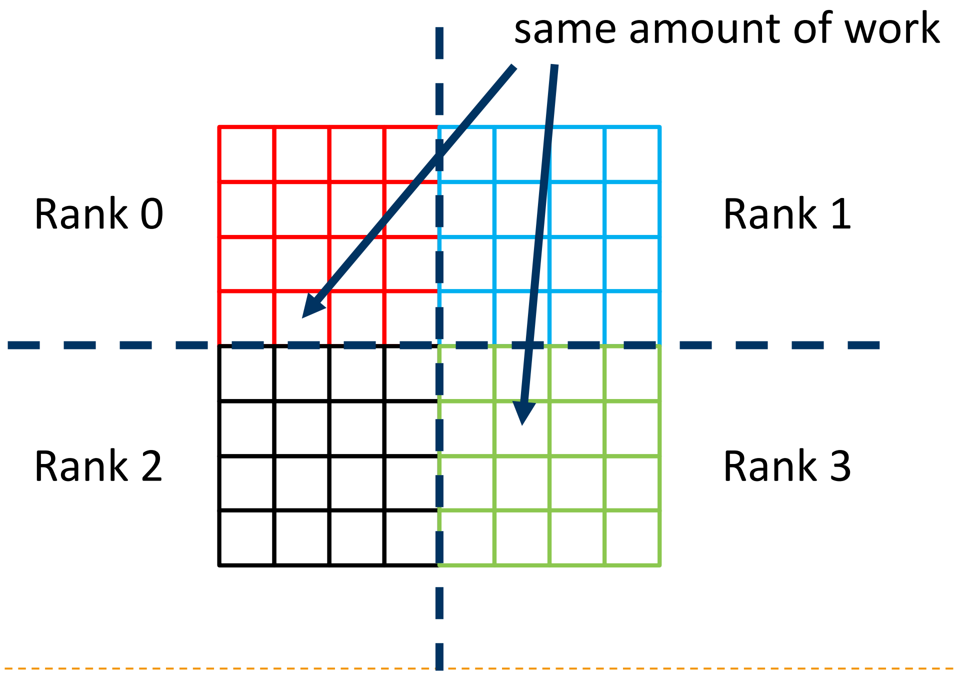
```
...
int localN = problemSize/numRanks
...
```

Motivation cont'd (Load Balancing)

- Monte Carlo π
  - amount of work per rank depends only on number of samples



- 2D heat stencil
  - amount of work per rank depends only on number of elements



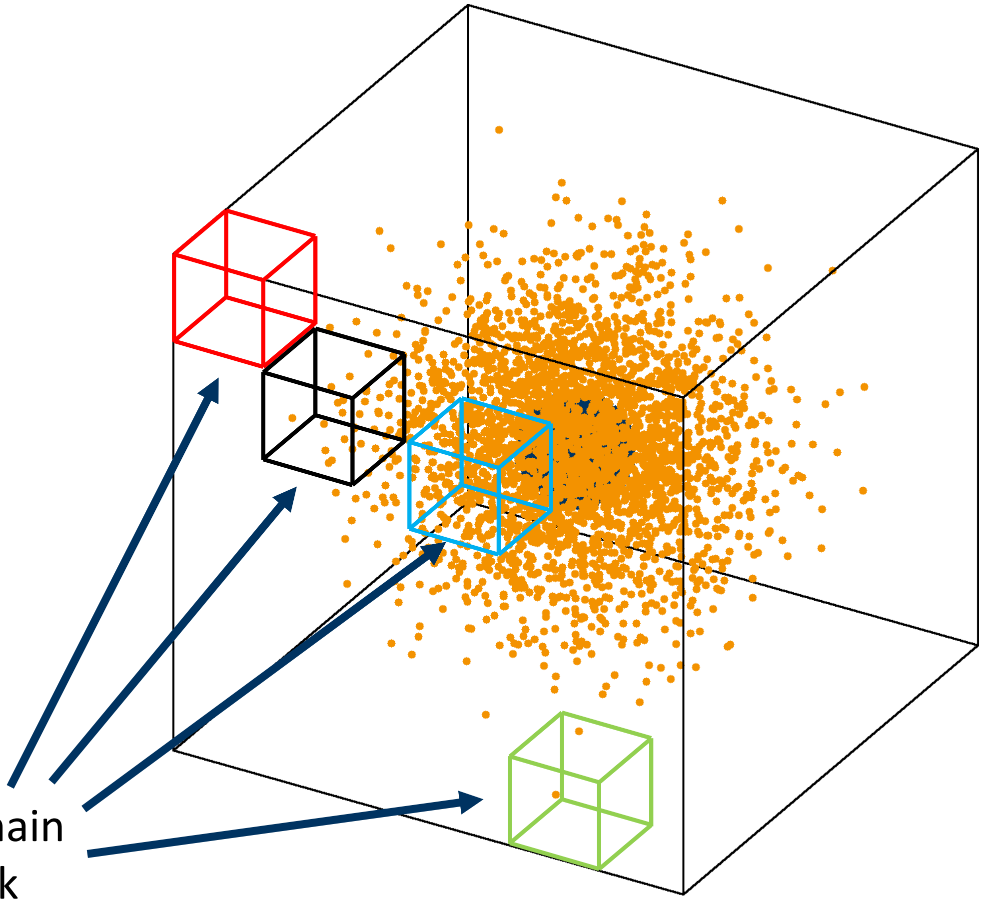
Motivation cont’d (Load Balancing)

- this is called “balanced load” or “load balance”
  - all the ranks have the same amount of work
  - easily achieved, as any sub-domains of equal size entail same amount of work, no matter in which part of your domain
    - only true for a subset of realistic applications

- there’s also “unbalanced load” or “load imbalance”
  - ranks do not have the same amount of work
  - either the sizes of sub-domains per rank vary, or their entailed amount of work
  - happens all the time for realistic use cases

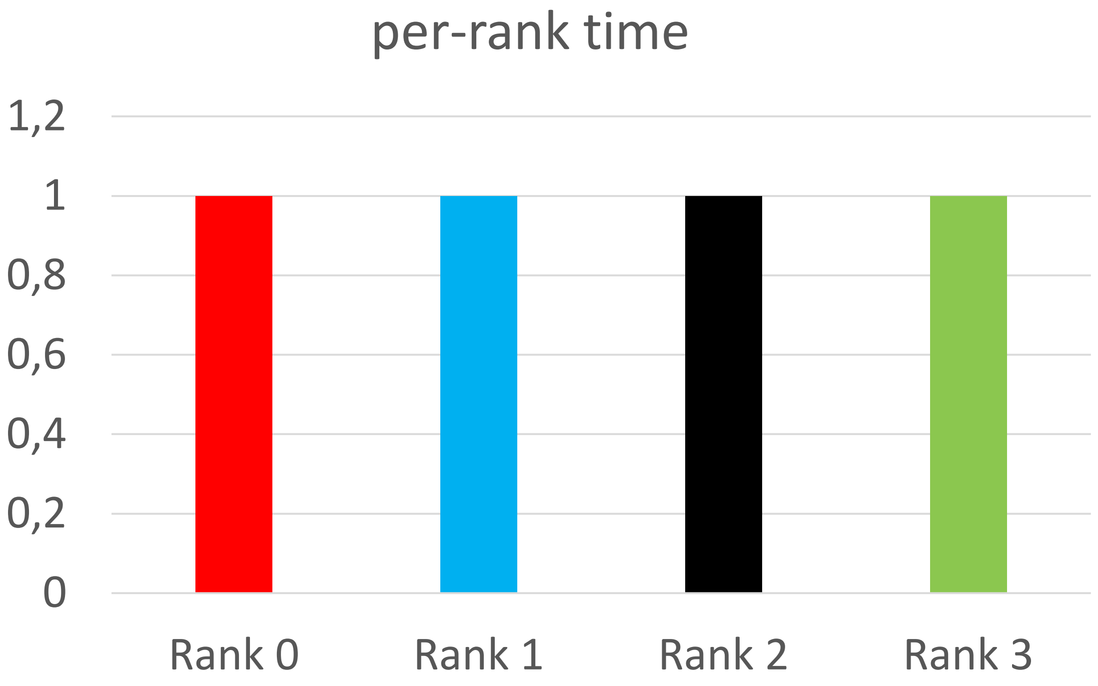
Motivation cont'd (Load Balancing)

- particle ("lagrangian") simulation
  - no fixed grid
  - particles can move inside the domain
  - particle distribution affects workload

