A hybrid adaptive mesh framework for finite volume schemes on a forest of locally refined Cartesian meshes

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Carsten Burstedde (University of Bonn, Germany)

SIAM Geosciences
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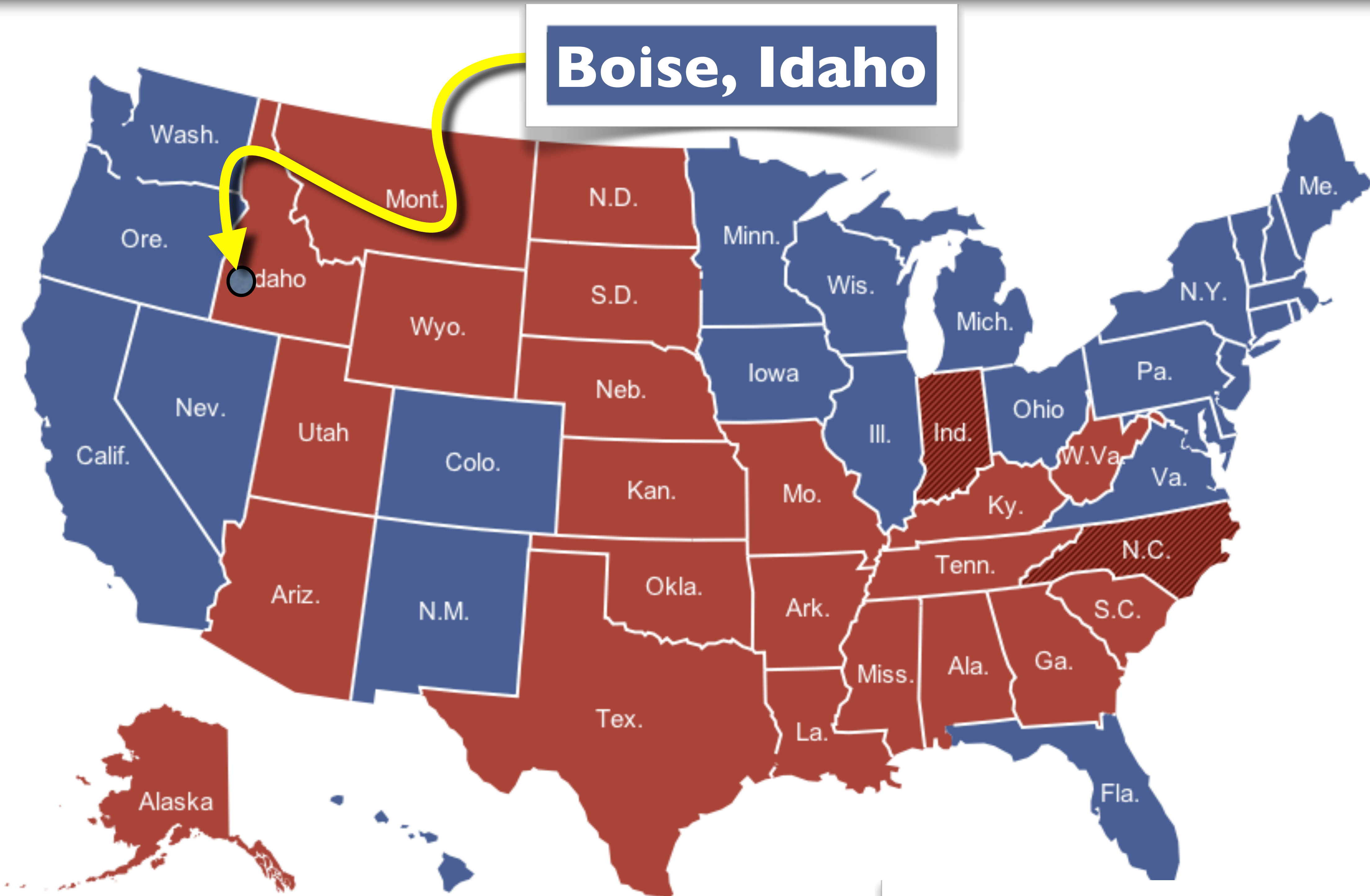
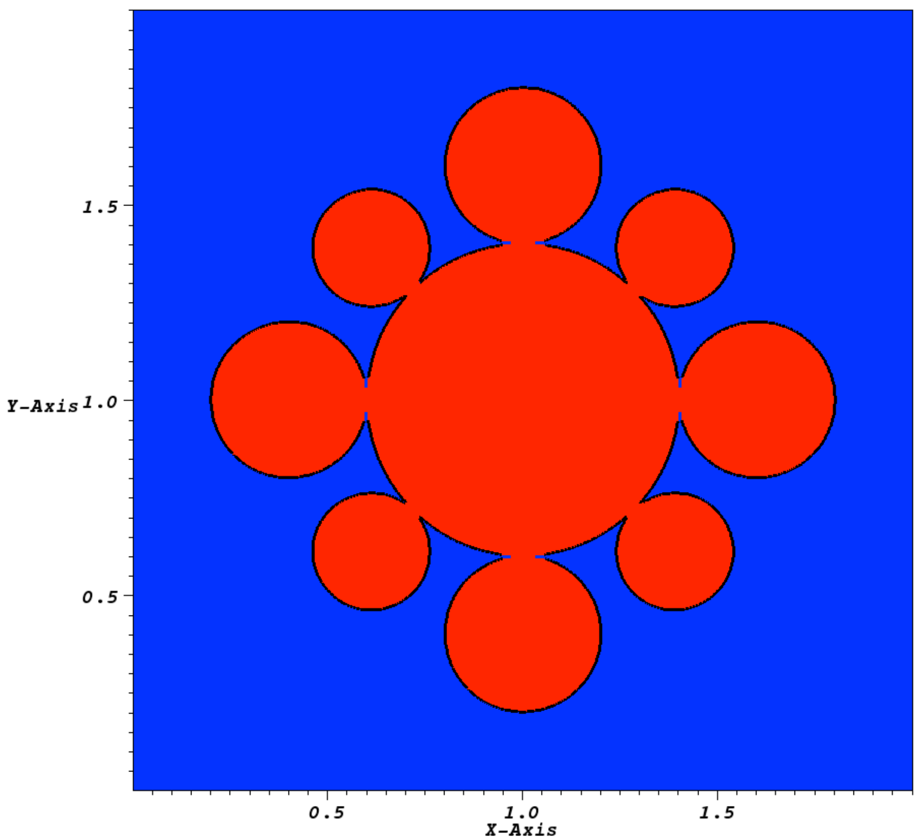
Where is Boise?

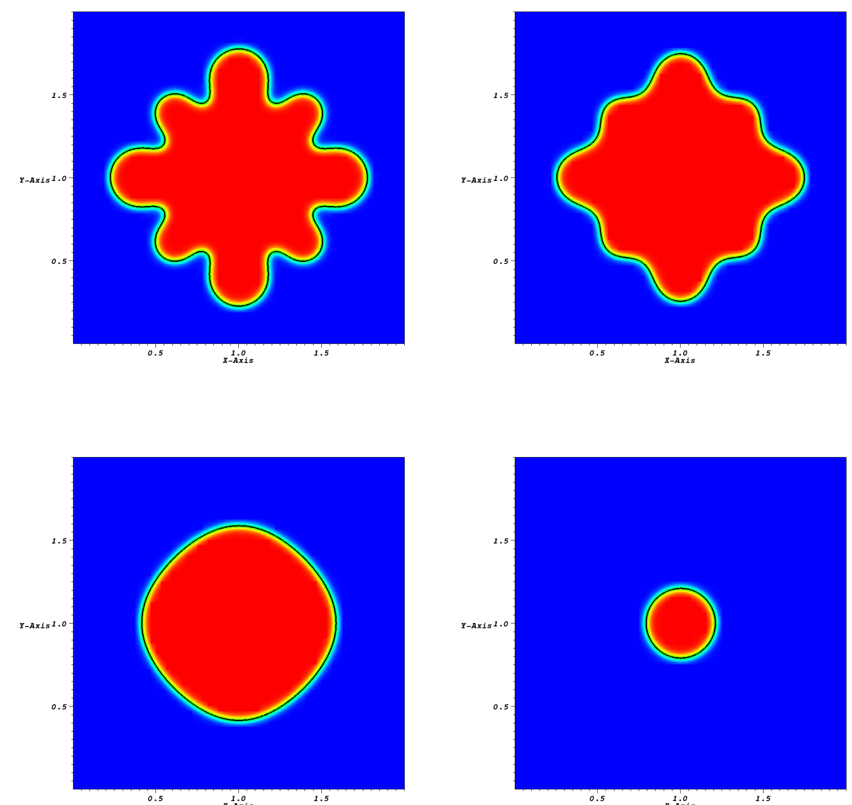


Boise comes from boisé which is French for 'wooded' or 'forested'.

Adaptive Mesh Refinement

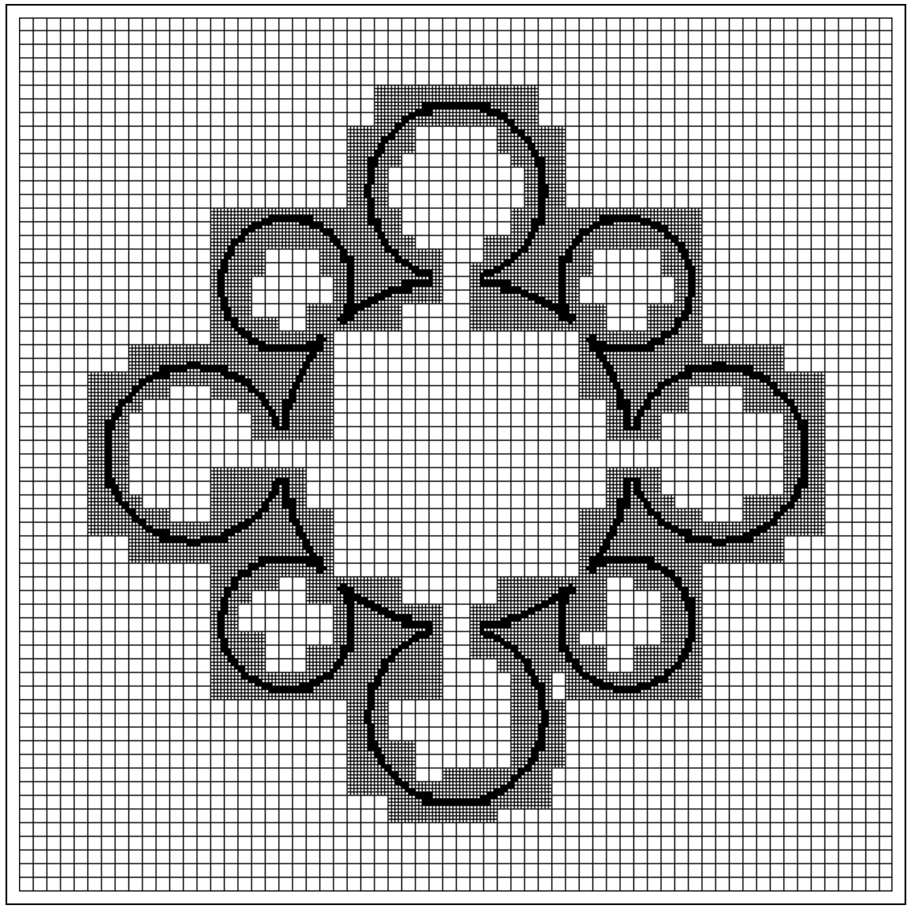
When solving PDEs using mesh based methods, it is generally recognized that many problems could benefit enormously from a multi-resolution grid, or spatial adaptivity.





Allen Cahn equation - Flow by mean curvature

Example : Flow by mean curvature



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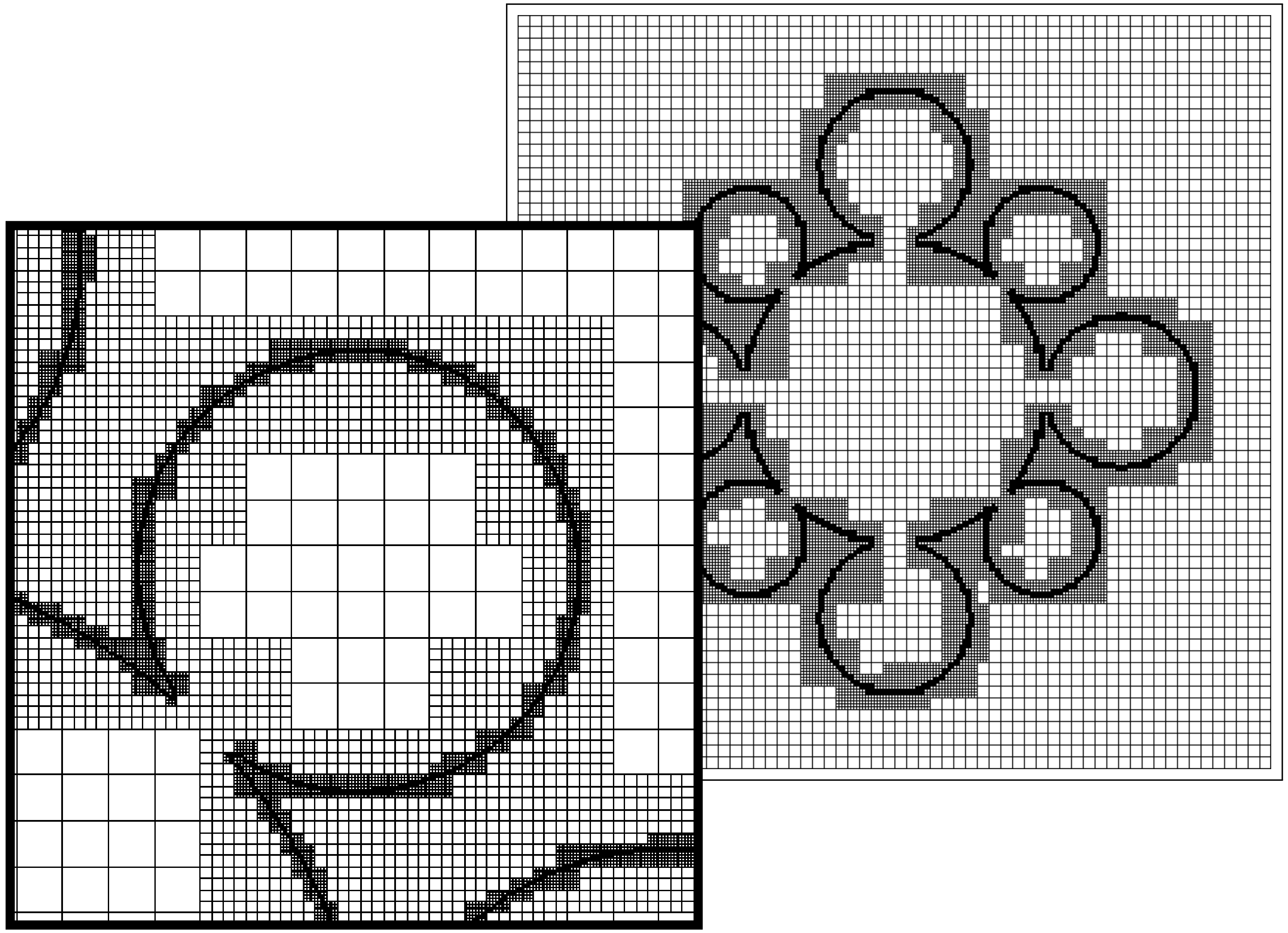

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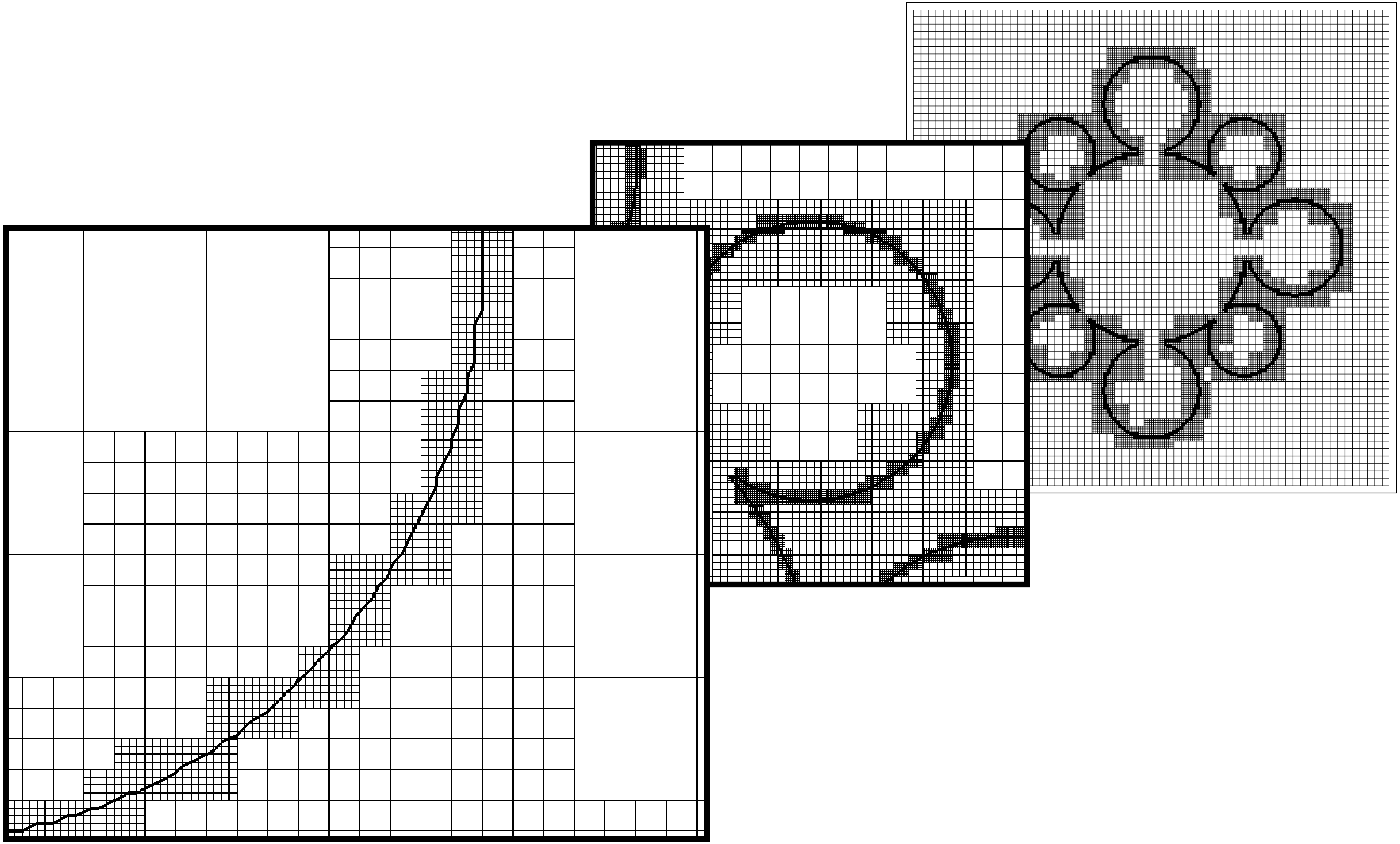

