TORSTEN HOEFLER

Accelerating weather and climate simulations on heterogeneous architectures

with support of Oliver Fuhrer @ MeteoSwiss
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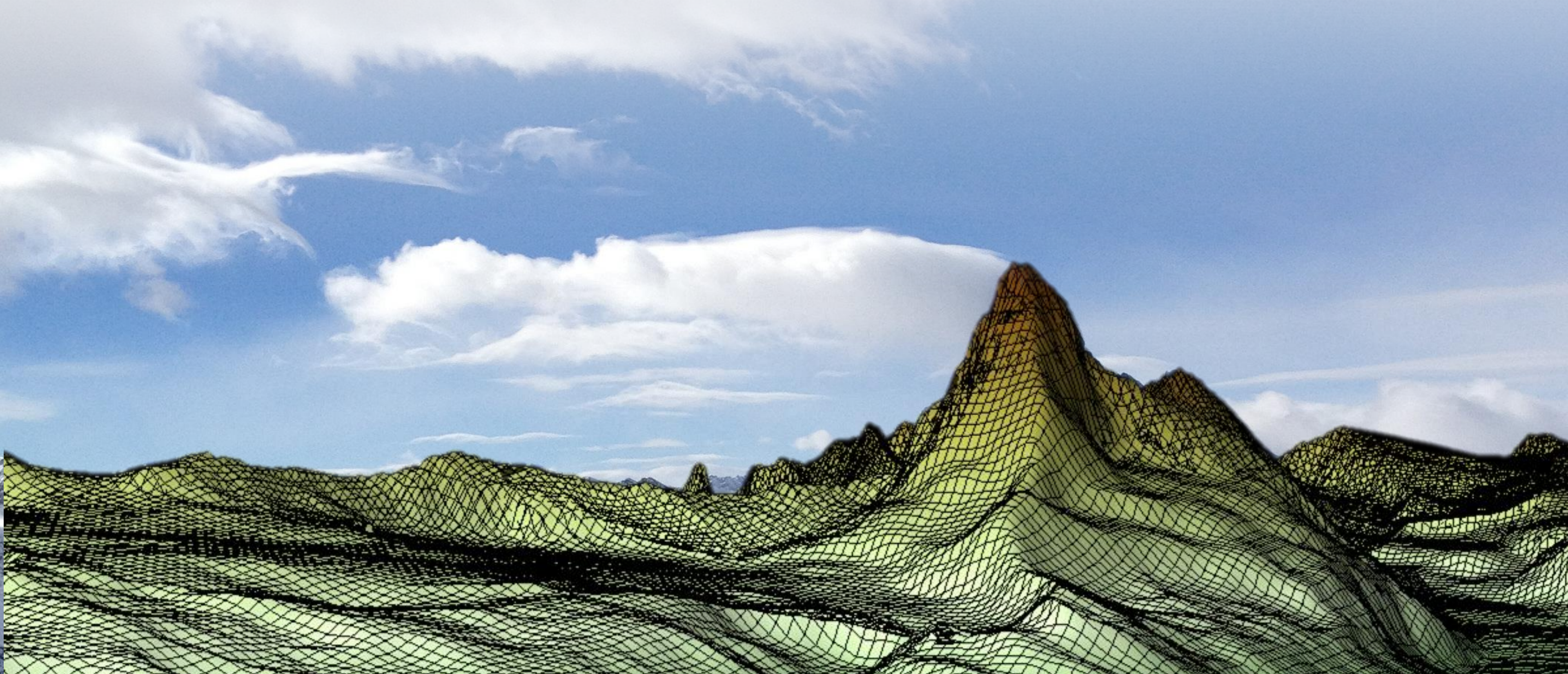
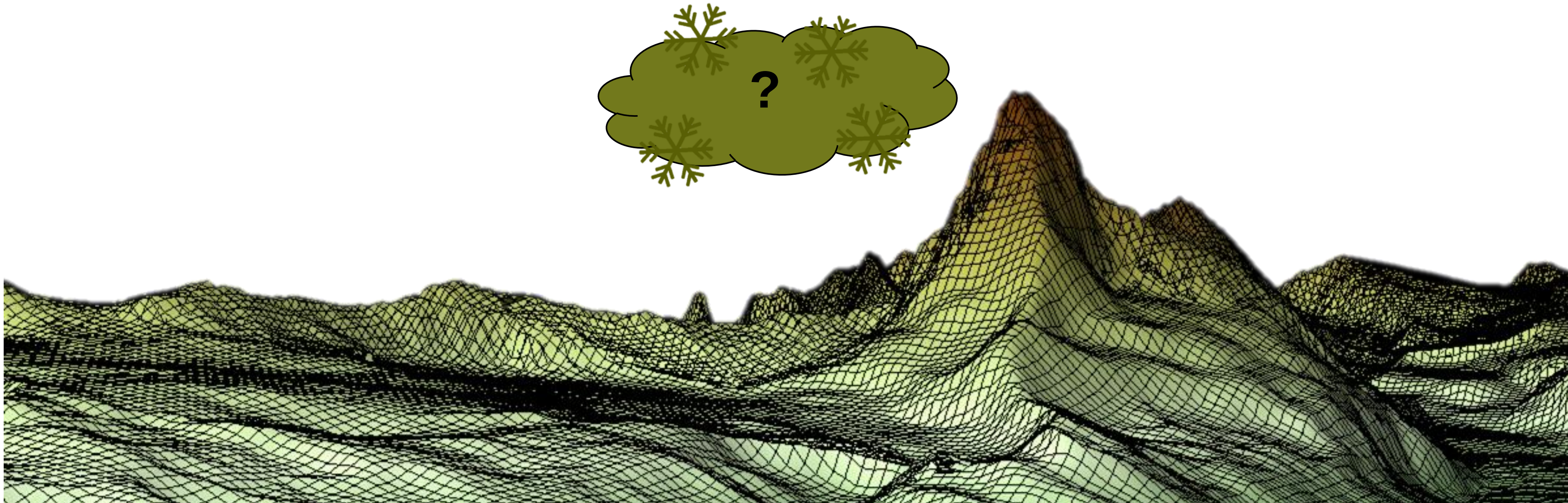


Will there be snow at the Matterhorn?

- **How much compute power is needed to predict if there is snow out of a "banner cloud" at the Matterhorn?**

- **A factor of 2x in resolution means a factor of 10x in compute effort!**

- **Δx = 35 m**



Will there be snow at the Matterhorn?

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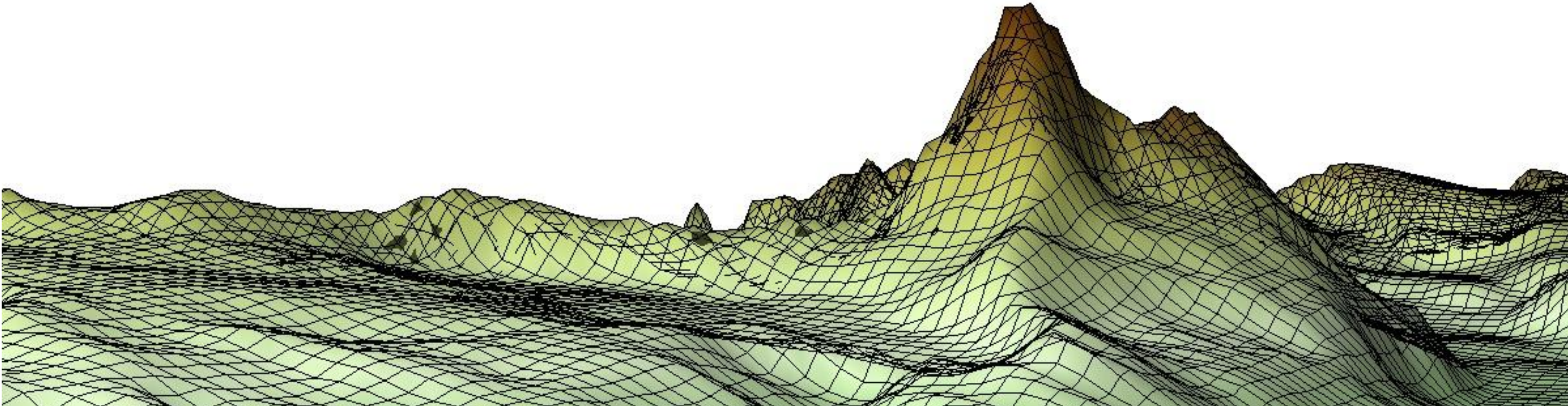
- $\Delta x = 70$ m



Will there be snow at the Matterhorn?

- **How much compute power is needed to predict if there is snow out of a "banner cloud" at the Matterhorn?**
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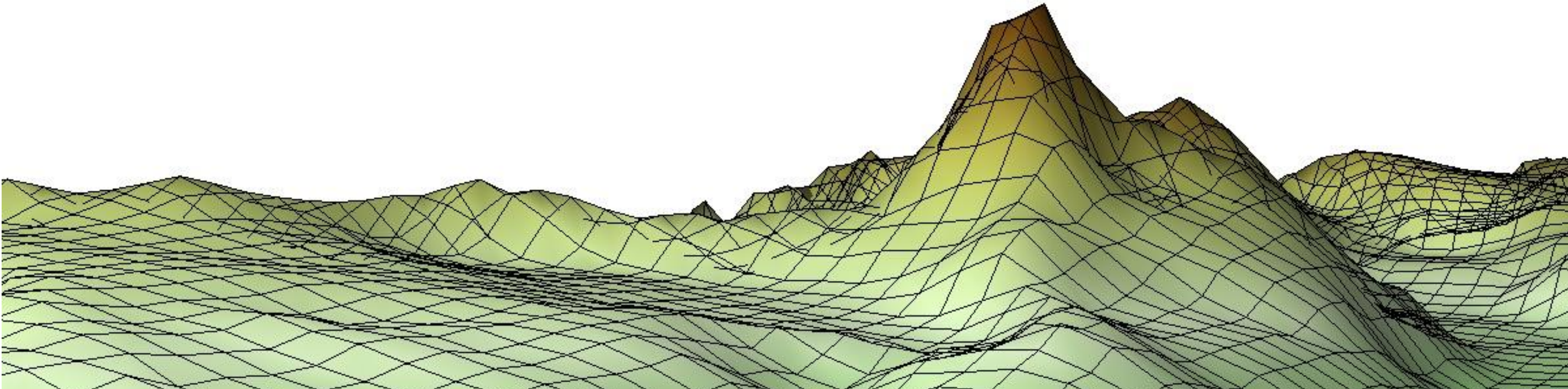
- **Δx = 140 m**

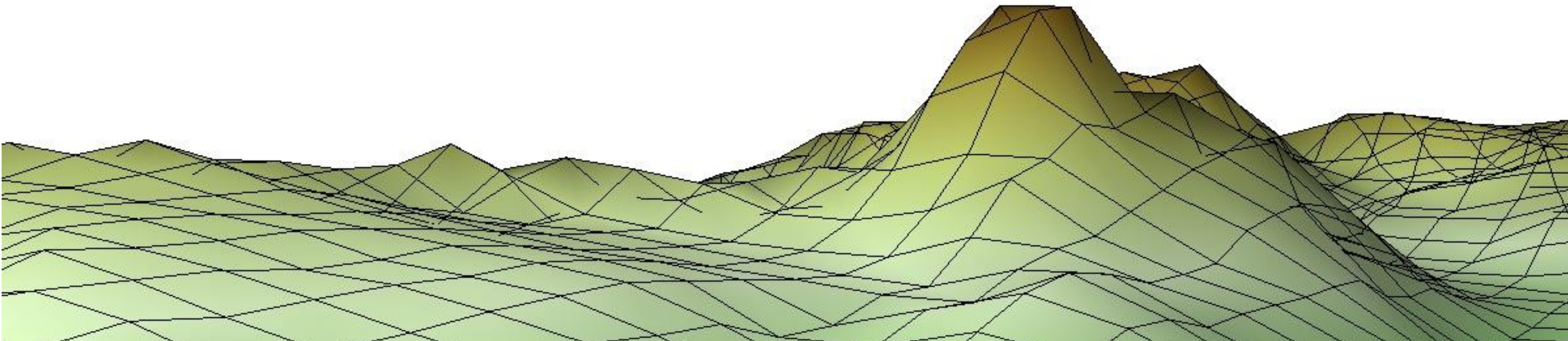


Will there be snow at the Matterhorn?

- How much compute power is needed to predict if there is snow out of a "banner cloud" at the Matterhorn?

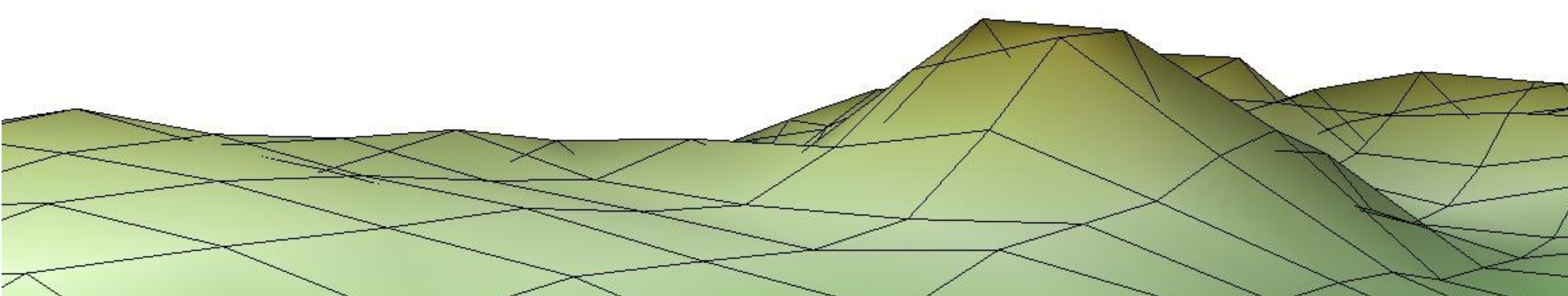
- A factor of 2x in resolution means a factor of 10x in compute effort!

- $\Delta x = 280$ m



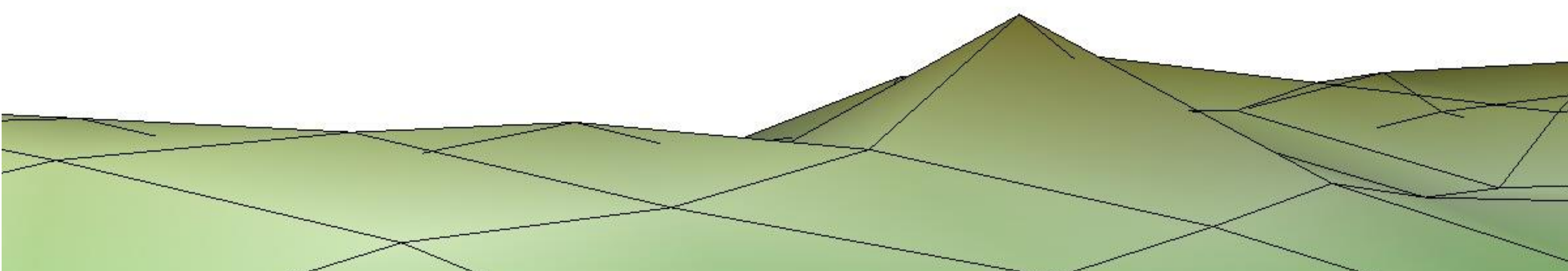
Will there be snow at the Matterhorn?