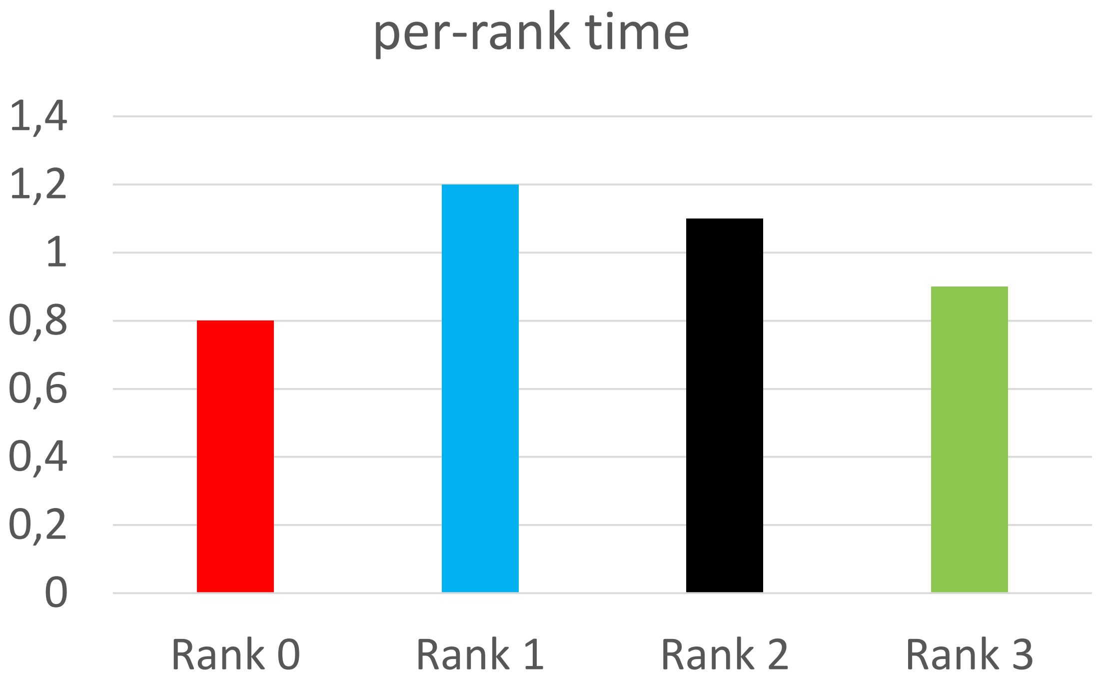


same-sized sub-regions of domain
but different amount of work

Motivation cont'd (Load Balancing)



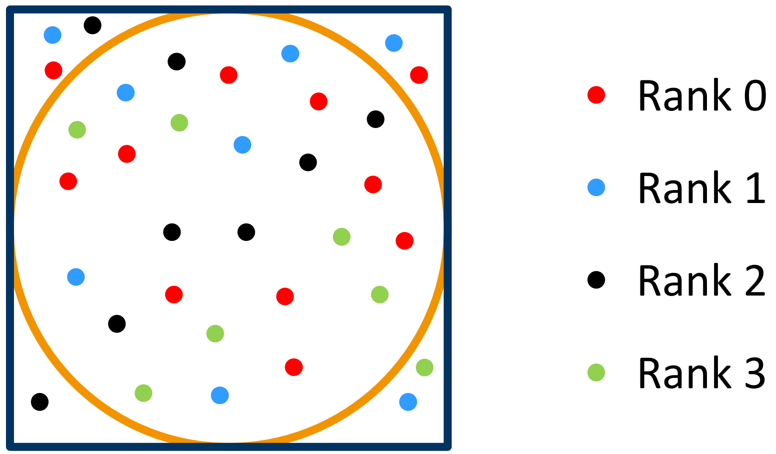
$$t_{\text{cpu}} = 4$$
$$t_{\text{wall}} = 1$$



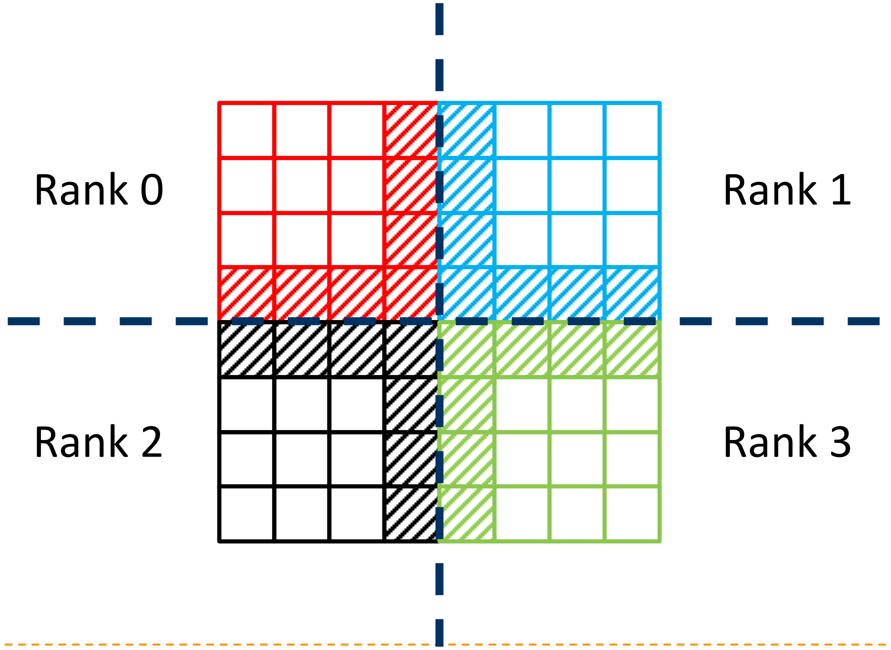
$$t_{\text{cpu}} = 4$$
$$t_{\text{wall}} = 1.2$$

Motivation cont'd (Domain Decomposition)

- Monte Carlo π
  - distributes samples among ranks
  - no communication except at the end
  - also called "embarrassingly parallel"



- 2D heat stencil
  - distributes grid cells among ranks
  - ghost cell exchange required at borders!



Domain Decomposition

Domain Decomposition

- discretize the problem space
  - grid cells, particles, samples, …
- split the workload among the given number of ranks
  - also reduces the memory footprint
- goal: minimizing overhead, meaning:
  - minimize amount of data to be transferred
  - minimize number of discrete communication steps (c.f. neighbor exchange!)
  - minimize load imbalance

The Bad News

- MPI does not offer domain decomposition
  - sure, there's `MPI_Scatter()` & alike
  - but it's only the underlying tool
- you need to take care of this yourself
  - or better yet, use a library

Cost of a Point-to-point Message

- $t = \text{latency} + \dfrac{\text{message size}}{\text{bandwidth}}$
- note: simplistic view, actual cost depends on
  - underlying protocols (eager, rendezvous, …)
  - additional data copies required

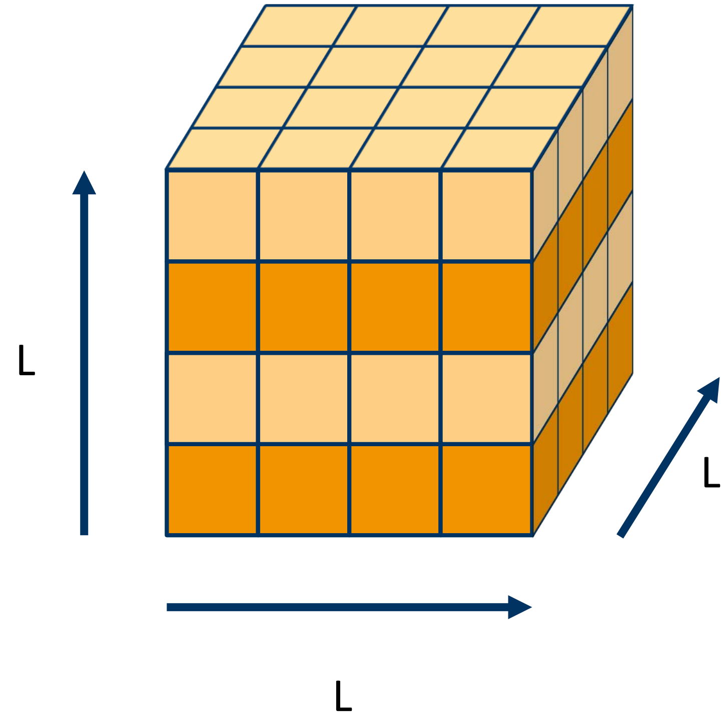
- latency and bandwidth are fixed properties of the network
  - note: rank-core mappings!
- message size (and their number) is what we can influence
- can be easily computed for simple, regular decompositions

3D Heat Stencil Example: Slabs

$$c_{1D}(L, N) = $$
$$L \cdot L \cdot w \cdot 2 = 2wL^2$$

L: size per dimension
N: number of ranks
w: amount of data per element

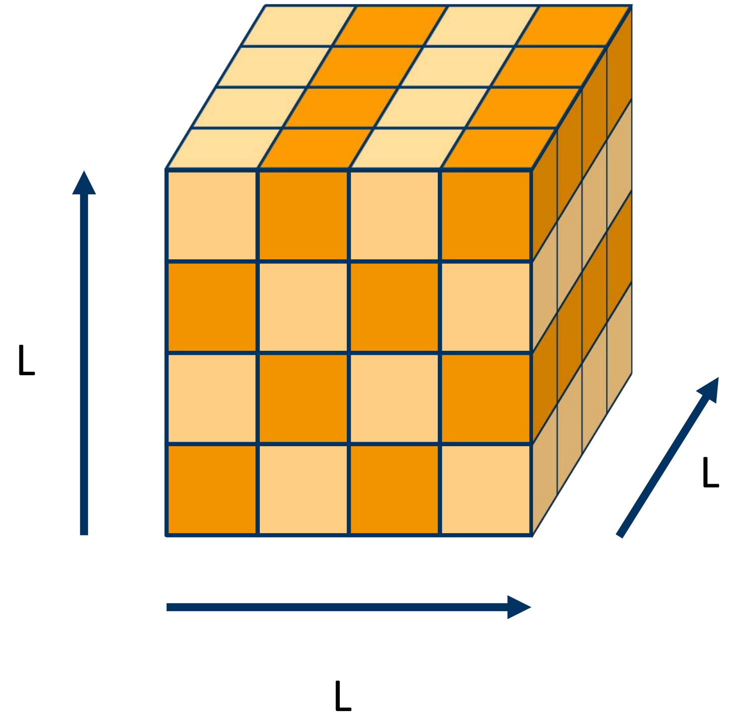
- pro: easy to implement
- con: communication volume does not decrease when increasing N