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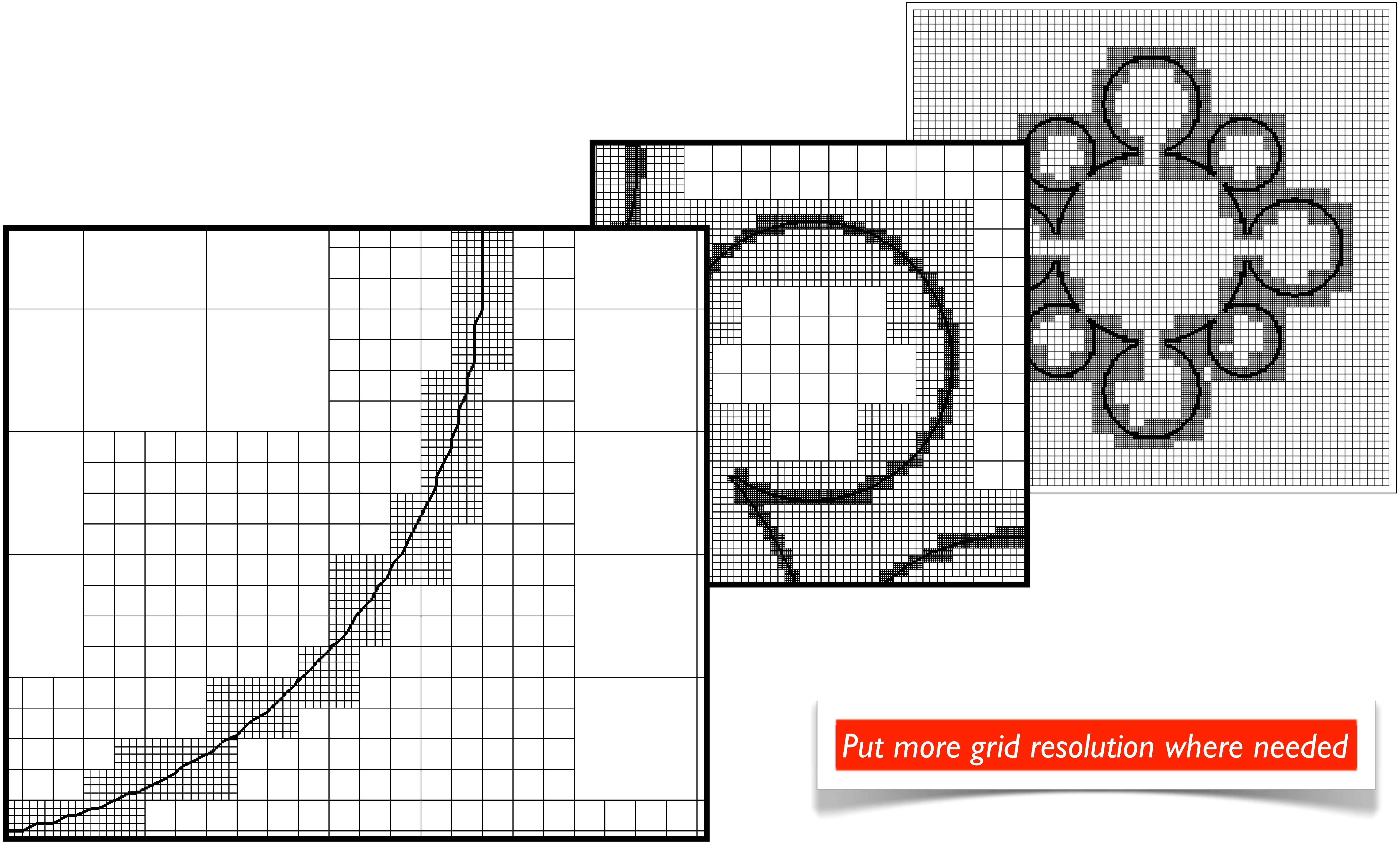
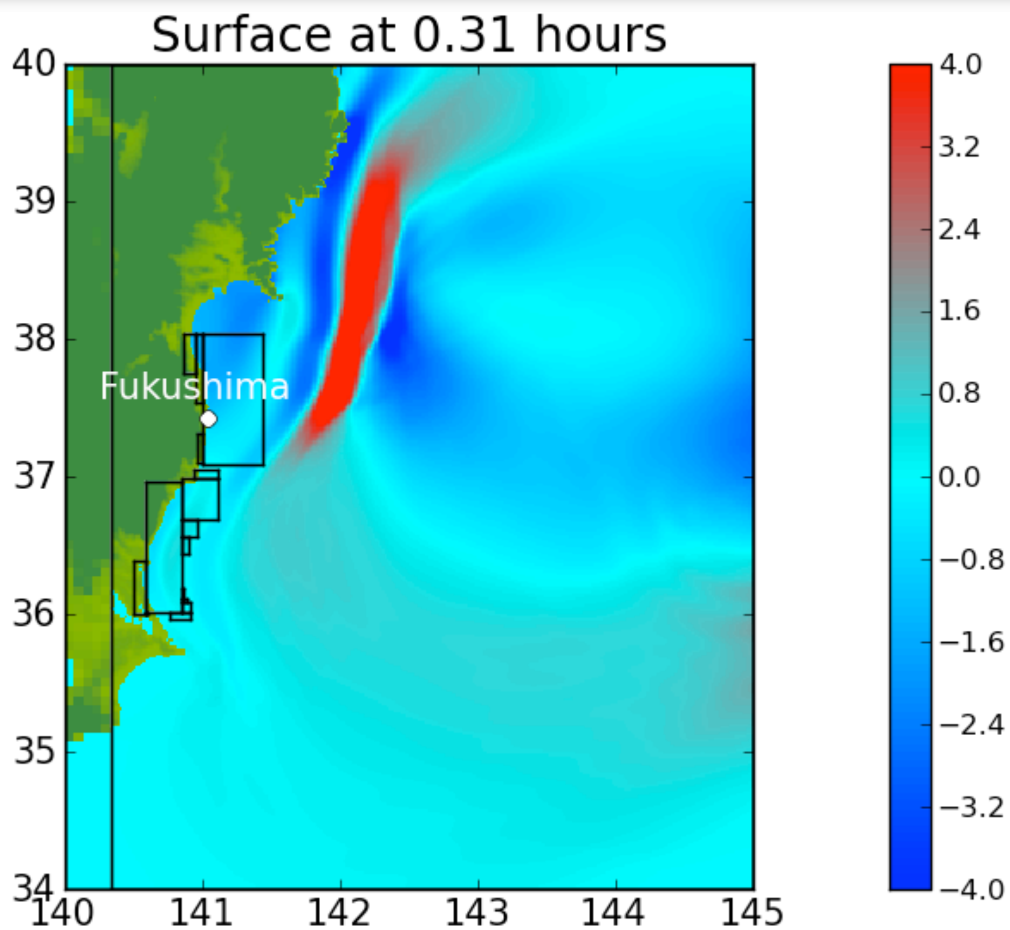
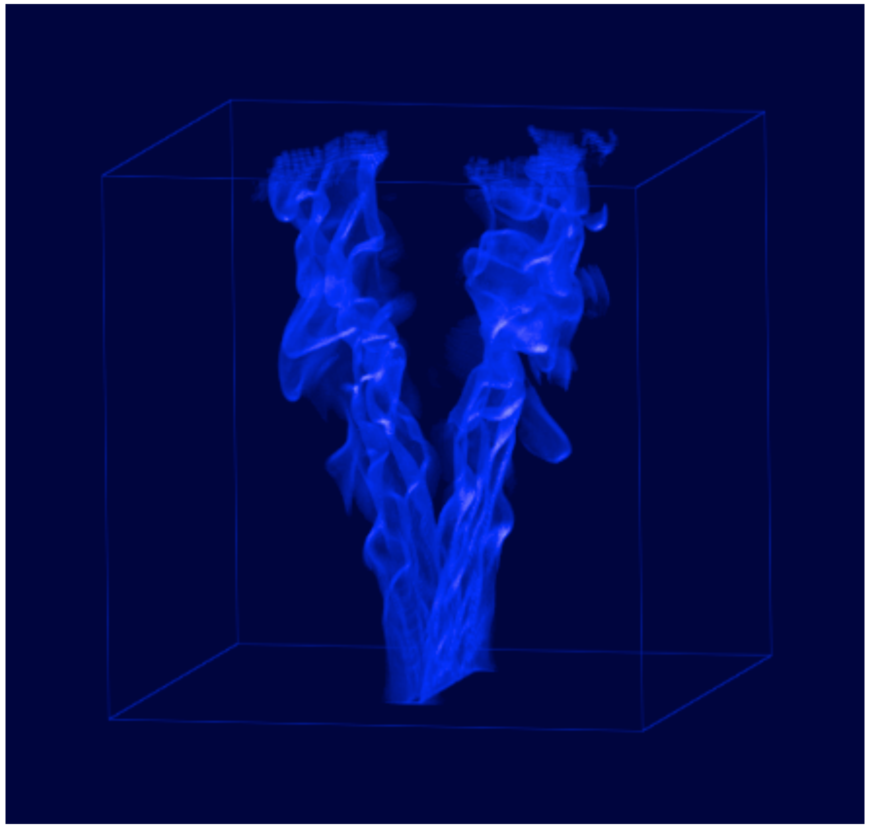


Put more grid resolution where needed

Applications for AMR



Tsunami modeling (R. LeVeque, D. George, M. Berger)



Rod stabilized V-flame (J. B. Bell, Lawrence Berkeley Lab)

- Tracer transport in the atmosphere
- Astrophysics
- Shock capturing for aerodynamic applications
- Regional weather forecasting, hurricanes, ...

Isaac Newton Institute, Fall 2012

"Multi-scale numerics for the ocean and atmosphere"

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- When AMR *is* used in numerical weather prediction, the goals are often modest : "Do no harm!"
- Grids are often only static; not dynamically refined.

Work with AMR

Mesh generation and mesh adaptation for large-scale Earth-system modelling, (Phil. Trans. Roy. Soc, 2009) compiled and edited by N. Nikiforakis

- M. Berger, et al (AMRClaw)
- C. Jablonowski et al
- H. Weller (INI organizer)
- C. Gatti-Bono and P. Colella (Chombo)
- R. Klein, N. Nikiforakis et al
- J. Behrens et al
- G. Pau, A. Almgren, J. Bell (LBL, California)
- C. Castro et al
- M. Piggot et al

Finite volume schemes

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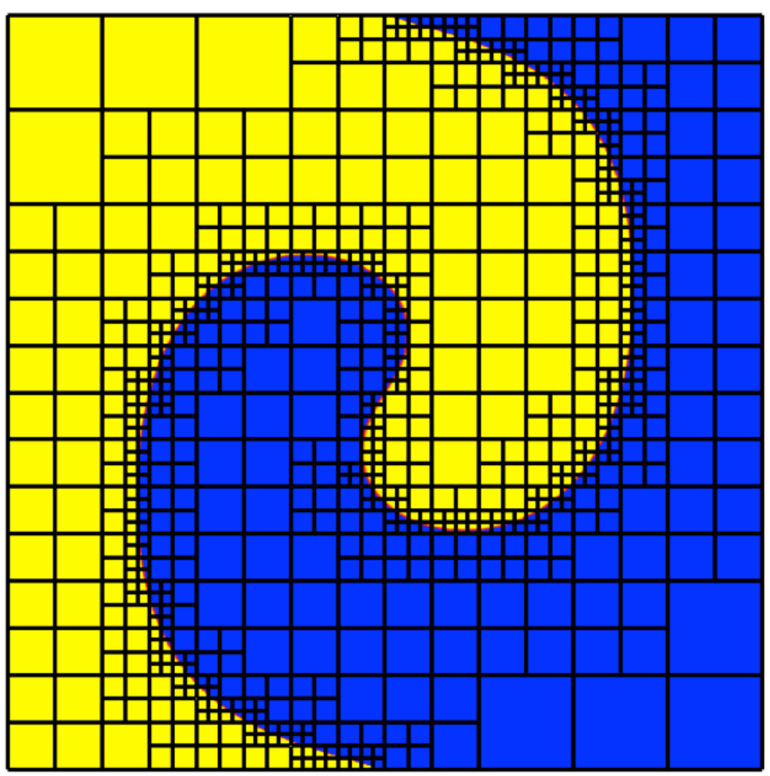
- Widespread use in science and engineering,
- "Collocated", "P0", "A-Grids", "ijk" grids, non-conforming (for AMR) meshes

Many flavors of adaptivity

- Block-structured AMR (Berger, Oliger, Colella, ...)
- Tree-based adaptivity (Popinet, Tessyier, ...)
- Finite-element adaptivity includes both h-refinement (increase mesh resolution) and p-refinement (increase order of accuracy)

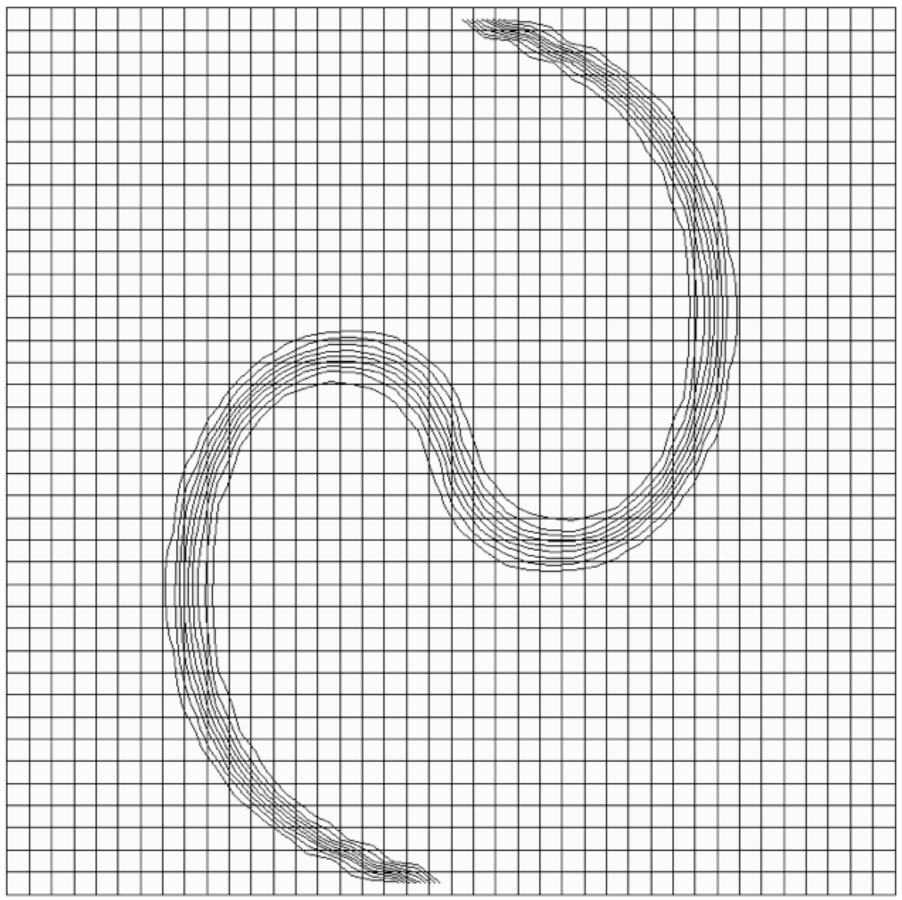
q(1) at time 0.7500



Tree-based adaptivity :

- *Gerris* (S. Popinet, NIWA, NZ),
- *Ramses* (R. Tessyier) and many other codes (including several in astrophysics)

Block structured AMR (Berger, Oliger 1984)



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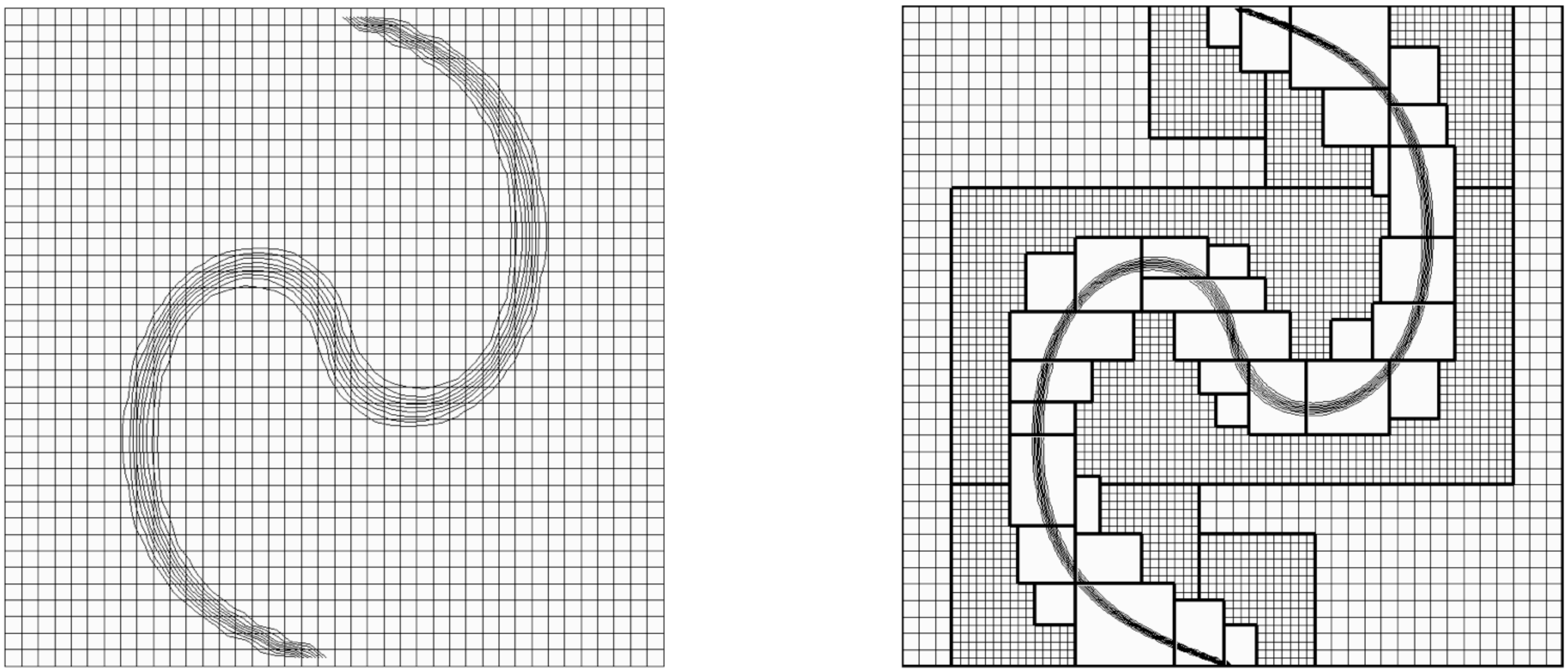

