Exascale-ready adaptive mesh refinement and applications in Earth system modelling

ECMWF - 19th workshop on HPC in meteorology, September 2021

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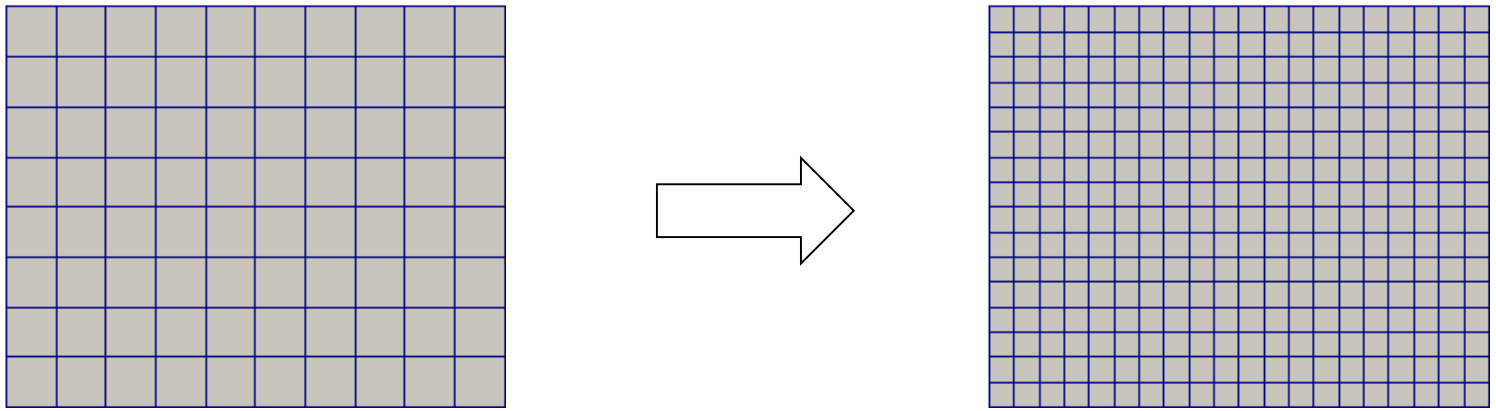
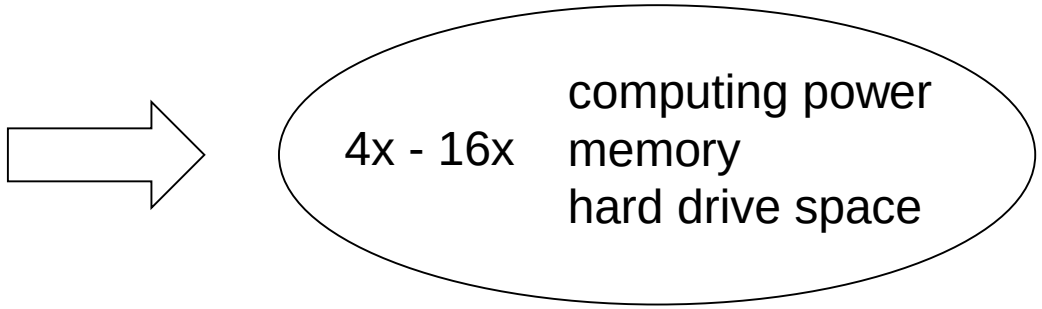
Why AMR

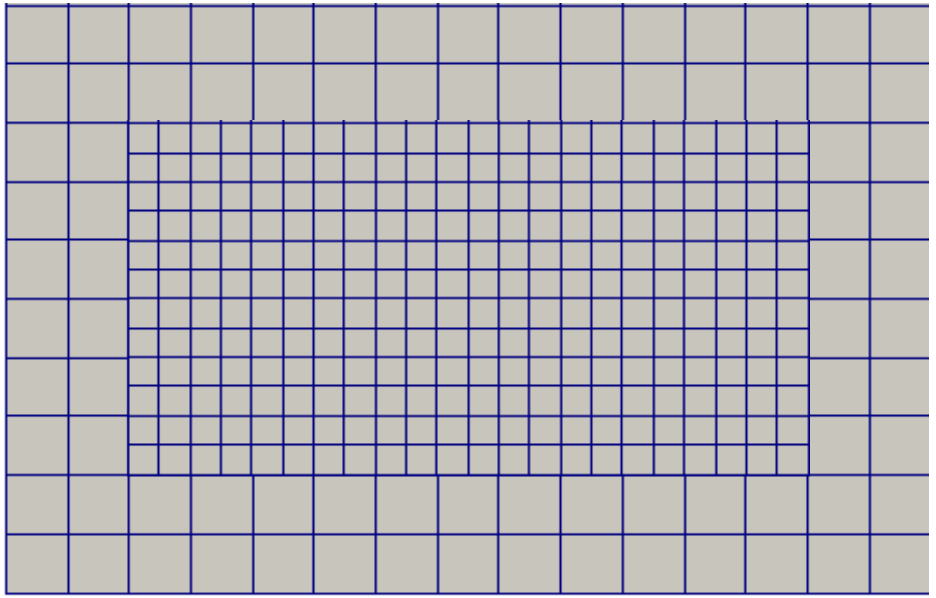
Increase resolution = increase simulation accuracy