3D Heat Stencil Example: Poles

$$c_{2D}(L, N) =$$
$$L \cdot \frac{L}{\sqrt{N}} \cdot w \cdot (2+2) = \frac{4wL^2}{\sqrt{N}}$$

- pro: communication volume does decrease with increasing N
- con: surface-to-volume ratio also increases with N
  - i.e. communication grows disproportionally fast compared to computation

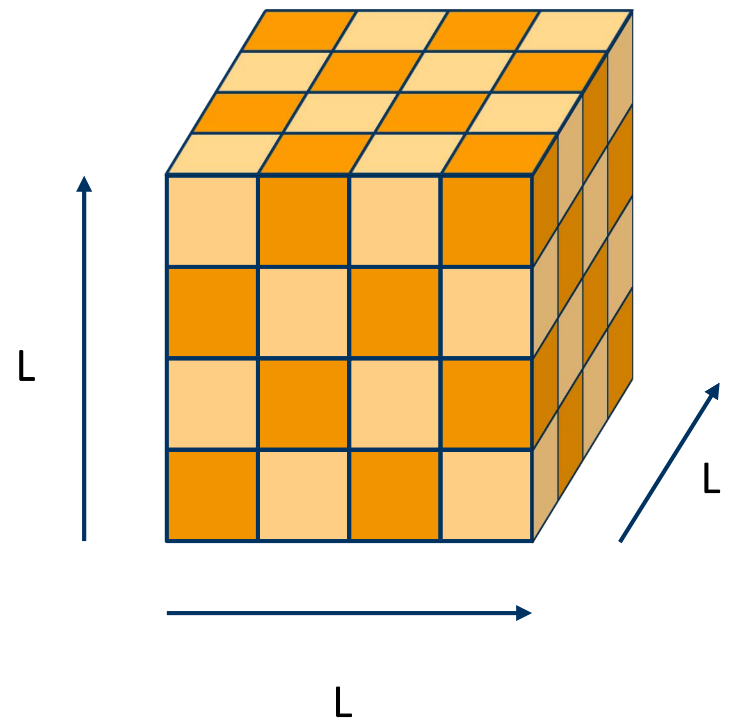


3D Heat Stencil Example: Cubes

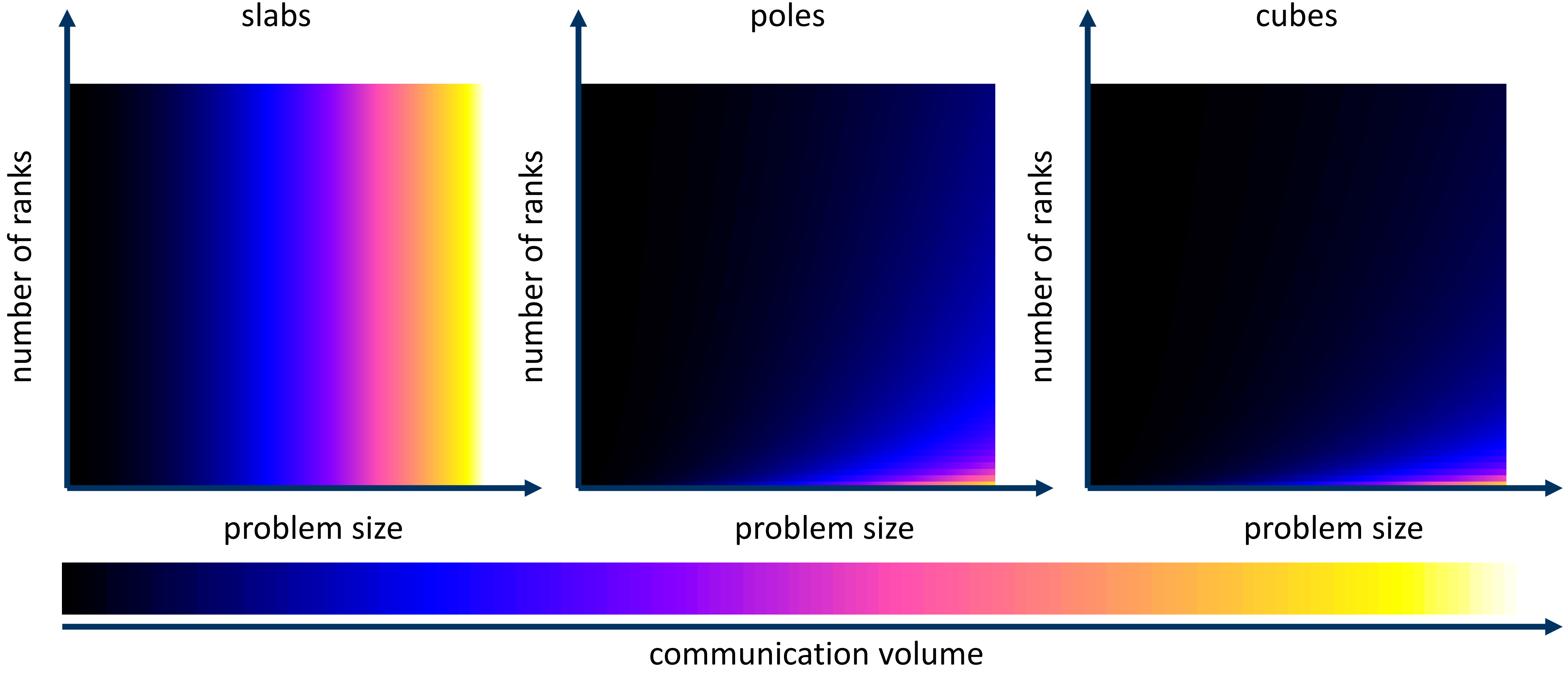
$$c_{3D}(L,N) =$$

$$\frac{L}{\sqrt[3]{N}} \cdot \frac{L}{\sqrt[3]{N}} \cdot w \cdot (2+2+2) = \frac{6wL^2}{\sqrt[3]{N}}$$

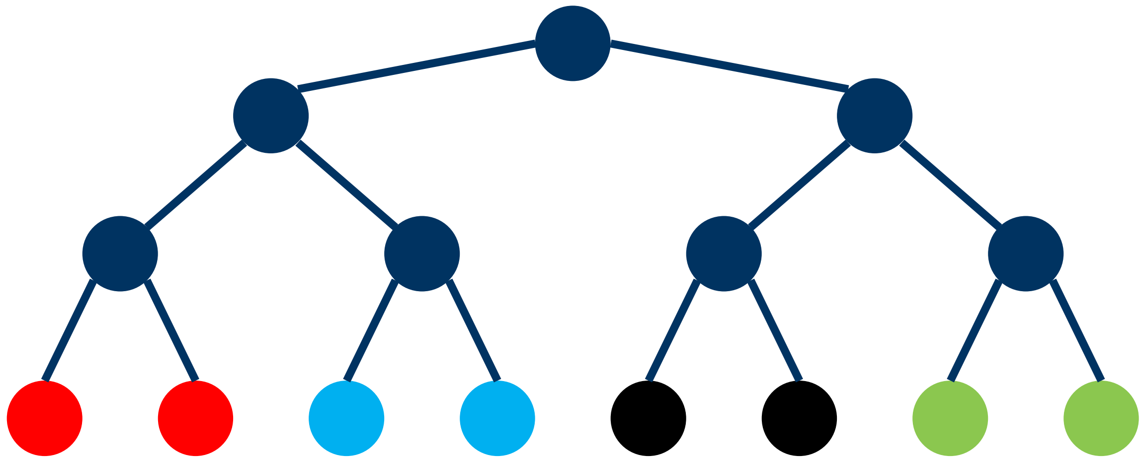
- pro: communication volume also decreases with increasing N
- con: still surface-to-volume-ratio issue
- but also further increase in number of messages, latency might be an issue

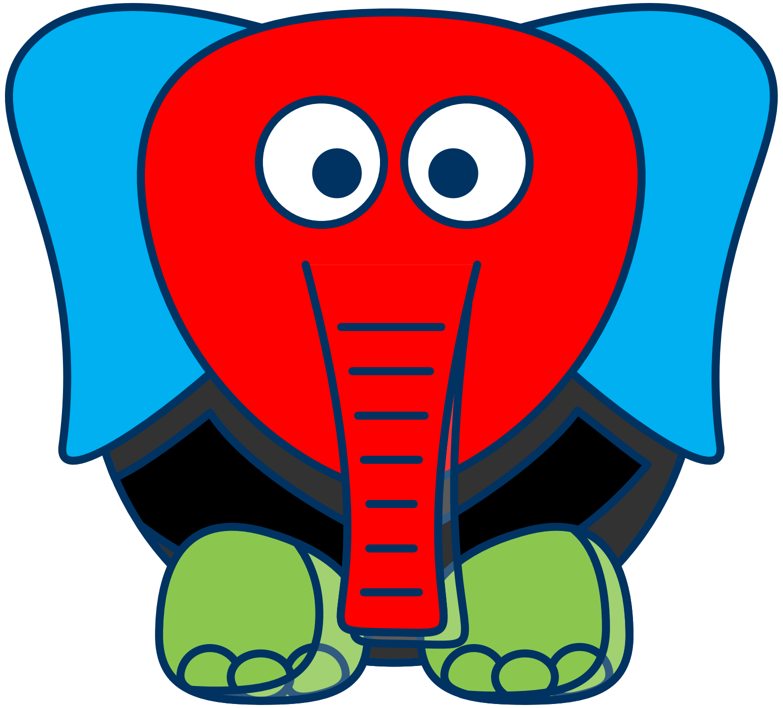


Comparing Communication Volumes



Non-rectangular Domain Decomposition





Domain Decomposition Considerations

- How much data will have to be transferred?
  - more data requires more bandwidth
- In how many messages do I need to transfer the data?
  - additional messages means additional latency and management overhead
- What’s the cache efficiency of the decomposition?
  - might only be an implementation issue, e.g. columns can be transposed
- How complicated is the implementation?
  - usual trade-off: e.g. 50% readability decrease for 2% performance increase?