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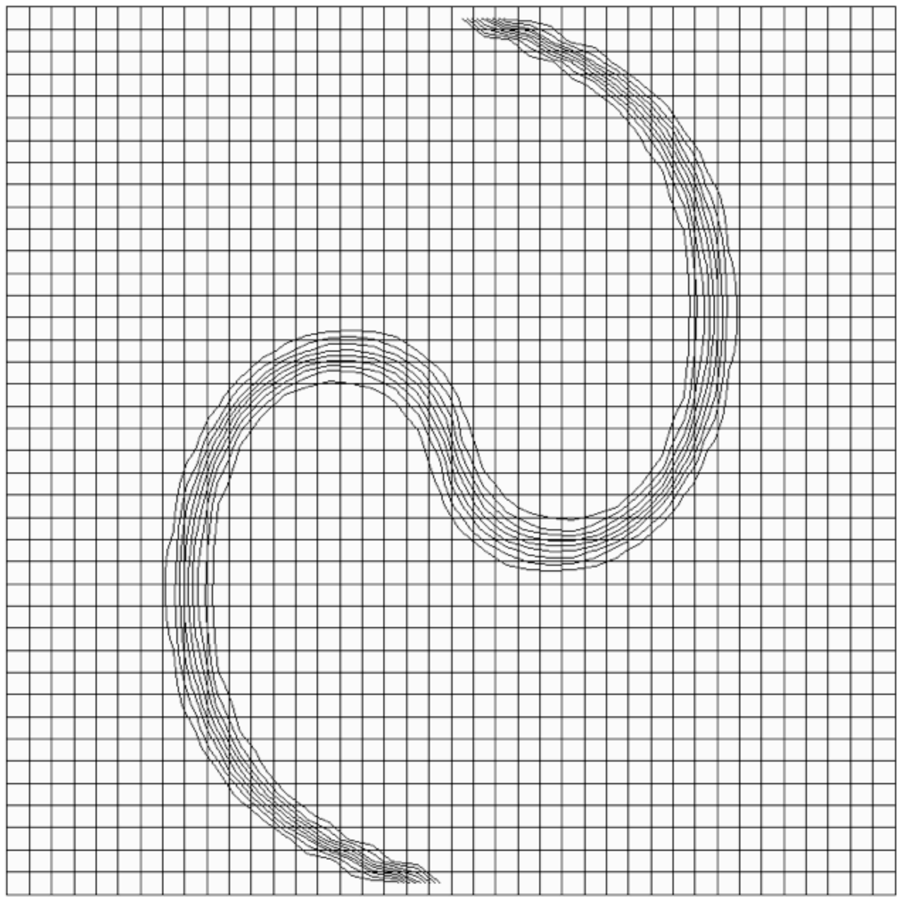

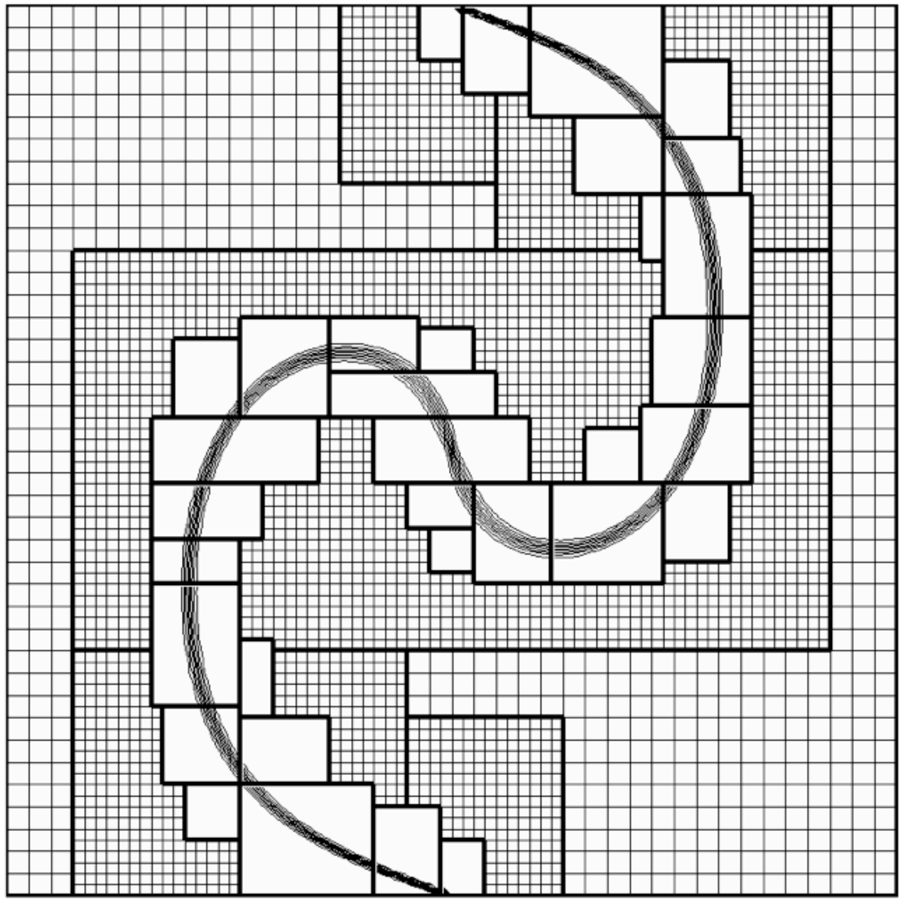

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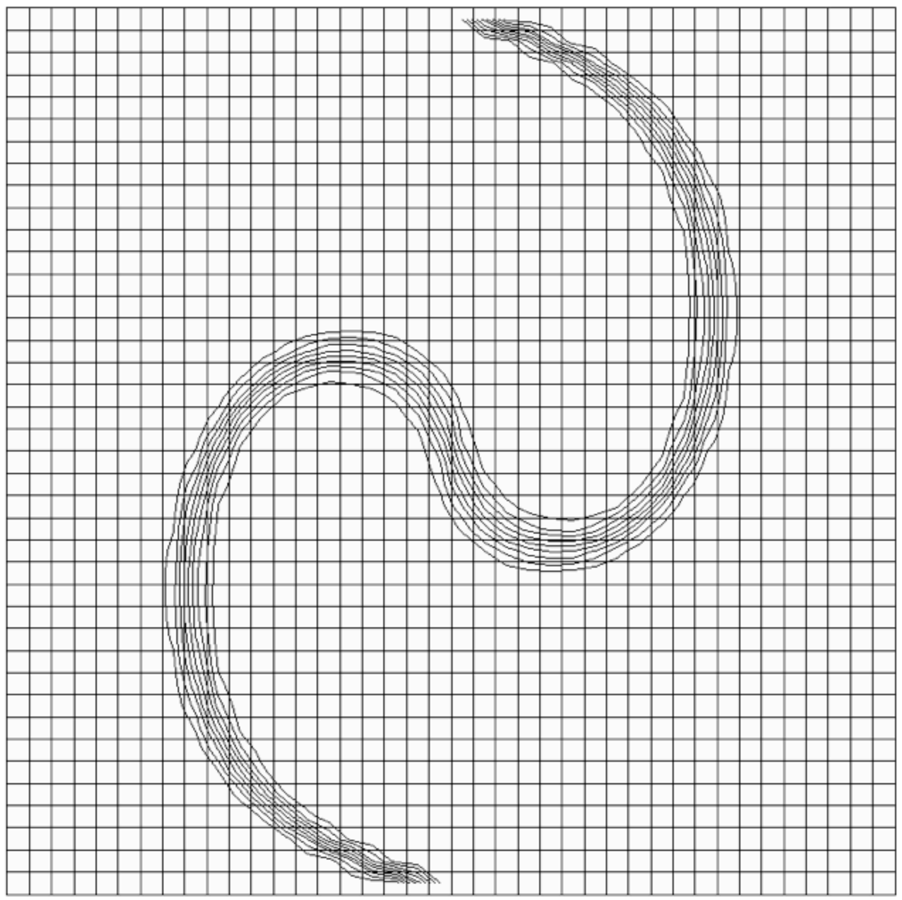

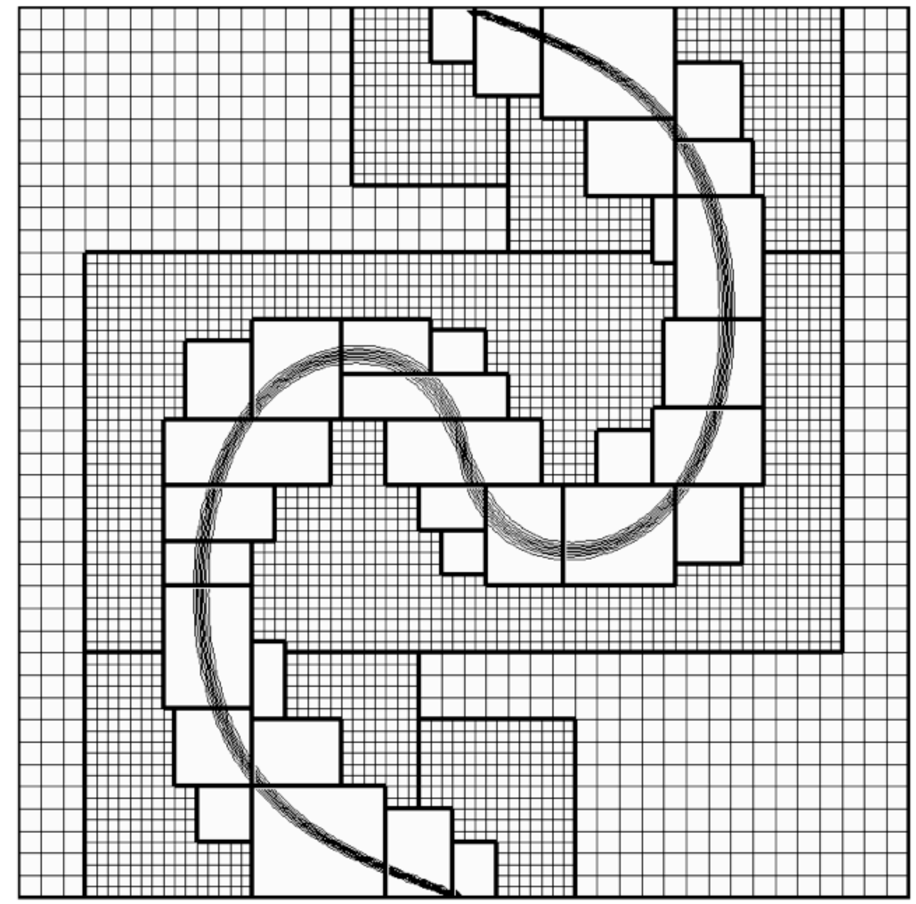

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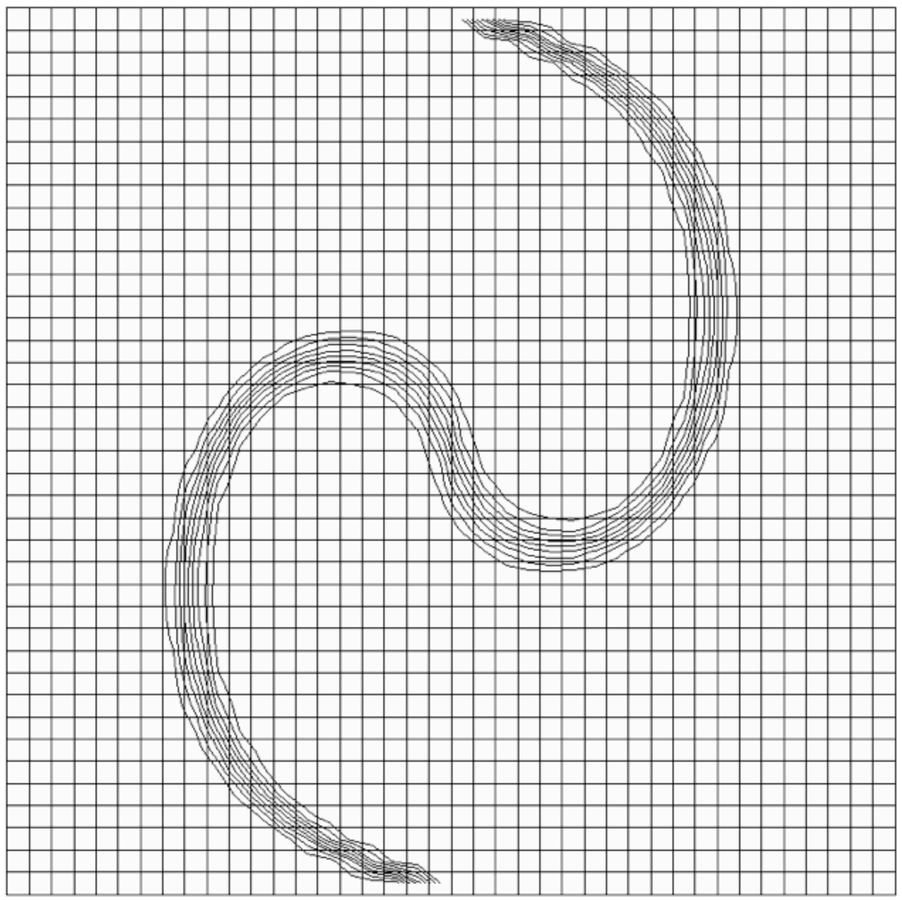

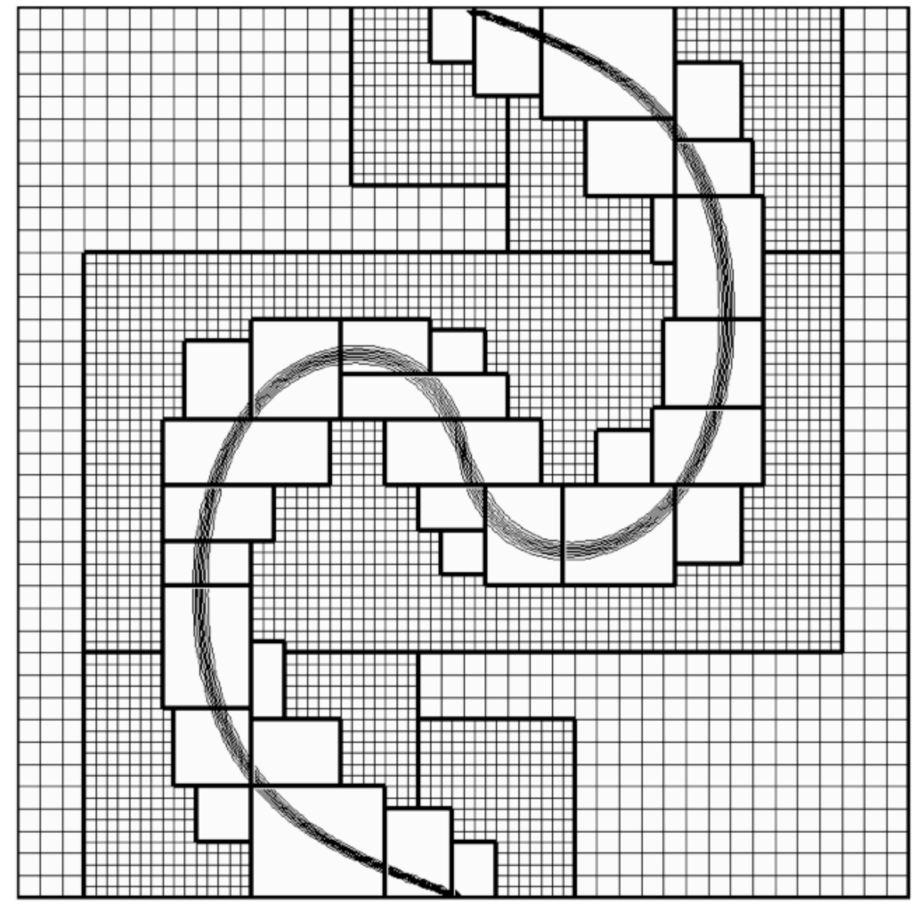

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- Colella, Bell, LeVeque, Almgren, Deiterding, and many others have developed methods and solvers

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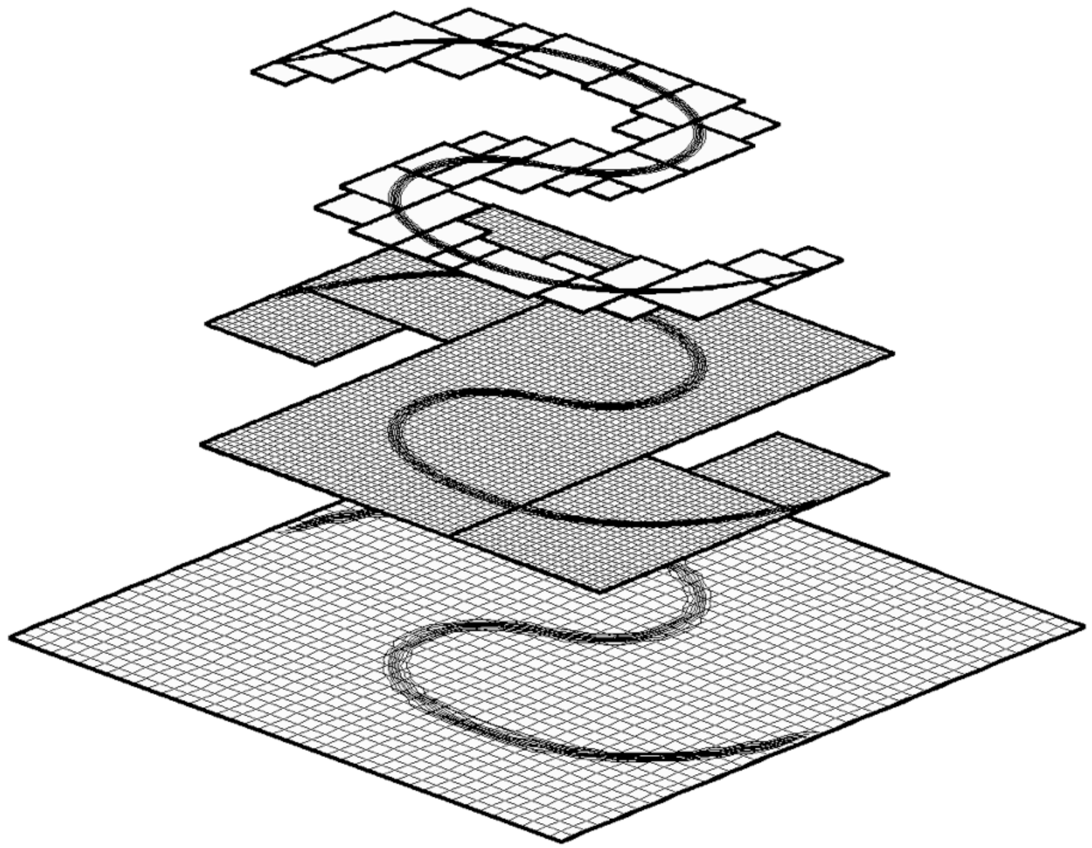