4x/8x more DOFs and data per time step

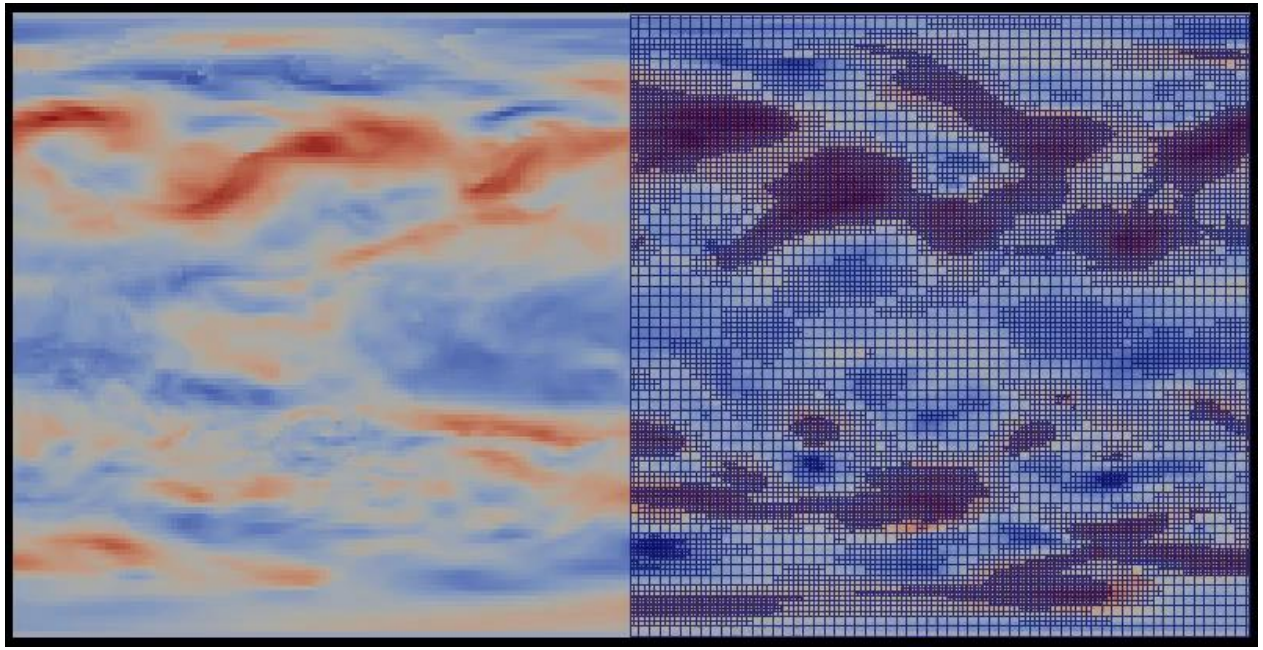


Common approach: Nested grids



- Increases resolution in large area of interest
- Can still use structured meshes (= implicit data and better performance)
- unflexible

Dynamic AMR

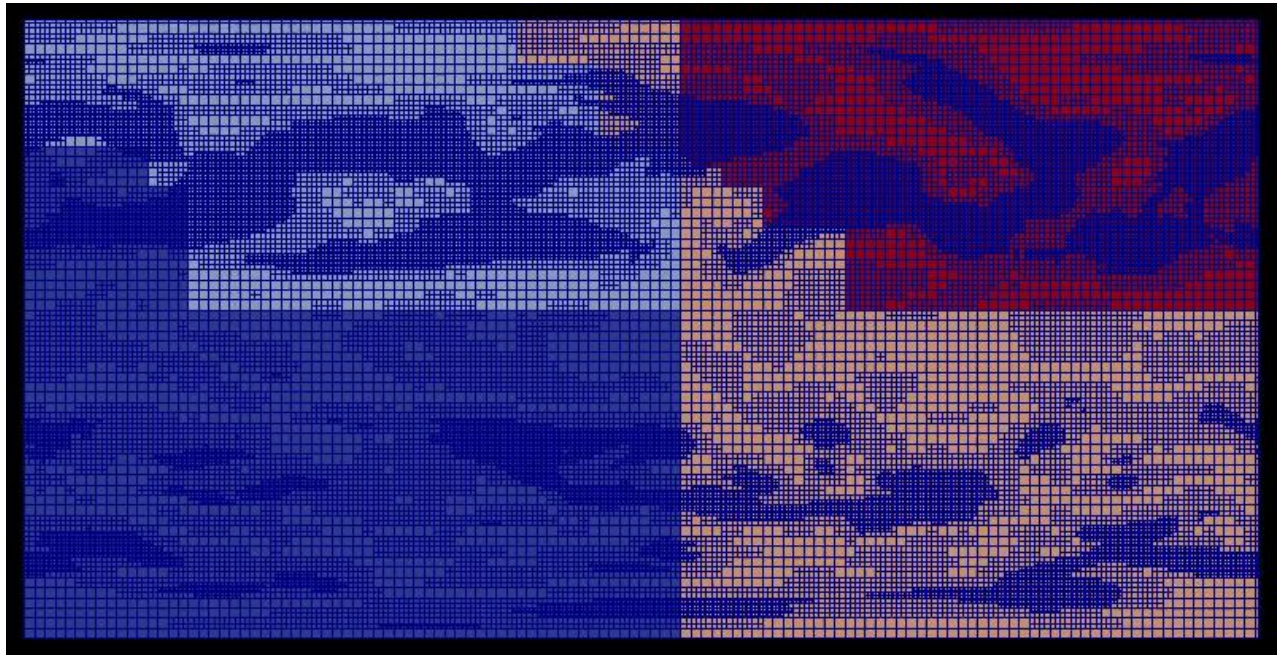


- Dynamic AMR:
  - Refine or coarse each element **individually**
  - Change over time

  - Reduce number of elements by orders of magnitude
  - Enable fine scale simulations that are not possible with uniform/nested grids

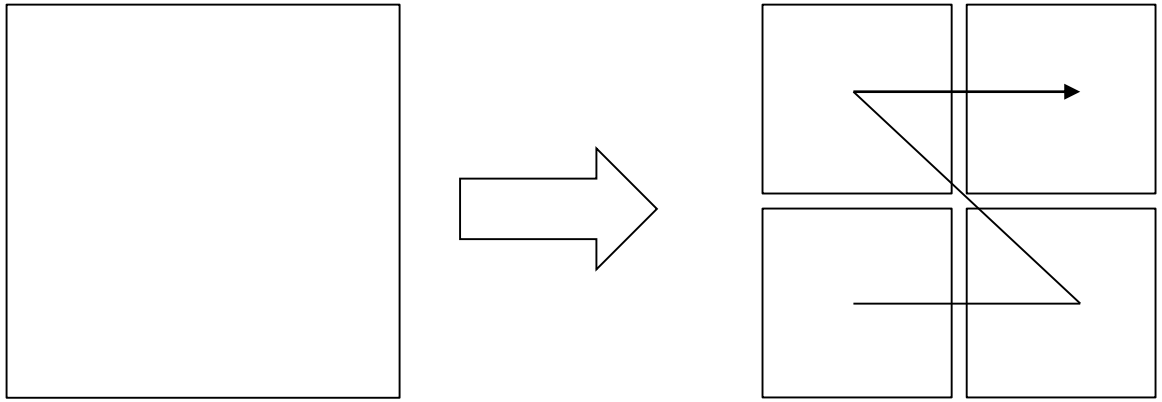
Challenges of AMR

- Storage of mesh elements
- Load-balancing
- Ghosts
- Etc.