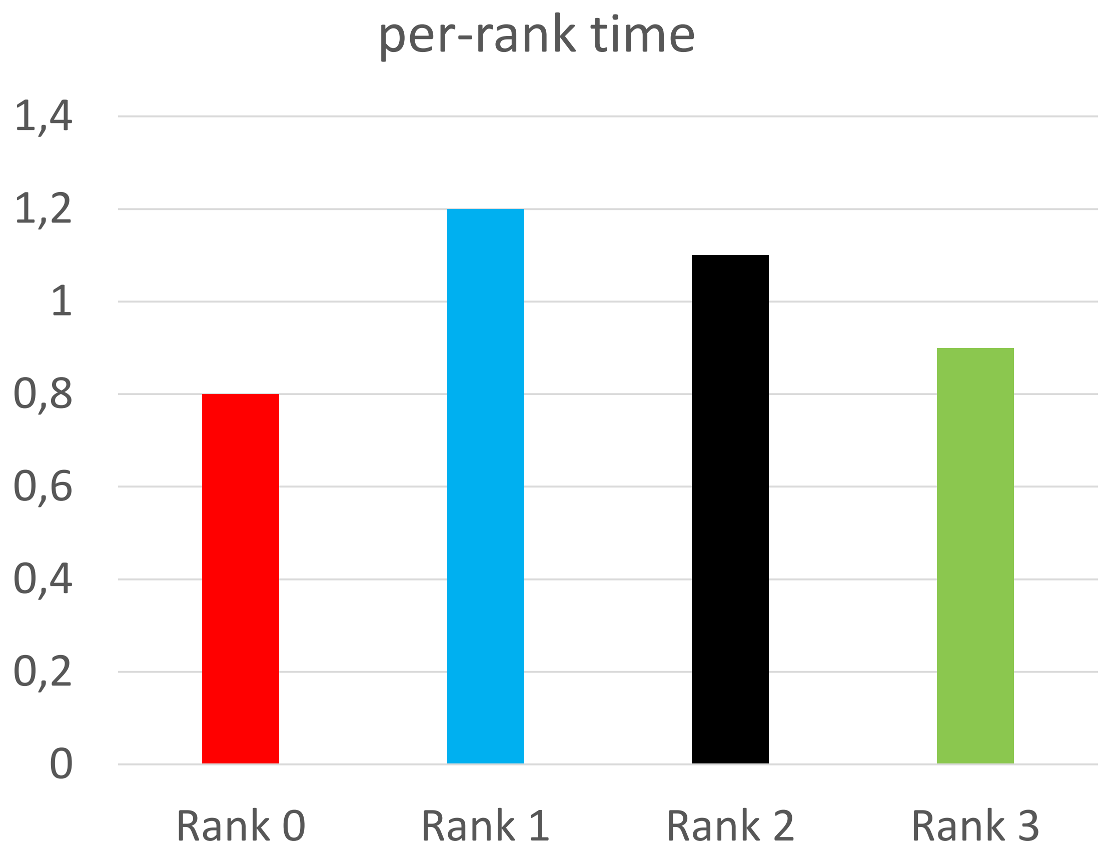
Possibly the Two Most Important Considerations

- Your domain cannot be decomposed efficiently?
  - change your algorithm
- Your data structure cannot be decomposed efficiently?
  - change your implementation

Load Imbalance

Load Imbalance

- refers to the phenomenon of not all ranks finishing their work at the same time
  - or ranks waiting on others
  - or ranks idling for longer periods
  - …



Static vs. Dynamic Load Imbalance

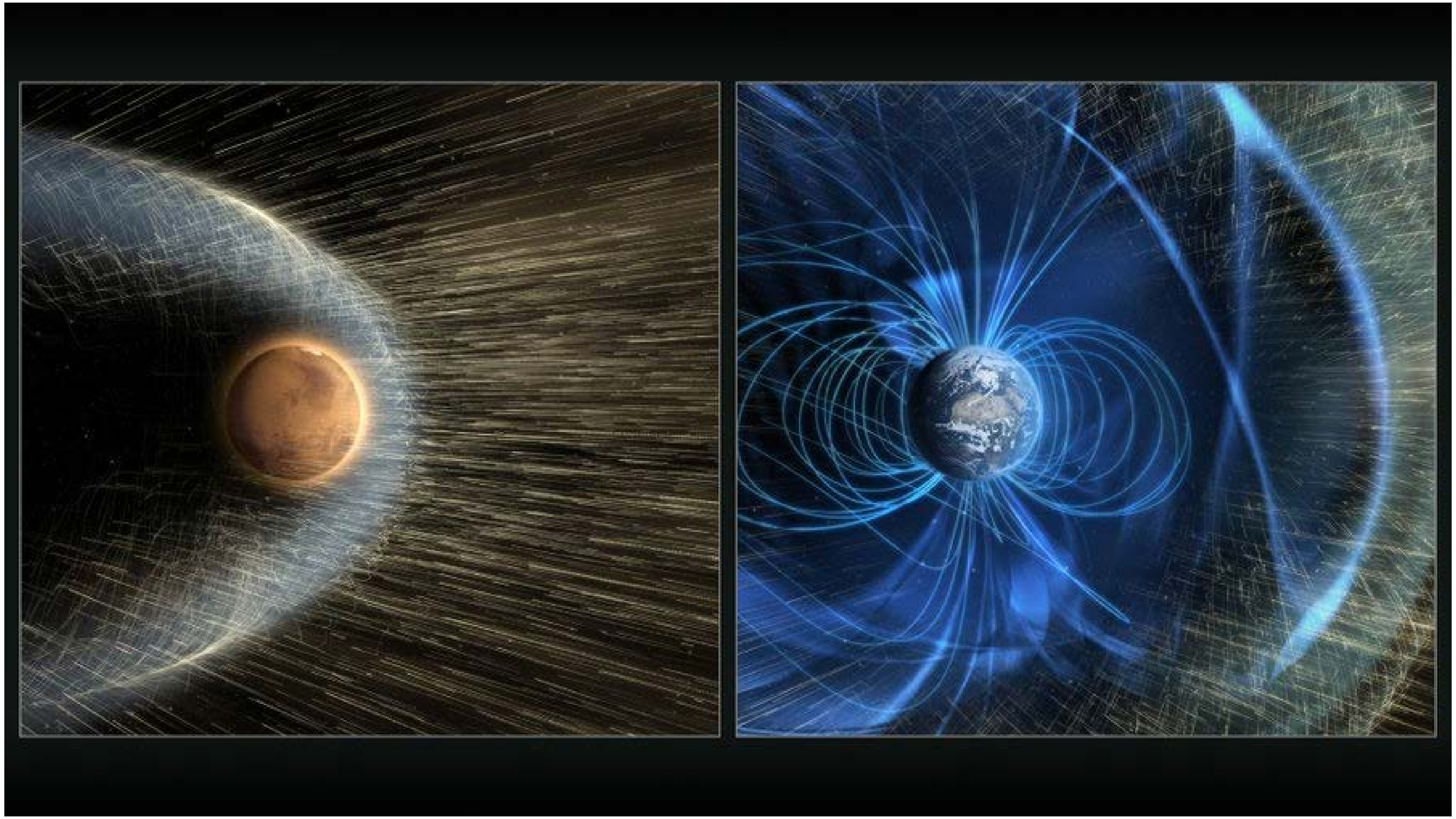
- static load imbalance
  - caused by initial conditions, e.g.
    - mountains vs. plains
    - ocean shore vs. open sea
    - remainder in integer division
  - does not change during application execution
  - mitigation usually incurs no runtime overhead after initial setup

- dynamic load imbalance
  - caused by application execution
    - moving particles (e.g. galaxy clusters)
    - partial availability of sensor data
    - convergence of iterative algorithms
  - does change during application execution
  - requires rebalancing (e.g. at fixed intervals, when reaching limits, …)
    - definitely incurs runtime overhead

