Enzo-P / Cello

Formation of the First Galaxies

James Bordner[1] Michael L. Norman[1] Brian O'Shea[2]

[1]University of California, San Diego
San Diego Supercomputer Center

[2]Michigan State University
Department of Physics and Astronomy

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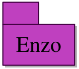
University of Illinois at Urbana-Champaign

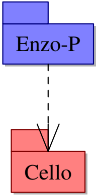
Introducing Enzo-P / Cello

Our group actively develops two related parallel applications:



Enzo: astrophysics / cosmology application

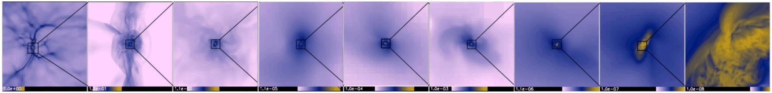
- patch-based adaptive mesh refinement (AMR)
- MPI or MPI/OpenMP
- almost 20 years development

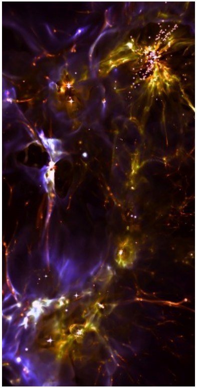


Enzo-P / **Cello**: "Petascale" fork of Enzo code

- "forest of octrees" AMR
- Charm++ or MPI
- ≈ 3 years development
- work in progress–AMR just coming online

Enzo's strengths



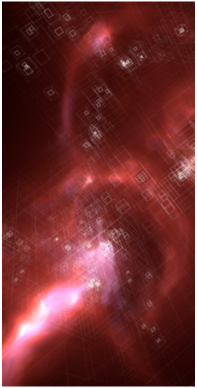


[John Wise]

- Spans multiple application domains
  - astrophysical fluid dynamics
  - hydrodynamic cosmology
- Rich multi-physics capabilities
  - fluid, particle, gravity, radiation, . . .
- Extreme resolution range
  - 34 levels of refinement by 2!
- Active global development community
  - ≈ 25 developers

Enzo's struggles

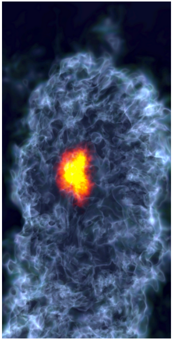
- Memory usage
  - ≈ 1.5KB/patch (MPI/OpenMP helps)
  - memory fragmentation
- Mesh quality
  - 2-to-1 constraint can be violated
  - asymmetric mesh for symmetric problem
- Load balancing
  - difficulty maintaining parent-child locality
- Parallel scaling
  - AMR overhead dominates computation



[Tom Abel, John Wise, Ralf Kaehler]

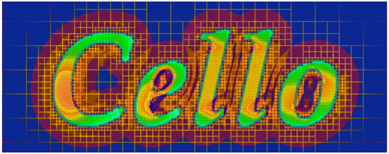
Enzo's pursuit of scalability

- Enzo was born in early 1990's
- "Extreme" meant 100 processors
- Continual scalability improvements
  - MPI/OpenMP parallelism
  - "neighbor-finding" algorithm
  - I/O optimizations
- Further improvement getting harder
  - increasing scalability requirements
  - easy improvements made already
- Motivates concurrent rewriting
  - **Enzo-P** "Petascale" Enzo fork
  - **Cello** AMR framework



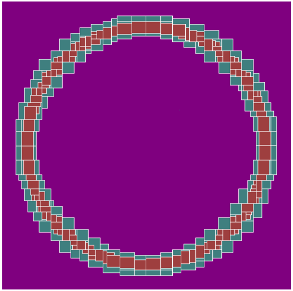
[Sam Skillman, Matt Turk]

Enzo-P / Cello design overview



- **Charm++** parallelism
  - asynchronous, data-driven
  - latency tolerant
  - dynamic load balancing
  - checkpoint / restart
- **Octree**-based AMR
  - "forest" for root mesh
  - easier to implement
  - scalability advantages
  - fast neighbor-finding