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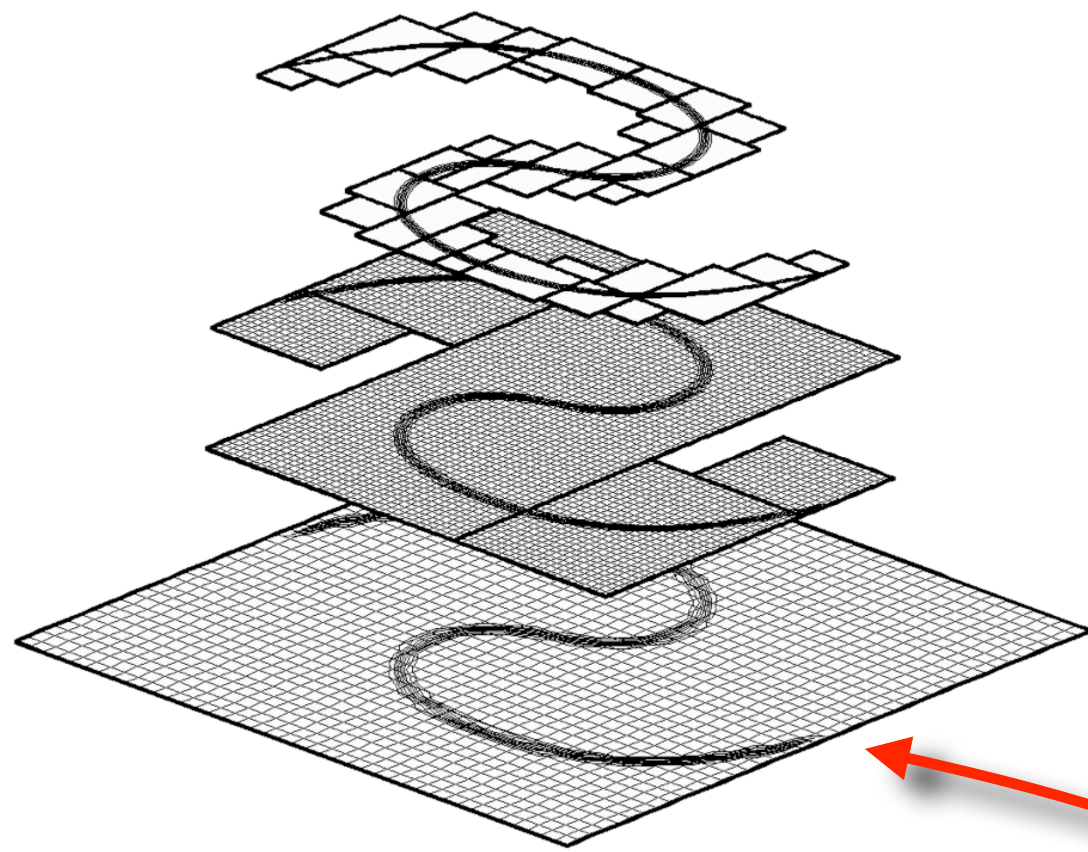

Coarsest level grids

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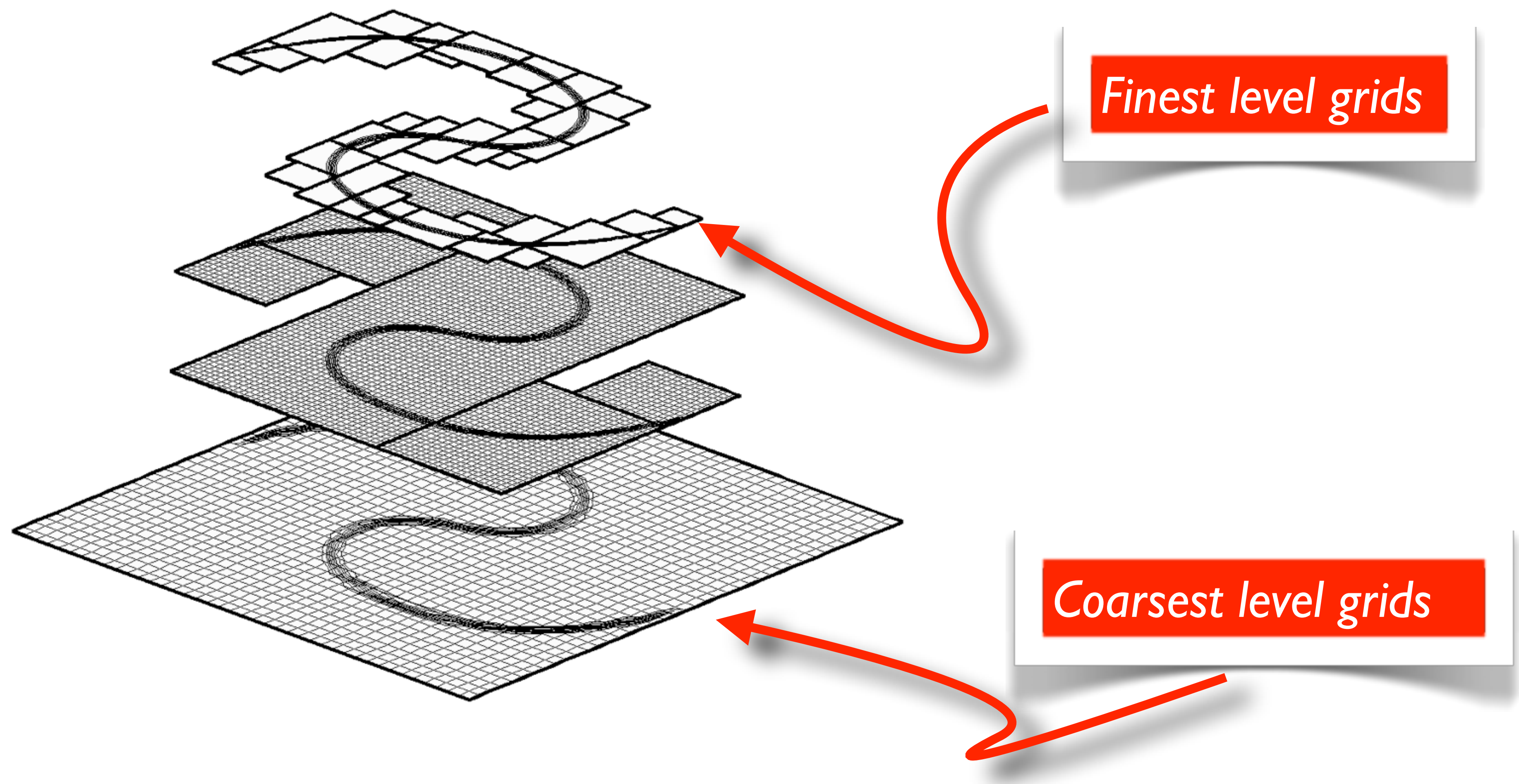

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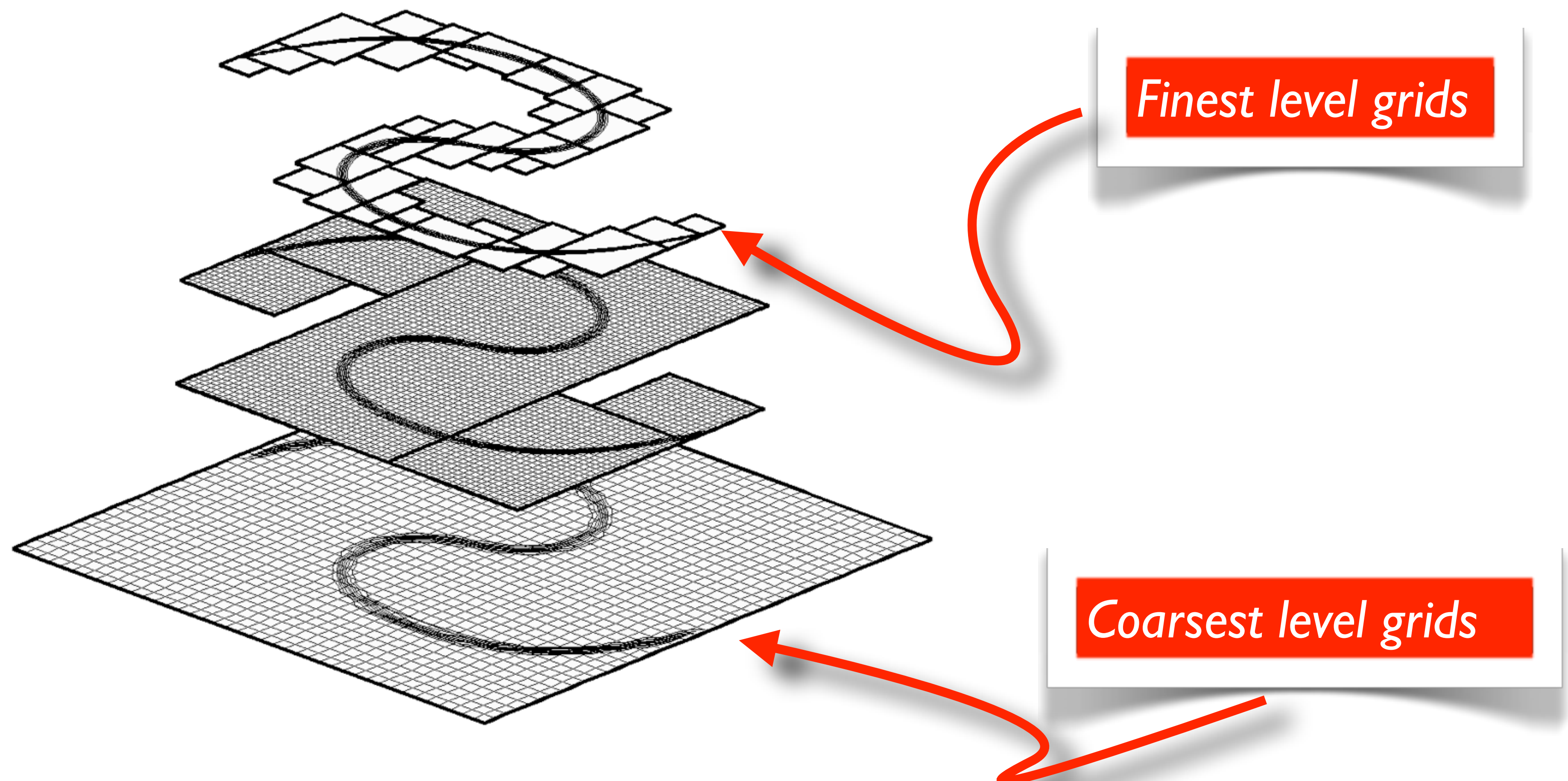

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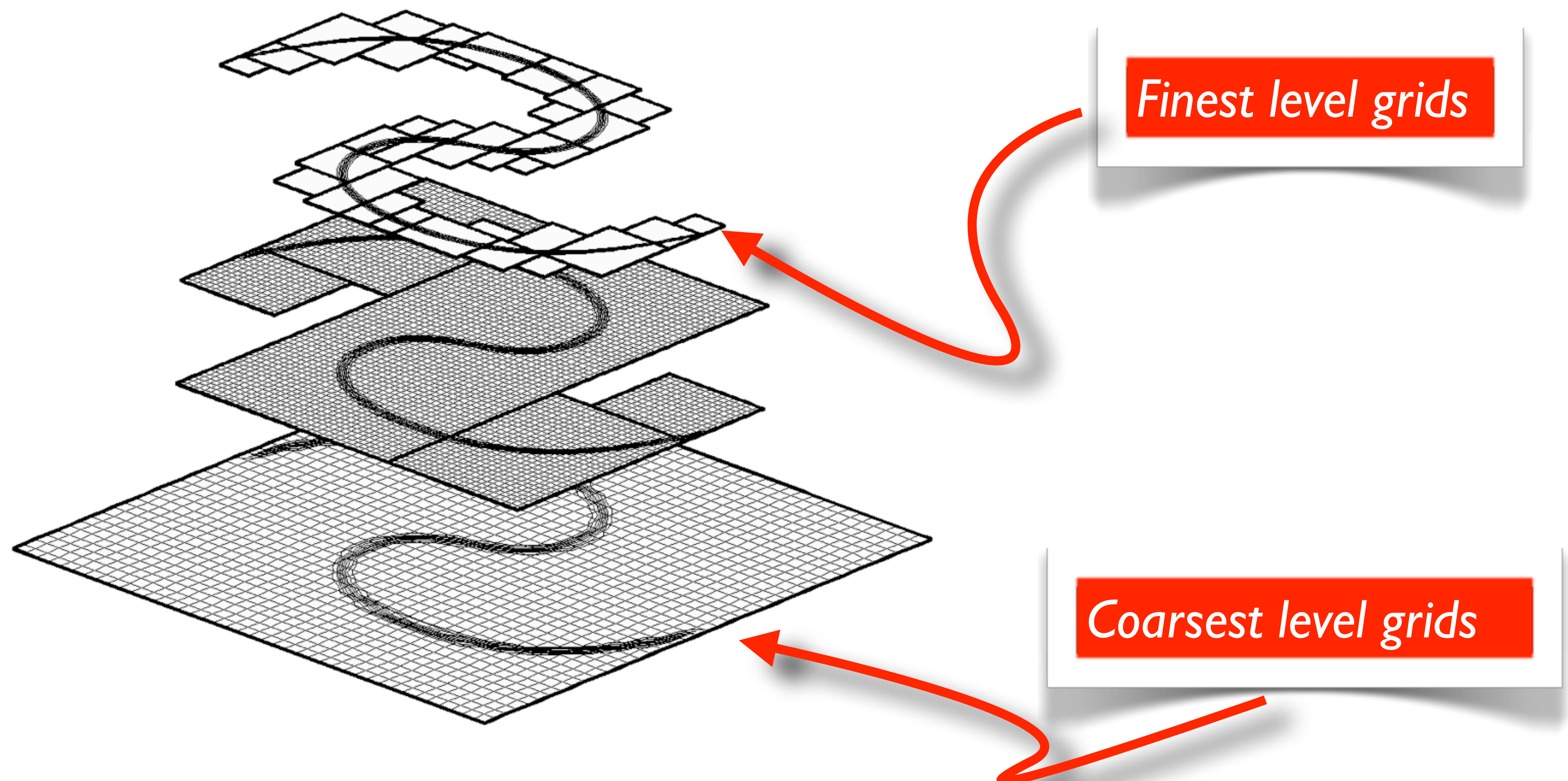

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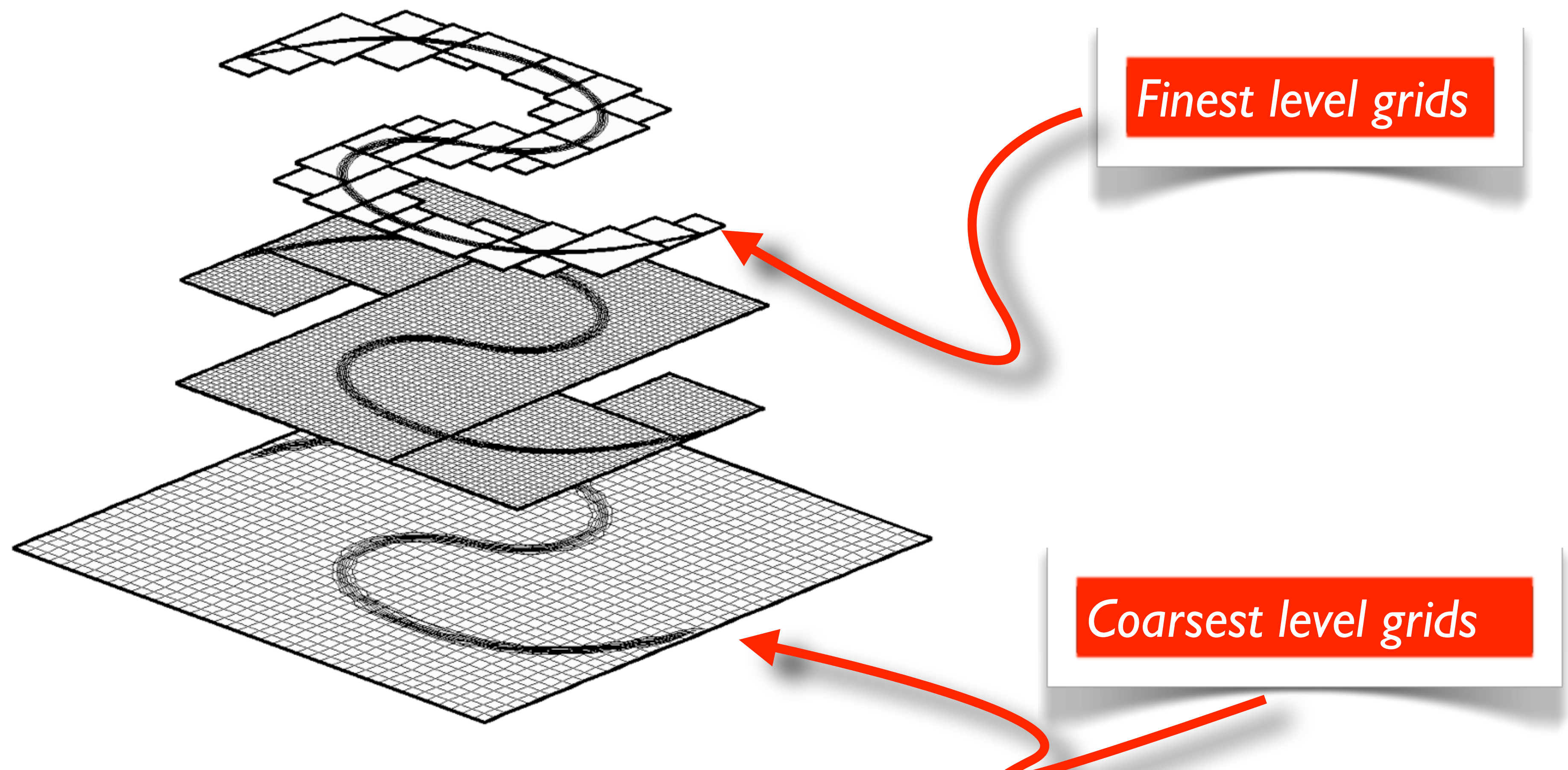