The Bad News Reloaded

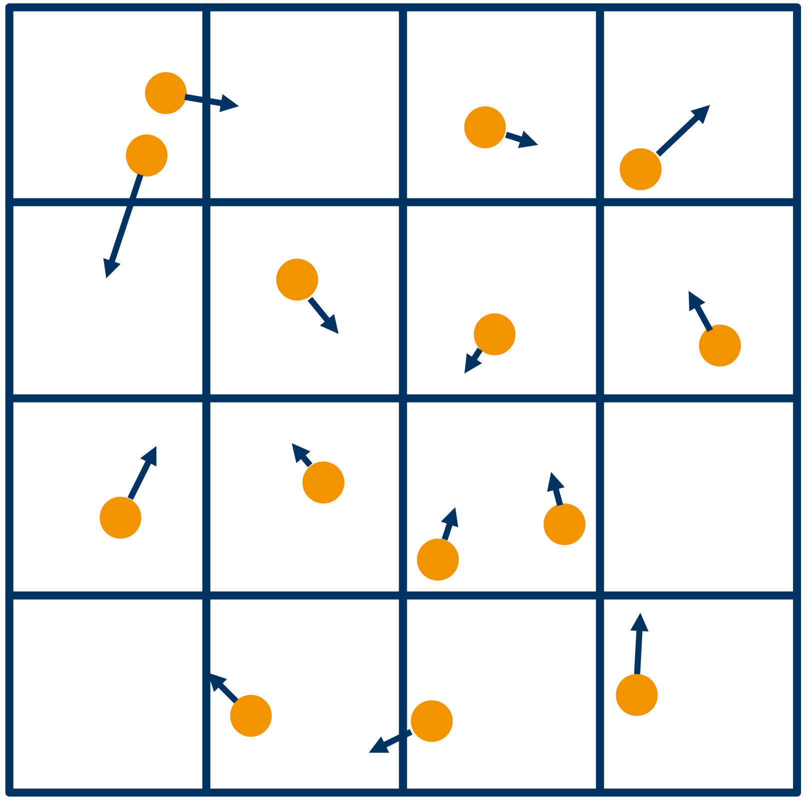
- MPI does not offer load balancing
  - yes, there's `MPI_Scatterv()` & alike
  - but it's only the underlying tool
- you need to take care of this yourself
  - or better yet, use a library

Recap: Space Weather Prediction (Particle-in-Cell Simulation)



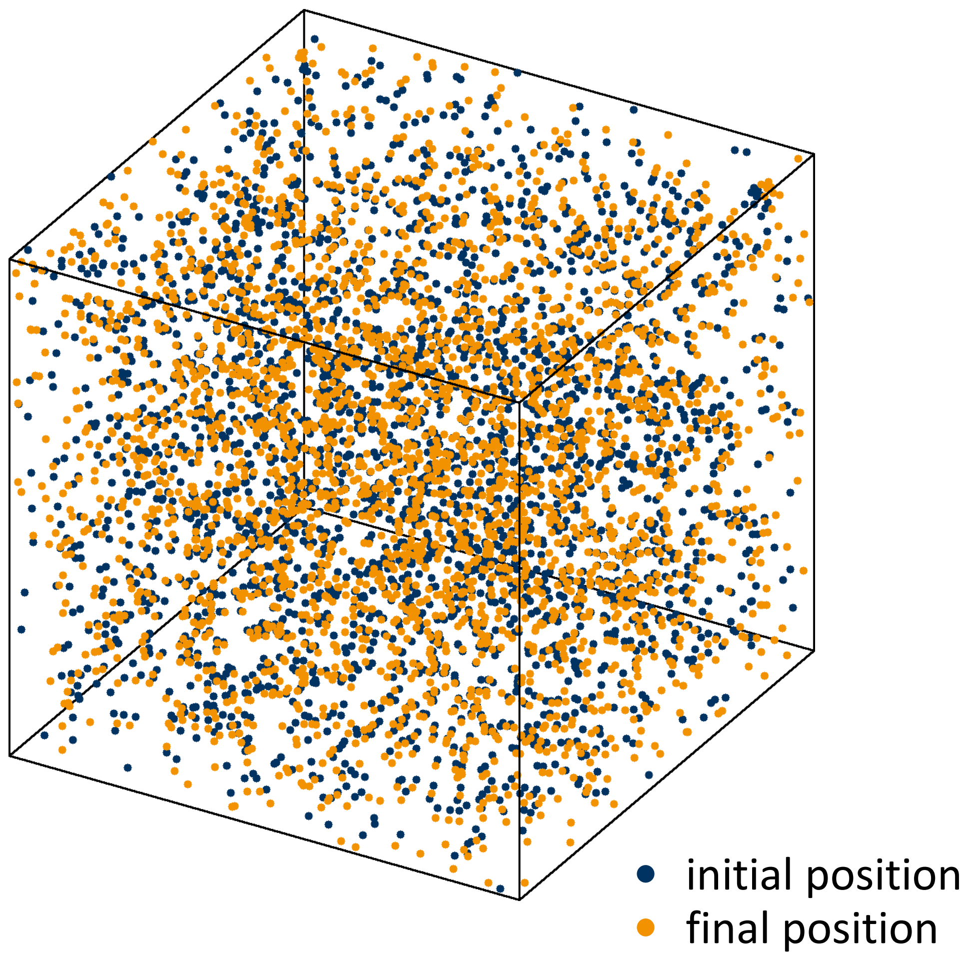
Particle-in-Cell

- moving, charged particles move through a grid of cells representing an electromagnetic field
  - the field exerts a force on the particles
  - the particle movement affects the field
  - e.g. electrons hitting Earth's magnetosphere



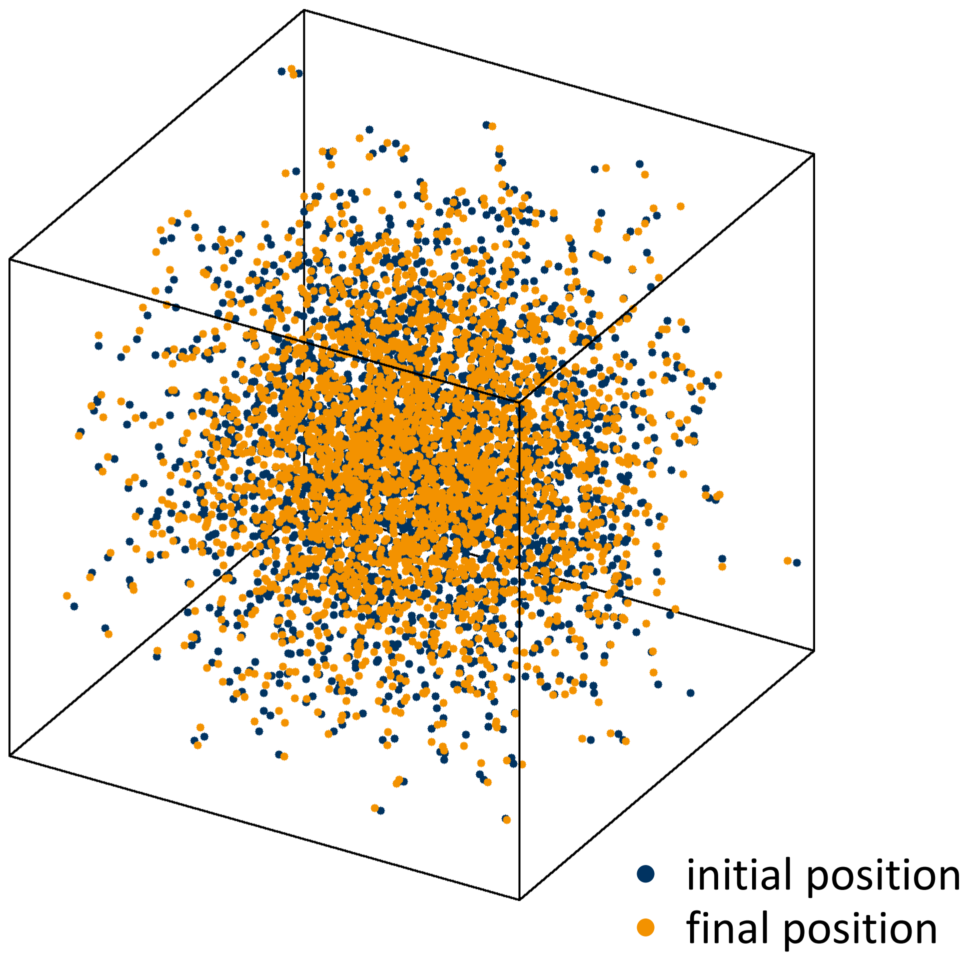
Particle-in-Cell Use Case: Uniform

- static load balance: particles uniformly distributed across domain
- dynamic load balance: particle positions almost constant