- **How much compute power is needed to predict if there is snow out of a "banner cloud" at the Matterhorn?**
- **A factor of 2x in resolution means a factor of 10x in compute effort!**
- **Δx = 550 m**



Will there be snow at the Matterhorn?

- How much compute power is needed to predict if there is snow out of a "banner cloud" at the Matterhorn?
- A factor of 2x in resolution means a factor of 10x in compute effort!
- Δx = 1100 m (operational model)



Will there be snow at the Matterhorn?

- How much compute power is needed to predict if there is snow out of a "banner cloud" at the Matterhorn?
- A factor of 2x in resolution means a factor of 10x in compute effort!
- Δx = 2200 m (last year's model in Switzerland)
- A factor of 1,000,000 in computation power!

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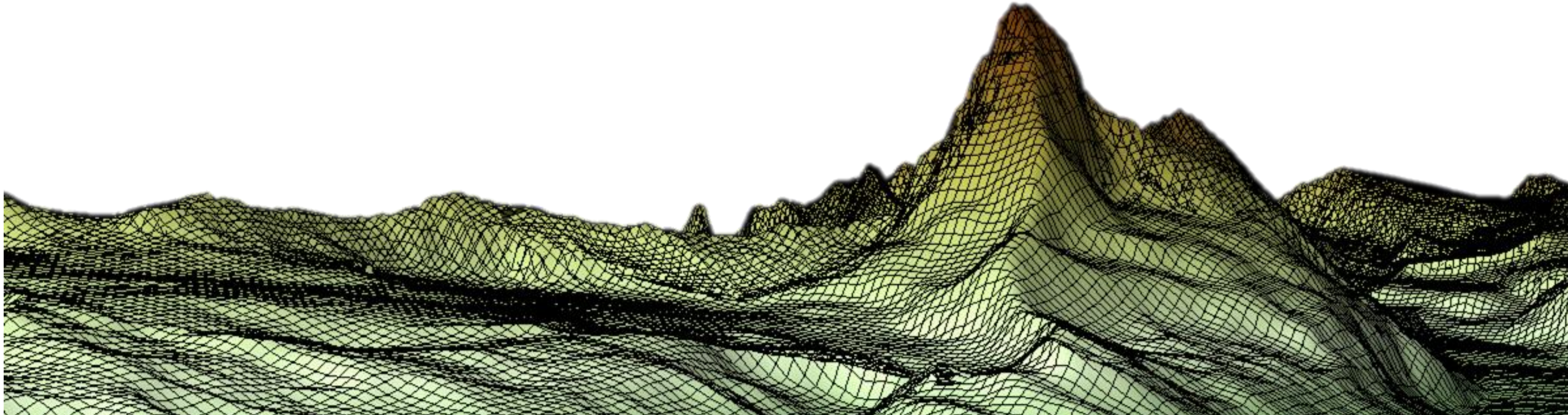
Accelerating weather and climate simulations on heterogeneous architectures

At the end, we need this resolution!
But how to get the required 100,000x improvement?



Basic Atmospheric Equations

Wind

$$\rho \frac{d\mathbf{v}}{dt} = -\nabla p + \rho \mathbf{g} - 2\mathbf{\Omega} \times (\rho \mathbf{v}) - \nabla \cdot (\underline{\mathbf{T}})$$

Pressure

$$\frac{dp}{dt} = -(c_{pd}/c_{vd}) p \nabla \cdot \mathbf{v} + (c_{pd}/c_{vd} - 1) Q_h$$

Temperature

$$\rho c_{pd} \frac{dT}{dt} = \frac{dp}{dt} + Q_h$$

Water

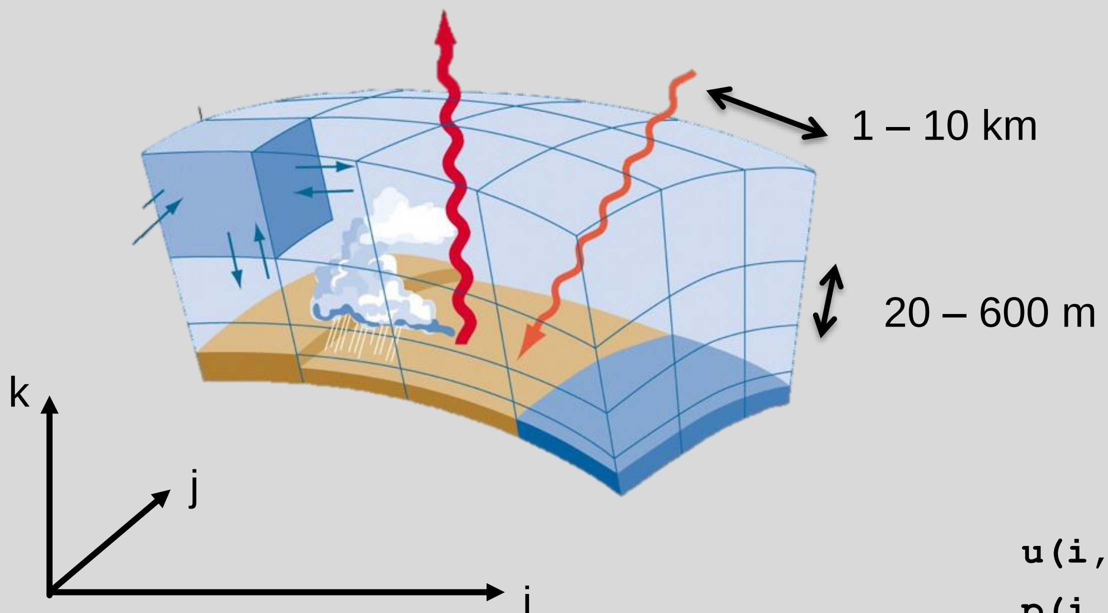
$$\rho \frac{dq^v}{dt} = -\nabla \cdot \mathbf{F}^v - (I^l + I^f)$$

$$\rho \frac{dq^{l,f}}{dt} = -\nabla \cdot (\mathbf{P}^{l,f} + \mathbf{F}^{l,f}) + I^{l,f}$$

Density

$$\rho = p\{R_d(1 + (R_v/R_d - 1)q^v - q^l - q^f)T\}^{-1}$$

Compute Grid



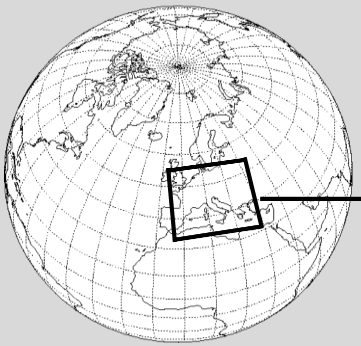

```
u(i,j,k), v(i,j,k), w(i,j,k),
p(i,j,k), t(i,j,k), qv(i,j,k)
qc(i,j,k), qi(i,j,k), rho(i,j,k)
```

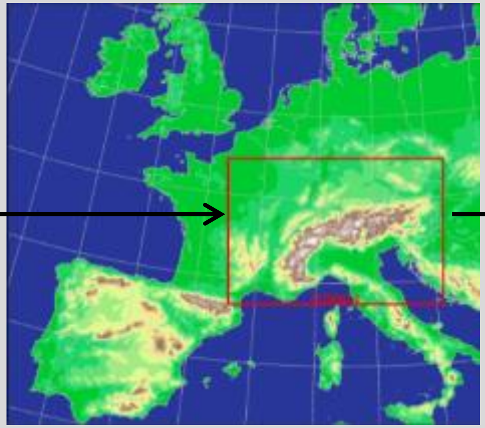
Prognostic models

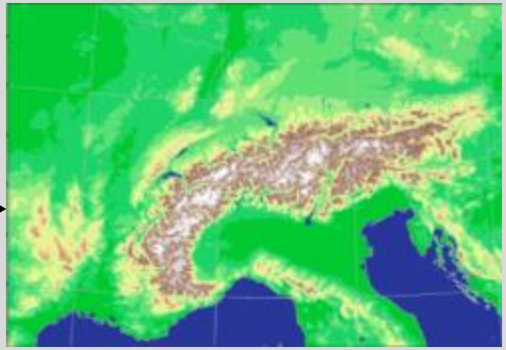
ECMWF-Model
16 km Grid
2 x per day
10 days prediction

COSMO-7
6.6 km Grid
3 x per day
72 h prediction

COSMO-1
1.1 km Grid
7 x pro day 33 h prediction
1 x pro day 45 h prediction







COSMO Workflow

Initializing

Δt

Boundary conditions

Parametriztion

Dynamics

Data assimilation

Relaxation

Diagnostics

Input / Output

Cleanup

Properties

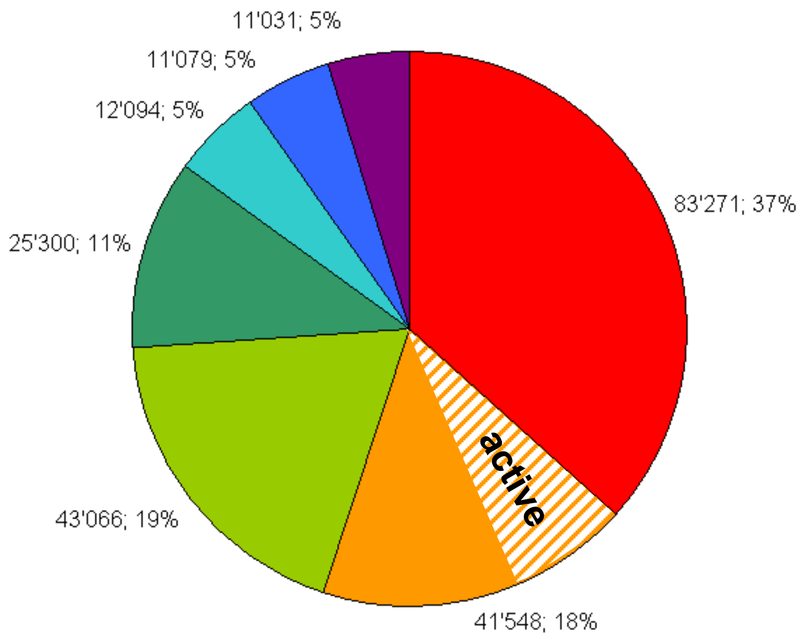
- PDEs
- Finite differences
- Structured grid
- Local operators
- Time splitting
- Sequential Workflow

Code structure and runtime

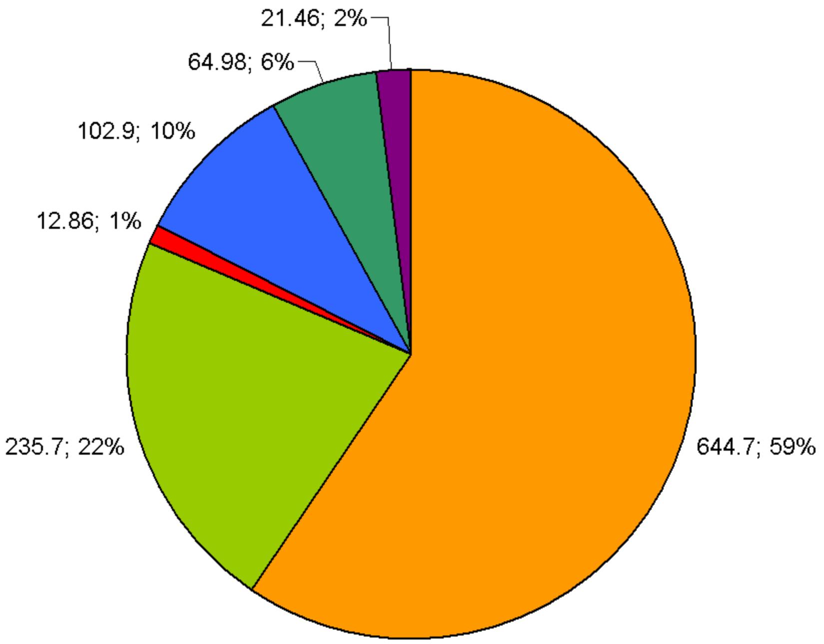
- **300’000 Lines Fortran 90 Code**

Assimilation
Dynamics
Physics
I/O
Structure
Diagnosis
Parallelization

% Code lines



% Runtime



Typical Code

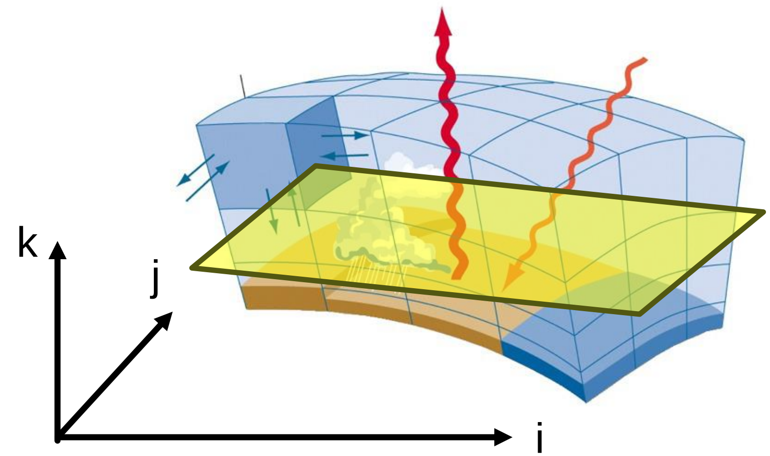
- "Dynamics" Code (niter = 48, nwork = 4,096,000)

```
do j = 1, niter
  do i = 1, nwork
    c(i) = a(i) + b(i) * ( a(i+1) - 2.0d0*a(i) + a(i-1) )
  end do
end do
```

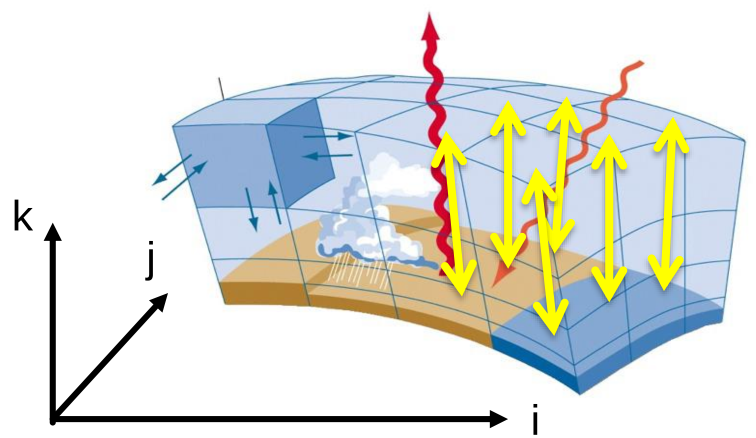
$$\frac{\partial a}{\partial t} = k \frac{\partial^2 a}{\partial x^2}$$