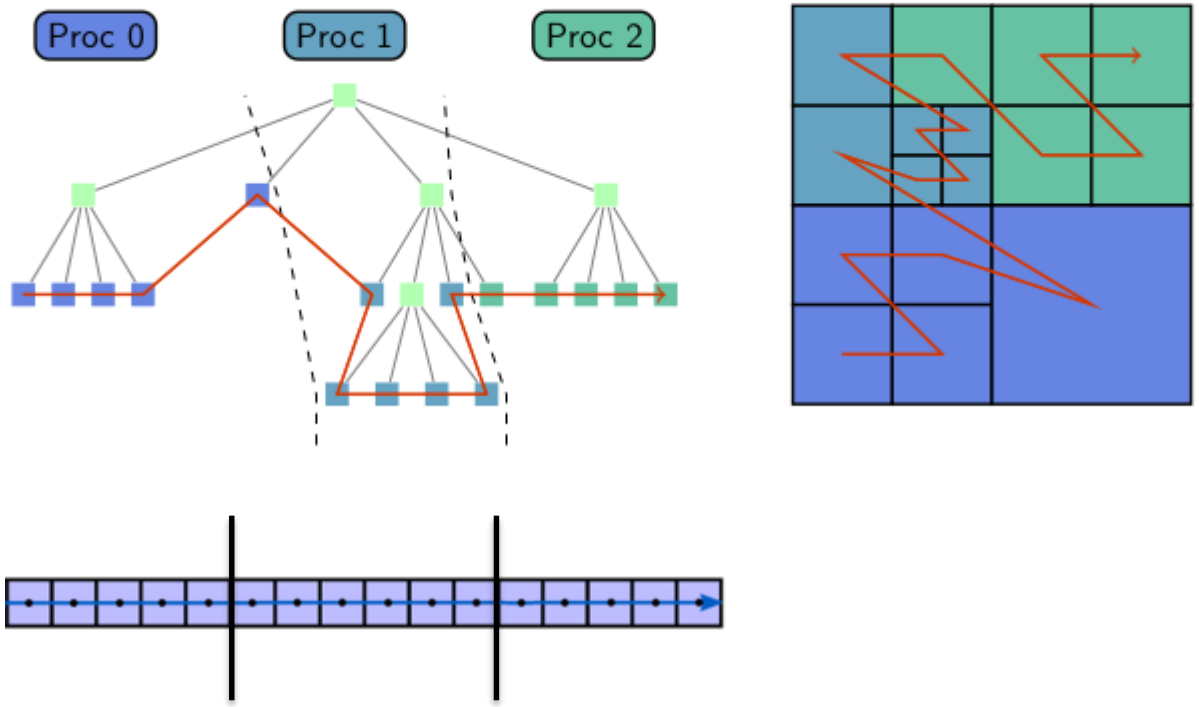


Unstructured meshes: memory usage, do not scale well, no implicit structure

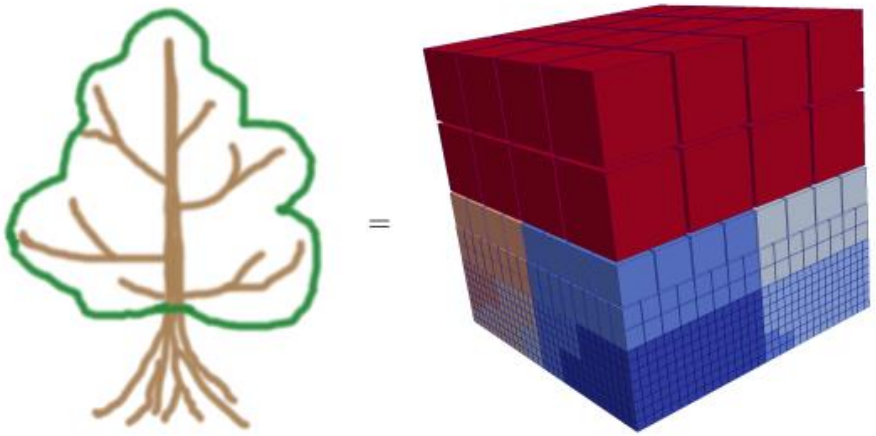
AMR data structure: Trees and SFCs

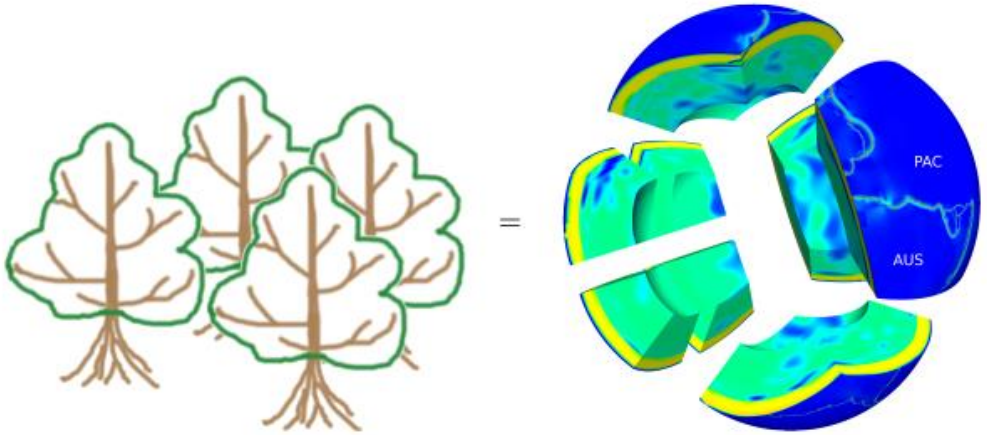


AMR data structure: Trees and SFCs



From tree to forest

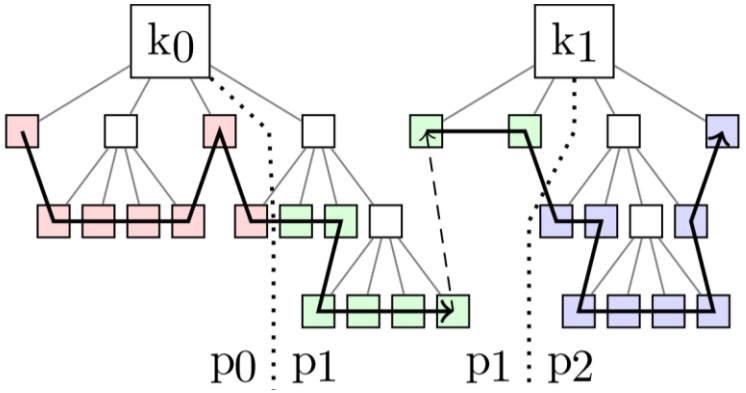


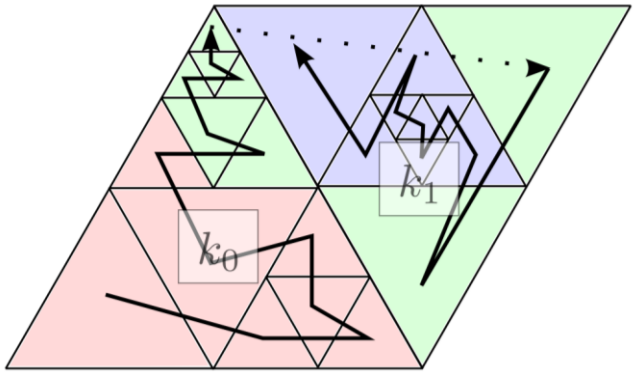