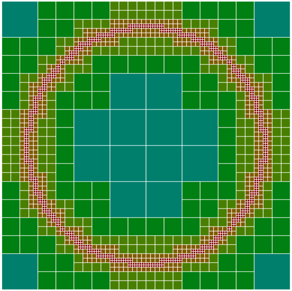
Some advantages of patch-based AMR



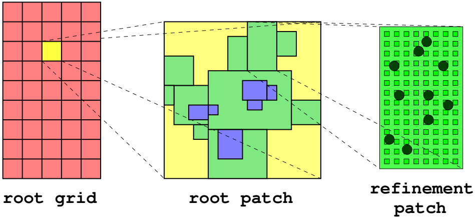
- Flexible patch size and shape
  - improved refinement efficiency
- Larger patches
  - smaller surface/volume ratio
  - reduced communication
  - amortized loop overhead
- Fewer patches
  - reduced AMR meta-data

Some advantages of octree-based AMR

- Fixed block size and shape
  - simplified load balancing
  - dynamic memory reuse
- More blocks
  - more parallelism available
- Smaller nodes
  - reduced AMR meta-data
- Compute only on leaf nodes
  - less communication

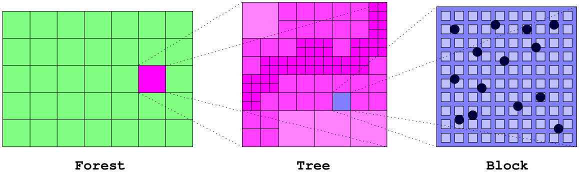


Enzo's AMR data structure



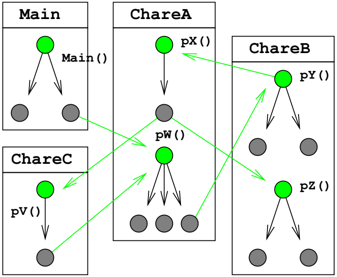
- Patches assigned to MPI processes
- Refinement patches created on root patch process
- Load balancing relocates refinement patches
- Patch data (grid, particle) are distributed
- Replicated AMR hierarchy structure

Enzo-P / Cello's AMR data structure



- Each block is a Charm++ chare
- Blocks initially mapped to root node process
- Charm++ load balances
- AMR hierarchy structure is fully distributed

Charm++ program structure

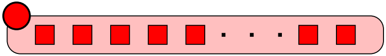


A Charm++ Program

- Charm++ program
  - Charm++ objects are *chares*
  - invoke remote *entry methods*
  - communicate via *messages*
- Charm++ runtime system
  - schedules entry methods
  - maps chares to processors
  - migrates chares to balance
- Additional scalability features
  - checkpoint / restart
  - sophisticated DLB strategies

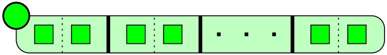
Charm++ collections of chares

Chare Array



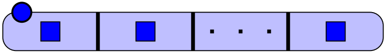
- distributed array of chares
- migrateable elements
- flexible indexing

Chare Group



- one chare per processor (non-migreateable)

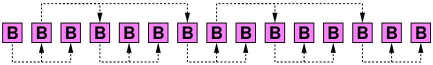
Chare Nodegroup



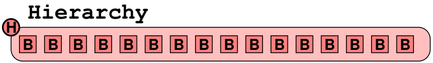
- one chare per node (non-migrateable)

Cello implementation options using Charm++

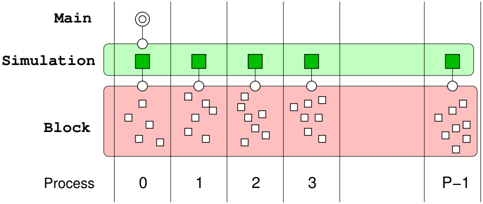
1. **Singleton chares**
    - unlimited hierarchy depth
    - tedious to program
    - limited Charm++ support



2. **Chare array**
    - efficient: single access
    - restricted hierarchy depth



Charm++ entities in Enzo-P / Cello

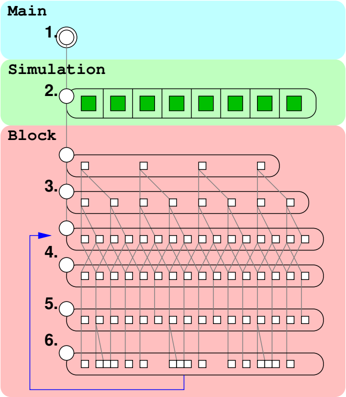


- "mainchare" called at program startup
- Simulation chare group holds global data
- Block chare array defines forest of octrees