COSMO Algorithmic Motifs

- **Stencils (finite Differences)**
  - horizontal dependencies
  - no loop carried dependencies

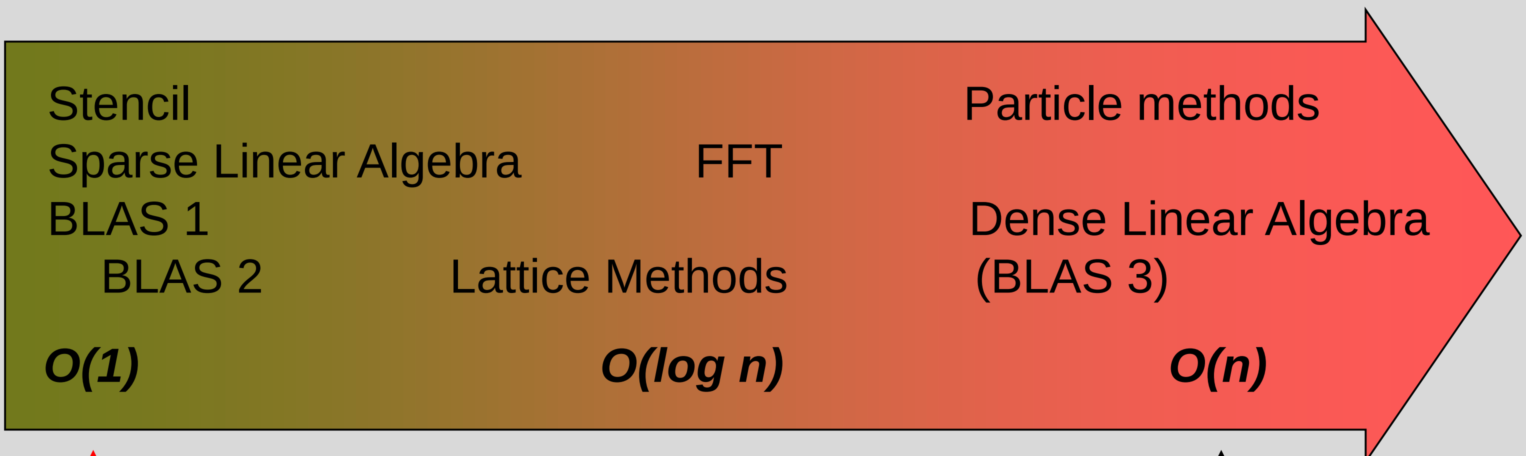


- **Tridiagonal Linears Systems**
  - vertical dependencies
  - loop carried dependencies
  - horizontally parallelisable



Algorithmic Motifs

- **Arithmetic Intensity (= FLOPs per memory access)**
  - High arithmetic intensity → processor bound
  - Low arithmetic intensity → memory bound



COSMO dynamical core
(stencils on structured grid)

Top500 (Linpack)
Focus for HPC system designs

- **Example: COSMO (original) runs with ~4% peak auf Cray XE6**

How to improve the arithmetic intensity?
A formalism for stencil programs (FD for now)

Stencil computations (oh

due to their low arithmetic intensity stencil computations are typically heavily memory bandwidth limited!

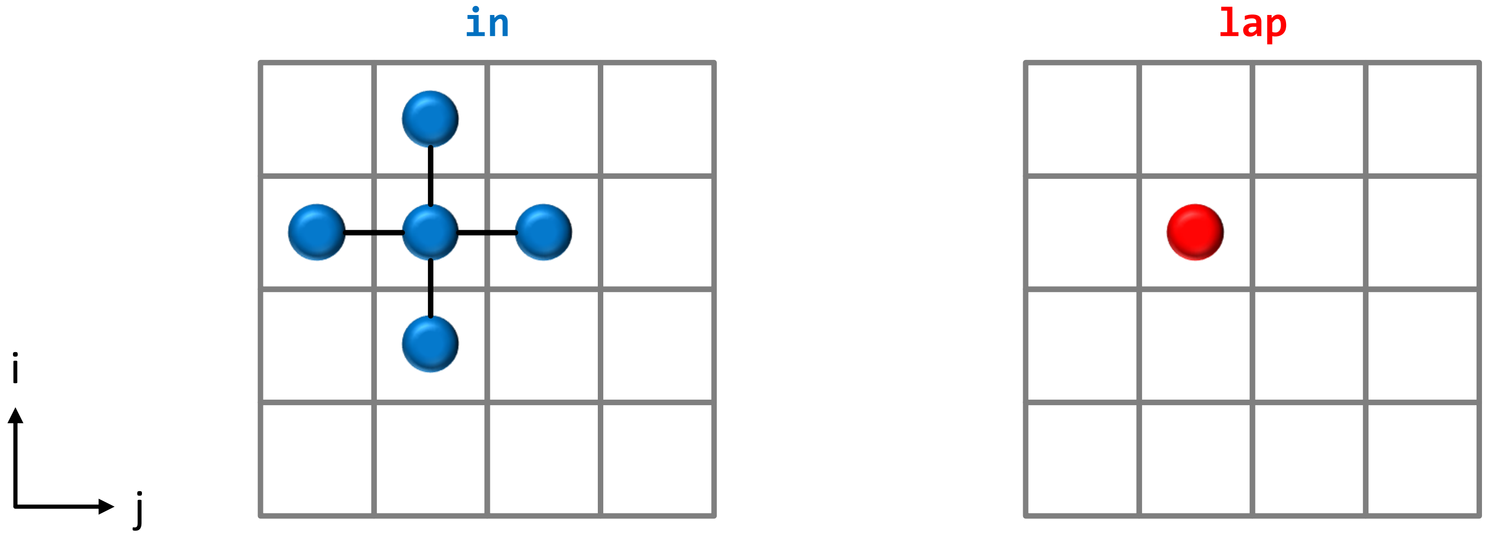
Motivation:

- **Important algorithmic motif (e.g., finite difference method)**

Definition:

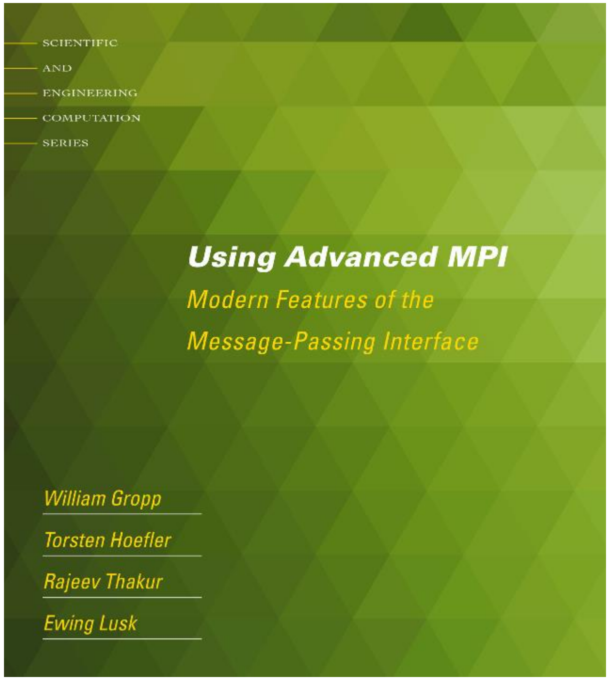
- **Element-wise computation on a regular grid using a fixed neighborhood**
- **Typically working on multiple input fields and writing a single output field**

```
lap(i,j) = -4.0 * in(i,j) + in(i-1,j) + in(i+1,j) + in(i,j-1) + in(i,j+1)
```



How to tune such stencils (most other stencil talks)

- **LOTS of related work!**
  - Compiler-based (e.g., Polyhedral such as PLUTO [1])
  - Auto-tuning (e.g., PATUS [2])
  - Manual model-based tuning (e.g., Datta et al. [3])
  - … essentially every micro-benchmark or tutorial, e.g.:



- **Common features**
  - Vectorization tricks (data layout)
  - Advanced communication (e.g., MPI neighbor colls)
  - Tiling in time, space (diamond etc.)
  - Pipelining

- **Much of that work DOES NOT compose well with practical complex <u>stencil programs</u>**

[1]: Uday Bondhugula, A. Hartono, J. Ramanujan, P. Sadayappan. *A Practical Automatic Polyhedral Parallelizer and Locality Optimizer* , PLDI'08
[2]: Matthias Christen, et al.: *PATUS: A Code Generation and Autotuning Framework for Parallel Iterative Stencil Computations …, IPDPS'11*
[3]: Kaushik Datta, et al., *Optimization and Performance Modeling of Stencil Computations on Modern Microprocessors,* SIAM review

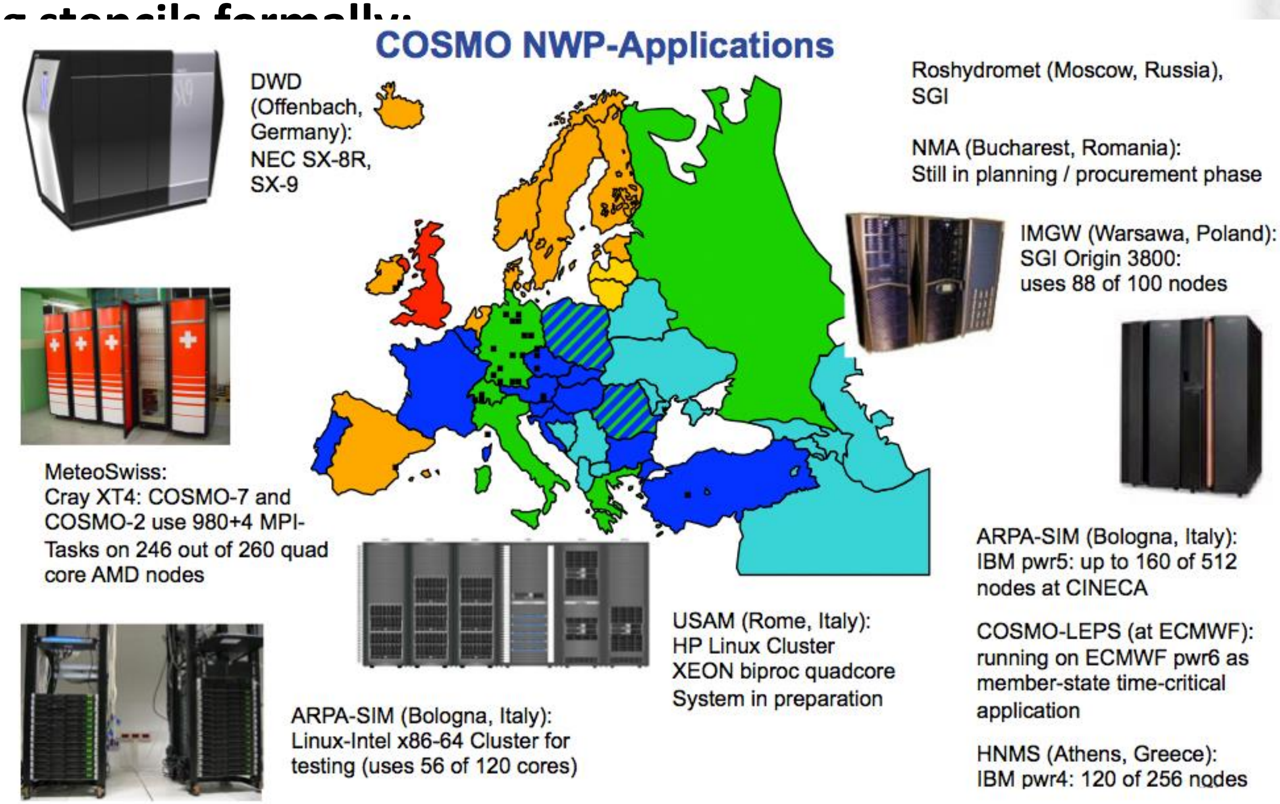
What is a “complex stencil program”? (this stencil talk)

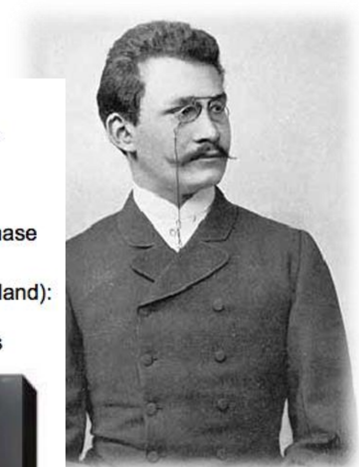
E.g., the COSMO weather code

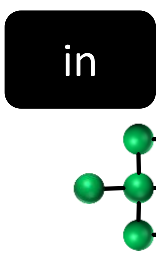
- **is a regional climate model used by 7 national weather services**
- **contains hundreds of different complex stencils**