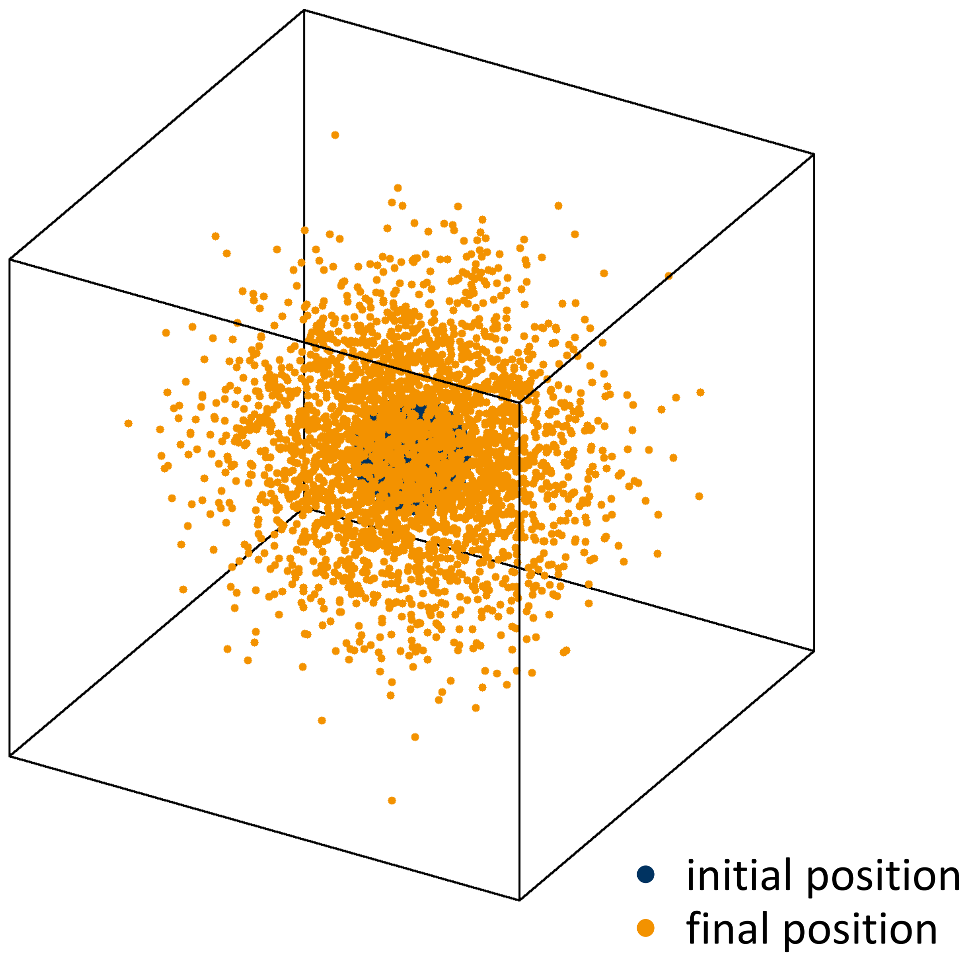
Particle-in-Cell Use Case: Cluster

- static load imbalance: particles non-uniformly distributed across domain
- dynamic load balance: particle positions almost constant



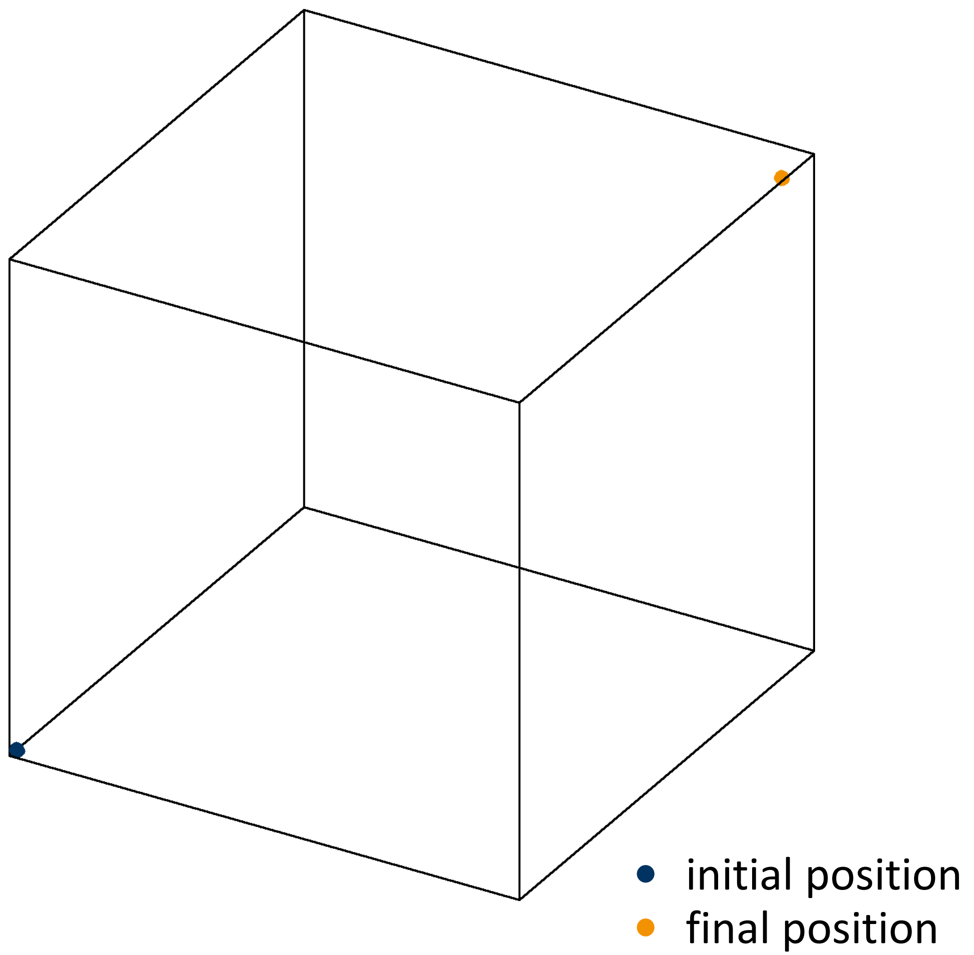
Particle-in-Cell Use Case: Explosion

- static load imbalance: particles non-uniformly distributed across domain
- dynamic load imbalance: particle positions changes drastically

