Enzo Lectures

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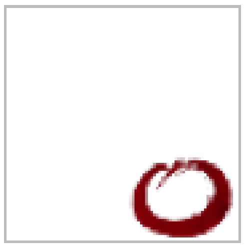
	Morning	Afternoon
Mon.	Introduction to Enzo	
Tue.	1. Setting Up and Running Enzo 2. Enzo Projects	Introduction to YT
Wed.	Enzo Algorithms	Lab session
Thu.	Applications to First Stars, First Galaxies, and Reionization	Lab session
Fri.	What's New in Enzo 2.0?	Q & A

Q. What is that name all about anyway?

- A. (according to Greg Bryan)



Zen Enzo

Ensō (円相) is a Japanese word meaning "circle" and a concept strongly associated with Zen. Ensō is one of the most common subjects of Japanese calligraphy even though it is a symbol and not a character. It symbolizes enlightenment, strength, elegance, the Universe, and the void; it can also symbolize the Japanese aesthetic itself. As an "expression of the moment" it is often considered a form of minimalist expressionist art.

Source: Wikipedia

Enzo Public Release History

Version	Date	Web Site
1.0	3/1/04	http://lca.ucsd.edu/software/enzo/v1.0.1/
1.5	11/6/08	http://lca.ucsd.edu/projects/enzo/
2.0	7/30/10	http://code.google.com/p/enzo/

Quick Tour of the V1.5 Trac Site

http://lca.ucsd.edu/projects/enzo

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Enzo Project Page

This is the development site for Enzo, an adaptive mesh refinement (AMR), grid-based hybrid code (hydro + N-Body) which is designed to do simulations of cosmological structure formation. Links to documentation and downloads for all versions of Enzo from 1.0 on are available.

Enzo development is supported by grants AST-0808184 and OCI-0832662 from the National Science Foundation.

Download

Releases

- Enzo1.5 (released Nov. 6, 2008)
- Enzo v1.0.1 download page.

Repository

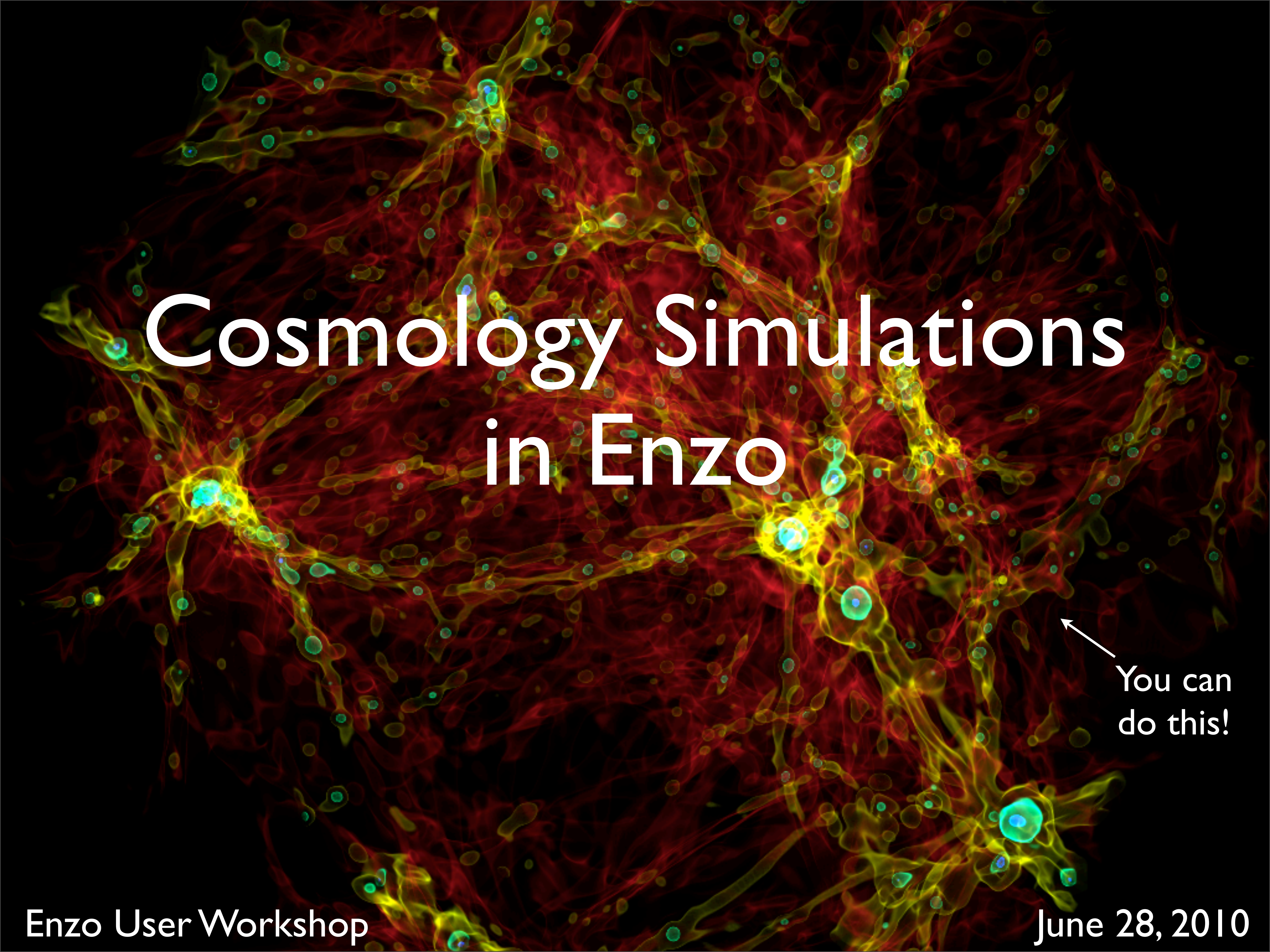
- Public Subversion repository http://lca.ucsd.edu/svn/Enzo/public/
- Browse public repository.