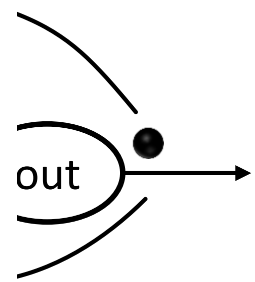
Modelin

- **Repr**
  - Mo



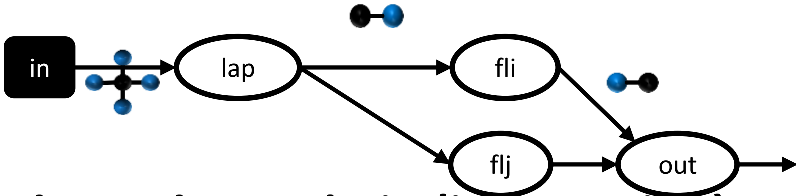




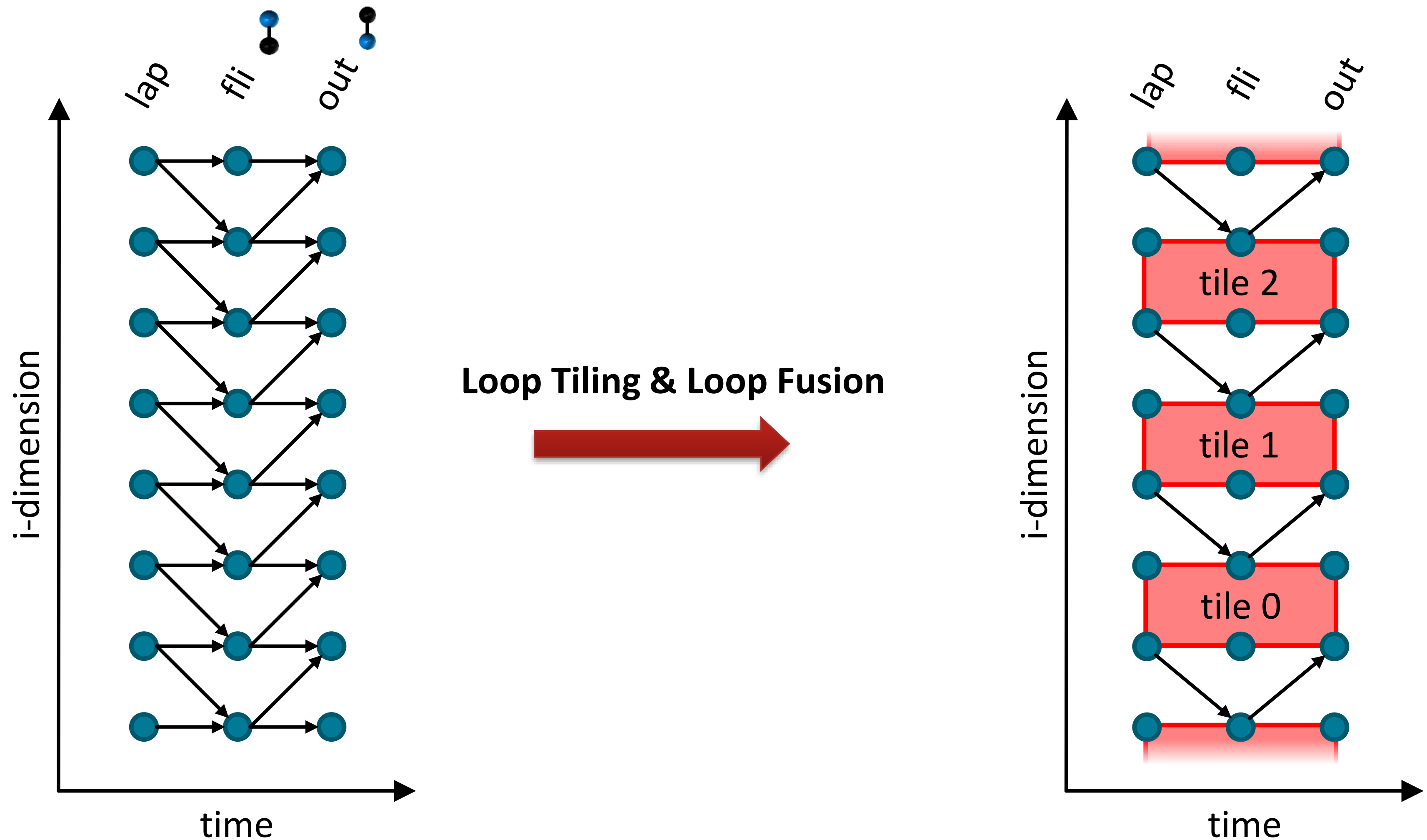


$$a \oplus b = \{a' + b' \mid a' \in a, b' \in b\}$$

Data-locality Transformations



- **Consider the horizontal diffusion lap-fli-out dependency chain (i-dimension)**



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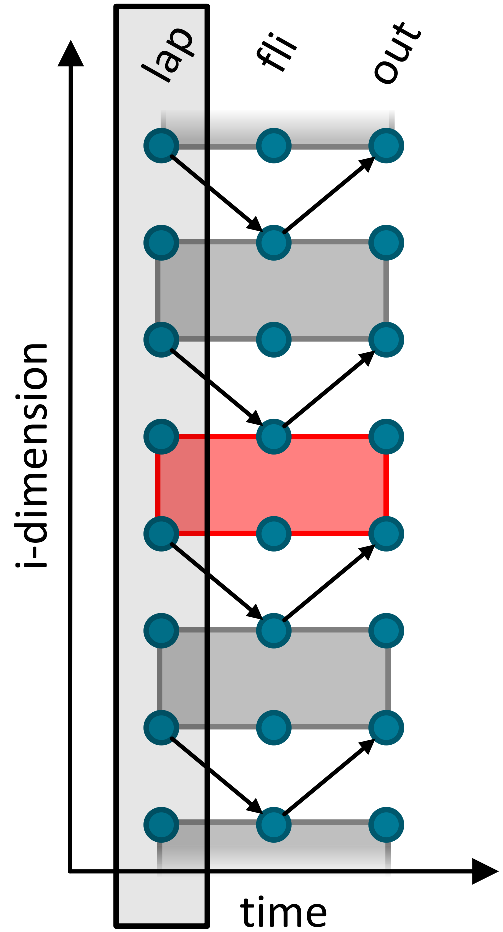
How to Deal with Data Dependencies (1/3)?

- **Consider the horizontal diffusion lap-fli-out dependency chain (i-dimension)**



Halo Exchange Parallel (hp):

- Update tiles in parallel
- Perform halo exchange communication

Pros and Cons:

- Avoid redundant computation
- At the cost of additional synchronization

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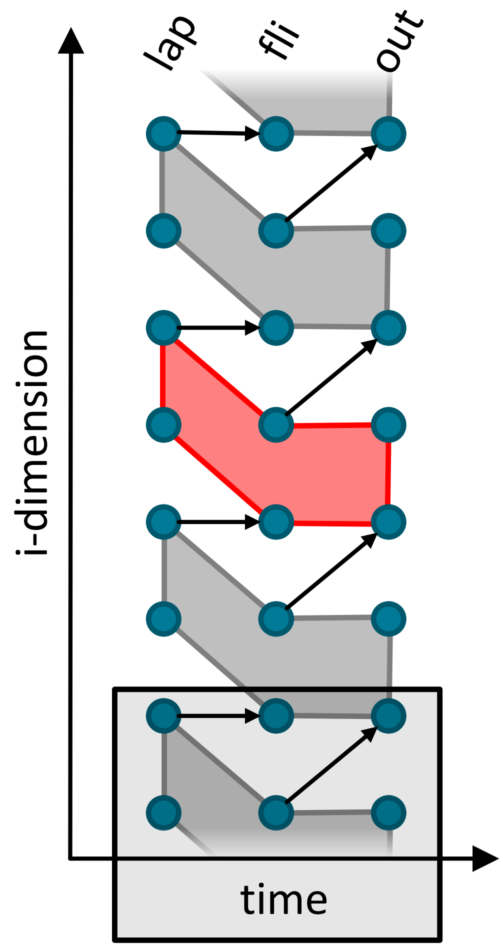
How to Deal with Data Dependencies (2/3)?

- **Consider the horizontal diffusion lap-fli-out dependency chain (i-dimension)**



Halo Exchange Sequential (hs):

- Update tiles sequentially
- Innermost loop updates tile-by-tile

Pros and Cons:

- Avoid redundant computation
- At cost of being sequential

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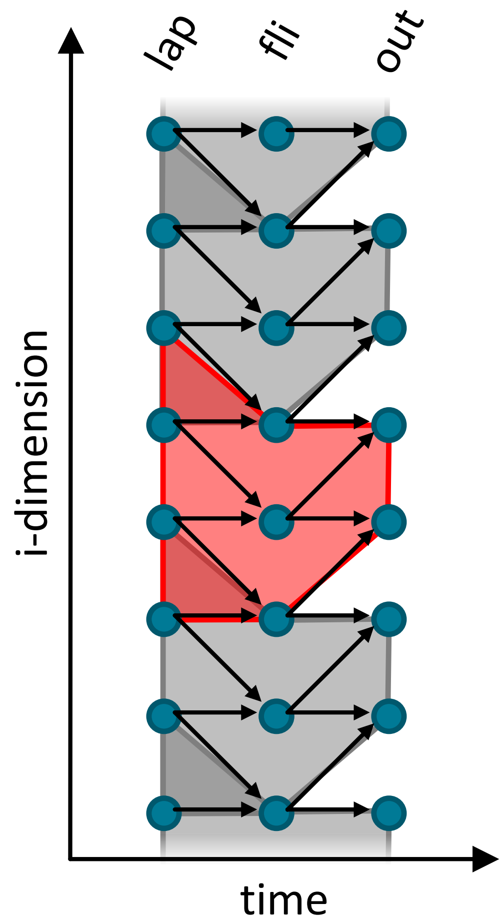
How to Deal with Data Dependencies (3/3)?

- **Consider the horizontal diffusion lap-fli-out dependency chain (i-dimension)**



Computation on-the-fly (of):
- Compute all dependencies on-the-fly
- Overlapped tiling

Pros and Cons:
- Avoid synchronization
- At the cost of redundant computation (and loads)

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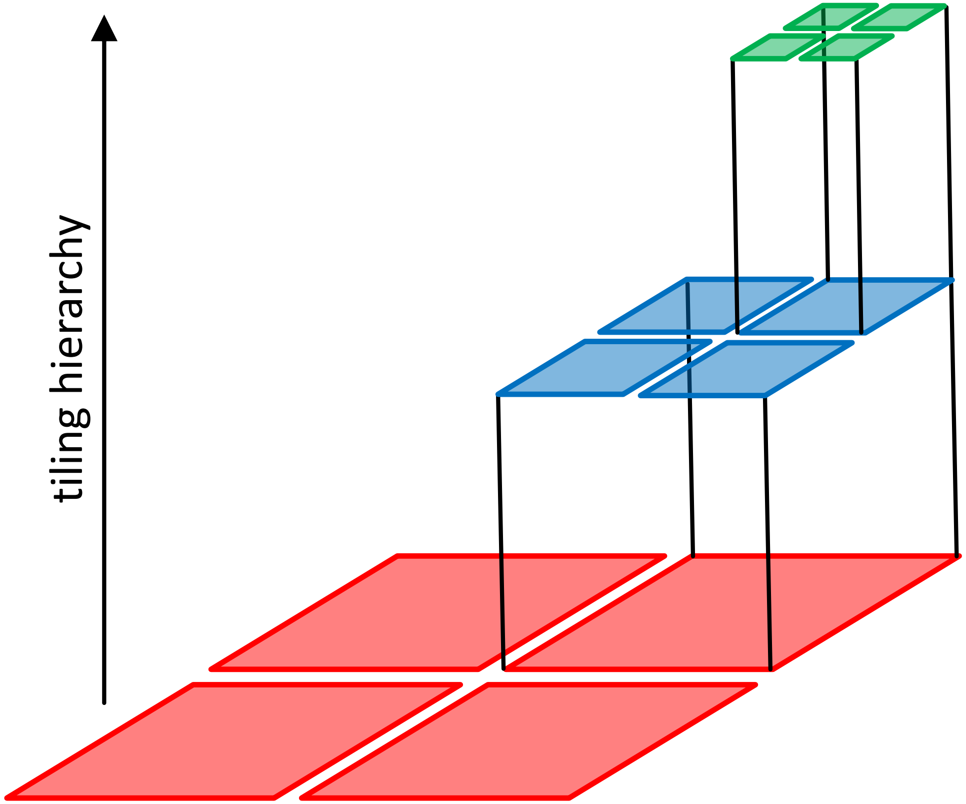
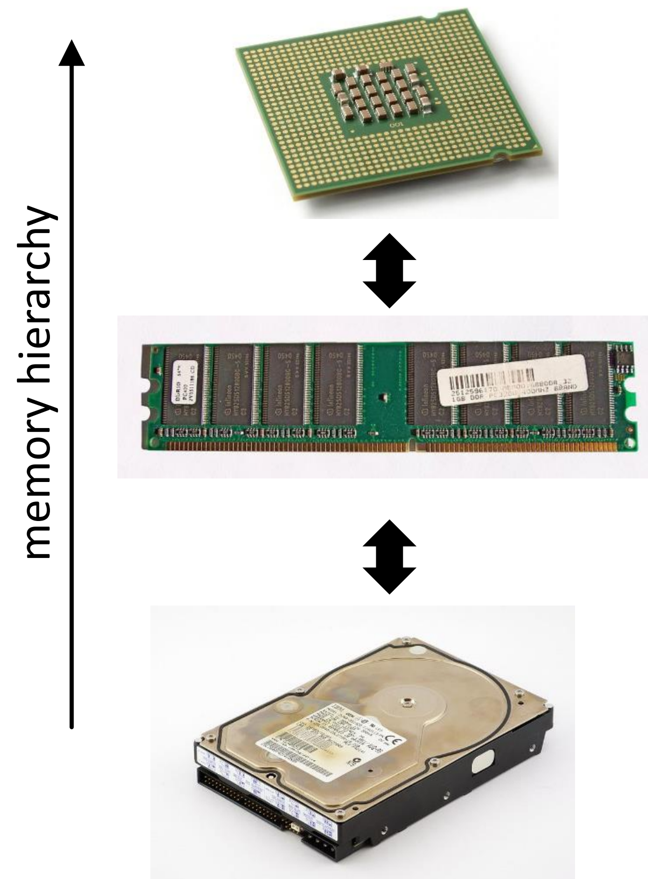
Hierarchical Tiling

- **By tiling the domain repeatedly we target multiple memory hierarchy levels**





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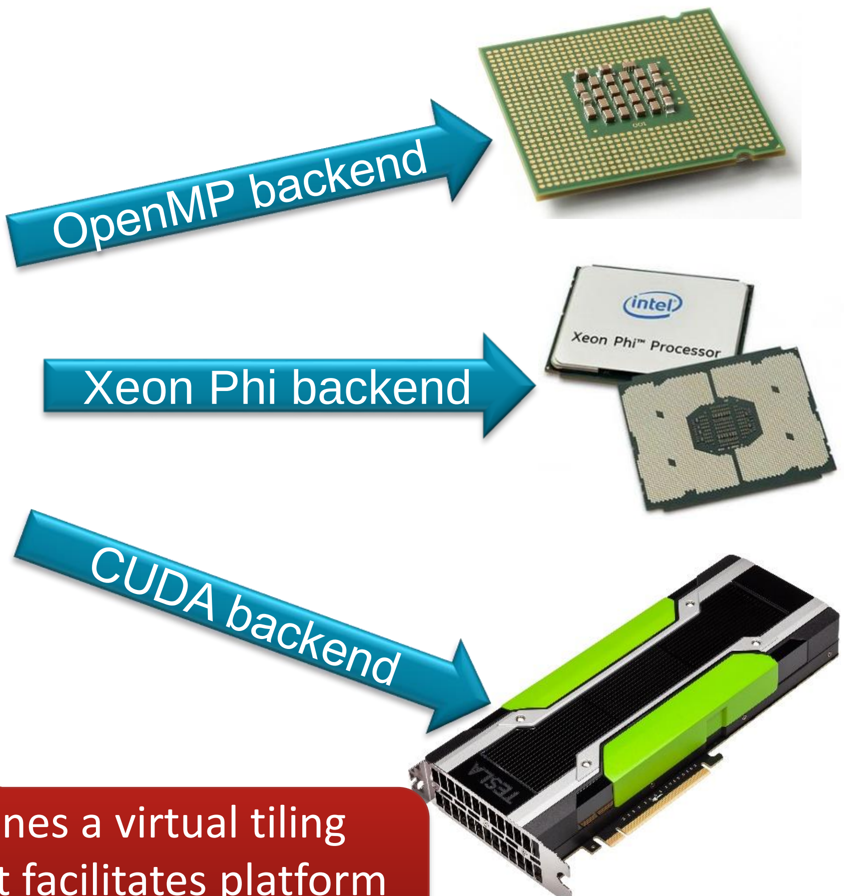
Case Study: STELLA (STEncil Loop LAnguage)