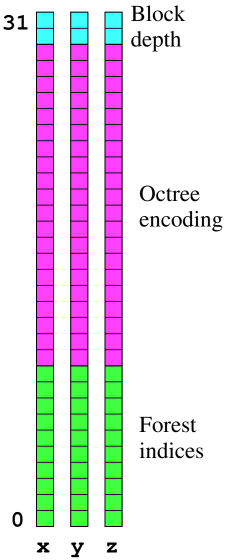
Control flow in Enzo-P / Cello

Current Enzo-P / Cello control flow

1. Startup
2. Initialize
3. Mesh creation
4. Ghost refresh
5. Computation
6. Mesh adaptation

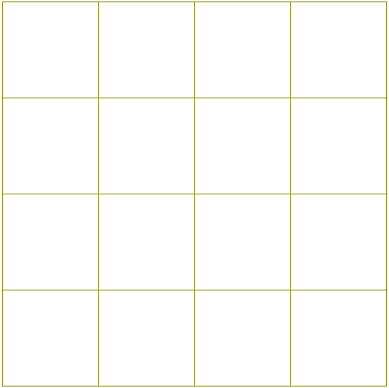


Block chare array indexing



- Charm++ supports user-defined array indices
- Default array indices are 3 integers
- Cello indexing for `Block` arrays:
  - 10 × 3 bits for *forest indices*
  - 20 × 3 bits for the *octree encoding*
  - 6 bits for the *block depth*
- Up to 1024^3 array of octrees
- Up to 21 octree levels

Cello mesh generation



- Begins with the forest root grid
- Proceeds level-by-level
- Blocks evaluate refinement criteria
  - if refine, create child blocks
  - if coarsen, notify parent block
- Refine can violate 2-1 constraint
  - tell coarse neighbors to refine
  - may recurse
- *Quiescence detection* between steps
- Keep track of neighbors and children

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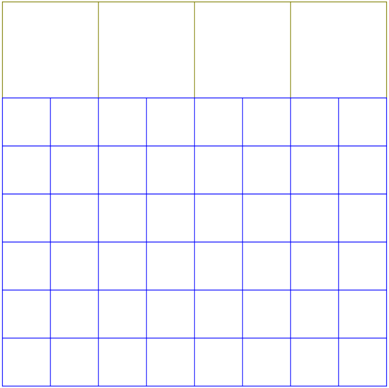

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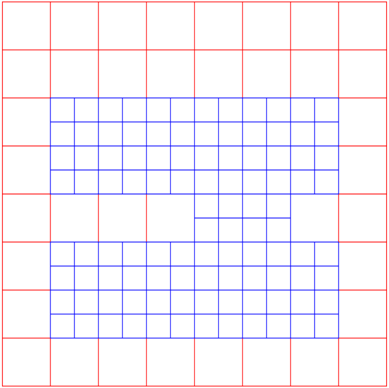

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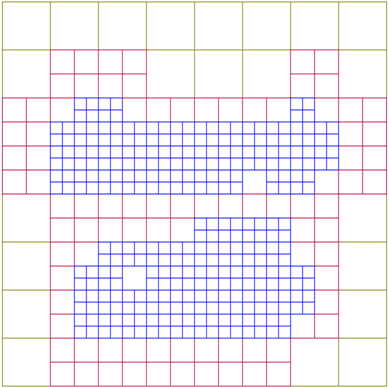

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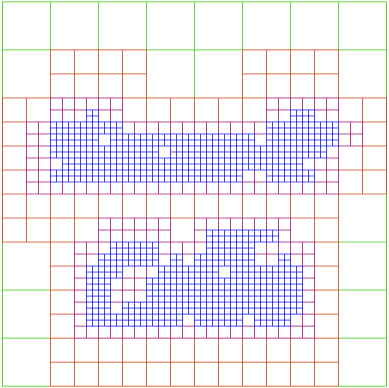

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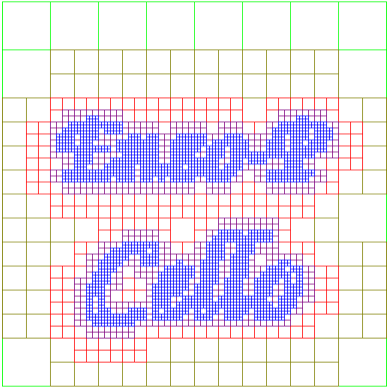