The Essentials

Topic	URL
home page	http://lca.ucsd.edu/projects/enzo
v1.5 page	http://lca.ucsd.edu/projects/enzo/wiki/Enzo1.5
tarball	http://lca.ucsd.edu/projects/enzo/wiki/DownloadInstructions
browse source	http://lca.ucsd.edu/projects/enzo/browser/public/trunk
user guide	http://lca.ucsd.edu/projects/enzo/wiki/UserGuide
executables	http://lca.ucsd.edu/projects/enzo/wiki/UserGuide/ExecutablesArgumentsOutputs
input parameters	http://lca.ucsd.edu/projects/enzo/wiki/UserGuide/EnzoParameters
running	http://lca.ucsd.edu/projects/enzo/wiki/UserGuide/RunningEnzo
test suite	http://lca.ucsd.edu/projects/enzo/wiki/UserGuide/EnzoTestSuite
tutorials	http://lca.ucsd.edu/projects/enzo/wiki/Tutorials
references	http://lca.ucsd.edu/projects/enzo/wiki/EnzoPrimaryReferences

Show Britton Smith's Slides

Cosmology Simulations in Enzo



Enzo User Workshop

June 28, 2010

Outline

I. Generating Initial Conditions
    I. Single grid
    II. Multi grid
II. Configuring the Simulation
    I. Setting Refinement Parameters for AMR
    II. Using Star Formation and Feedback

Generating Initial Conditions

Initial Conditions

- inits: the initial conditions generator.
- This gives you 4 files:
  - Baryon Density: 1 x N x N x N
  - Baryon Velocities: 3 x N x N x N
  - Particle Positions: $3 \times N^3$
  - Particle Velocities: $3 \times N^3$

Inits Parameters

http://lca.ucsd.edu/projects/enzo/wiki/UserGuide/RunningInits#InitsParameterList

1. Cosmology Parameters: box size, initial redshift, hubble constant, Omegas.
2. Power Spectrum Parameters: power spectrum type, σ_8, random seed, etc.
3. Grid Parameters

*Keep in Mind

- Using the same random seed with different grid dimensions will give you the same realization.
- Using the same random seed with different box size will give you very similar looking simulations.