- **STELLA is a C++ stencil DS(e)L of COSMO's dynamical core (50k LOC, 60% RT)**

```
// define stencil functors
struct Lap { ... };
struct Fli { ... };
...
// stencil assembly
Stencil stencil;
StencilCompiler::Build(
 stencil,
 pack_parameters( ... ),
 define_temporaries(
  StencilBuffer<lap, double>(),
  StencilBuffer<fli, double>(),
  ...
 ),
 define_loops(
  define_sweep(
   StencilStage<Lap, IJRange<-1,1,-1,1> >(),
   StencilStage<Fli, IJRange<-1,0,0,0> >(),
   ...
)));
// stencil execution
stencil.Apply();
```

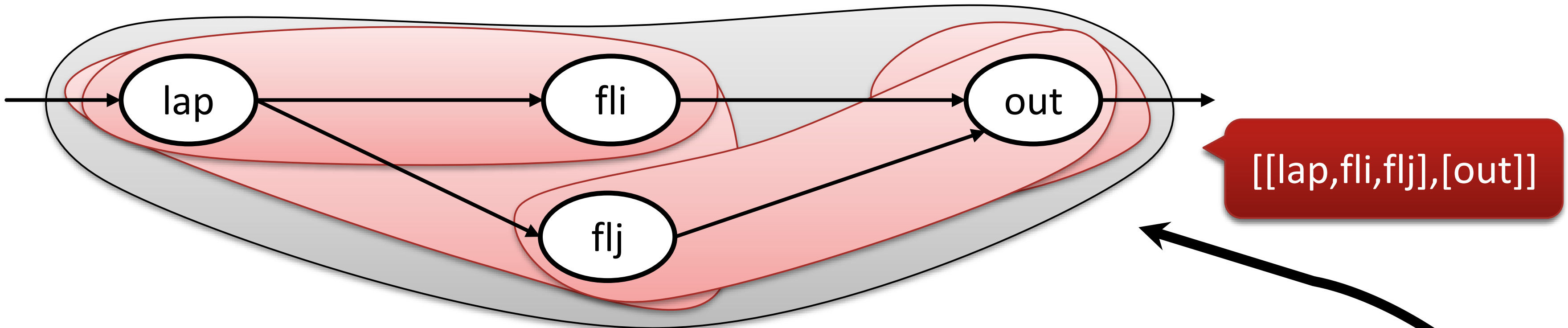
using C++ template metaprogramming:



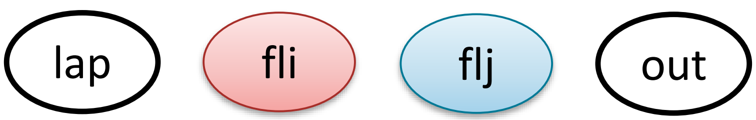
STELLA defines a virtual tiling hierarchy that facilitates platform independent code generation

Compact representation: Stencil Program Algebra

- **Map stencils to the tiling hierarchy using a bracket expression**



- **Enumerate the stencil execution orders that respect the dependencies**



- **Enumerate implementation variants by adding/removing brackets**

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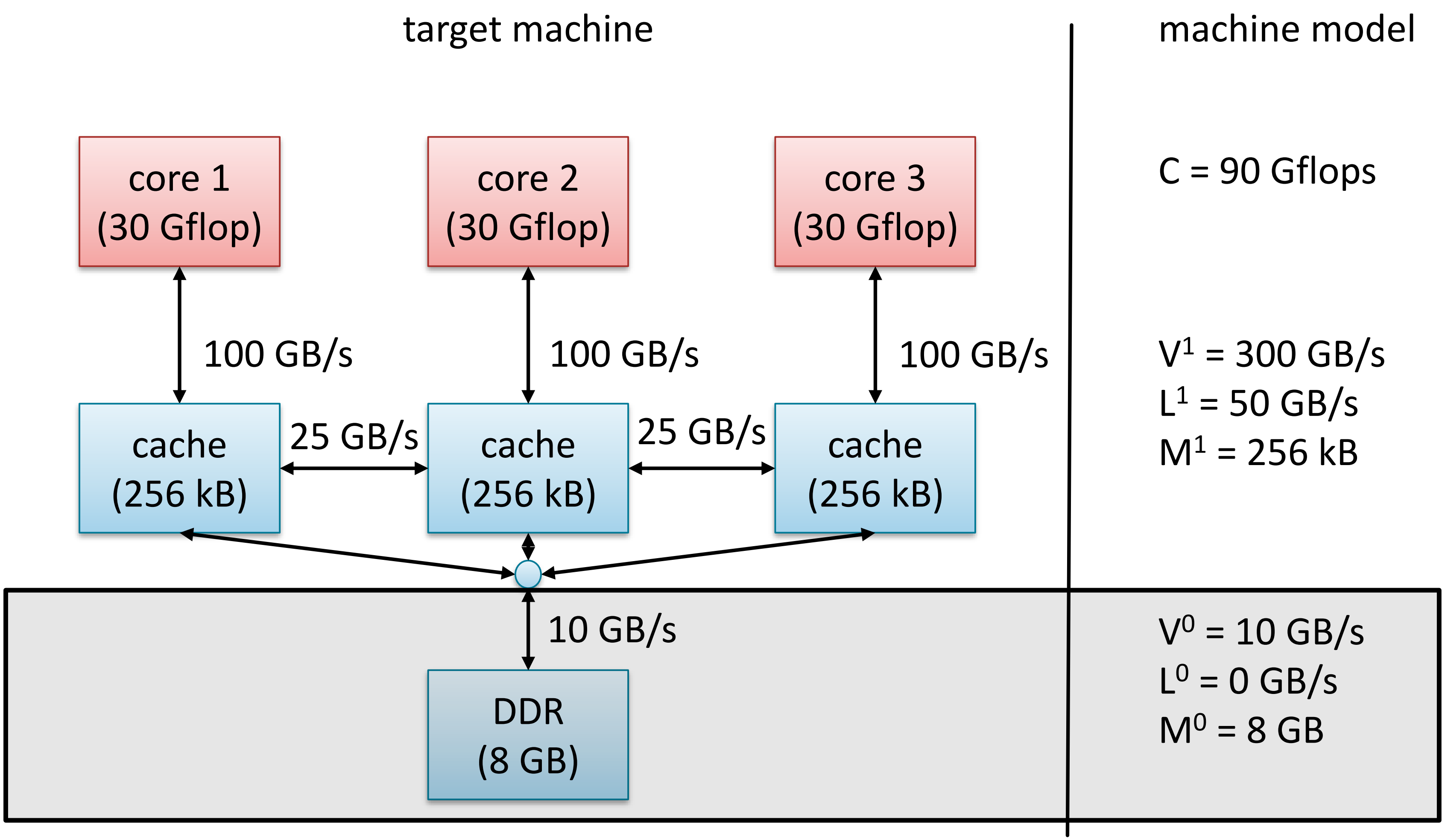
lateral and vertical communication refer to communication within one respectively between different tiling hierarchy levels

Machine Performance Mo

- **Our model considers peak computation and communication throughputs**



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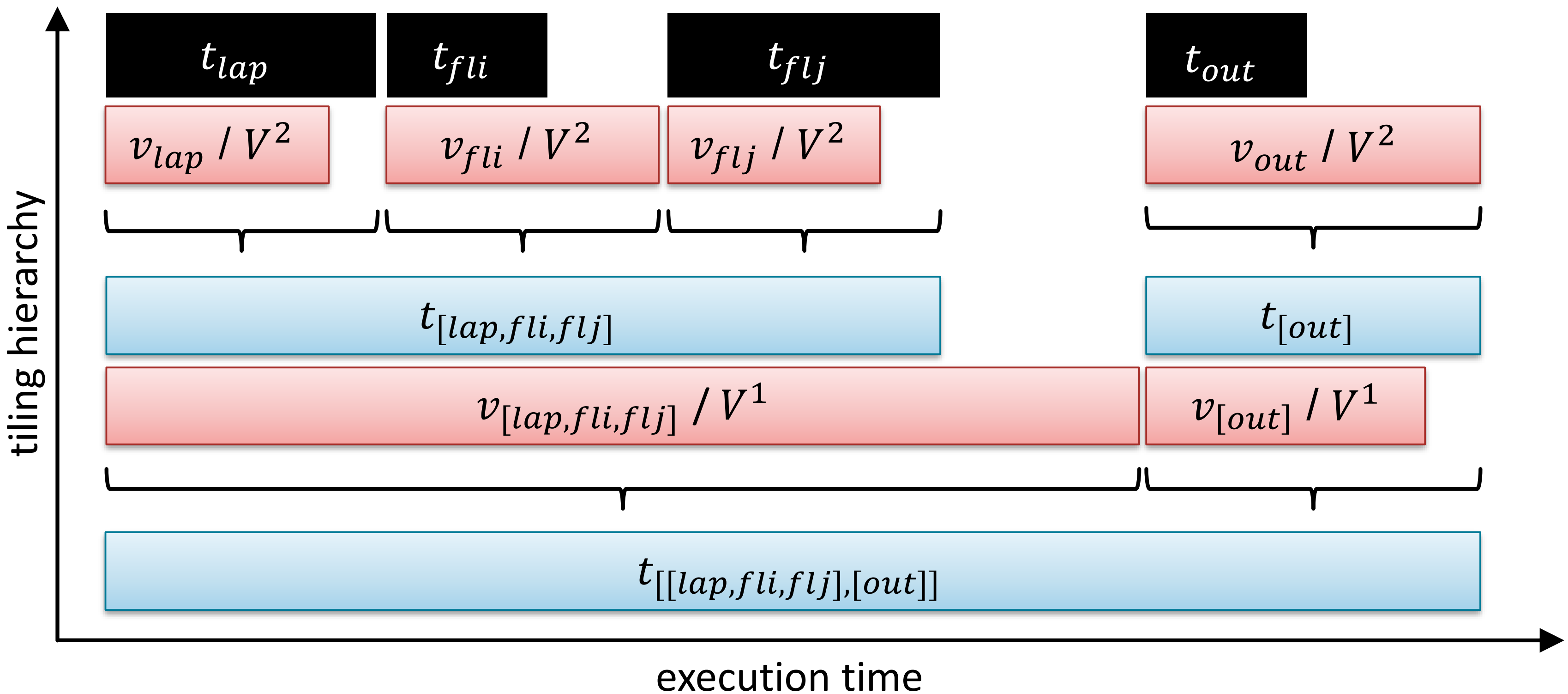
Stencil Performance Model - Overview

- **Given a stencil s given and the amount of computation c_s**

$$t_s = c_s / C$$

- **Given a group g and the vertical and lateral communication v_c and $l_c^1, \dots, l_c^m$**

$$t_g = \sum_{c \in g.child} \max(t_c, v_c / V^m, l_c^1 / L^1, \dots, l_c^m / L^m)$$



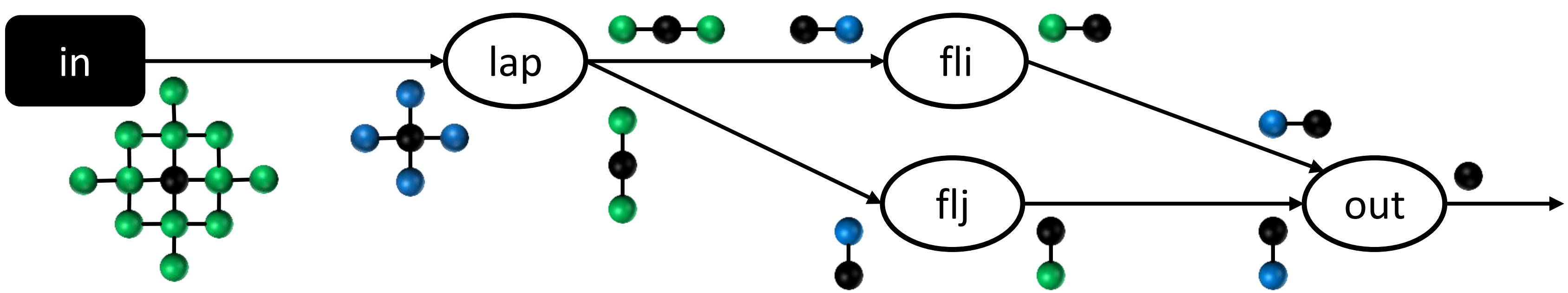
Stencil Performance Model - Affine Sets and Maps

- **The stencil program analysis is based on (quasi-) affine sets and maps**

$$S = \{\vec{\imath} \mid \vec{\imath} \in \mathbb{Z}^n \wedge (0, \ldots, 0) < \vec{\imath} < (10, \ldots, 10)\}$$
$$M = \{\vec{\imath} \rightarrow \vec{\jmath} \mid \vec{\imath} \in \mathbb{Z}^n, \vec{\jmath} \in \mathbb{Z}^n \wedge \vec{\jmath} = 2 \cdot \vec{\imath}\}$$

- **For example, data dependencies can be expressed using named maps**

$$D_{fli} = \{(fli, \vec{\imath}) \rightarrow (lap, \vec{\imath} + \vec{\jmath}) \mid \vec{\imath} \in \mathbb{Z}^2, \vec{\jmath} \in \{(0,0), (1,0)\}\}$$



$$D = D_{lap} \cup D_{fli} \cup D_{flj} \cup D_{out}$$

$$E = \mathrm{D}^{+}(\{\, (out, \vec{0})\, \})$$

apply the out origin vector to the transitive closure of all dependencies

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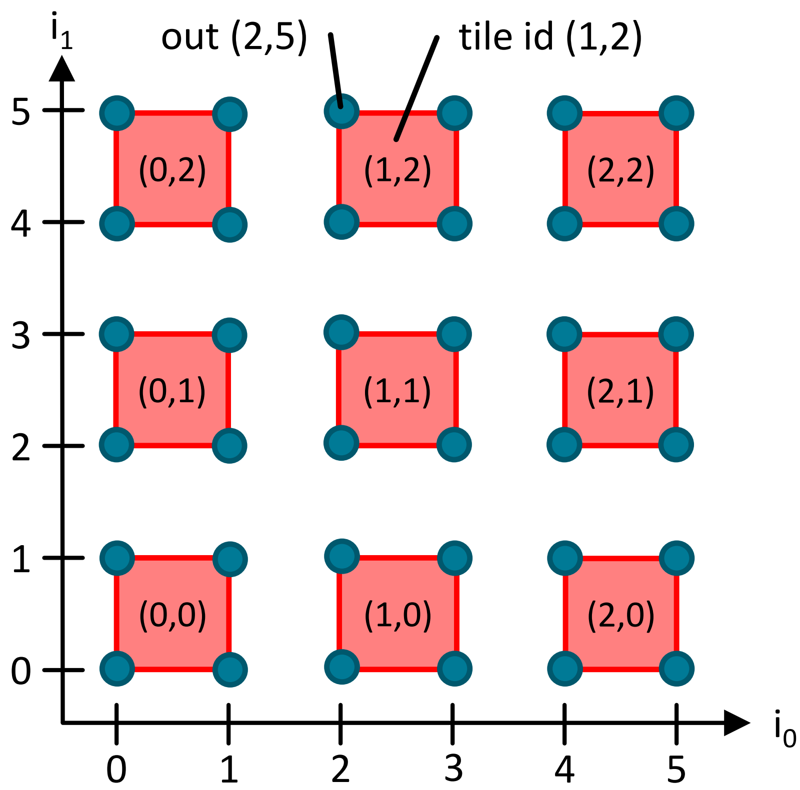
Stencil Performance Model - Tiling Transformations