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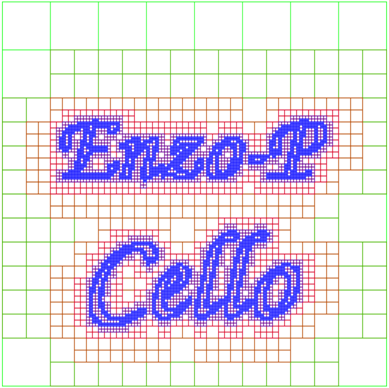

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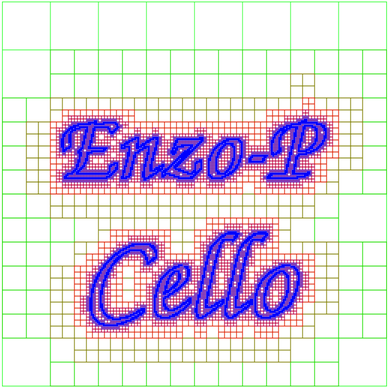

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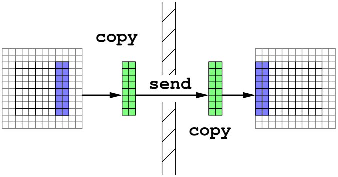
Cello AMR ghost zone refresh

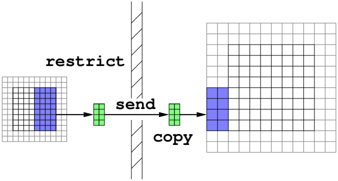
Intra-level refresh

1. `FaceBlock` loads face cells
2. Charm++ entry method send
3. `FaceBlock` stores ghost cells



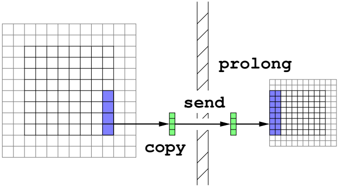
Fine-to-coarse refresh

1. `FaceBlock` coarsens face cells
2. Charm++ entry method send
3. `FaceBlock` stores ghost cells

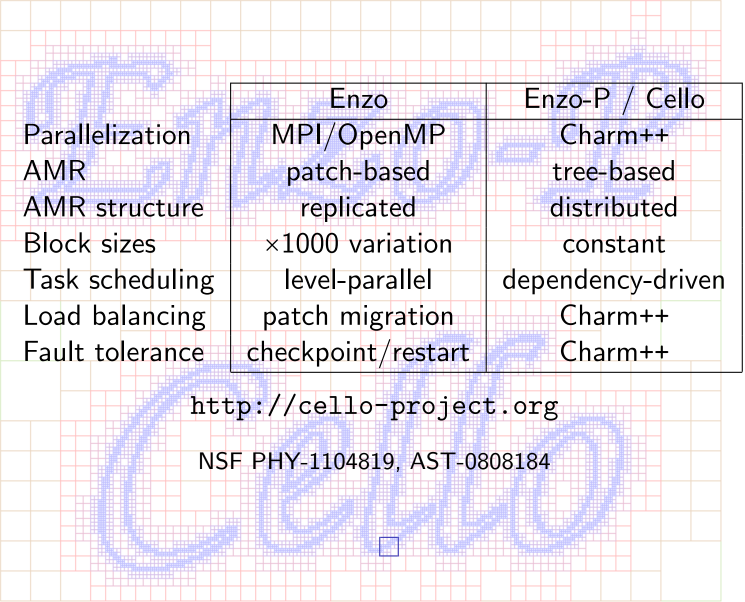


Coarse-to-fine refresh

1. `FaceBlock` loads face cells
2. Charm++ entry method send
3. `FaceBlock` interpolates ghost cells



Summary



	Enzo	Enzo-P / Cello
Parallelization	MPI/OpenMP	Charm++
AMR	patch-based	tree-based
AMR structure	replicated	distributed
Block sizes	×1000 variation	constant
Task scheduling	level-parallel	dependency-driven
Load balancing	patch migration	Charm++
Fault tolerance	checkpoint/restart	Charm++

`http://cello-project.org`

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