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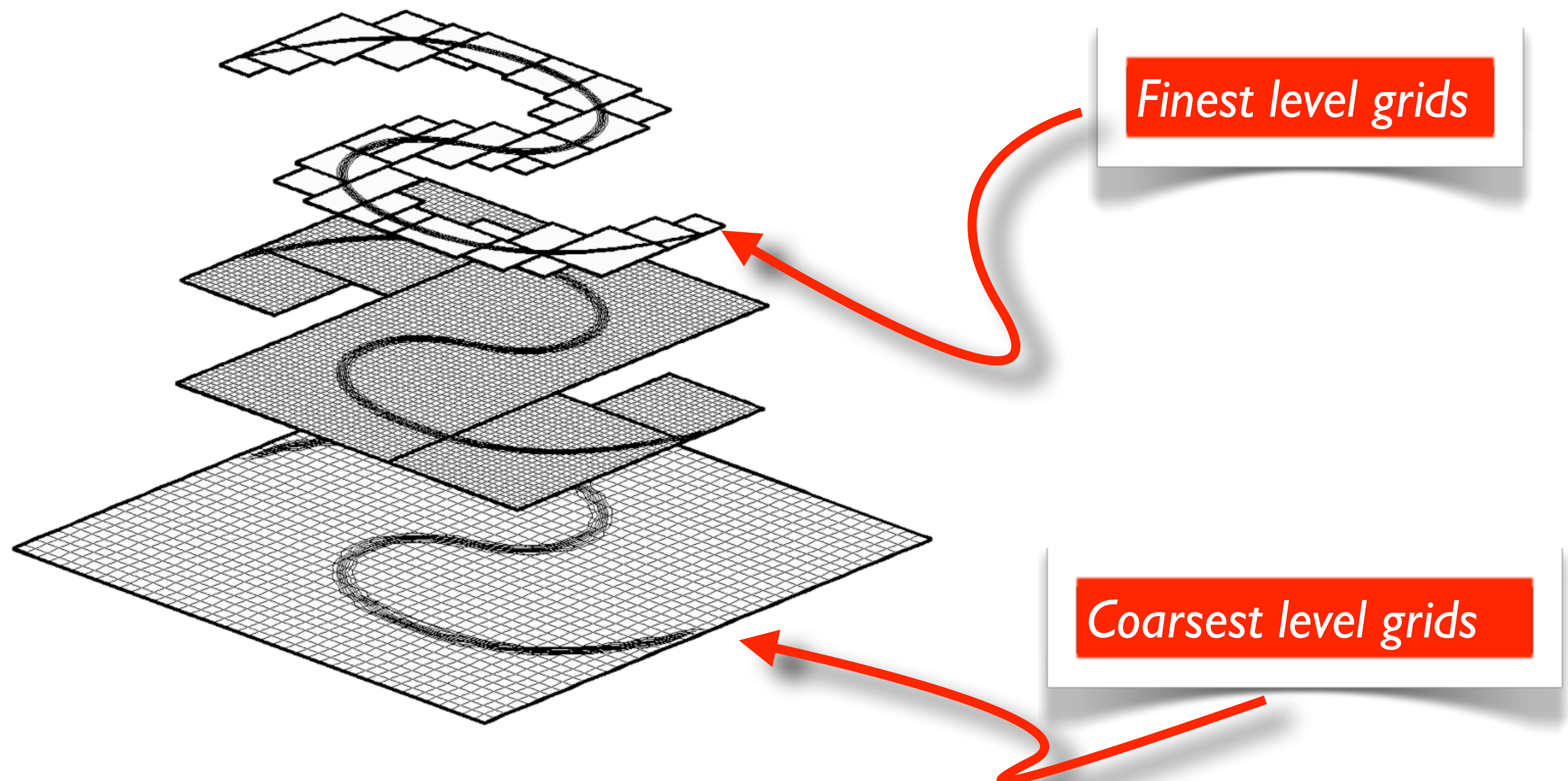

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- Communication between grids is done via ghost cells.

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- Grid clustering algorithm balances number of grids and refinement efficiency.

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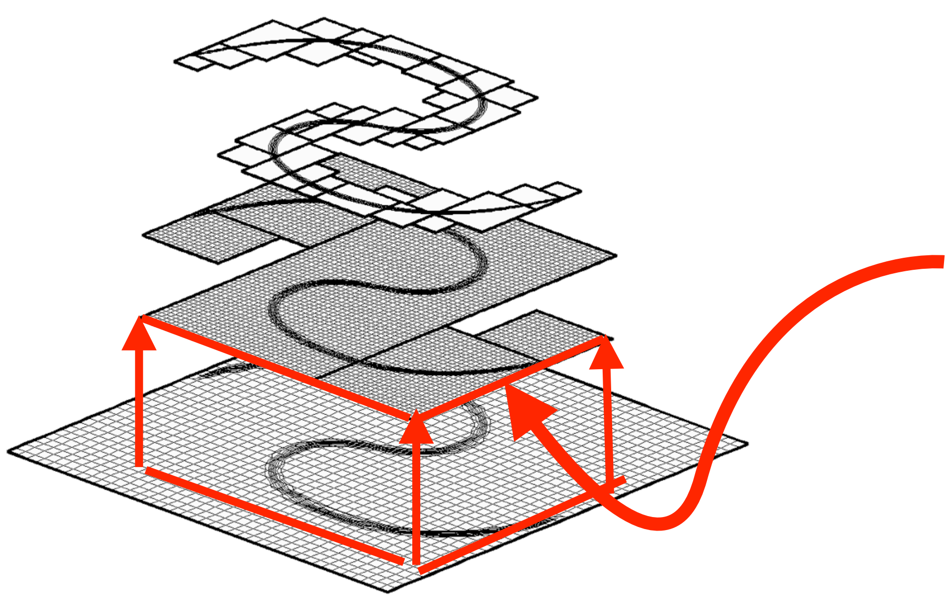
- Subcycle finer grid time steps (multi-rate time stepping)

Explicit, single step multi-rate time stepping

A single time step advance, assuming a refinement factor of R.

1. Advance at the coarsest level by time step Δt
2. Interpolate coarse grid solution to fine grid ghost cells
3. Advance fine grid R time steps, by a time step $\Delta t/R$
4. Average solution from fine grids to coarse grid,
5. Adjust coarse grid solution to assure flux continuity at the coarse/fine boundaries,
6. Tag cells for refinement and regrid

Grids at the same level exchange ghost cell values directly



Fine grid boundary conditions interpolated in space and time from coarse grid

Software for AMR

How can I add adaptivity to my existing (Cartesian) code?

- It is much harder than it looks (and you don't really just "add" adaptivity)
- And there are several general purpose codes already available which can use your single grid solver.

Block structured AMR codes

- General purpose (freely available) block-structured codes
  - **PARAMESH** (NASA/Goddard)
  - **SAMRAI** (Lawrence Livermore National Lab)
  - **BoxLib** (Lawrence Berkeley Lab)
  - **Chombo** (Lawrence Berkeley Lab)
  - **AMRClaw** (University of Washington/NYU)
- All are large frameworks, with many developers
- Mostly C++ and Fortran libraries (no GUIs) that started life as research codes.

See my website for a list of several more application specific codes

Block structured AMR codes

"PARAMESH is a package of Fortran 90 subroutines designed to provide an application developer with an easy route to extend an existing serial code which uses logically Cartesian structured mesh into a parallel code with adaptive mesh refinement"

SAMRAI - "Object oriented C++ library developed to provide algorithmic and software support to large scale multiphysics problems relevant to the US Department of Energy (DOE)"

Boxlib - "These libraries provide the software infrastructure for the computational activities (combustion, astrophysics, porous media flow) at the Center for Computational Sciences and Engineering (CCSE) at Lawrence Berkeley Labs"

Using block structured AMR codes

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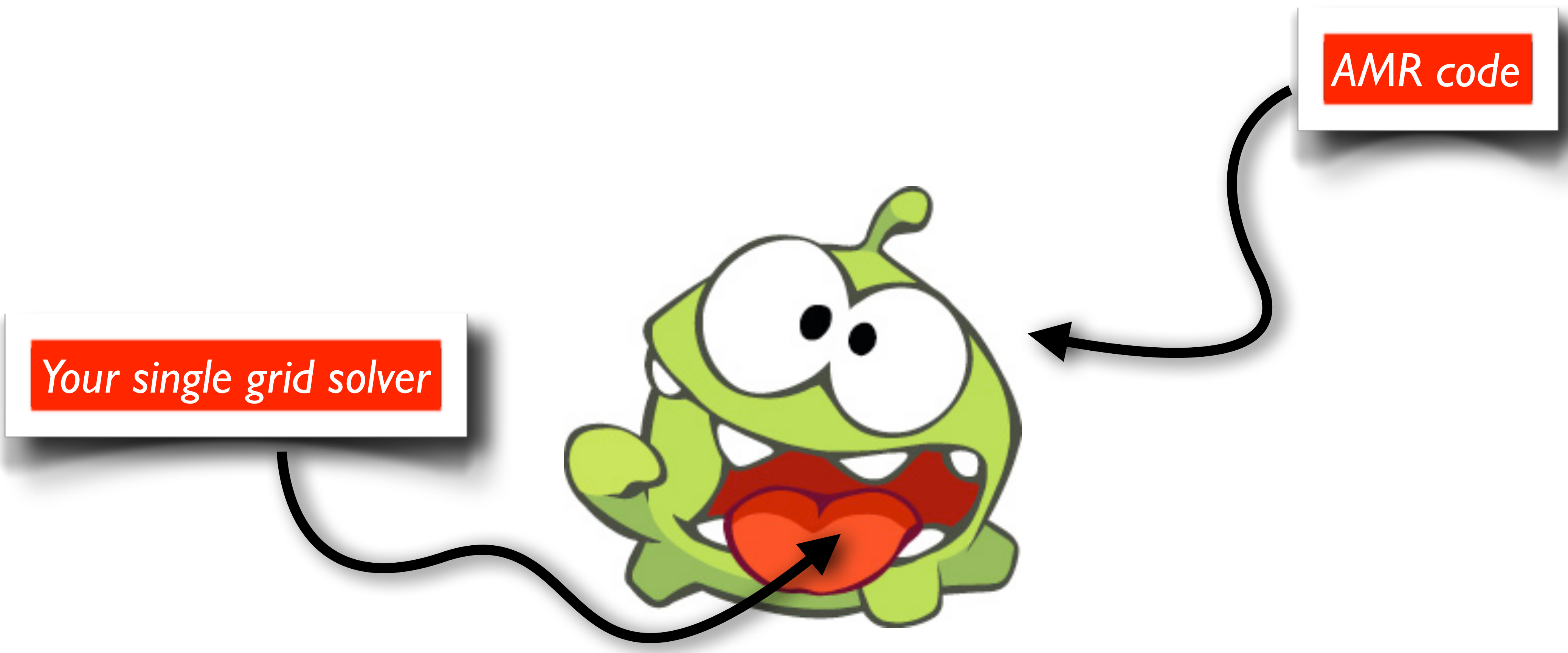

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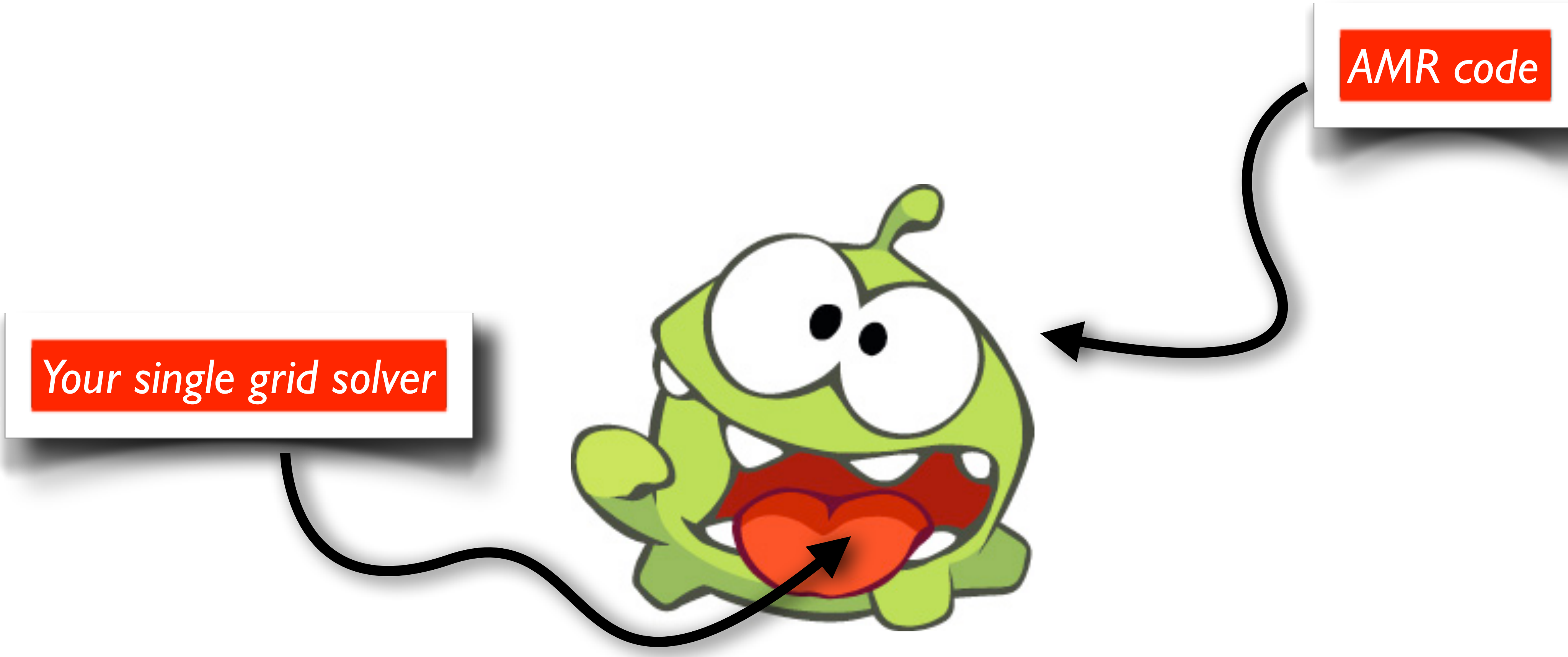

** Idea for code name : OmNum*

Block structured AMR codes

The Dream

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```
AMR.run(max_time, max_steps);
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Block structured AMR codes

The Reality

```
Tuple< RefCountedPtr<AMRLevelOpFactory<
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for (int idir = 0; idir < SpaceDim; idir++)
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Your single grid solver

you

Retro...

```
node(ndjhi,mptrnx) = node(ndjhi,mptr)
node(ndjhi,mptr)   = node(ndjlo,mptr) + nyl - 1
node(ndjlo,mptrnx) = node(ndjhi,mptr) + 1
node(ndihi,mptrnx) = node(ndihi,mptr)
node(ndilo,mptrnx) = node(ndilo,mptr)

rnode(cornxlo,mptrnx)   = cxlo
rnode(cornylo,mptrnx)   = cymid
rnode(cornyhi,mptrnx)   = cyhi
rnode(cornxhi,mptrnx)   = cxhi
node(nestlevel,mptrnx)  = node(nestlevel,mptr)
rnode(timemult,mptrnx)  = rnode(timemult,mptr)
go to 10
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rnode(cornylo,mptrnx)    = cymid
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- Heterogeneous data structures associated with storing hierarchy of grids,
- Dynamically creating and destroying grids :
    - Need a “factory” paradigm to create new grids and any auxiliary data arrays (material properties, metric terms, bathymetry, etc) that go with each new grid,
- Periodic boundary conditions and multi-block domains,
- Providing support for multi-rate time stepping,
- Storing information at grid boundaries needed to couple the solution on grids
- Parallel load balancing for both the solution step and refinement step

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- Computing diagnostics on a nested grid hierarchy,
- Error estimation, tuning for efficient use of grids, ...

But what if you have ideas about ...

- Multi-stage, multi-step, IMEX, SSP, parallel-in-time, exponential integrators, and other time stepping schemes in an adaptive setting,
- Accuracy of multi-rate schemes for PDEs with mixed elliptic/parabolic/hyperbolic terms.
- Elliptic and parabolic solvers (iterative? direct? Explicit? Fast multipole?)
- Parallelism in the AMR setting?
- Error estimation
- Higher order accuracy
- Complex physics

Should you write yet-another-AMR code?