- **Define a tiling using a map that associates stencil evaluations to tile ids**

$$T_{out} = \{(\text{out}, (i_0, i_1)) \rightarrow (\lfloor i_0/2 \rfloor, \lfloor i_1/2 \rfloor)\}$$



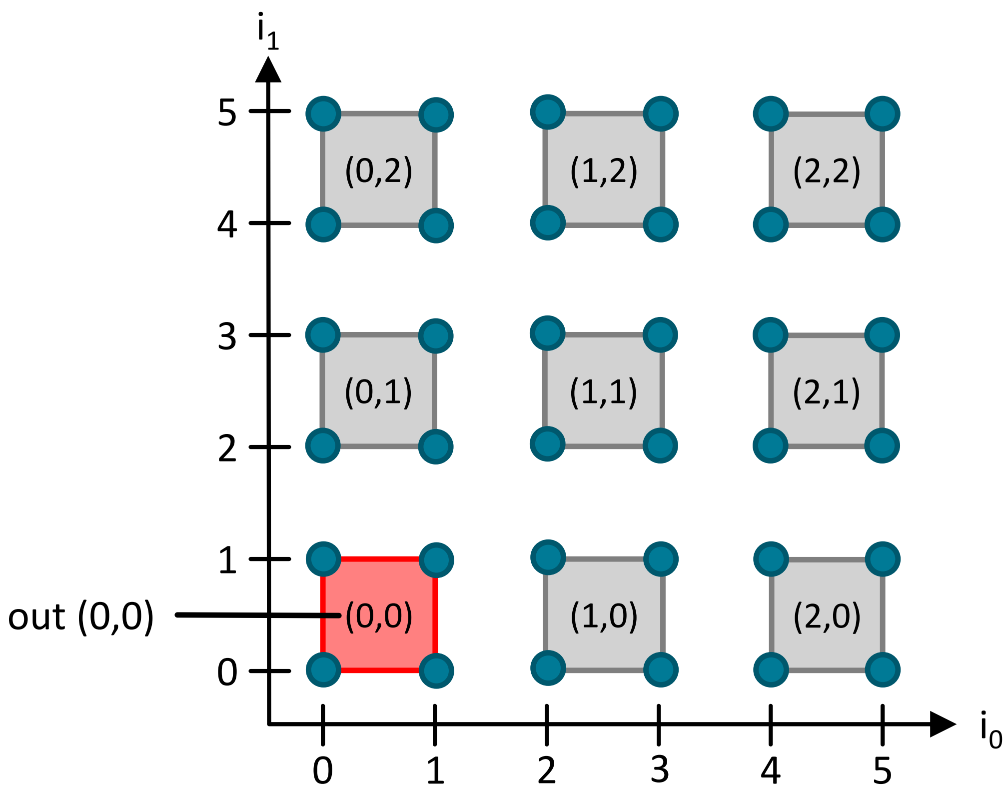
Stencil Performance Model – Comp & Comm

- **Count floating point operations necessary to update tile (0,0)**

$$c_{out} = |T_{out} \cap_{ran} \{(0,0)\}| \cdot \#flops$$

- **Count the number of loads necessary to update tile (0,0)**

$$l_{out} = |(T_{out} \circ D_{out}^{-1}) \cap_{ran} \{(0,0)\}|$$



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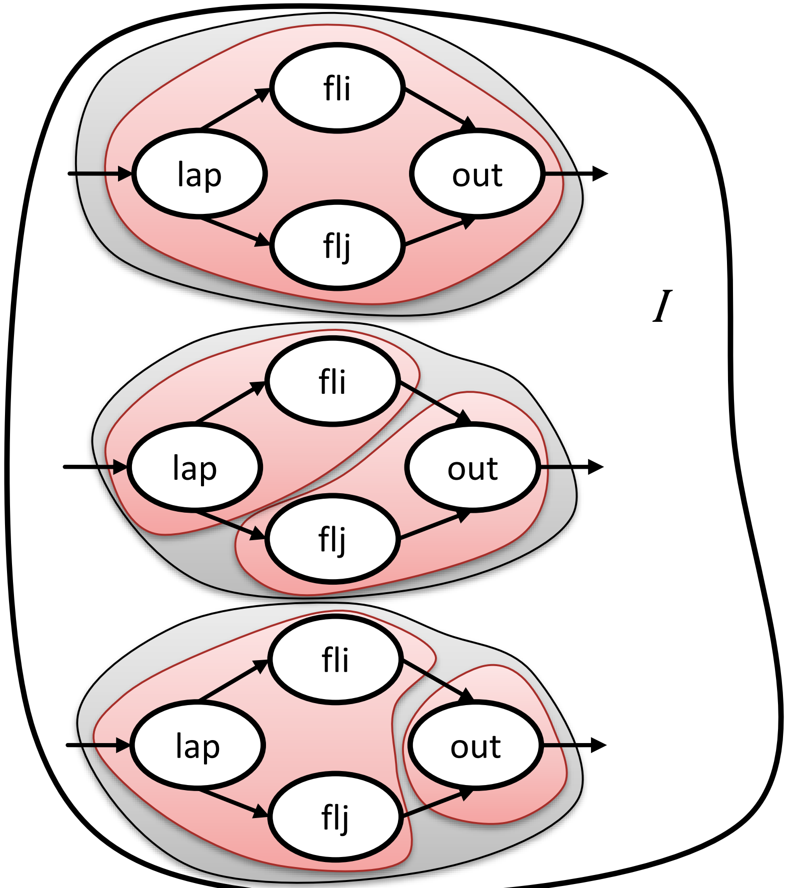
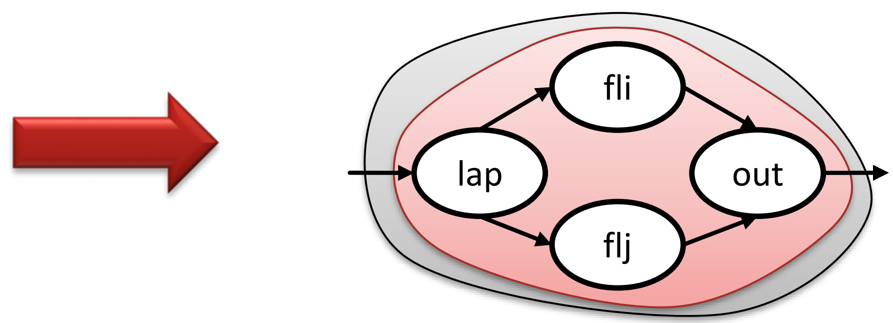
Analytic Stencil Program Optimization

- **Put it all together (stencil algebra, performance model, stencil analysis)**
  1. Optimize the stencil execution order (brute force search)
  2. Optimize the stencil grouping (dynamic programming / brute force search)



$$\underset{x \in I}{\text{minimize}}\, t(x)$$
$$\text{subject to } m(x) \leq M$$



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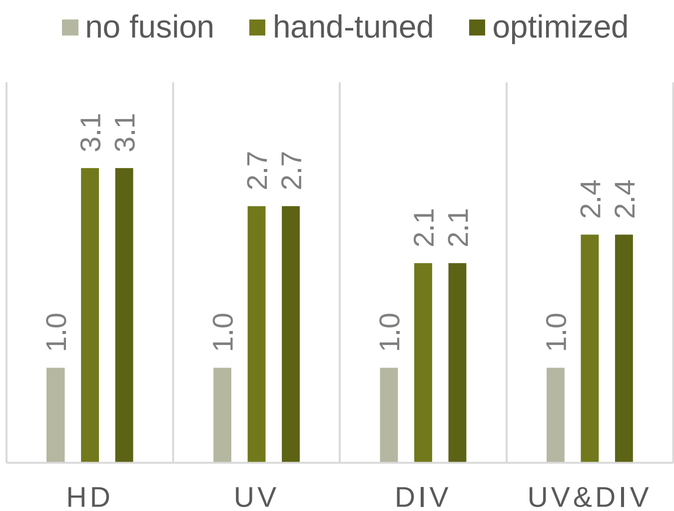
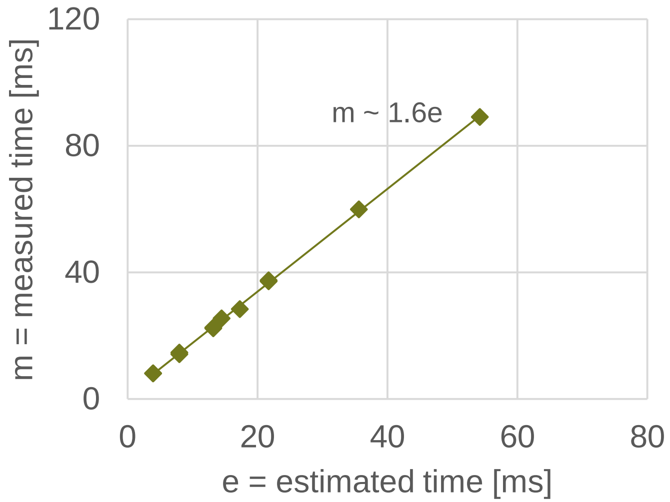
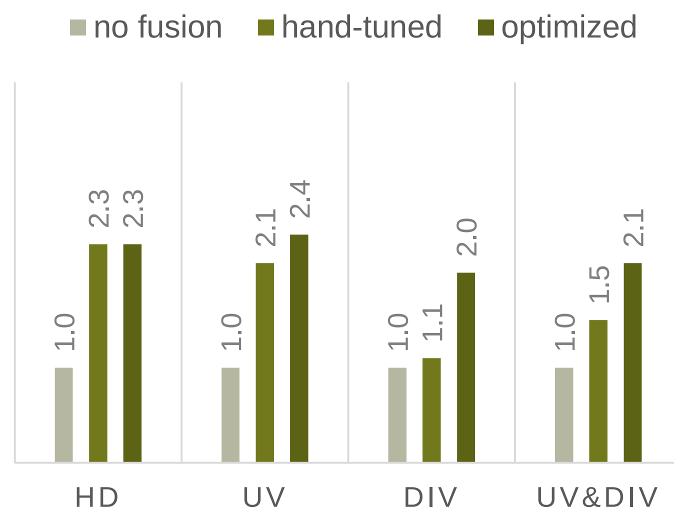
Evaluation – single CPU/GPU

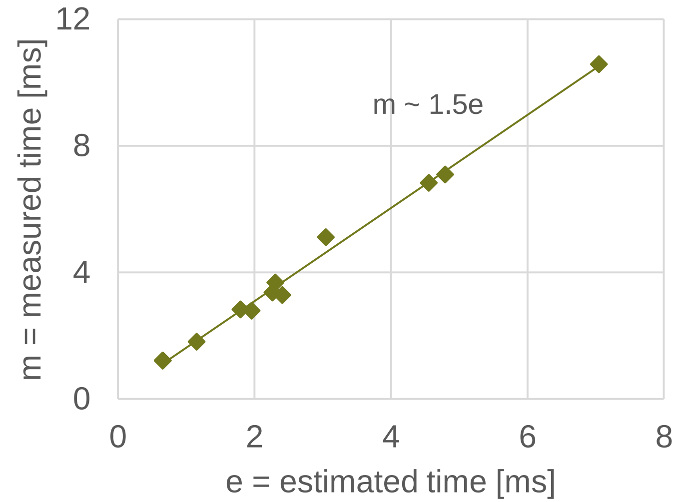
CPU Experiments (i5-3330):





GPU Experiments (Tesla K20c):





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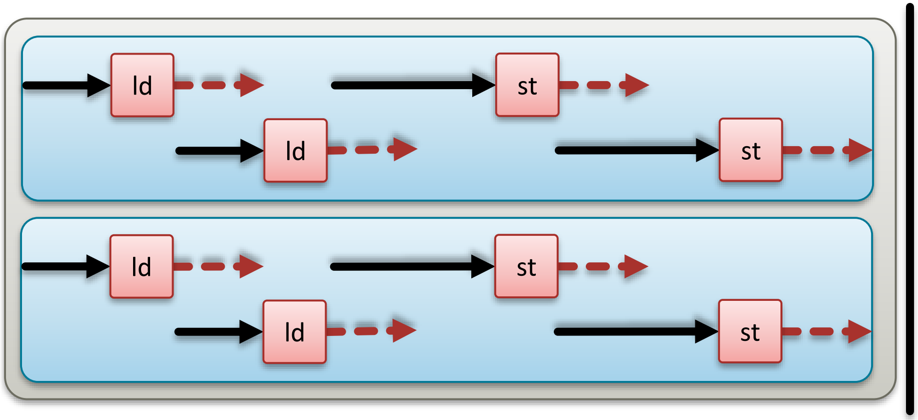
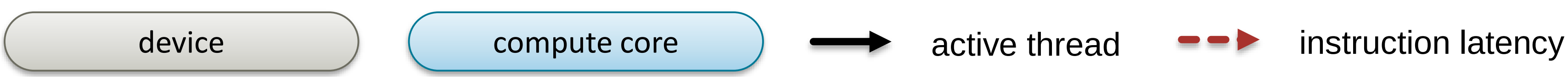
From GPUs to the cluster!