Cosmology Parameters

```
#
#  Cosmology Parameters
#
CosmologyOmegaMatterNow       = 0.268
CosmologyOmegaLambdaNow       = 0.732
CosmologyOmegaBaryonNow       = 0.0441
CosmologyComovingBoxSize      = 32.0       // in Mpc/h
CosmologyHubbleConstantNow    = 0.704      // in units of 100 km/s/Mpc
CosmologyInitialRedshift      = 50
```

Power Spectrum Parameters

```
#
#  Power spectrum Parameters
#
PowerSpectrumType              = 11            // Eisenstein & Hu
PowerSpectrumSigma8            = 0.9
PowerSpectrumPrimordialIndex = 1.0
PowerSpectrumRandomSeed        = -312367047
```

Single Grid Setup: The Baryons

```
#
#  Grid info
#
Rank                    = 3
InitializeGrids         = 1
GridDims = 64 64 64
```

- GridRank: dimensionality of the simulation
- InitializeGrids: 1/0 for baryons on/off
- GridDims: # of cells in each dimension

Single Grid Setup: The Dark Matter

```
#
#  Particle info
#
InitializeParticles = 1
ParticleDims = 64 64 64
```

- InitializeParticles: 1/0 for particles on/off
- ParticleDims: # of particles in each direction

Output Filenames

```
#
#  Names
#
ParticlePositionName = ParticlePositions
ParticleVelocityName = ParticleVelocities
GridDensityName      = GridDensity
GridVelocityName     = GridVelocities
```

Make it go!

./inits.exe -d my_cosmology_run.inits

*do an h5ls on your files to check them.