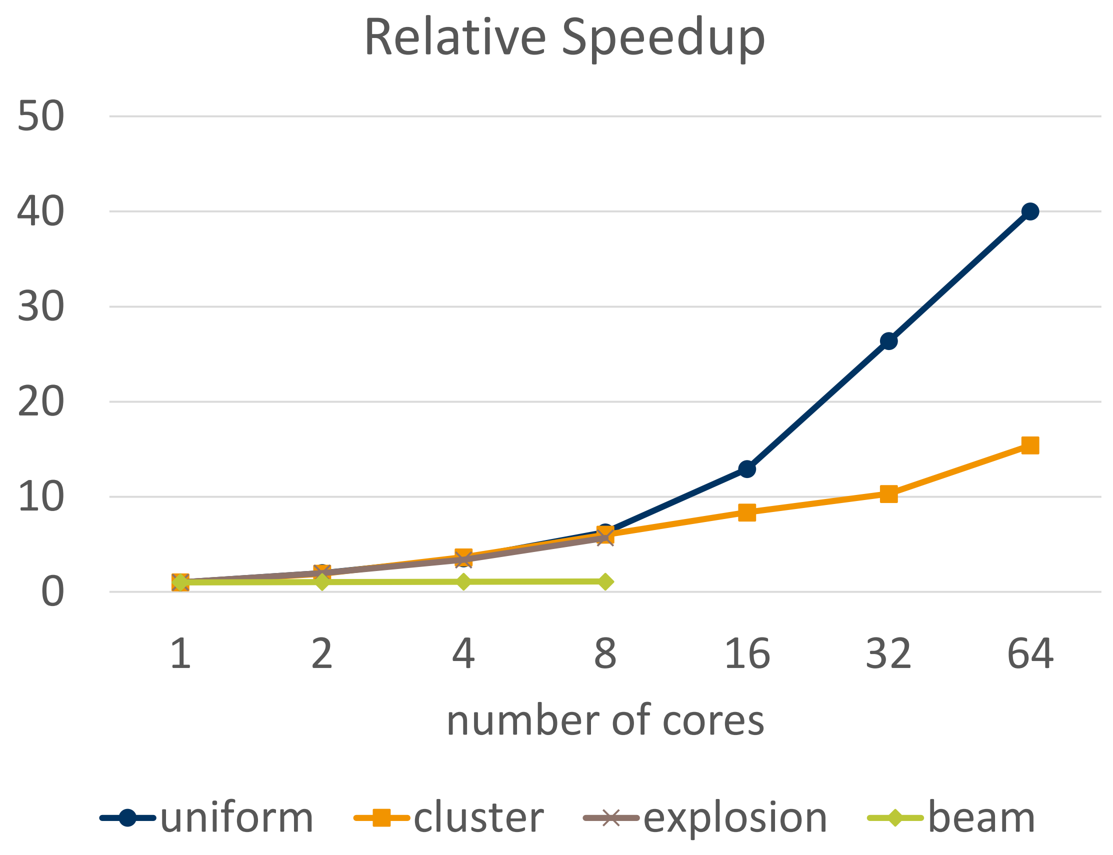


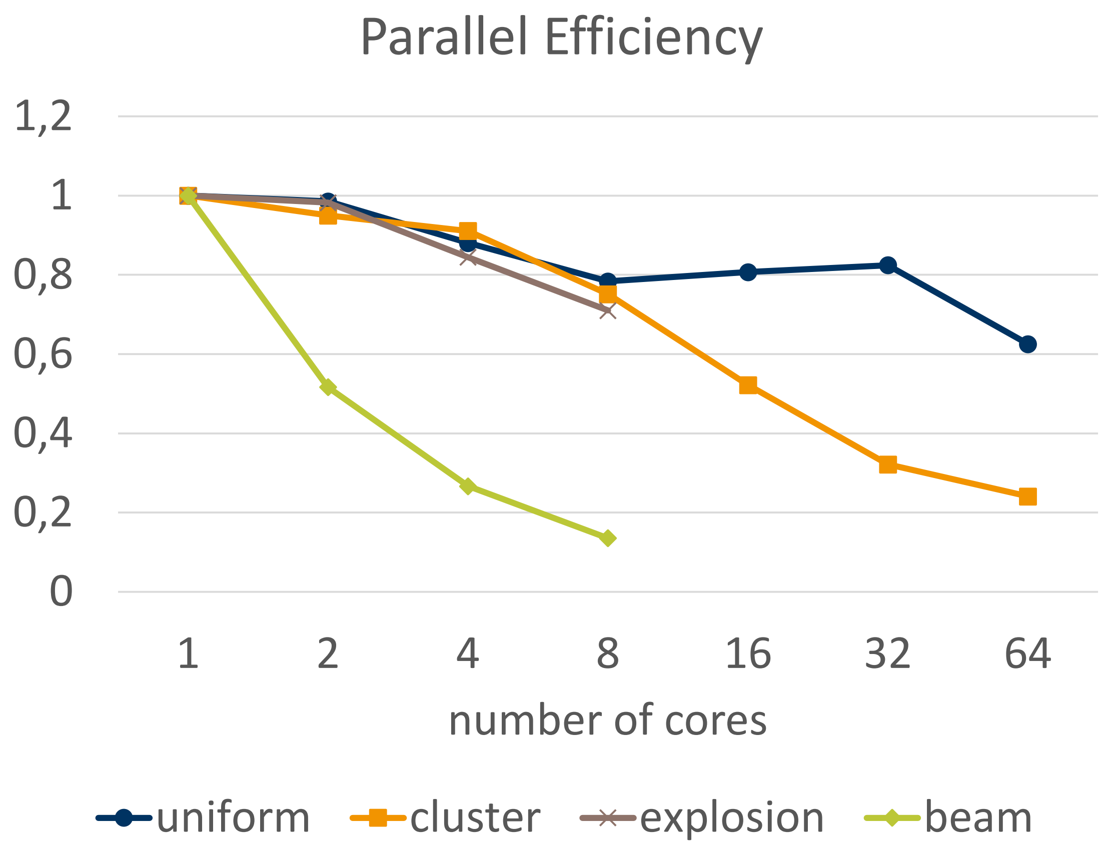
Particle-in-Cell Use Case: Beam

- static load imbalance: particles non-uniformly distributed across domain
- dynamic load imbalance: particle positions changes drastically
- extreme case for testing load-balancing algorithms
  - but could be real, e.g. beam of electrons



iPIC3D Use Case Comparison, Strong Scaling, 1M Particles, LCC2

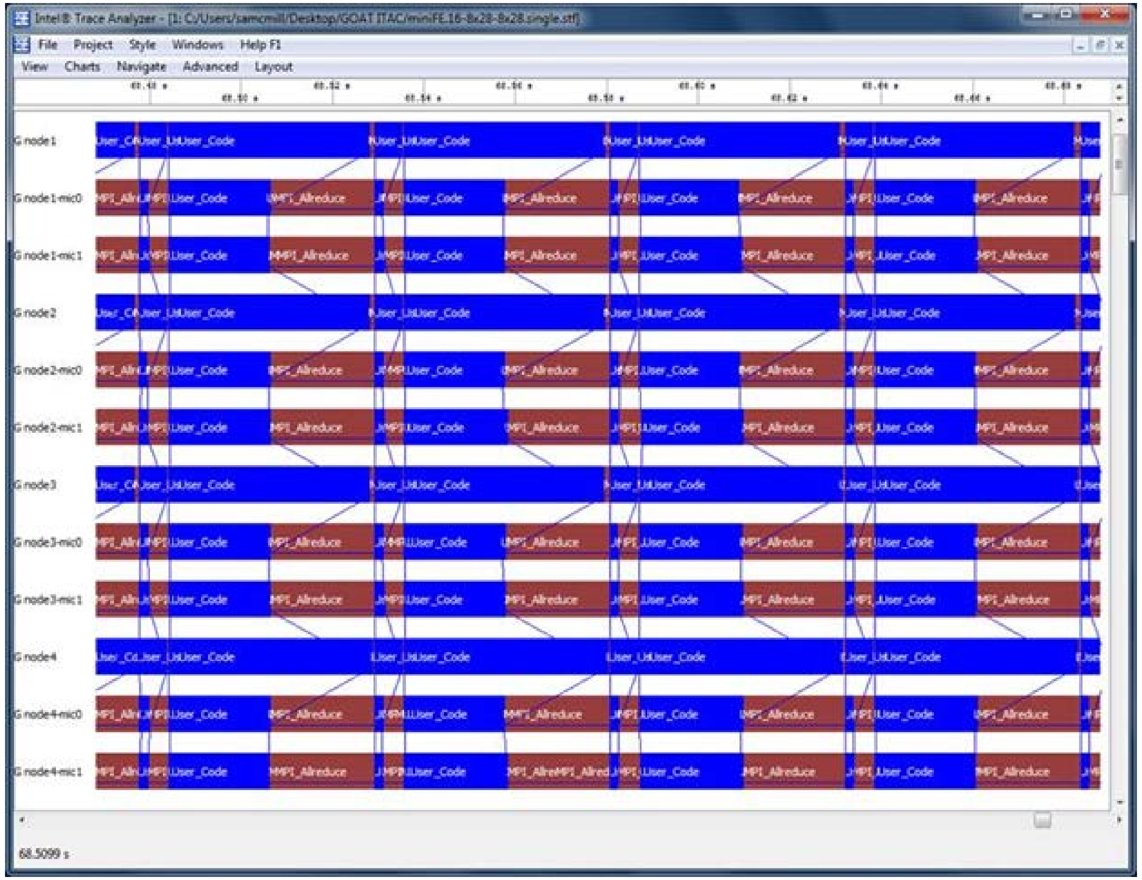




Detecting Load Imbalance with Tools

- screenshot on the right shows Intel Trace Analyzer
  - miniFE benchmark of Sandia National Labs
  - work shared between CPU (lines 1, 4, 7 and 12) and Xeon Phi accelerators
  - blue bars are application work
  - red bars are MPI synchronization

- Xeon Phis are waiting 50% of the time for the CPUs!



Dealing with Load Imbalance

- quantify the amount of work of domain ranges (e.g. elements)

- choose a domain decomposition that allows
  - to split the workload between the given number of ranks in even shares
  - if required, rebalance the workload during runtime
    - also known as “adaptive refinement”

- trade-off with black box problems
  - many chunks: easy to balance load but increased management overhead
  - few chunks: little overhead, but difficult to balance load
  - note: decomposition itself is also overhead!

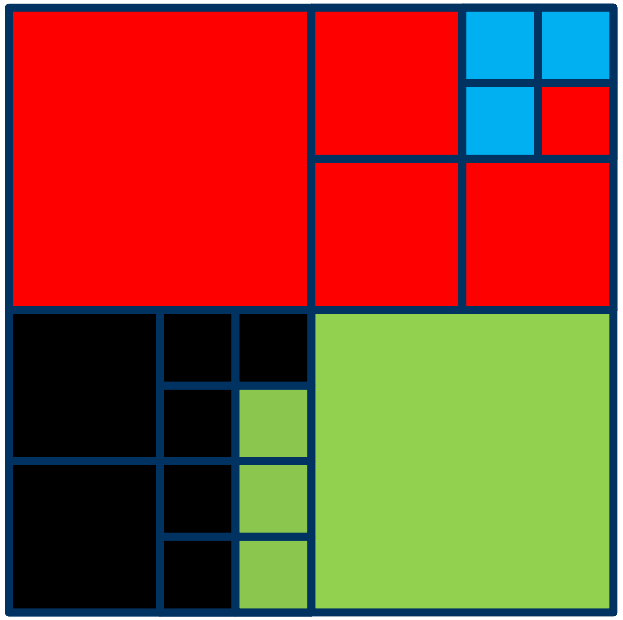
Dealing with Load Imbalance cont'd

- reactive
  - monitor system state
  - when load imbalance is detected, try to mitigate
- predictive
  - build a load imbalance model
  - query the model for the state of the system in the near future
  - shift the workload before load imbalance occurs
- huge (!) amount of research dedicated to this field
  - a) find approaches of mitigating load imbalance
  - b) find ways of doing this automatically without user intervention (holy grail)

Dealing with Load Imbalance: Static Case

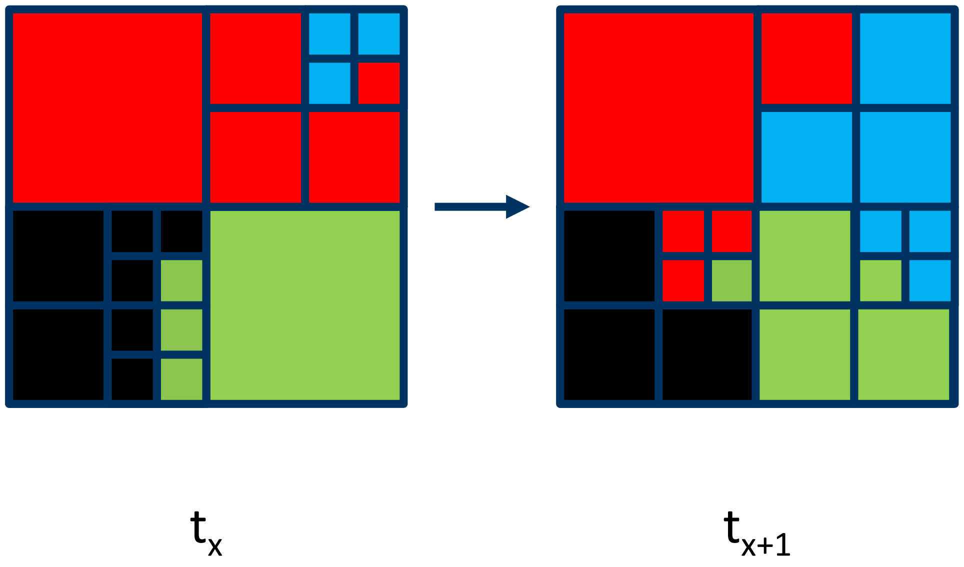
- static
  - first choose smart domain decomposition depending on predicted workload
  - then just execute as normal