CUDA
- over-subscribe hardware
- use spare parallel slack for latency hiding

MPI
- host controlled
- full device synchronization



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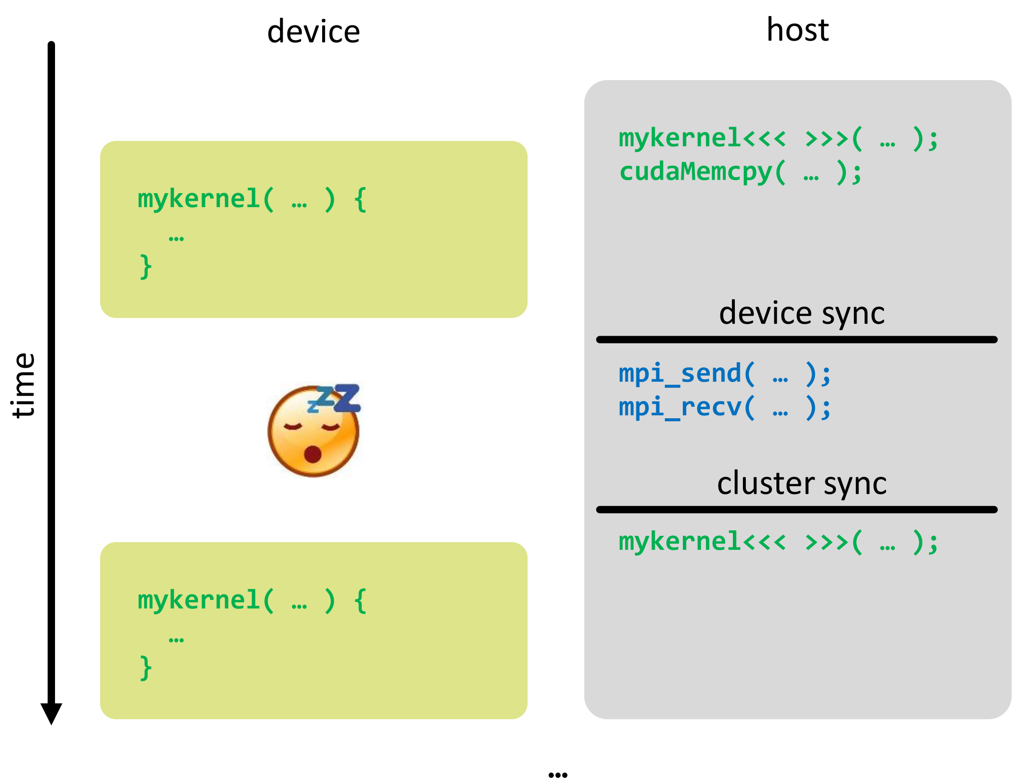
Disadvantages of the MPI-CUDA approach



complexity
- two programming models
- duplicated functionality

performance
- encourages sequential execution
- low utilization of the costly hardware

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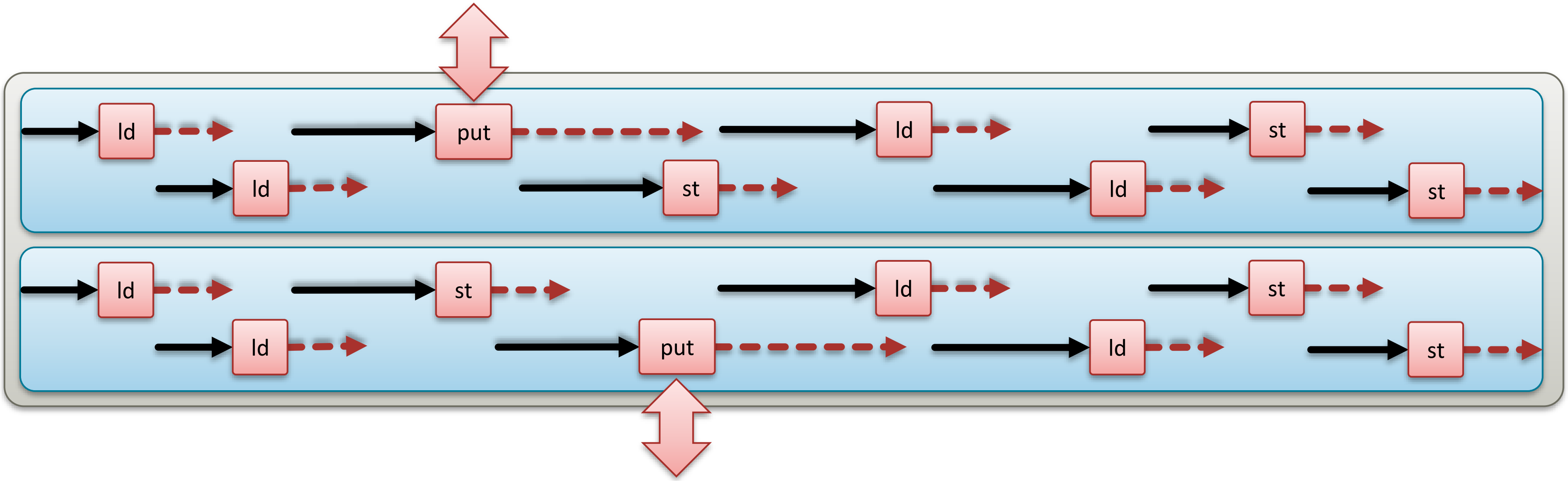
Latency hiding at the cluster level?



dCUDA (distributed CUDA)

- unified programming model for GPU clusters
- avoid unnecessary device synchronization to enable system wide latency hiding

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Achieve high resource utilization using oversubscription & hardware threads

code

```
ld  %r0,%r1
mul %r0,%r0,3
st  %r0,%r1
```

GPU cores use "parallel slack" to hide instruction pipeline latencies

time

thread 1	thread 2	thread 3	instruction pipeline	
ld %r0,%r1	ready	ready	ld	
stall	ld %r0,%r1	ready	ld	ld
ready	stall	ld %r0,%r1	ld	ld
mul %r0,%r0,3	ready	stall	mul	ld
stall	mul %r0,%r0,3	ready	mul	mul
ready	stall	mul %r0,%r0,3	mul	mul
st %r0,%r1	ready	stall	st	mul
stall	st %r0,%r1	ready	st	st
ready	stall	st %r0,%r1	st	st

…

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Use oversubscription & hardware threads to hide remote memory latencies

code	thread 1	thread 2	thread 3	instruction pipeline	
`get …`	`get …`	`ready`	`ready`	`get`	
`mul %r0,%r0,3`	`stall`	`get …`	`ready`	`get`	`get`
`put …`	`stall`	`stall`	`get …`	`get`	`get`
	`stall`	`stall`	`stall`	`!`	`get`
	`ready`	`stall`	`stall`	`!`	`!`
	`mul %r0,%r0,3`	`ready`	`stall`	`mul`	`!`
	`stall`	`mul %r0,%r0,3`	`ready`	`mul`	`mul`
	`ready`	`stall`	`mul %r0,%r0,3`	`mul`	`mul`
	`put …`	`ready`	`stall`	`put`	`mul`

…

time

introduce put & get operations to access distributed memory

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How much "parallel slack" is necessary to fully utilize the interconnect?

Little's law

$$concurrency = latency \ * throughput$$

	device memory
latency	1µs
bandwidth	200GB/s
concurrency	200kB
#threads	~12000

>>

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dCUDA extends CUDA with MPI-3 RMA and notifications

```
for (int i = 0; i < steps; ++i) {
  for (int idx = from; idx < to; idx += jstride)
    out[idx] = -4.0 * in[idx] +
      in[idx + 1] + in[idx - 1] +
      in[idx + jstride] + in[idx - jstride];

  if (lsend)
    dcuda_put_notify(ctx, wout, rank - 1,
      len + jstride, jstride, &out[jstride], tag);
  if (rsend)
    dcuda_put_notify(ctx, wout, rank + 1,
      0, jstride, &out[len], tag);

  dcuda_wait_notifications(ctx, wout,
    DCUDA_ANY_SOURCE, tag, lsend + rsend);

  swap(in, out); swap(win, wout);
}
```

computation

communication

- iterative stencil kernel
- thread specific idx

- map ranks to blocks
- device-side put/get operations
- notifications for synchronization
- shared and distributed memory

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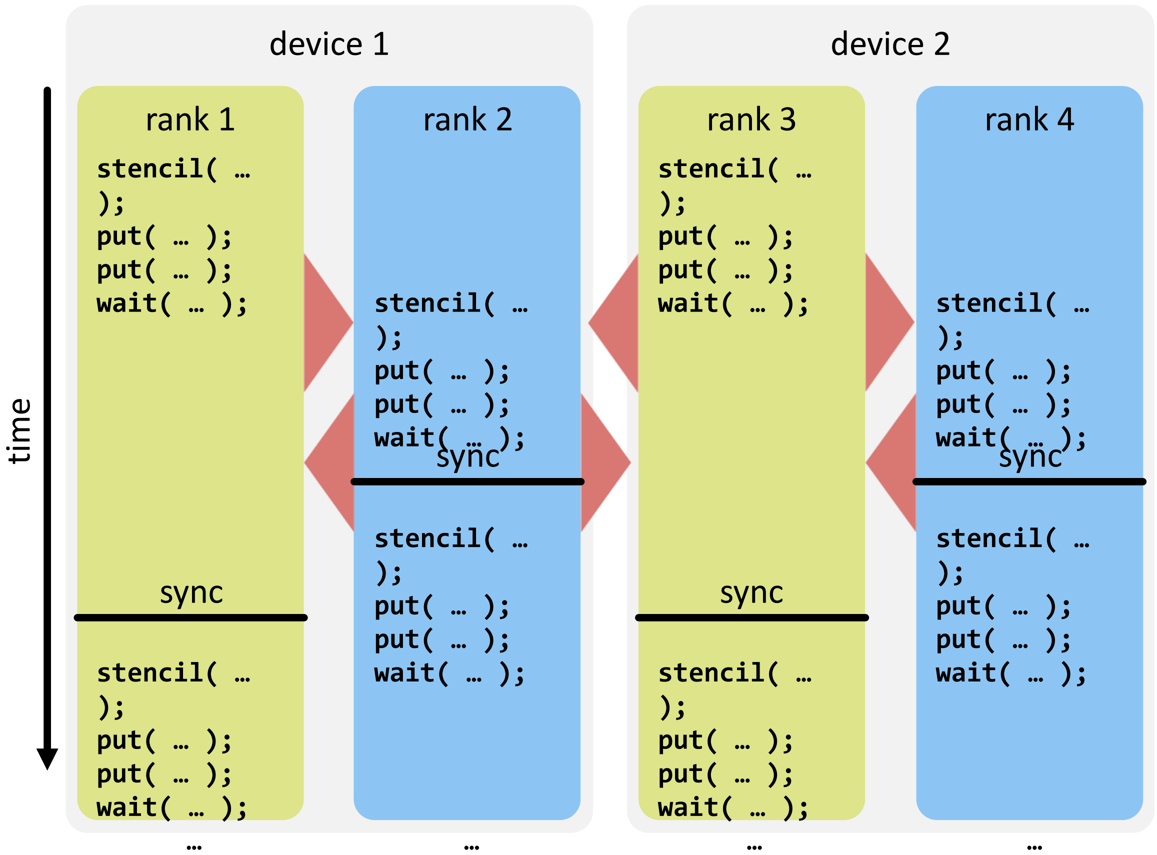
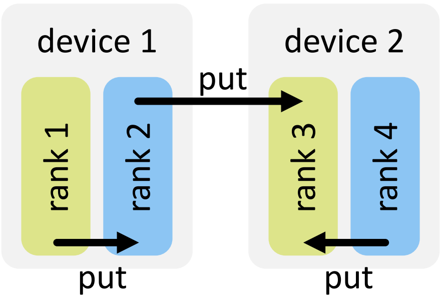
Advantages of the dCUDA approach



performance
- avoid device synchronization
- latency hiding at cluster scale

complexity
- unified programming model
- one communication mechanism



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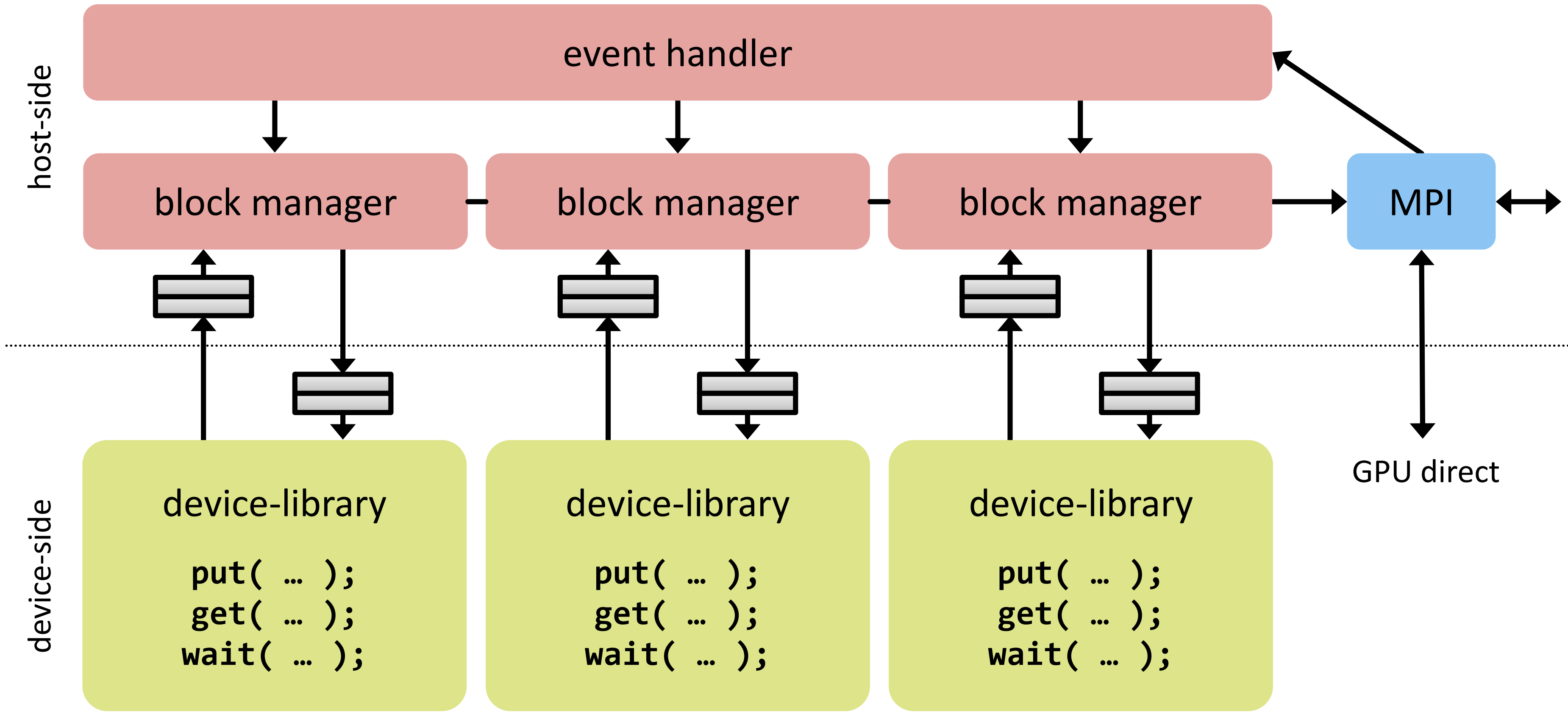
Implementation of the dCUDA runtime system