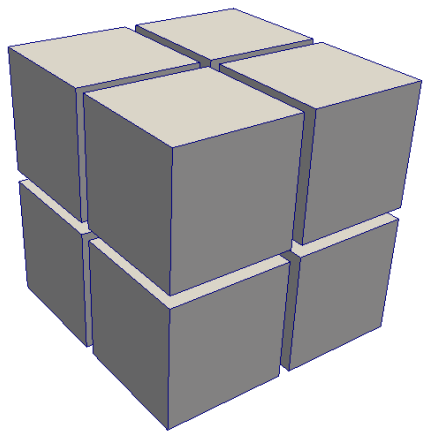
Science 329 (5995), p. 1033-1038

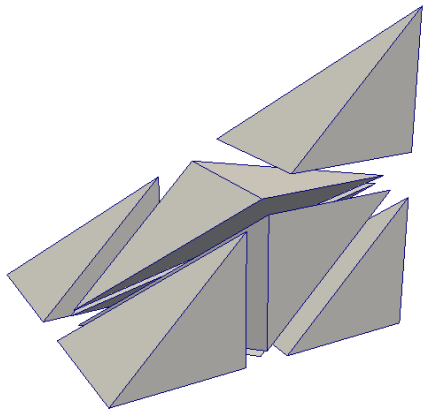
Images by Carsten Burstedde

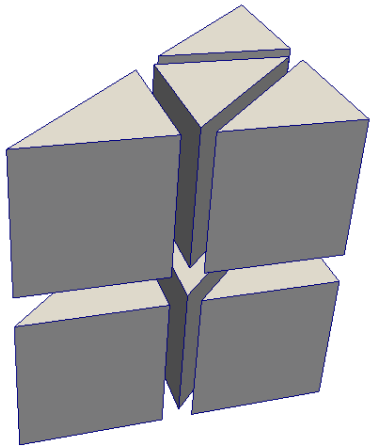
From Quad to all

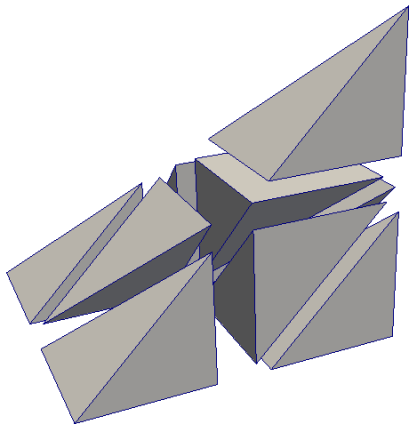












t8code (“tetcode”) – AMR library

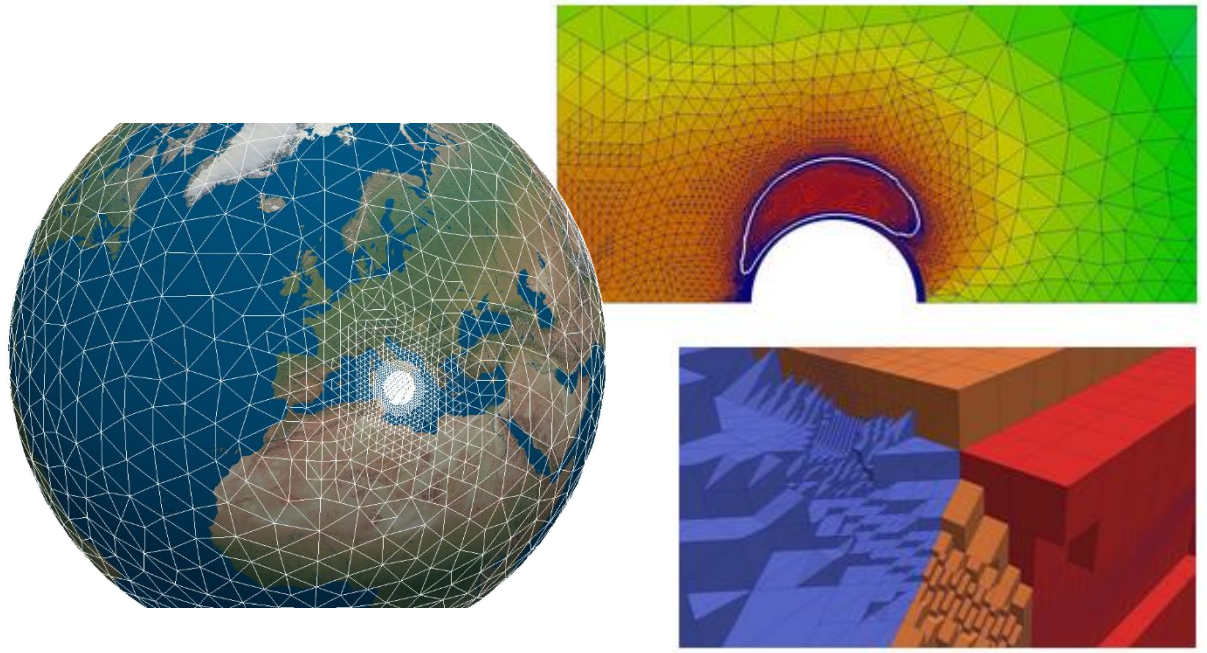
holke / t8code

github.com/holke/t8code