ForestClaw : A hybrid approach to AMR

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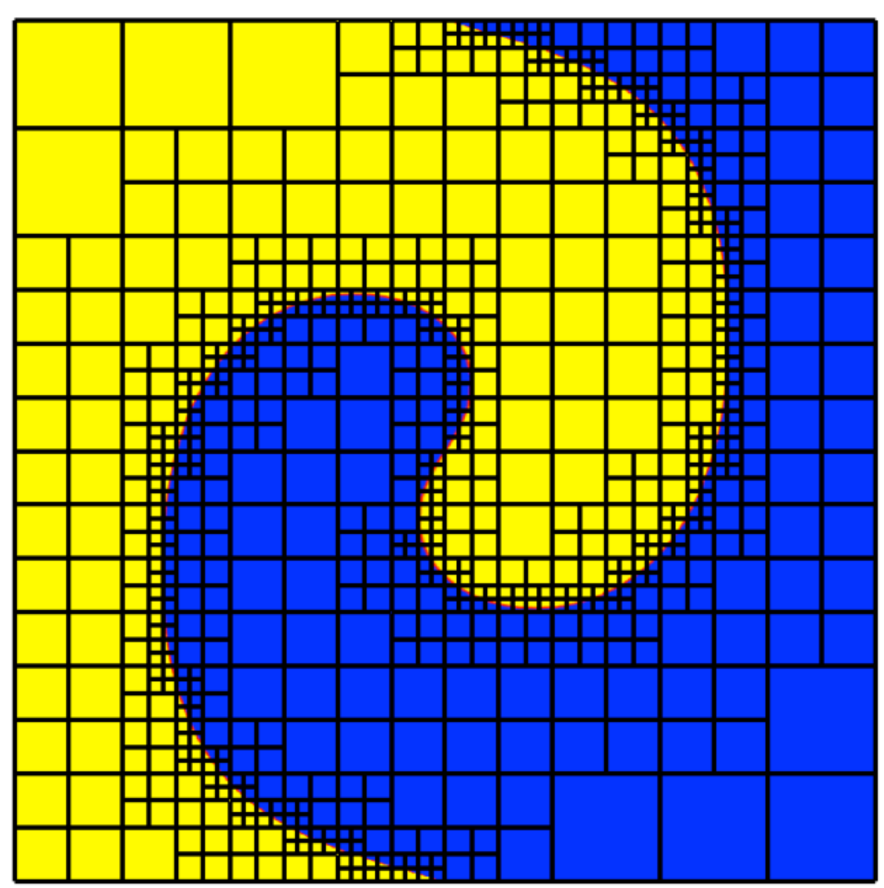

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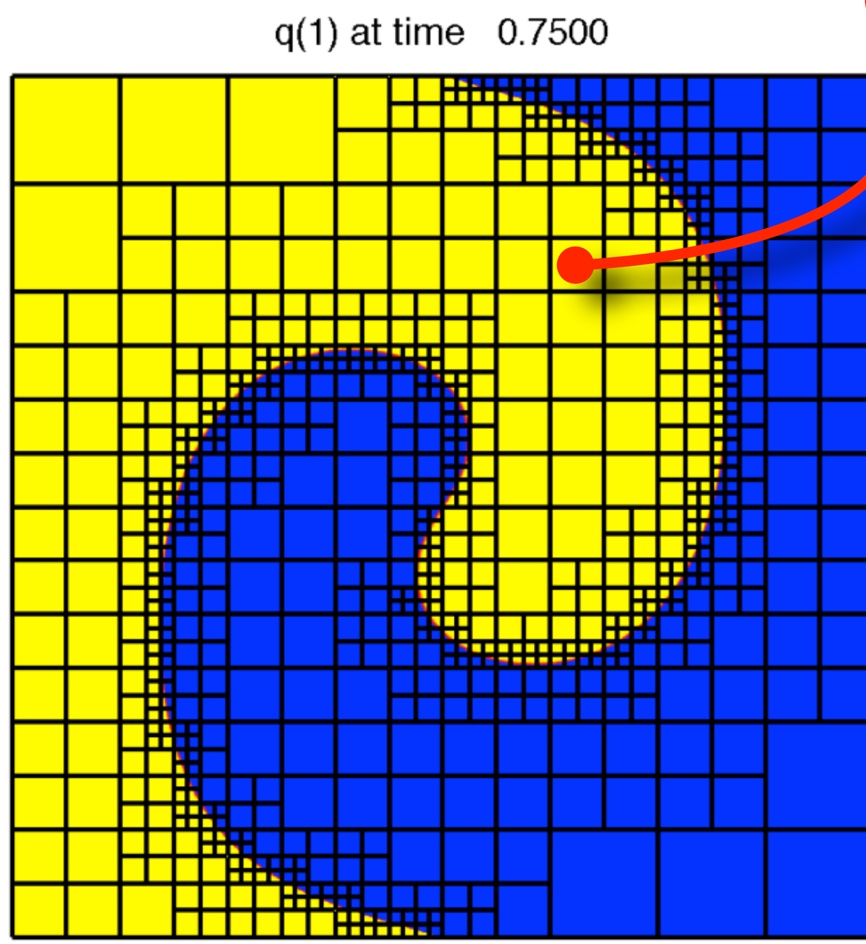
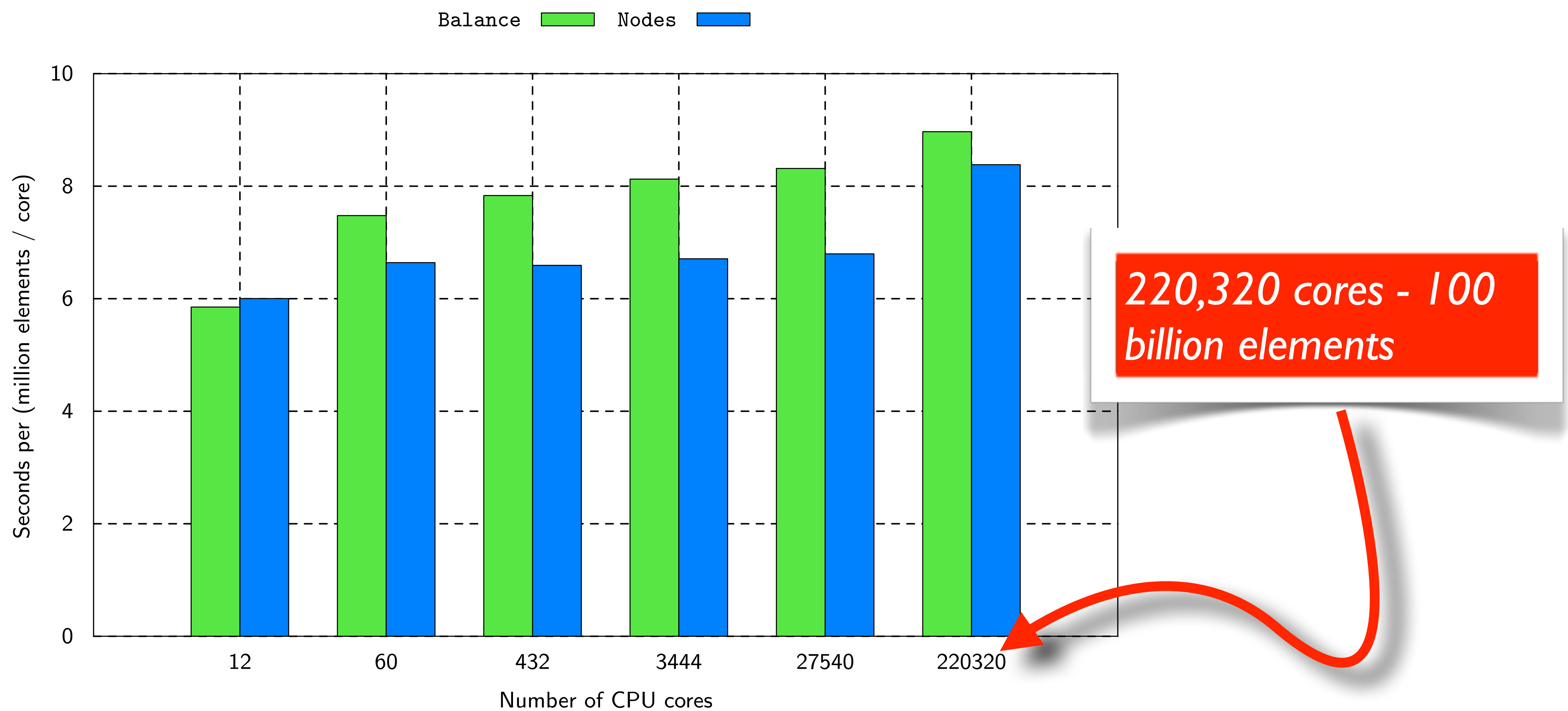


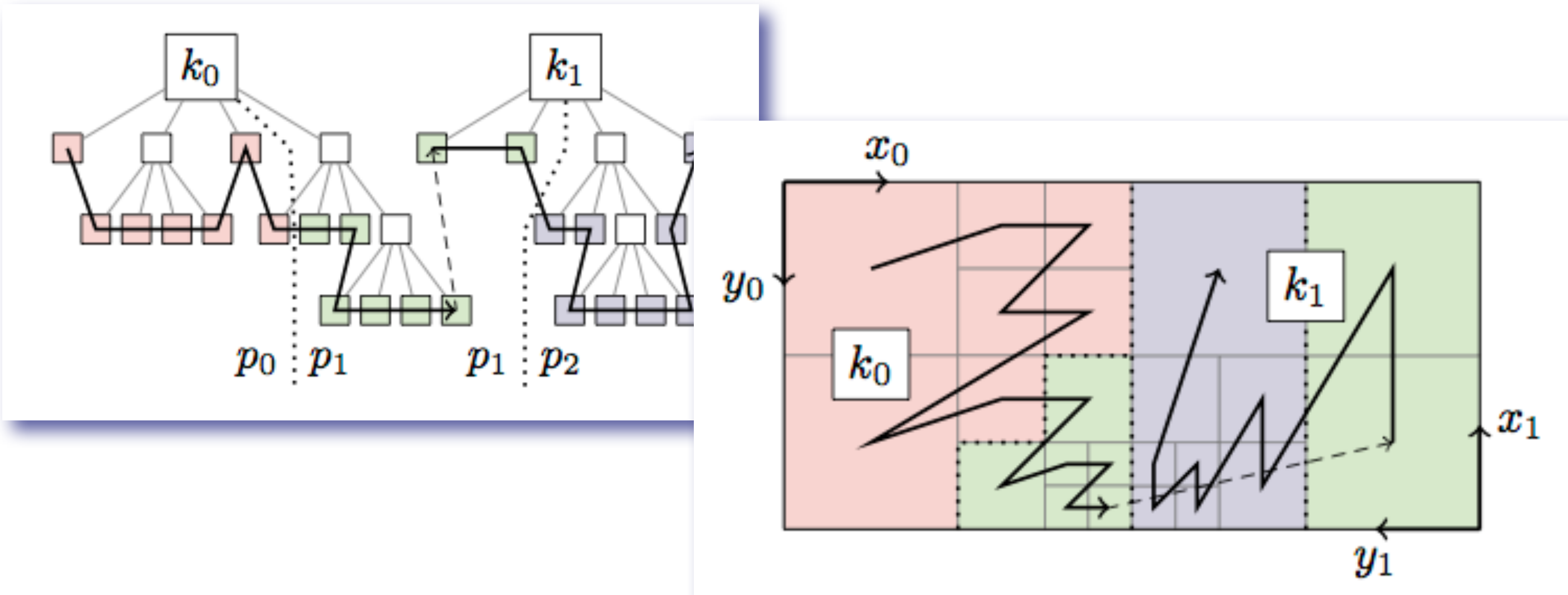
Tree structure based on refining quadrants, but each quadrant is itself a grid

p4est

- Parallel, multi-block code for managing a forest of adaptive quad- or octrees.
- Highly scalable on realistic applications of interest
- Developed by Carsten Burstedde (Univ. of Bonn), with Wilcox, Ghattas and others



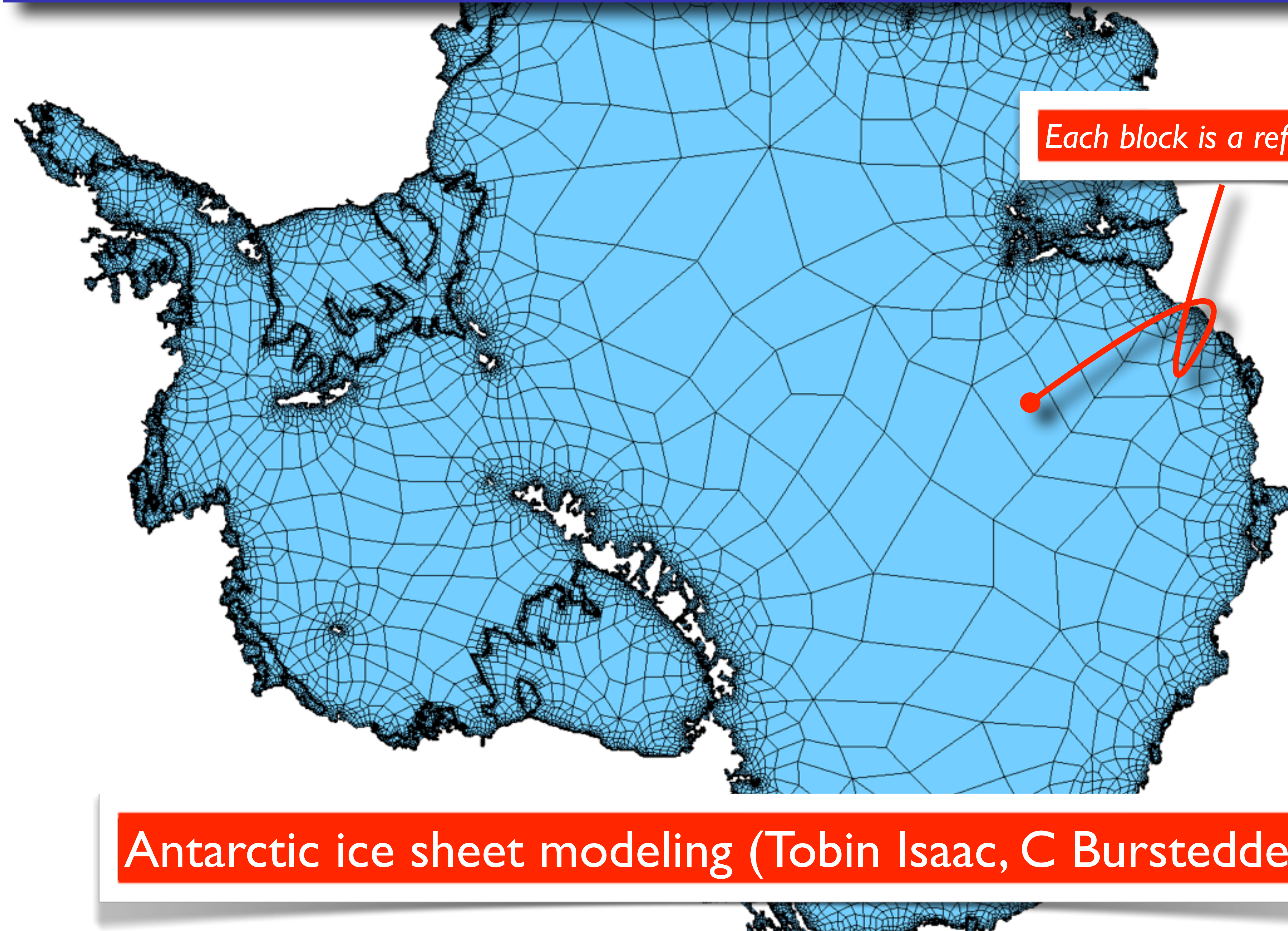
p4est



High scalability is achieved while preserving data locality by using space-filling curves.

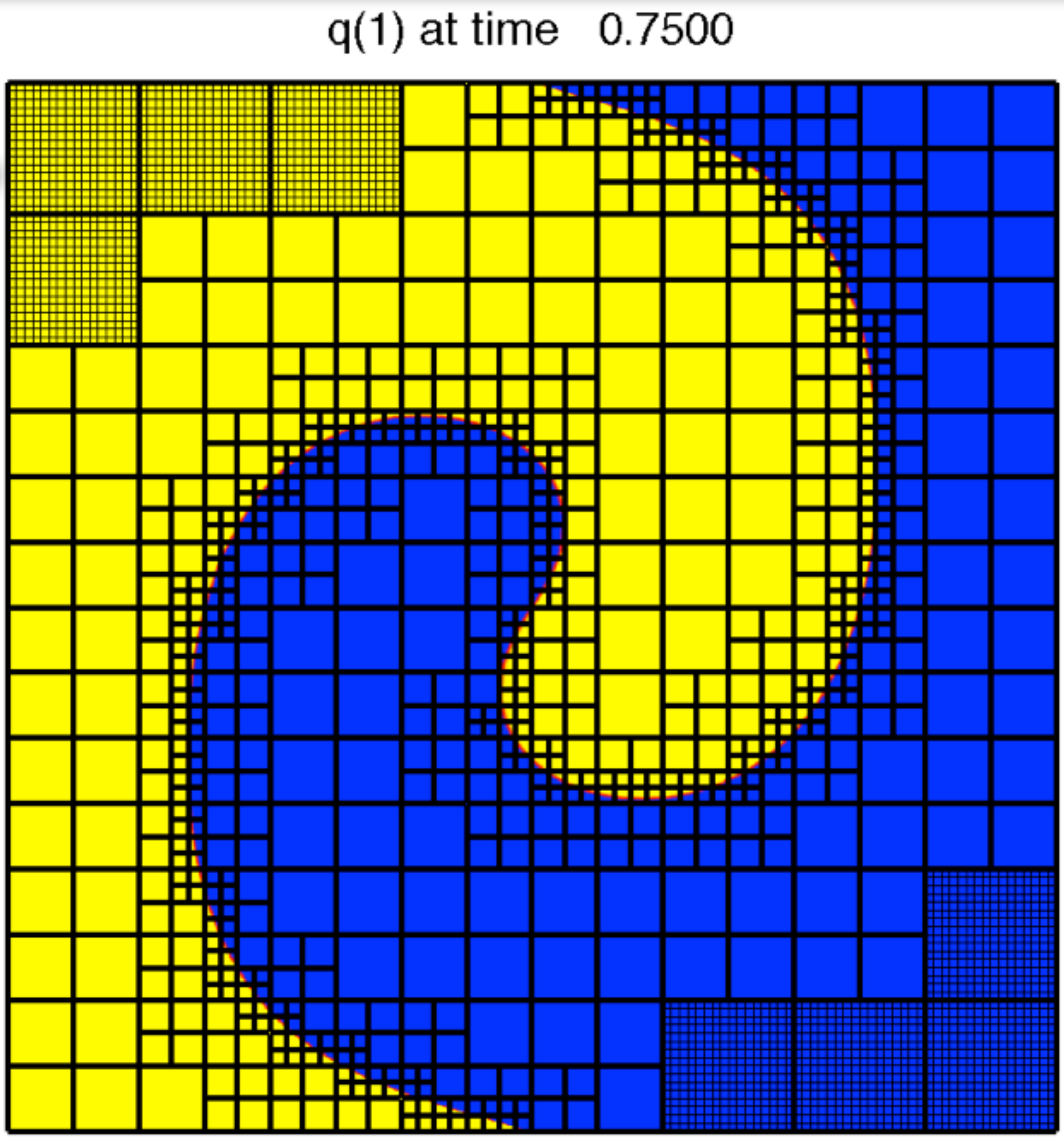
Carsten Burstedde, Lucas C. Wilcox, and Omar Ghattas, "p4est: Scalable Algorithms for Parallel Adaptive Mesh Refinement on Forests of Octrees", SISC (2011)

Multi-block support in p4est



Antarctic ice sheet modeling (Tobin Isaac, C Burstedde)