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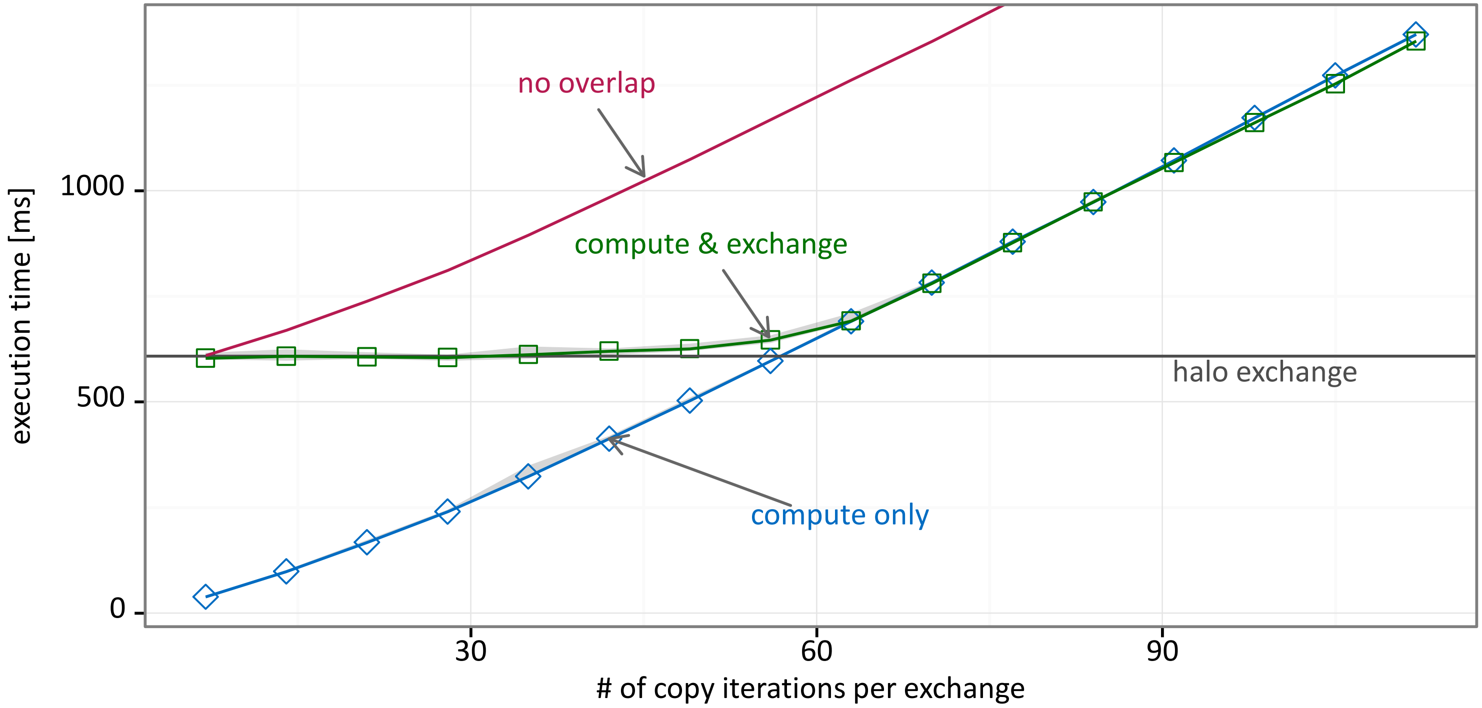
Overlap of a copy kernel with halo exchange communication

benchmarked on Greina (8 Haswell nodes with 1x Tesla K80 per node)



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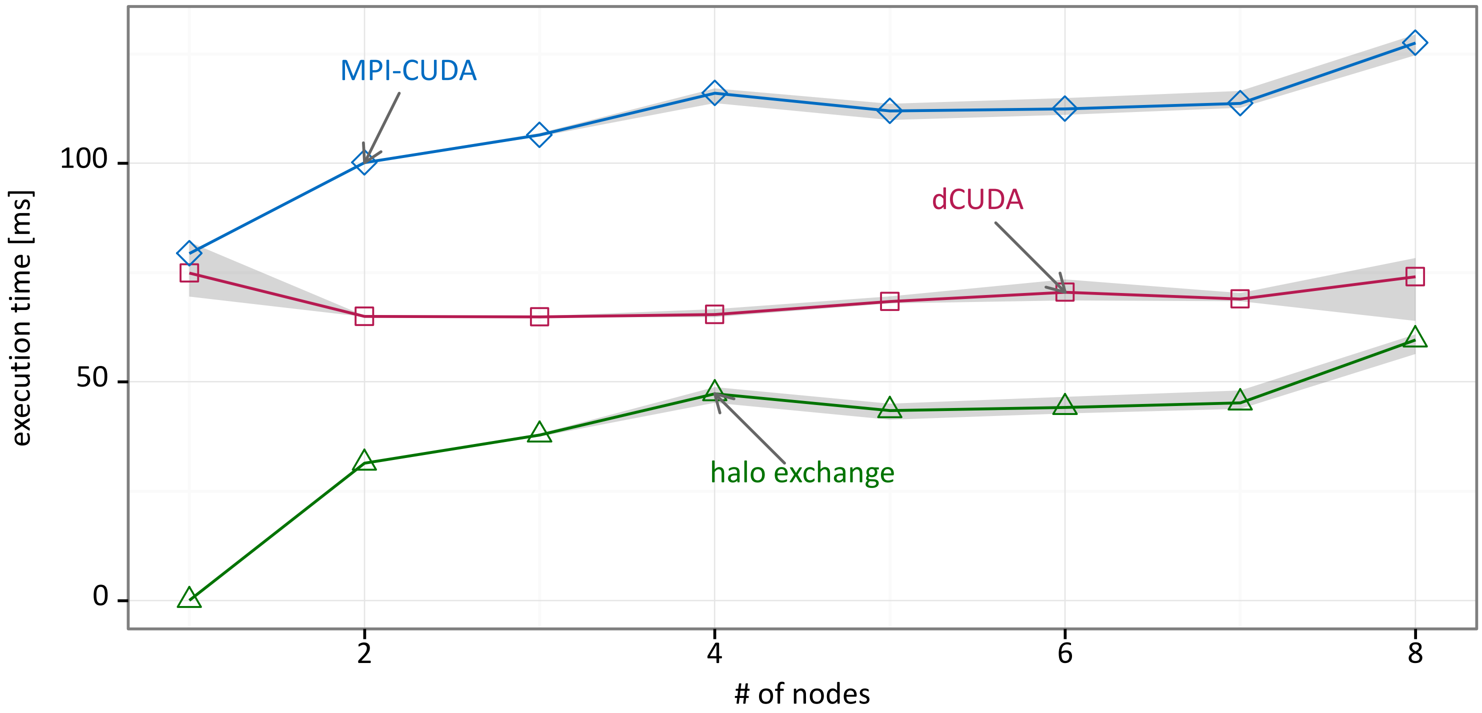
Weak scaling of MPI-CUDA and dCUDA for a stencil program

- **Benchmarked on Greina (8 Haswell nodes with 1x Tesla K80 per node)**



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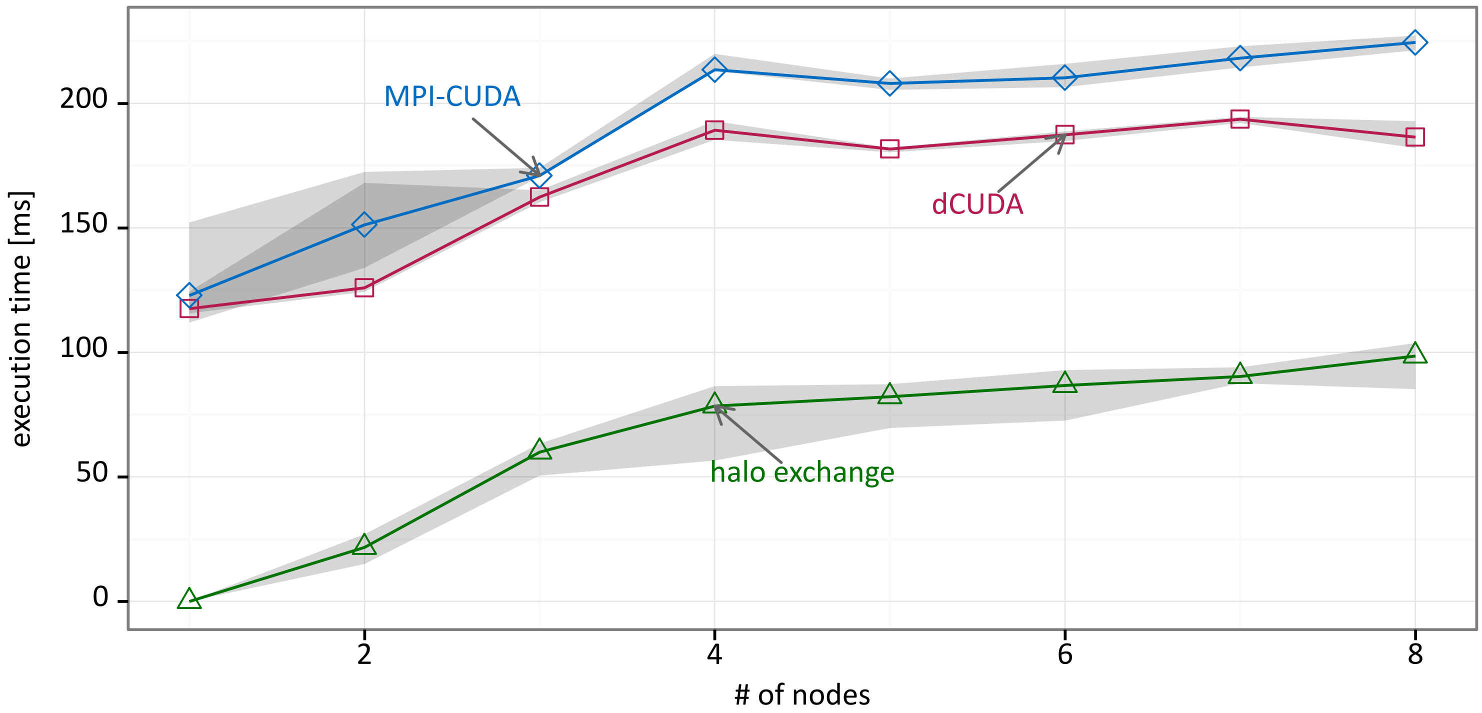
Weak scaling of MPI-CUDA and dCUDA for a particle simulation

- **Benchmarked on Greina (8 Haswell nodes with 1x Tesla K80 per node)**



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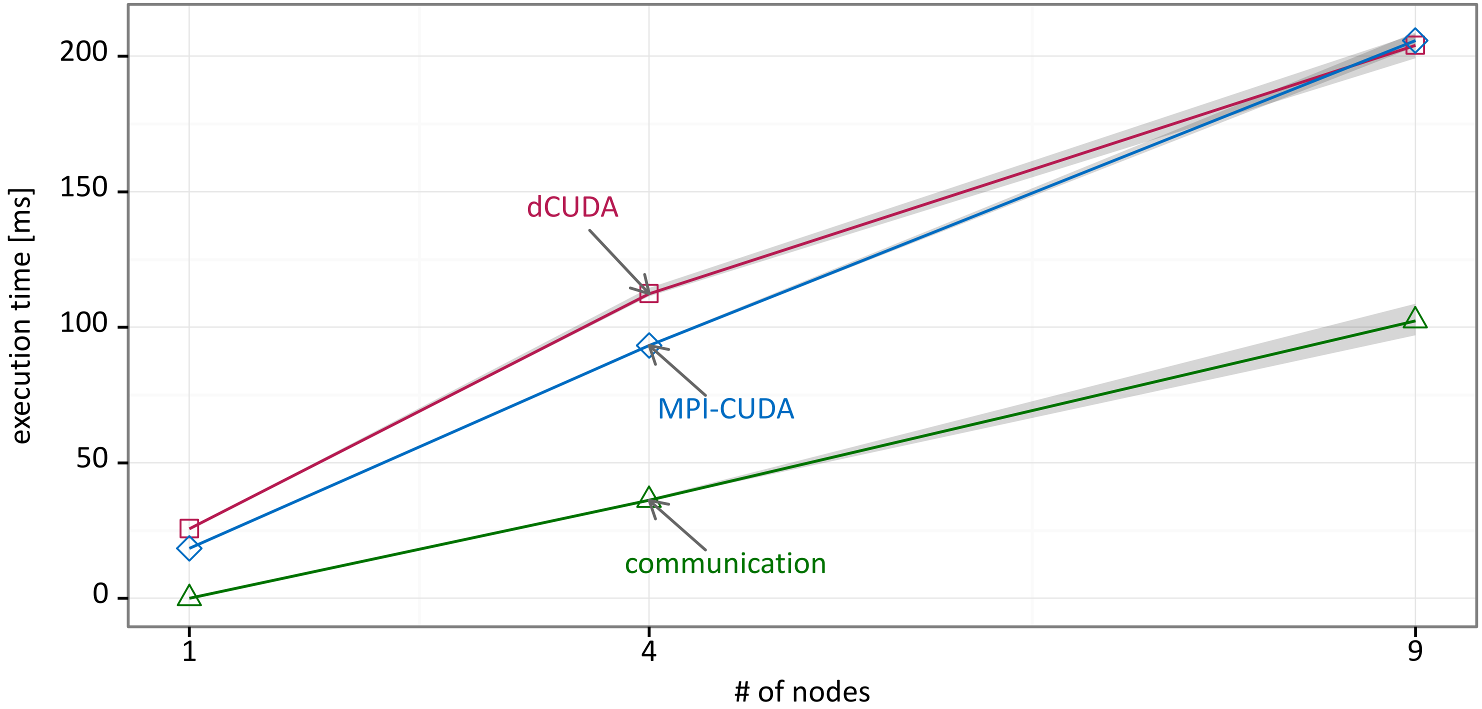
Weak scaling of MPI-CUDA and dCUDA for sparse-matrix vector multiplication

- **Benchmarked on Greina (8 Haswell nodes with 1x Tesla K80 per node)**



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Not just your basic, average, everyday, ordinary, run-of-the-mill, ho-hum stencil optimizer

- **Complete performance models for:**
  - Computation (very simple)
  - Communication (somewhat tricky, using sets and Minkowski sums, parts of the PM)
- **Established a stencil algebra**
  - Complete enumeration of **all** program variants
- **Analytic tuning of stencil programs (using STELLA)**
  - 2.0-3.1x speedup against naive implementations
  - 1.0-1.8x speedup against expert tuned implementations
- **dCUDA enables overlap of communication and computation**
  - Similar to the throughput computing/CUDA idea, just distributed memory
  - Also simplifies programming (no kernel/host code separation)

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