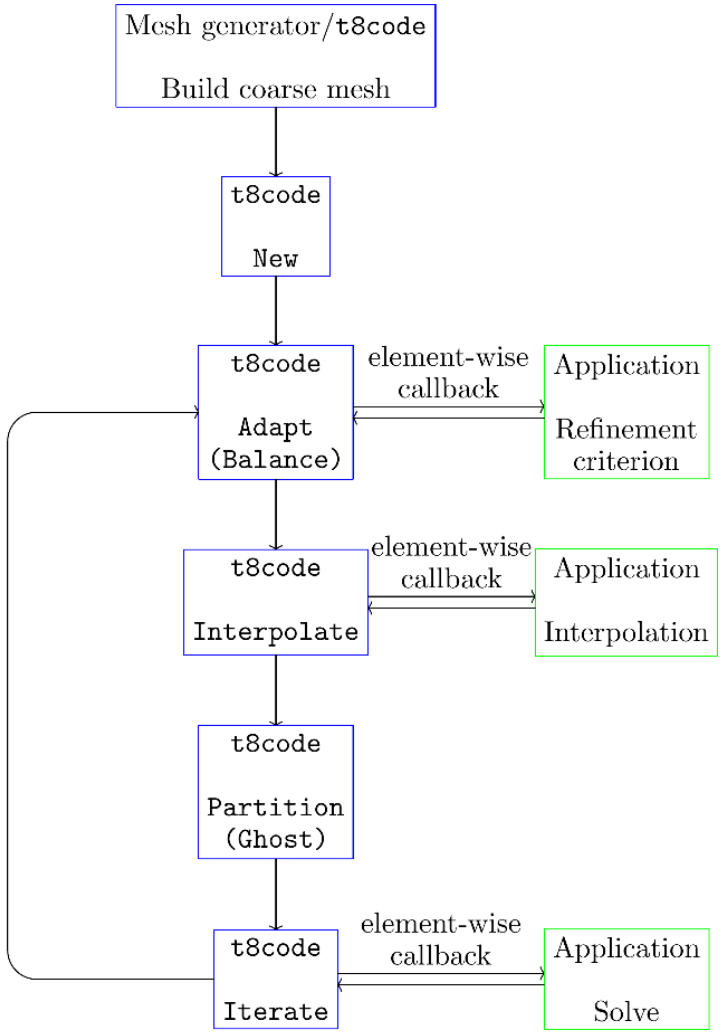
Application developer should not be concerned with mesh management

Parallel mesh and data management library

C/C++ with MPI



The AMR simulation cycle

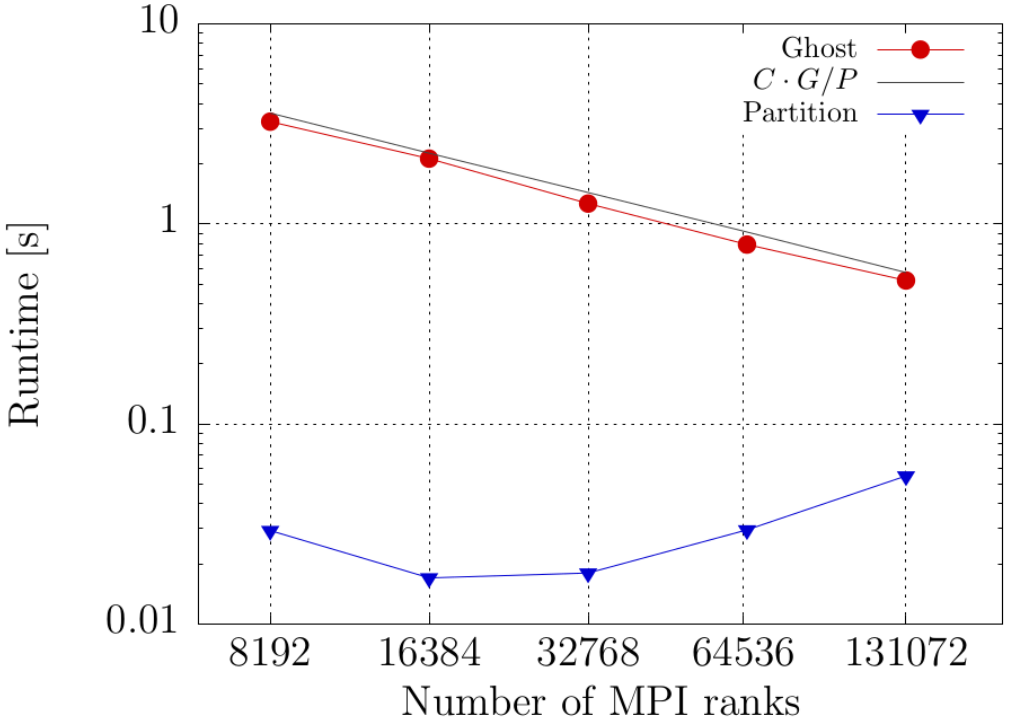


Application can freely speficy how to

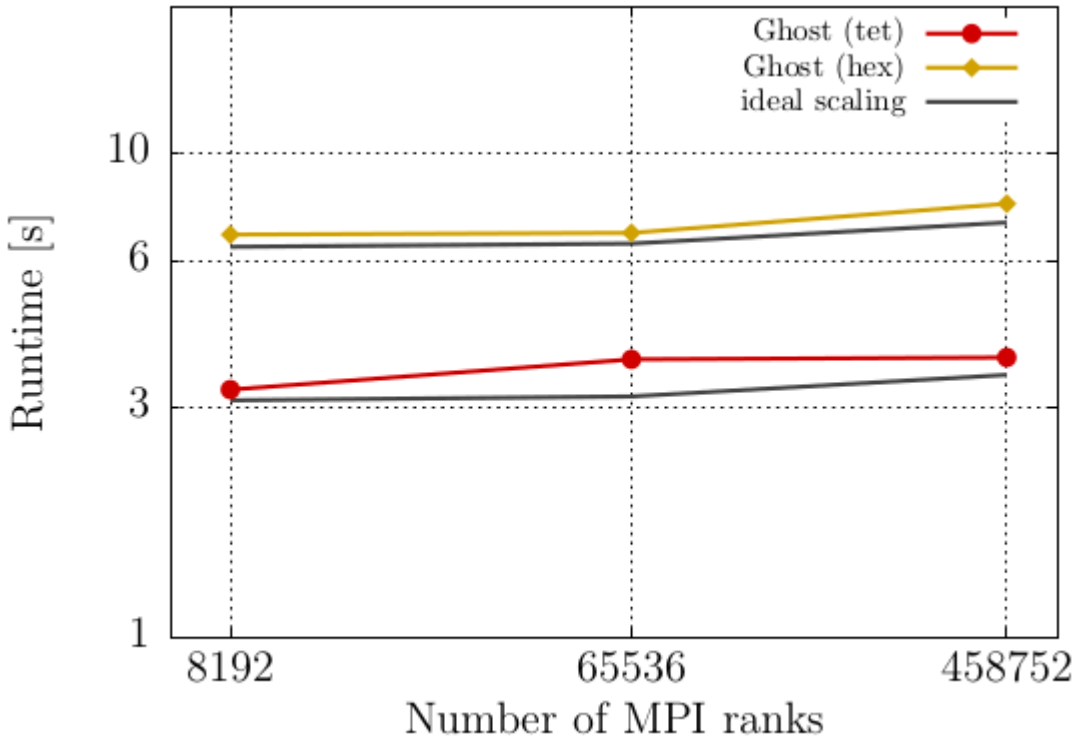
- Adapt the mesh
- Interpolate the data
- Solve the equation