A hybrid approach to AMR



Each leaf is a fixed size grid

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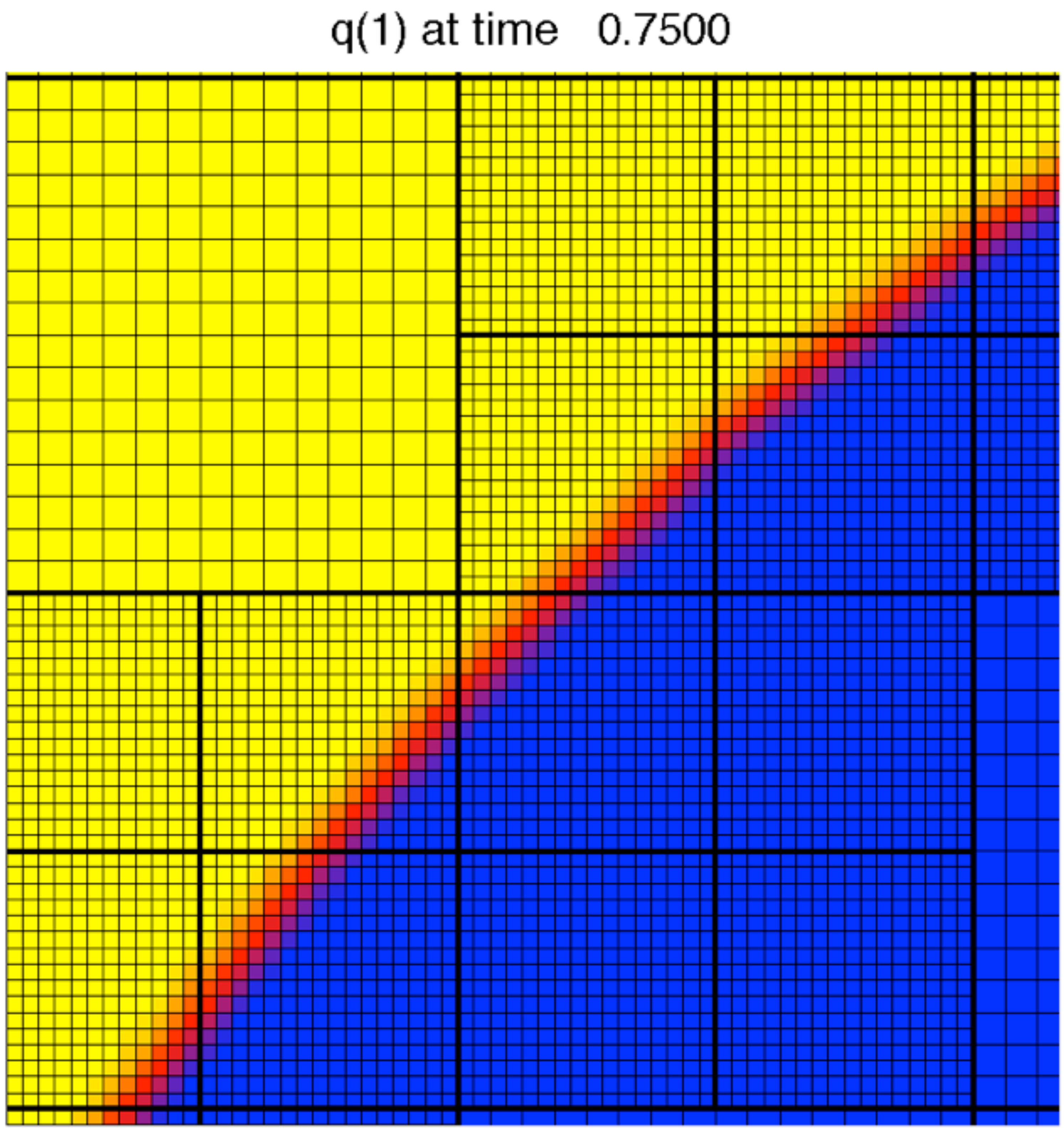

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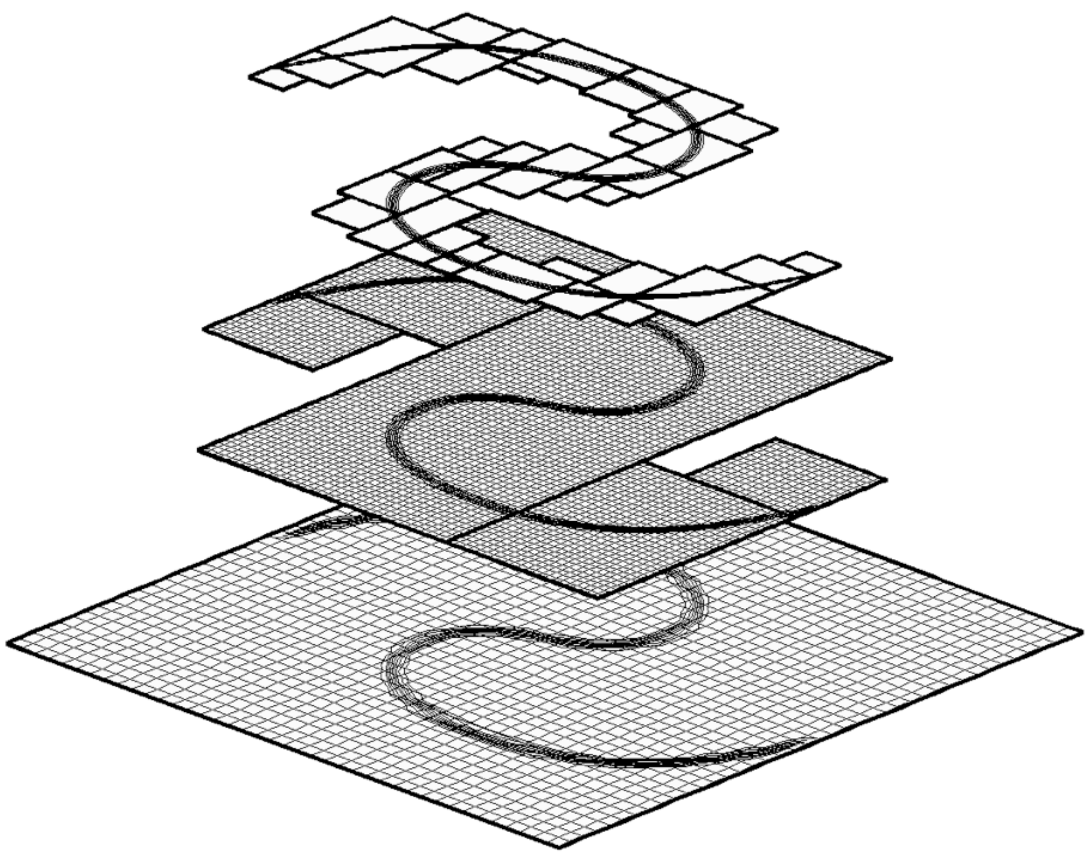
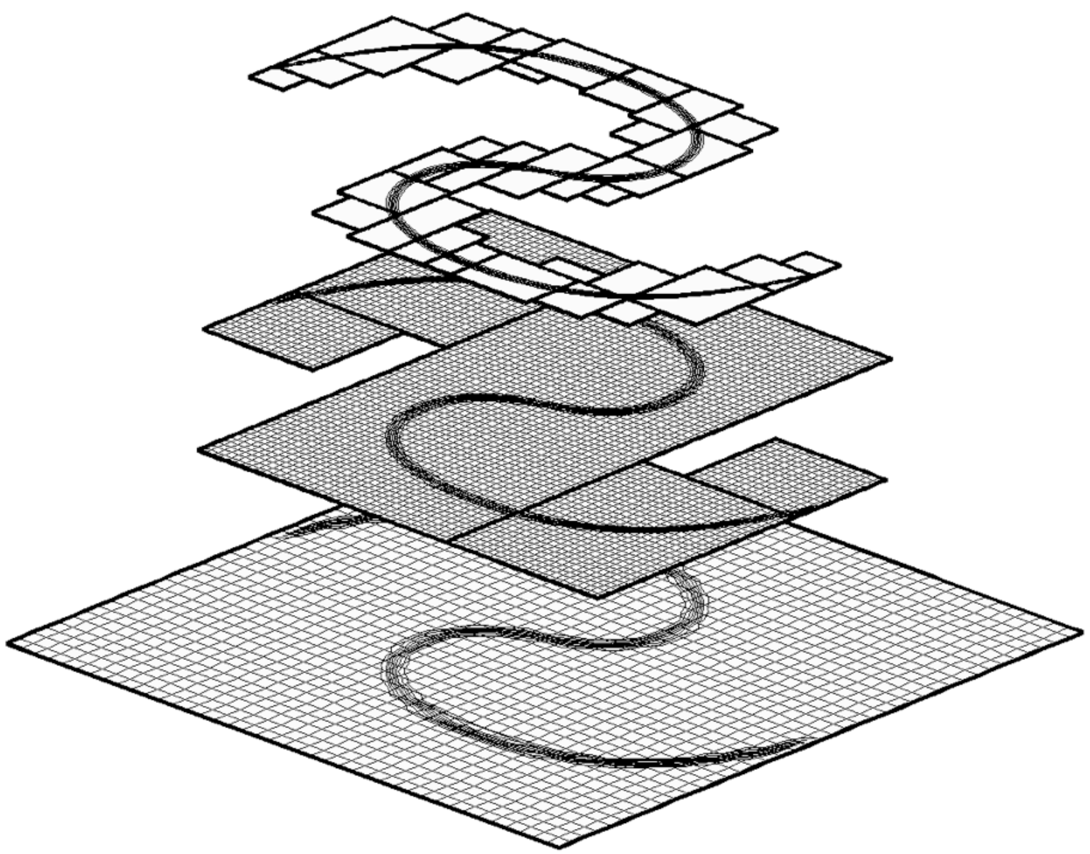


Berger-Oliger approach

A hybrid approach to AMR



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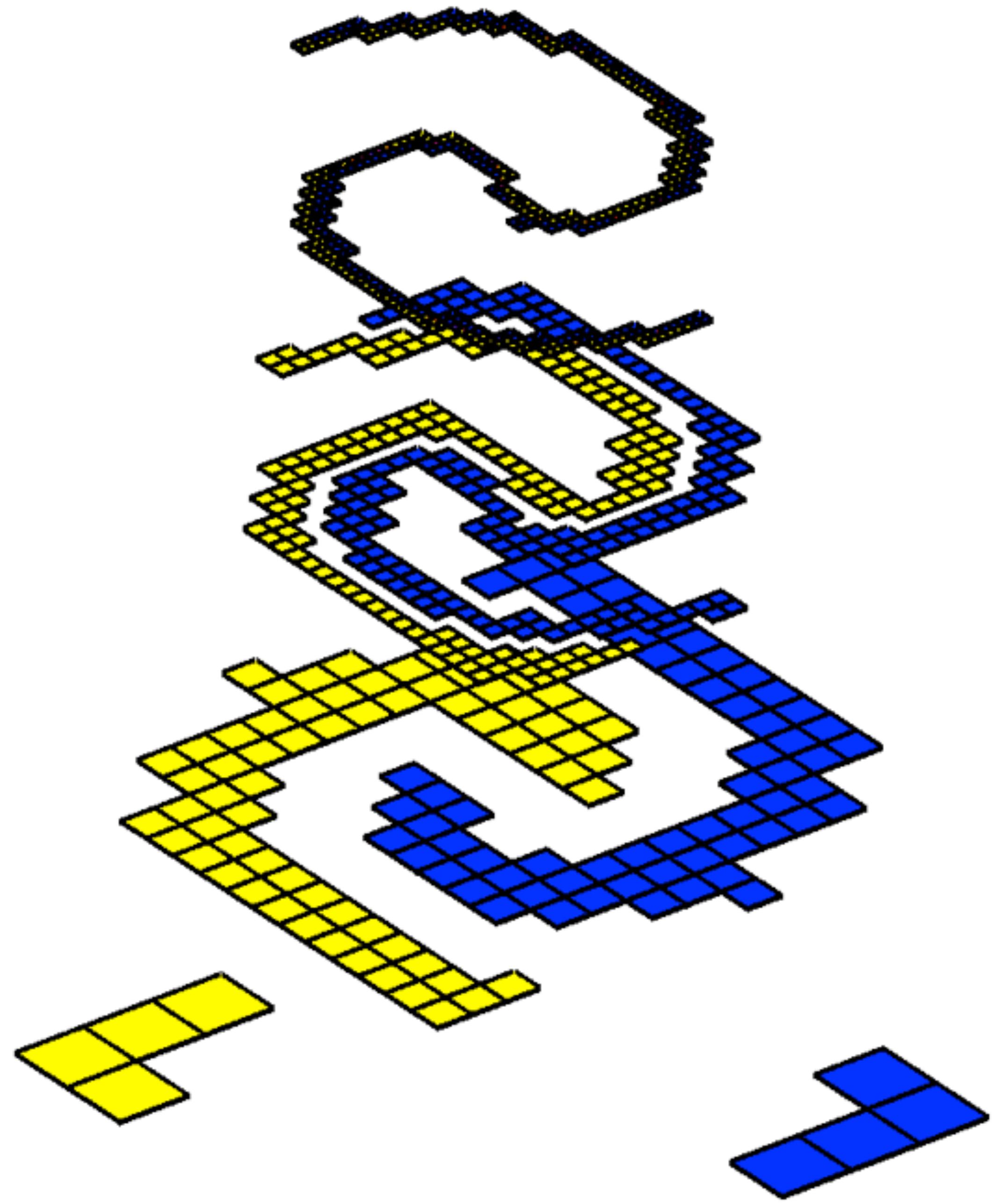

ForestClaw

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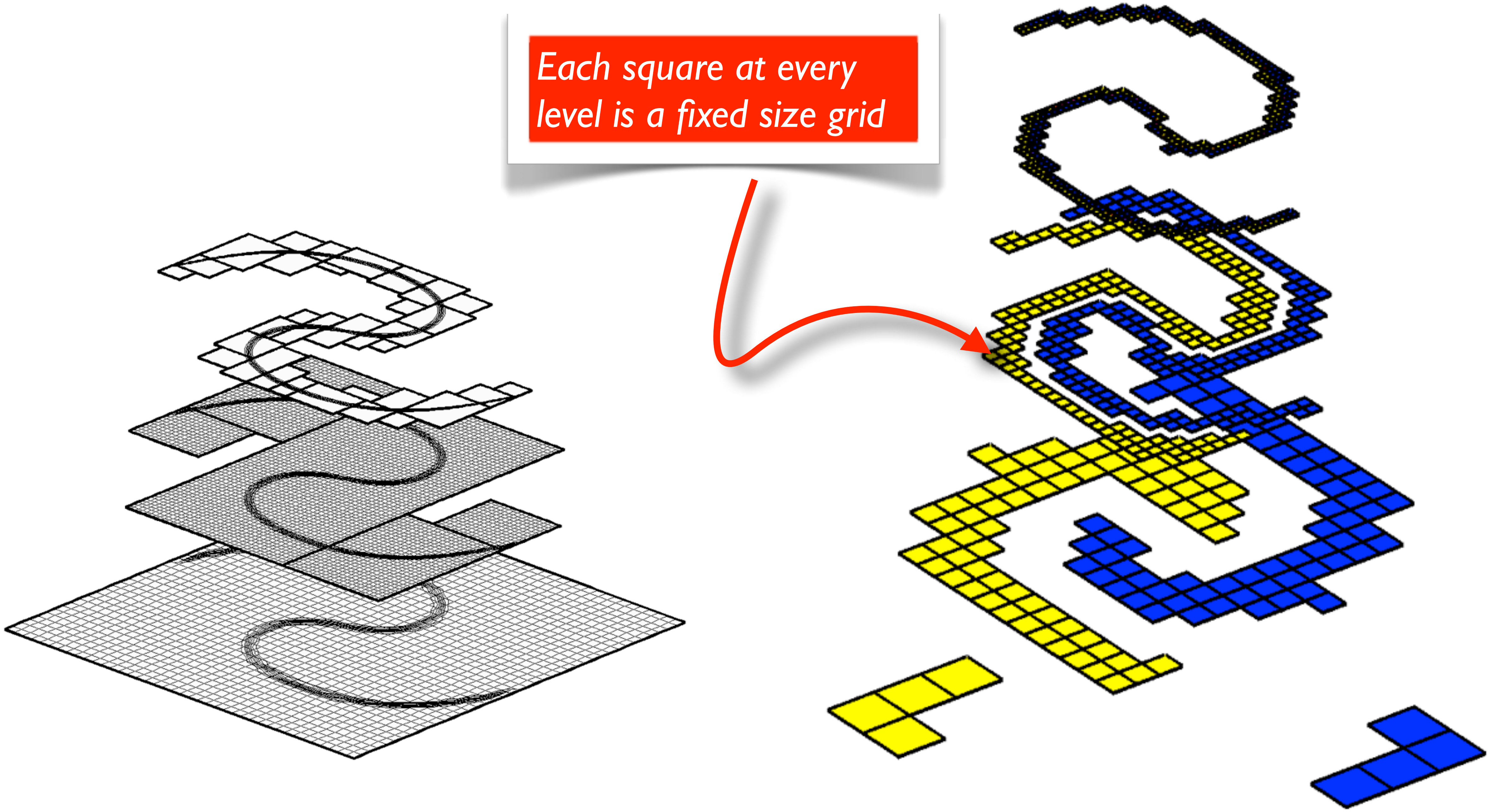

Berger-Oliger approach

ForestClaw

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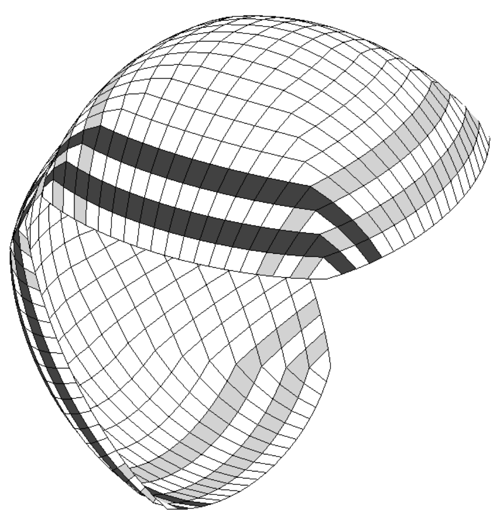
- Composite view of the grid hierarchy provides a cleaner mental map of what the solution looks like (no overlapping grids)
- Generic multi-block interface allows user to construct complicated domains
- Has the aesthetic appeal of a quad/octree refinement with the superior performance of the Berger-Oliger approach to AMR.

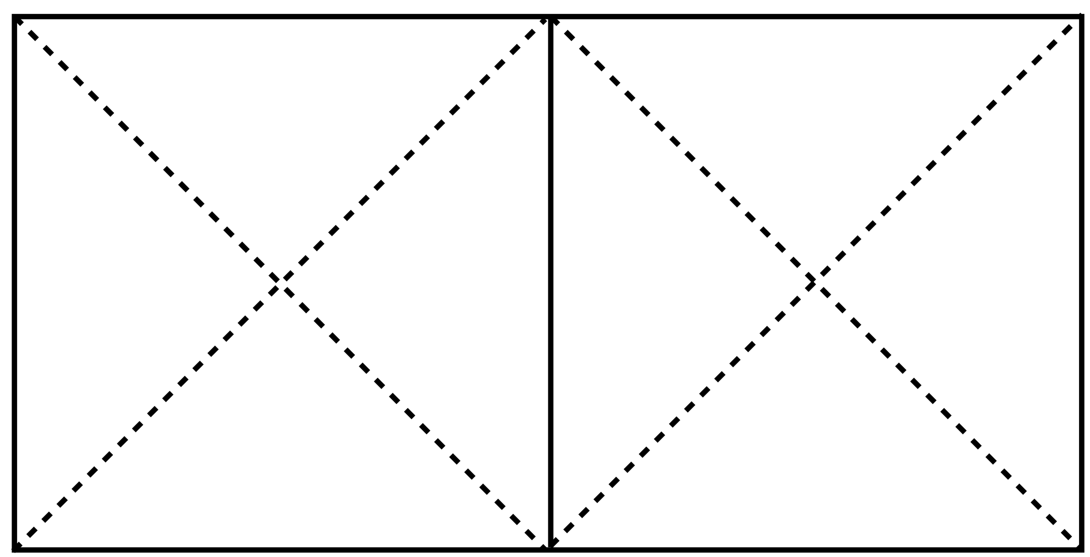
Other AMR approaches using quad/octrees

- "Building Cubes Method" (Sasaki, Akahito, Yamazaki, ...)
- Parallel adaptive methods for weather prediction C. Jablonowski, Oehmke, Stout and others
- NIRVANA (U. Ziegler)
- Racoon II (J. Dreher)
- PARAMESH (NASA,/Drexel, MacNeice, Olson)
- Block-structured AMR codes (Chombo, Boxlib, AMRClaw, SAMRAI, AMROC, ...) could probably be run with fixed size grids and prescribed refinement regions

A two-patch sphere grid?