- example on the right: quadtree
  - more work ➔ smaller subregions
  - 3D version: octtree



Dealing with Load Imbalance: Dynamic Case

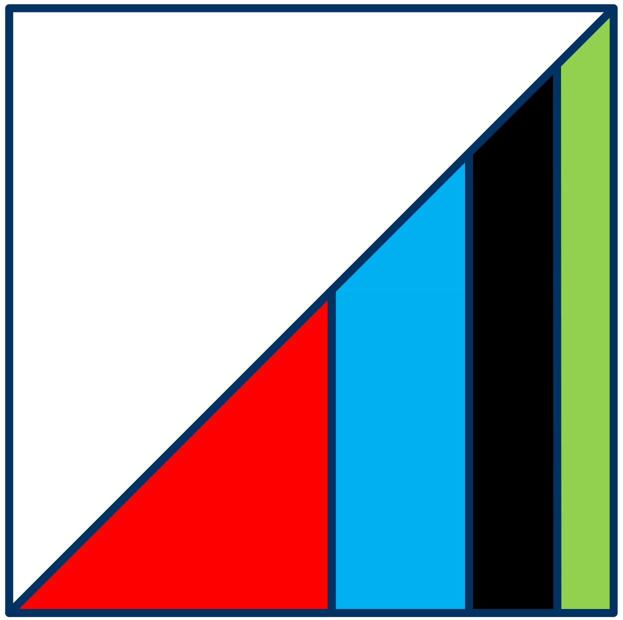
- dynamic
  - some form of repeated balancing required, e.g.
    - at certain intervals
    - when reaching certain thresholds
  - use e.g. worker queues and work stealing



Dealing with Load Imbalance: Domain-specific Knowledge

- if present, use domain-specific knowledge about the problem
  - e.g. structured problem with a workload gradient depending on an index

```
for(int i = 0; i < N; ++i) {
    for(int j = 0; j < i; ++j) {
        ...
    }
}c
```



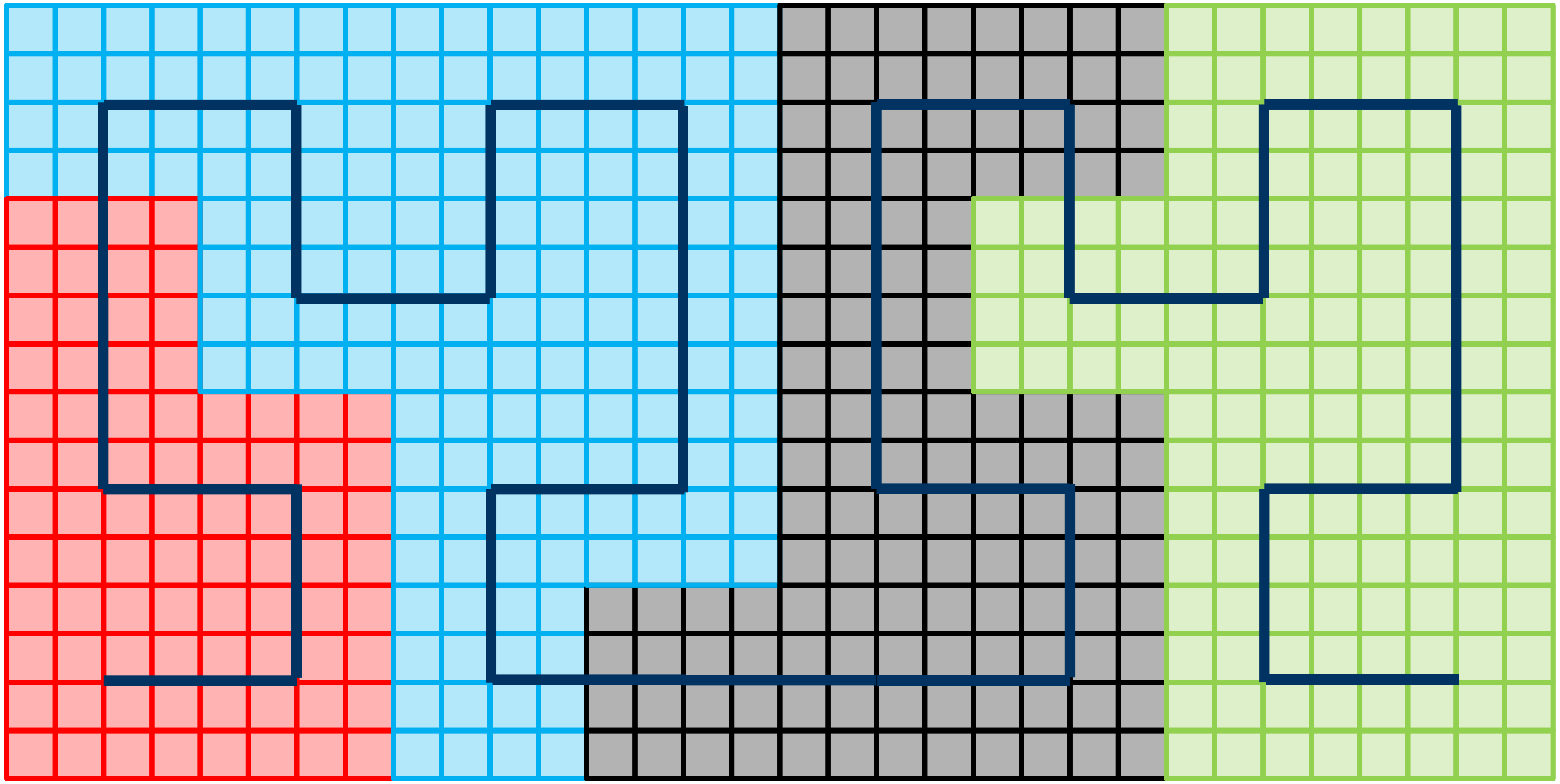
Further Means of Load Balancing

- use “smart” work assignment strategies instead of smart domain decomposition
  - assign small chunks of work in round robin fashion
  - assign small chunks in random order
  - assign small chunks using space-filling curves, diffusion models, etc…
  - remember tradeoff between balanced load and overheads

- configure hardware
  - change CPU clock frequencies, e.g. slow down cores with little work
  - doesn’t reduce wall time but saves power and energy

- biggest issue of all: which strategy to select for which problem…

Space-filling Curves (Hilbert)

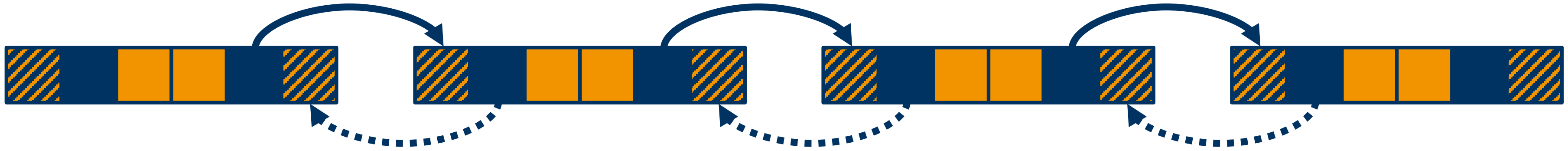


Additional Reasons for Load Balancing

- external load caused by other users
  - not only on the CPUs, consider e.g. network or I/O
- heterogeneous systems
  - e.g. decide how to split work between CPUs and GPUs
- dynamic availability of additional resources
  - c.f. cloud computing

Tales from the Proseminar

Tales from the Proseminar: Efficient Ghost Cell Exchange



```
if(myRank > 0) {
    // recv(left)
}
if(myRank < N-1) {
    // send(right)
}
```

time	rank 0	rank 1	rank 2	rank 3
0	send(right)	recv(left)	recv(left)	recv(left)
1		send(right)	recv(left)	recv(left)
2			send(right)	recv(left)
3				send(right)

unnecessary serialization!

Tales from the Proseminar: Efficient Ghost Cell Exchange cont'd

```
if(myRank % 2) {
    // recv, send
} else {
    // send, recv
}
// or
MPI_Sendrecv(...)
```

time	rank 0	rank 1	rank 2	rank 3
0	send(right)	recv(left)	send(right)	recv(left)
1		send(right)	recv(left)	send(right)

....

done!

Summary

- domain decomposition
  - means of controlling communication overhead

- load (im)balance
  - static: split the workload evenly among ranks
  - dynamic: continuously rebalance as required

- “Tales from the Proseminar”
  - efficient ghost cell exchange

Image Sources

- Space Weather Prediction: https://twitter.com/maven2mars/status/984440044659159040
- Intel Trace Analyzer: https://software.intel.com/en-us/articles/understanding-mpi-load-imbalance-with-intel-trace-analyzer-and-collector