Performance
Juqueen

Strong scale 1.9 billion tets



Weak scale, up to 142 billion elements



Performance

milestone: >1 Trillion elements on JUWELS

#processes	#Elements	#Elements/process	Ghost	Partition
98,304	1,099,511,627,776 ≙ 1.1e12	11,184,811	1.43s	0.33s

Two applications in ESM

ExaESM
Pilot Lab Exascale Earth System Modelling

www.exaesm.de

„Explore potential of dynamic AMR in ESM“

1. Reduce I/O file size of MESSy
2. Full AMR Advection/Diffusion solver

MESSy – lossy data compression

ExaESM
Pilot Lab Exascale
Earth System Modelling

Technische Universität München

messy-interface.org

The highly structured
Modular Earth Submodel System (MESSy)

developed by the consortium of

DLR Deutsches Zentrum für Luft- und Raumfahrt German Aerospace Center
KIT Karlsruher Institut für Technologie
JÜLICH Forschungszentrum
MAX-PLANCK-INSTITUT FÜR CHEMIE
The Cyprus Institute
Freie Universität Berlin
JGU Johannes Gutenberg Universität Mainz
University of Connecticut 1881
CMA China Meteorological Administration
IGCE Institute of Global Climate and Ecology Roshydromet & RAS
UH Universität Hamburg DER FORSCHUNG | DER LEHRE | DER BILDUNG
institut für geowissenschaften METEOROLOGIE
TU Delft
AARHUS UNIVERSITY
SUN YAT-SEN UNIVERSITY
King Abdullah University of Science and Technology
UNI FREIBURG
LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN
nlr

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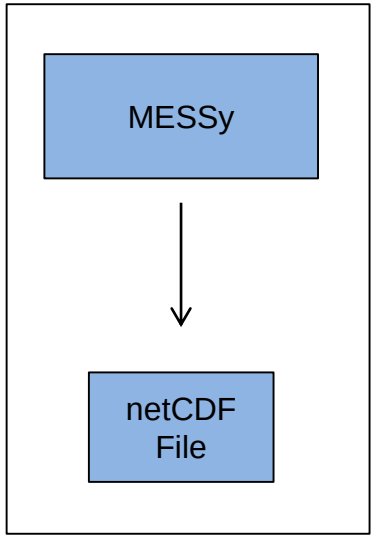
MPG Rechenzentrum (RZG), Garching, Germany

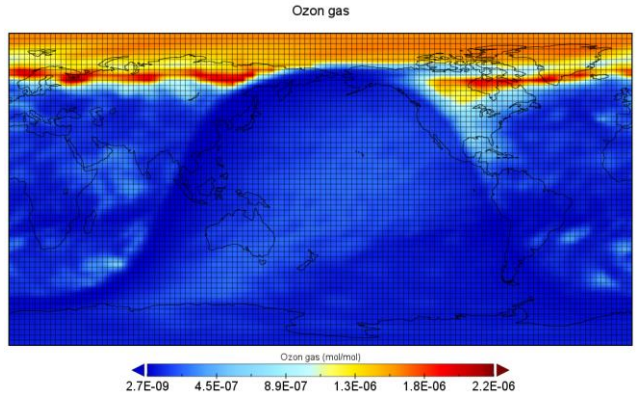
Leibniz Rechenzentrum (LRZ), Garching, Germany

DLR

MESSy – lossy data compression

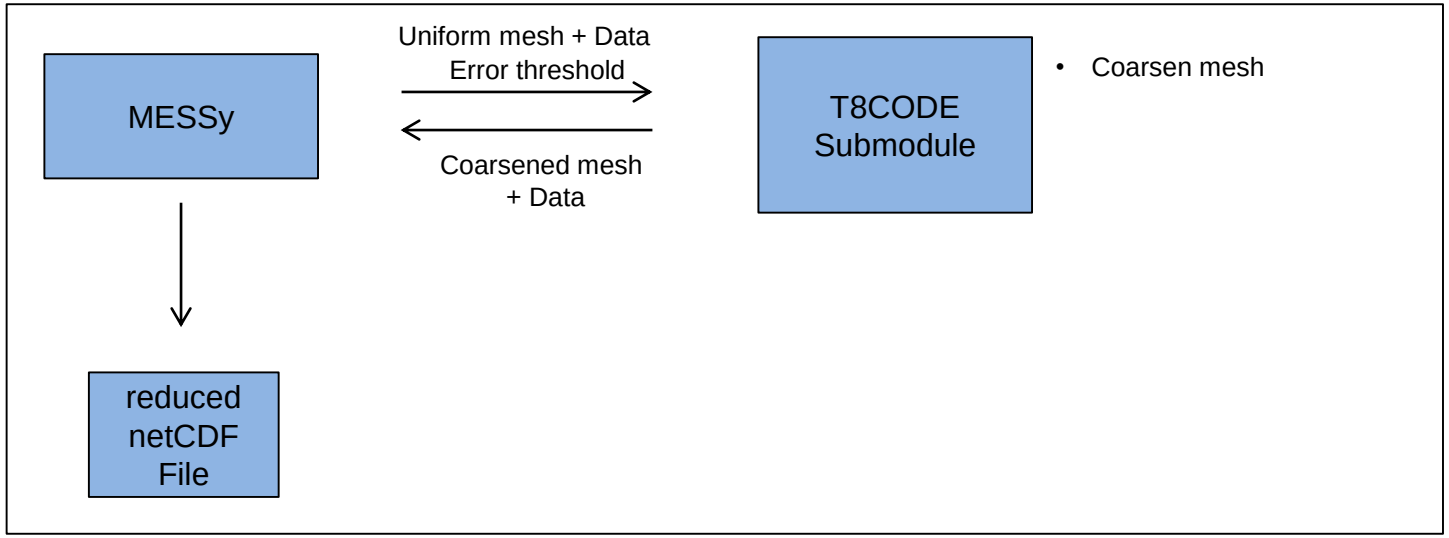
Simulation Hundreds of chemical species result in very large output files