- Our sphere grid is like the cubed-sphere grid, but with two patches
- We will refer to the grid resolution by the number of grid cells on a patch edge, which is approximately 90 degrees.

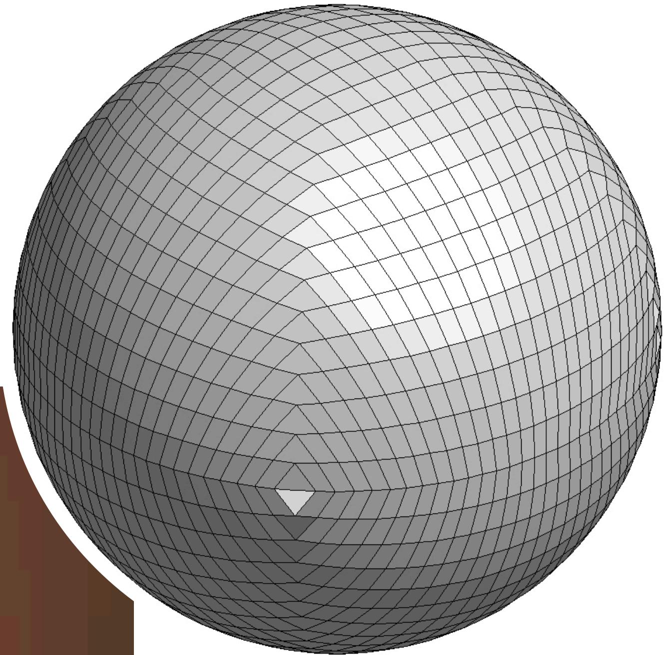




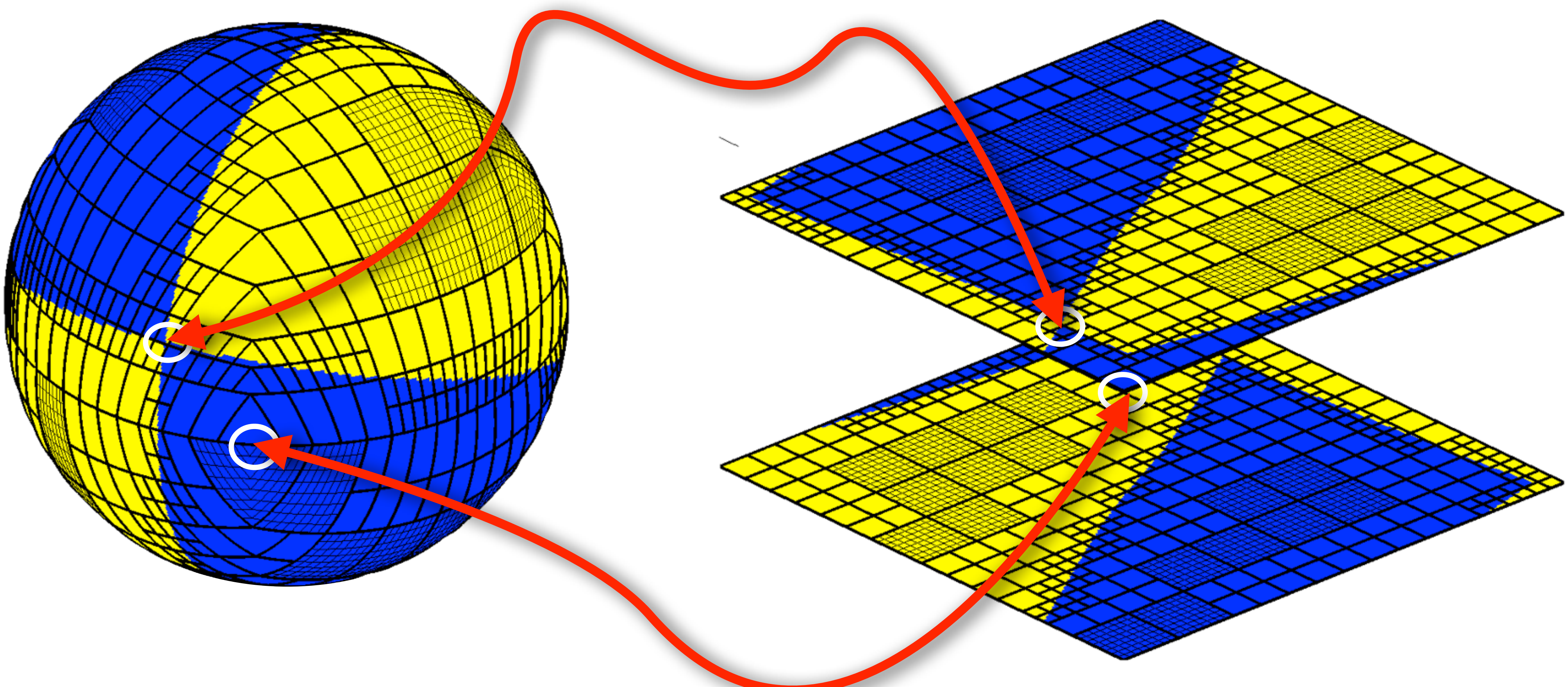
90 degrees =
N mesh cells

Dashed and solid lines are discontinuities in the mapping

A Pillow grid?



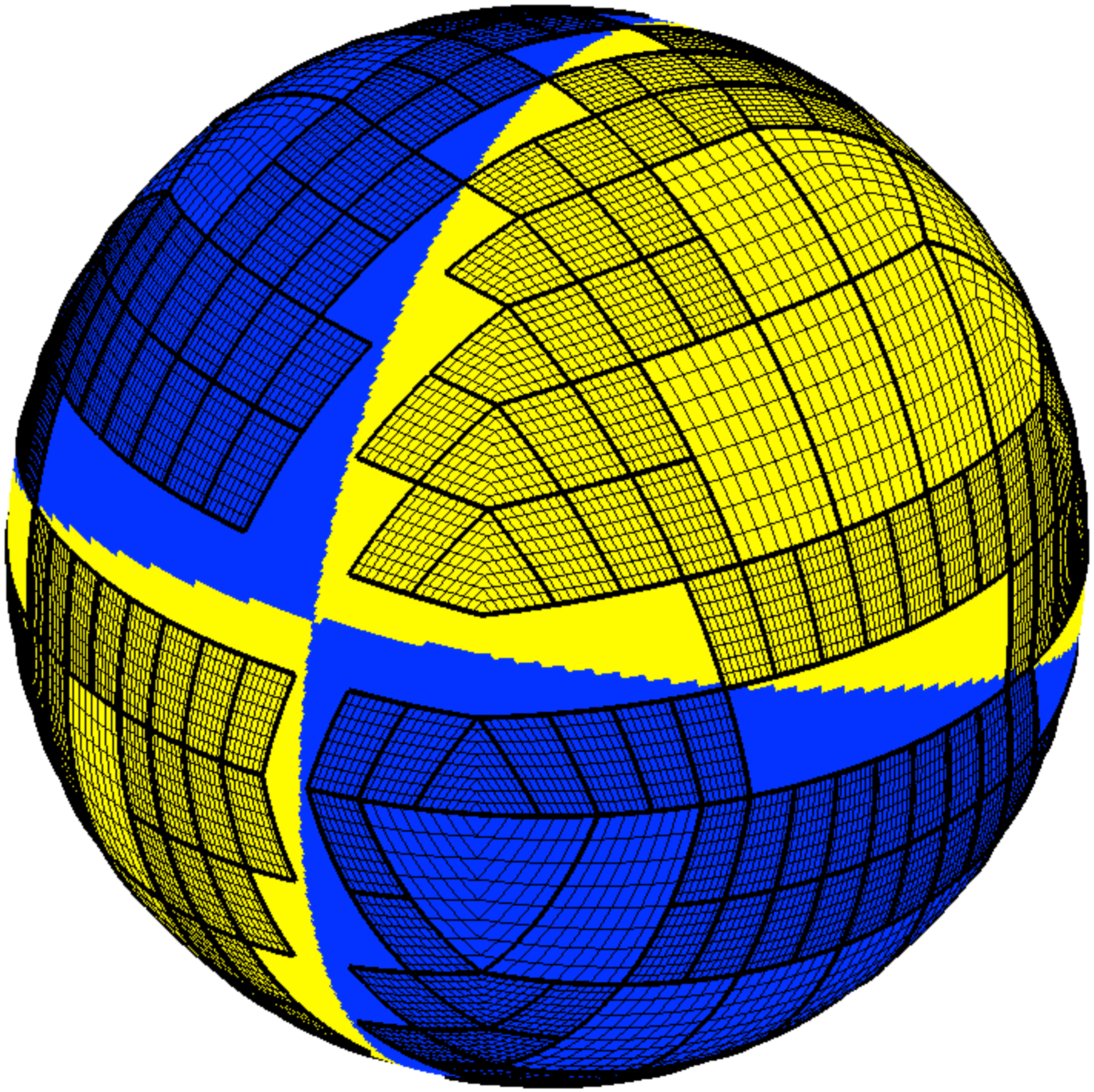
Scalar transport on the sphere



Scalar advection using finite volume wave propagation algorithms (ClawPACK, R. J. LeVeque)

Scalar advection

Scalar advection



Spiral waves (Barkely model)

Reaction-diffusion using an explicit Runge-Kutta Chebychev (RKC) time stepping

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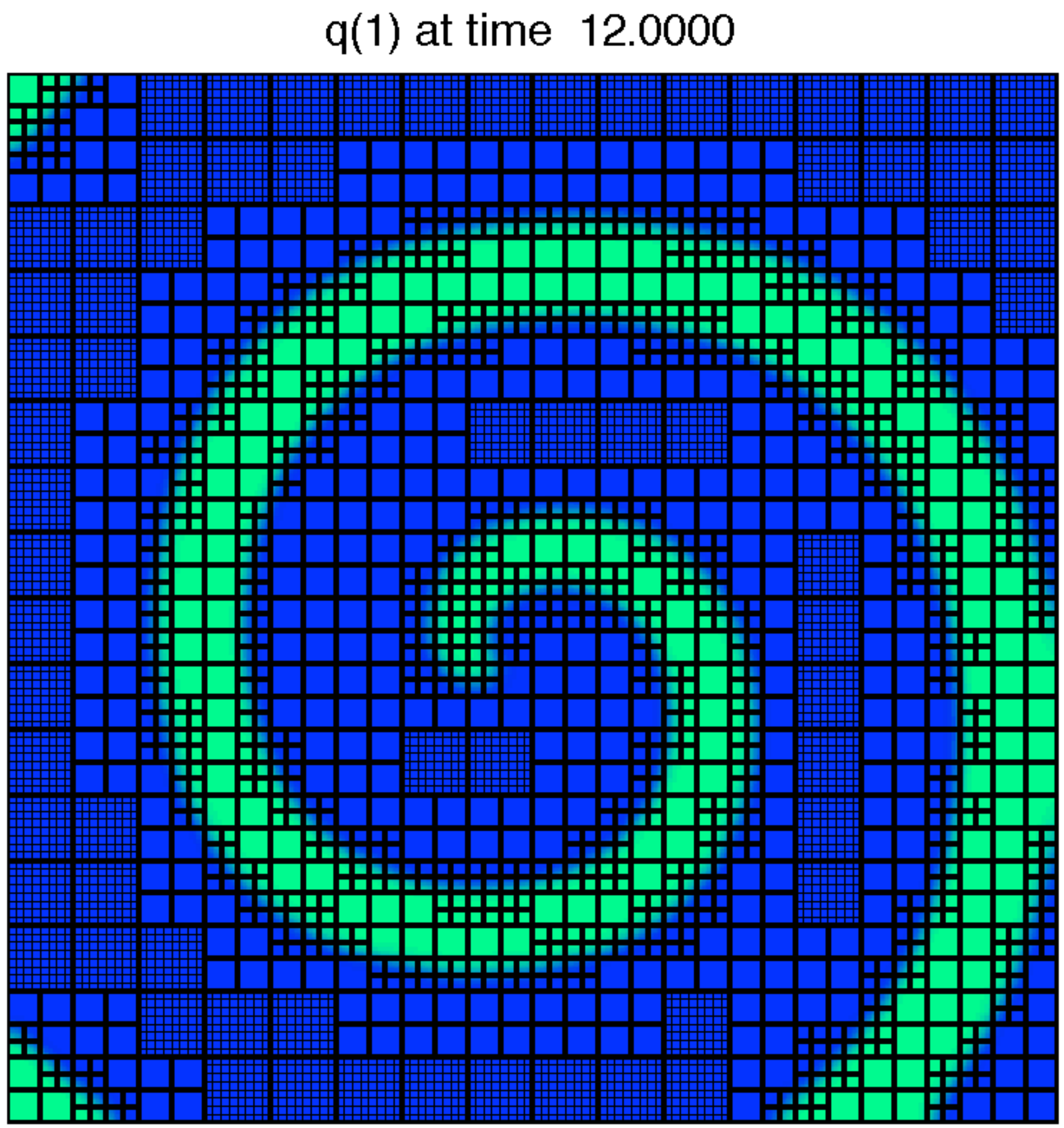


Reaction-diffusion using an explicit Runge-Kutta Chebychev (RKC) time stepping

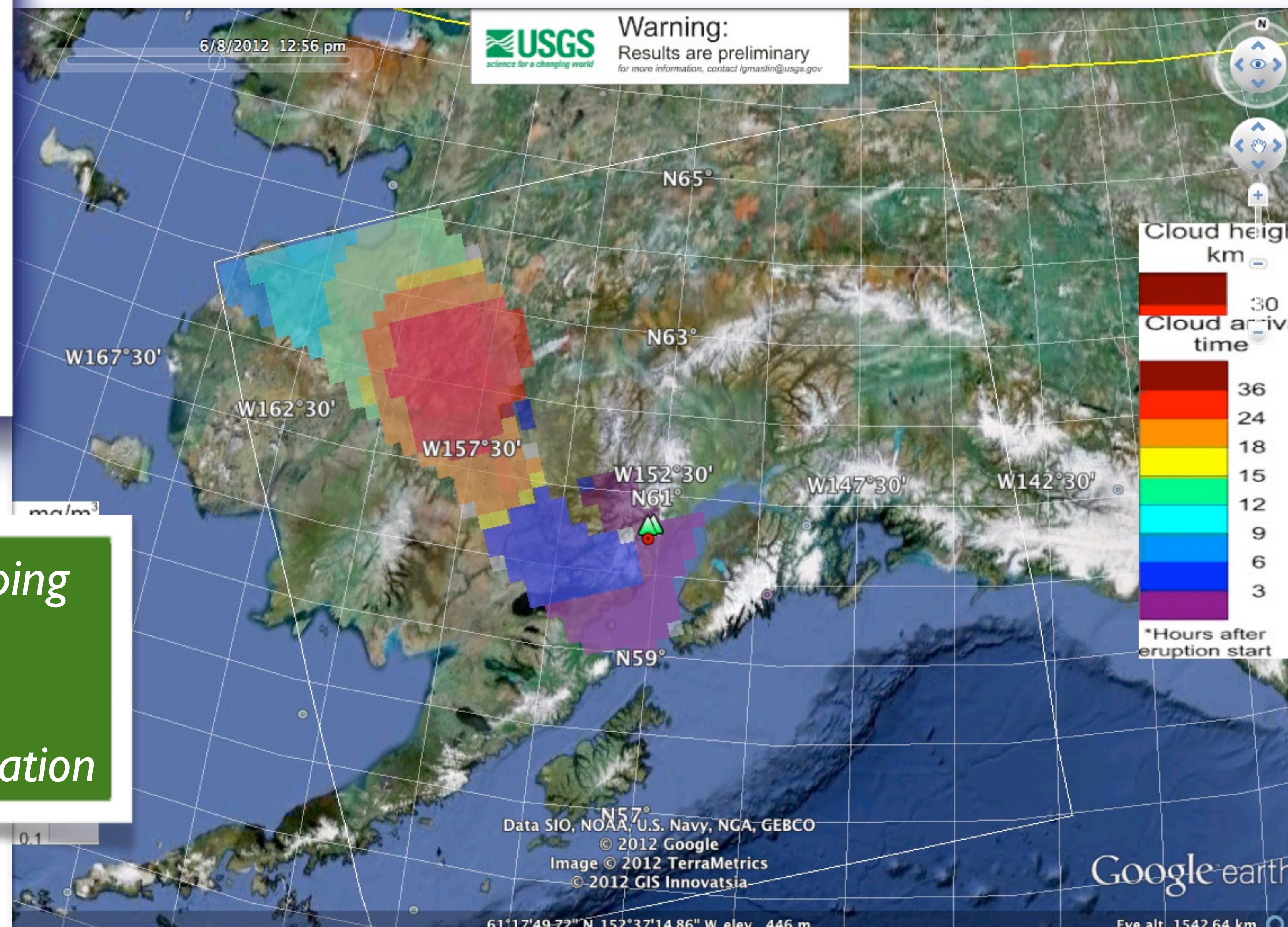
Near future challenges

- Include anisotropic refinement for atmospheric applications by putting 3d grids into 2d quadtrees
- Parallel ghost cell exchanges (p4est is already fully parallelized; parallel exchanges between ghost cells need to be worked out)
- General handling of grid orientations in multi-block setting,
- New topologies, i.e. the cubed-sphere (already available in p4est)

see *http://www.forestclaw.org*

Ash cloud modeling

Ash3d



- *Split horizontal, vertical time stepping*
- *Fully conservative,*
- *Eulerian, finite volume*
- *Algorithms based on wave propagation*

Ash3d :A finite-volume, conservative numerical model for ash transport and tephra deposition, Schwaiger, Denlinger, Mastin, JGR (2012)