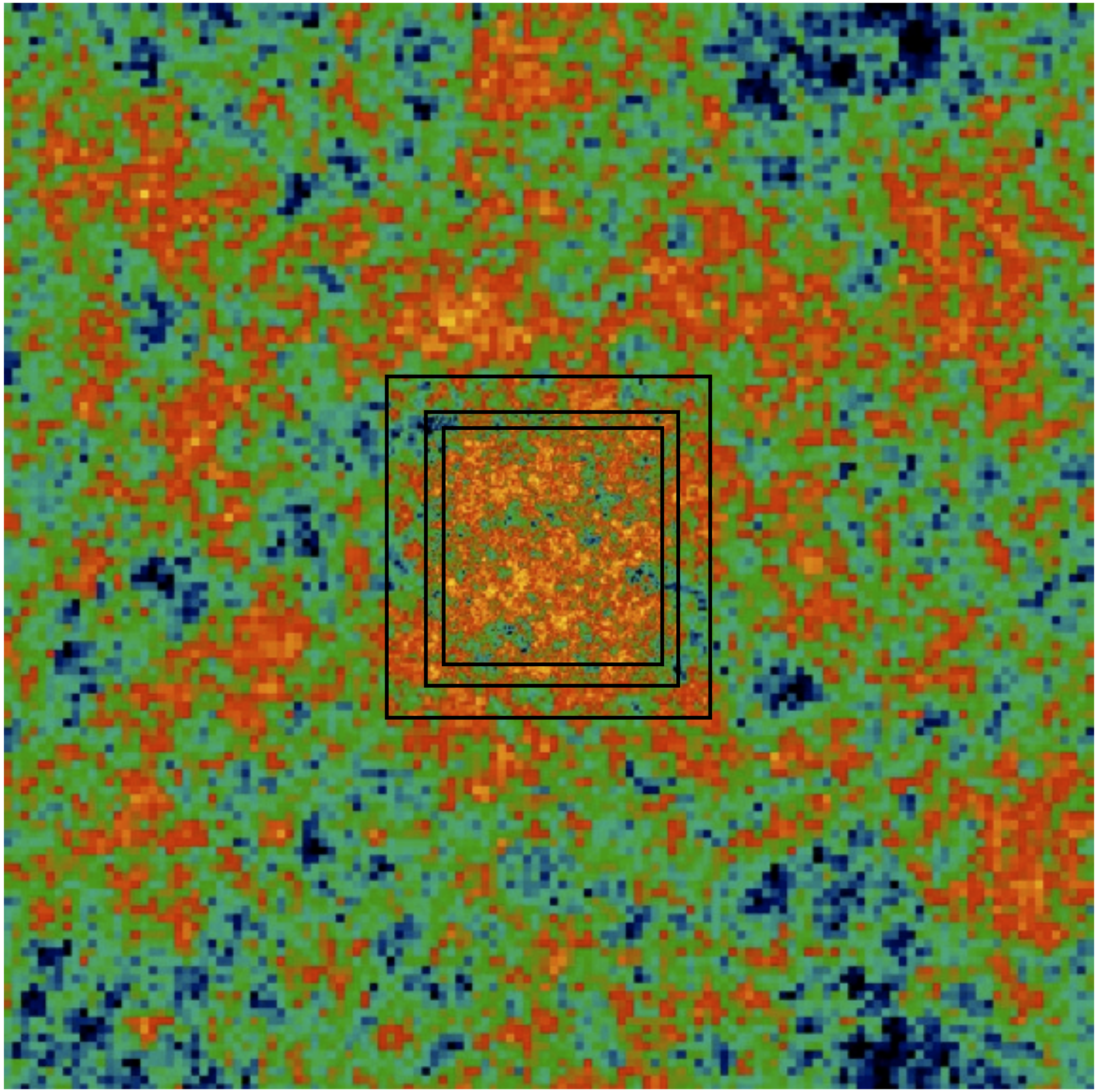
Multi-grid Setup

- What is that? - nested grids with initial refinement
- Why? - simulate a sub-region with higher resolution.
- How? - run inits multiple times with a different parameter file for each level.
- What you get: 4 files for each level.

Nested Grid Cosmology Simulations

aka Zoom-in calculations

1. *n*-Body Simulation
2. Locate region of interest, e.g. most massive halo
3. Generate nested grid initial conditions
4. Run simulation!



Inits Parameters: Multi-grid Setup

1. Cosmology Parameters: same as before.
2. Power Spectrum Parameters: same as before.
3. Grid Parameters: a little different.

Multi-grid Setup: The Baryons

Top Grid

```
#
#  Grid info
#
Rank                    = 3
GridDims = 32 32 32
GridRefinement          = 4
InitializeGrids         = 1
```

- GridDims: # of cells in each dimension for this grid.
- GridRefinement: the sampling on this grid relative to the top grid (1 cell on this level is equal to X cells on the most refined level).

This example: 32^3 top grid + 2 x 32^3 subgrids. (Refine by 2)

Multi-grid Setup: The Baryons

Sub Grid
1 of 2

```
#
#  Grid info
#
Rank                  = 3
InitializeGrids       = 1
GridRefinement        = 2
GridDims = 32 32 32
```

- GridDims: # of cells in each dimension for this grid.
- GridRefinement: the sampling on this grid relative to the top grid (1 cell on this level is equal to X cells on the most refined level).

This example: 32^3 top grid + 2 x 32^3 subgrids. (Refine by 2)

Multi-grid Setup: The Baryons

Sub Grid
2 of 2

```
#
#  Grid info
#
Rank                = 3
InitializeGrids     = 1
GridRefinement      = 1
GridDims = 32 32 32
```

- GridDims: # of cells in each dimension for this grid.
- GridRefinement: the sampling on this grid relative to the top grid (1 cell on this level is equal to X cells on the most refined level).

This example: 32^3 top grid + 2 x 32^3 subgrids. (Refine by 2)

Multi-grid Setup: The Dark Matter

Top Grid

```
#
#  Particle info
#
InitializeParticles = 1
ParticleRefinement  = 4
ParticleDims = 32 32 32
```

- ParticleDims: # of particles in each dimension for this grid.
- ParticleRefinement: the sampling on this grid relative to the top grid (1 particle on this level is equal to X particles on the most refined level).

This example: 32^3 top grid + 2 x 32^3 subgrids. (Refine by 2)

Multi-grid Setup: The Dark Matter

Sub Grid
1 of 2

```
#
#  Particle info
#
InitializeParticles = 1
ParticleRefinement  = 2
ParticleDims = 32 32 32
```

- ParticleDims: # of particles in each dimension for this grid.
- ParticleRefinement: the sampling on this grid relative to the top grid (1 particle on this level is equal to X particles on the most refined level).

This example: 32^3 top grid + 2 x 32^3 subgrids. (Refine by 2)

Multi-grid Setup: The Dark Matter

Sub Grid
2 of 2

```
#
#  Particle info
#
InitializeParticles = 1
ParticleRefinement  = 1
ParticleDims = 32 32 32
```

- ParticleDims: # of particles in each dimension for this grid.
- ParticleRefinement: the sampling on this grid relative to the top grid (1 particle on this level is equal to X particles on the most refined level).