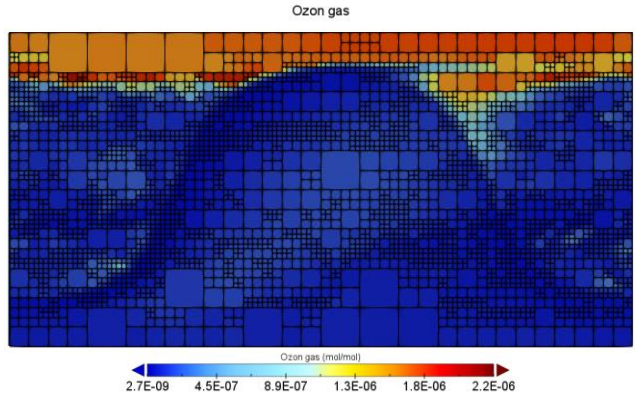




MESSy – lossy data compression

- Prototype/proof of concept

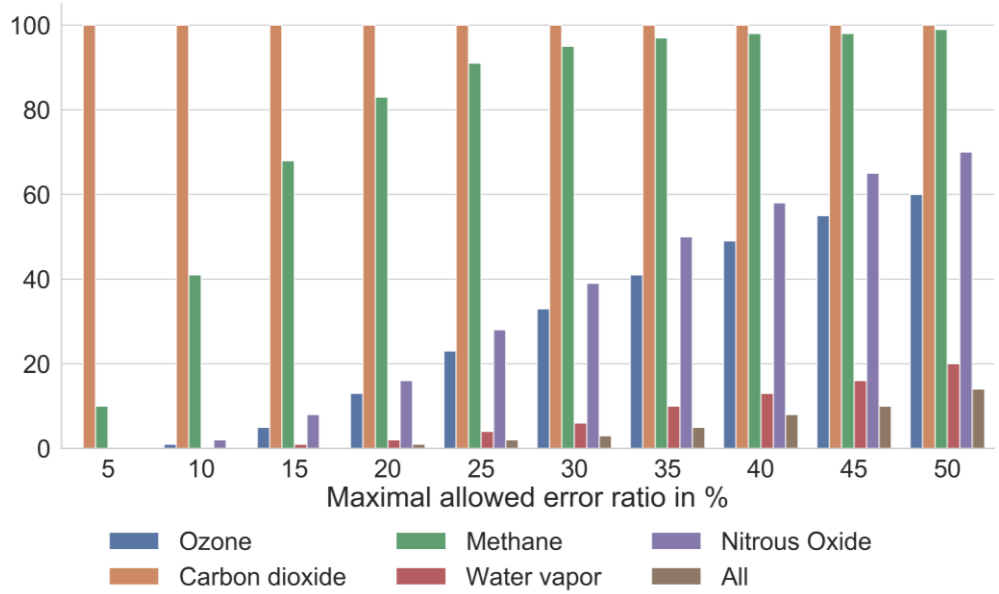




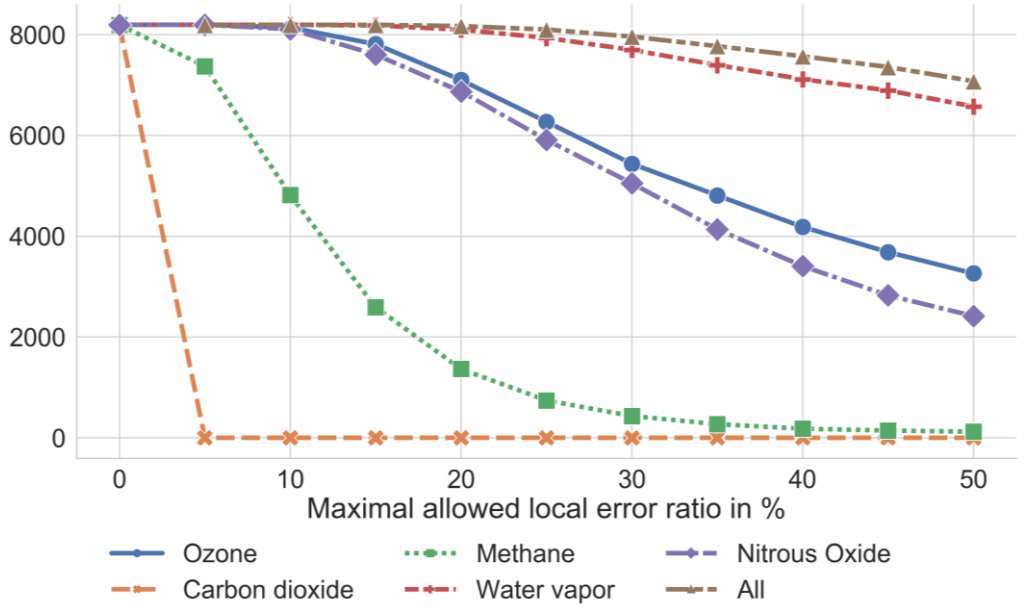
First results

RC1-base-07[1] ECHAM, 128 x 64 x 90

File size reduction in %



Number of mesh elements

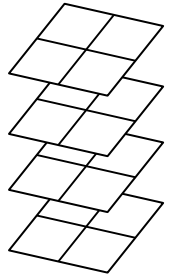


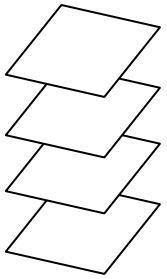
Lossy data compression for atmospheric chemistry using adaptive mesh coarsening
Master's Thesis by Luca Spataro at TU Munich

[1]Earth system chemistry integrated modelling (ESCIMO) with the modular earth submodel system (MESSy) version 2.51, Jöckel et. al., 2016

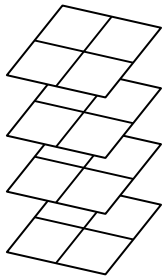
Results

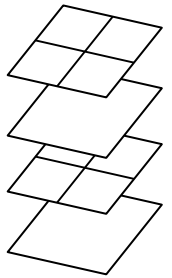
The first results are promising.
Currently Coarsening over all z-levels simultaneously:





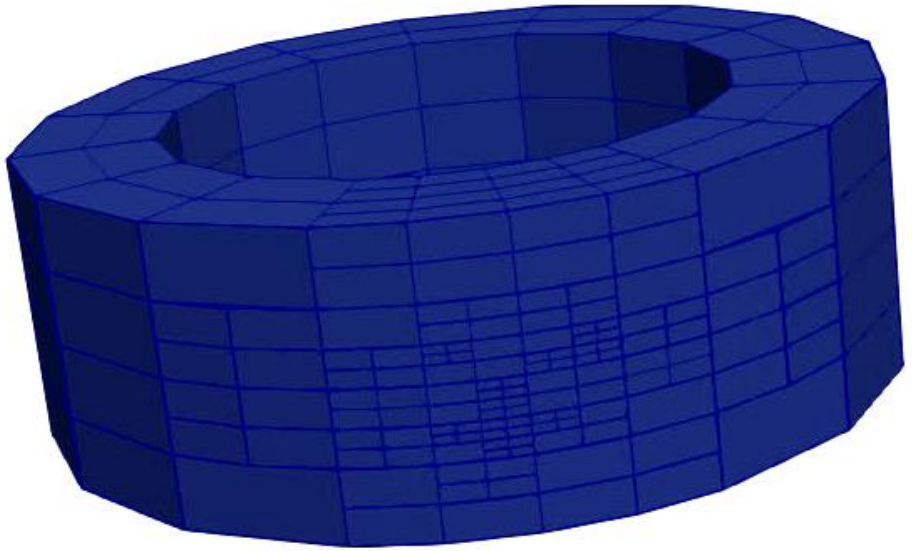
Much better compression rates expected when handling z-levels independently:





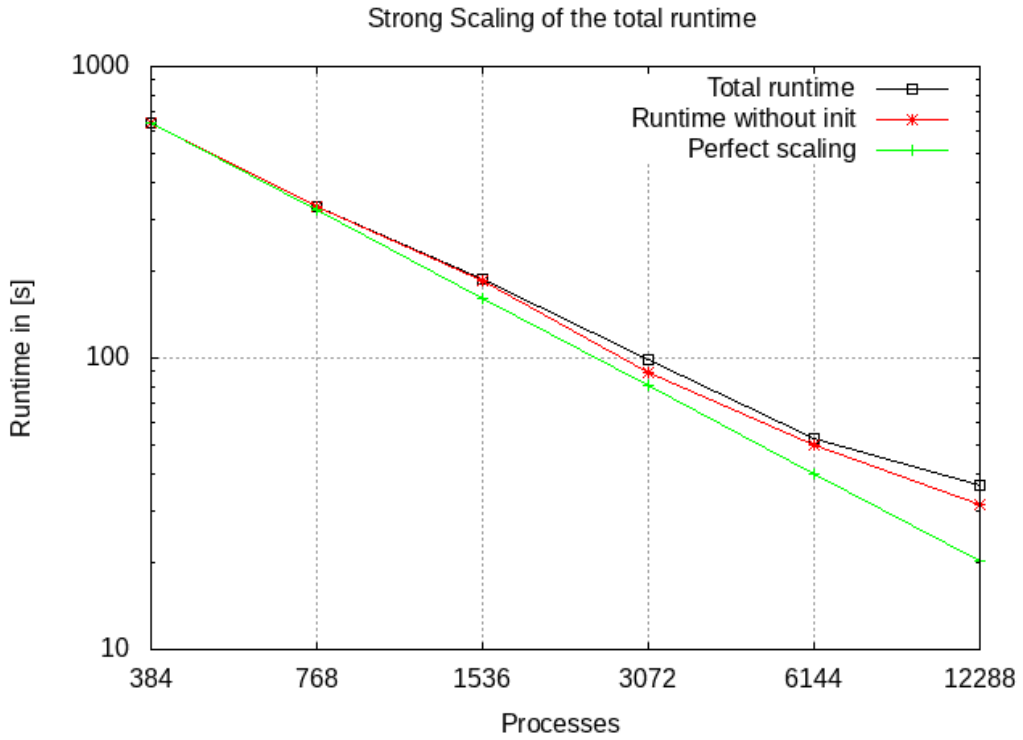
T8DG Advection/Diffusion

- Motivating example: Volcanic ash distribution
- High-order discontinuous Galerkin
- Matrix free
- Geometry support
- Implicit
- Multigrid



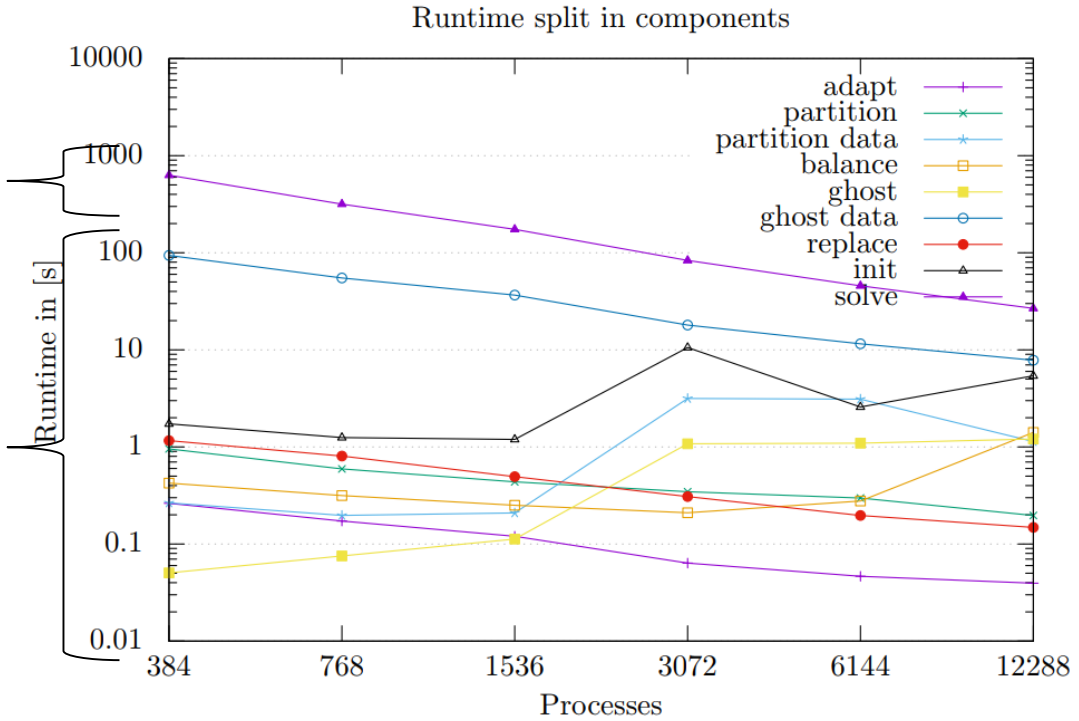
The Local Discontinuous Galerkin Method for the Advection-Diffusion Equation on adaptive meshes
Master's Thesis by Lukas Dreyer at Uni Bonn

Scaling on JUWELS



Solver

AMR



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Adaptive vs. non-adaptive

	Runtime	Error	#DOFs
Uniform 3D	7057s	1.3e-3	16.777.216
Adaptive 3D	561s	1.5e-3	~1.920.000

12.6x speedup
8.7x less DOFs

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Conclusion/Outlook

- AMR can significantly reduce computing time and memory/disk usage
- AMR is efficient and scales (for all element shapes)
- You should not do AMR yourself
- Stronger Coupling MESSy + t8code plannend
- Ongoing Coupling to MPTRAC from JSC
- Suitable adaptation criteria in ESM?

Thank you

Special thanks to
Luca Spataro, Lukas Dreyer, Niklas Böing, David Knapp
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