This example: 32^3 top grid + 2 x 32^3 subgrids. (Refine by 2)

Multi-grid Setup: Additional Parameters

Top Grid

```
#
#  Overall field parameters
#
MaxDims = 128 128 128
NewCenterFloat =  0.480763 0.674363 0.285945
StartIndex = 0 0 0
RootGridDims = 32 32 32
```

- MaxDims: the effective max dimension.
- NewCenterFloat: coordinate position of new center.
- StartIndex: index of the left grid corner.

This example: 32^3 top grid + 2 x 32^3 subgrids. (Refine by 2)

Multi-grid Setup: Additional Parameters

Sub Grid
1 of 2

```
#
#  Overall field parameters
#
MaxDims = 128 128 128
NewCenterFloat = 0.480763 0.674363 0.285945
StartIndexInNewCenterTopGridSystem = 8 8 8
EndIndexInNewCenterTopGridSystem   = 23 23 23
RootGridDims = 32 32 32
```

Left corner at 0.25, 0.25, 0.25

Right corner at 0.75, 0.75, 0.75

- StartIndexInNewCenterTopGridSystem: index on top grid of left corner of this grid (left coordinate * RootGridDim).
- EndIndexInNewCenterTopGridSystem: index on top grid of right corner of this grid (right coordinate * RootGridDim - 1).
- RootGridDims: dimension of top grid.

This example: 32^3 top grid + 2 x 32^3 subgrids. (Refine by 2)

Multi-grid Setup: Additional Parameters

Sub Grid
2 of 2

```
#
#  Overall field parameters
#
MaxDims = 128 128 128
NewCenterFloat = 0.480763 0.674363 0.285945
StartIndexInNewCenterTopGridSystem = 12 12 12
EndIndexInNewCenterTopGridSystem   = 19 19 19
RootGridDims = 32 32 32
```

Left corner at
0.375, 0.375, 0.375

Right corner at
0.625, 0.625, 0.625

- StartIndexInNewCenterTopGridSystem: index on top grid of left corner of this grid (left coordinate * RootGridDim).
- EndIndexInNewCenterTopGridSystem: index on top grid of right corner of this grid (right coordinate * RootGridDim - 1).
- RootGridDims: dimension of top grid.

This example: 32^3 top grid + 2 x 32^3 subgrids. (Refine by 2)

Multi-grid Setup: Filenames

Top Grid

```
ParticlePositionName = ParticlePositions.0
ParticleVelocityName = ParticleVelocities.0
GridDensityName      = GridDensity.0
GridVelocityName     = GridVelocities.0
```

Sub Grid 1 of 2

```
ParticlePositionName = ParticlePositions.1
ParticleVelocityName = ParticleVelocities.1
GridDensityName      = GridDensity.1
GridVelocityName     = GridVelocities.1
```

Sub Grid 2 of 2

```
ParticlePositionName = ParticlePositions.2
ParticleVelocityName = ParticleVelocities.2
GridDensityName      = GridDensity.2
GridVelocityName     = GridVelocities.2
```

This example: 32^3 top grid + 2 x 32^3 subgrids. (Refine by 2)

Make it go!

```
./inits.exe -d -s subgrid_1.par topgrid.par
./inits.exe -d -s subgrid_2.par subgrid_1.par
./inits.exe -d subgrid_2.par
```

*do an h5ls on your files to check them.

Particle files have this many particles: $N_i^3 - (N_{i+1} / 2)^3$

This example: 32^3 top grid + 2 x 32^3 subgrids. (Refine by 2)

*Keep in Mind

- Inits only runs in serial.
- For multi-grid setup, inits must create initial conditions for the entire domain at the max resolution, so RAM will become an issue.
- Multi-grid simulations require extra parameters. See John Wise's talk on Wed.

Configuring the Simulation

Problem Parameters

http://lca.ucsd.edu/projects/enzo/wiki/UserGuide/EnzoParameters#CosmologySimulation30

```
CosmologySimulationOmegaBaryonNow        = 0.0441
CosmologySimulationOmegaCDMNow           = 0.2239
CosmologySimulationInitialTemperature    = 35.0
CosmologySimulationDensityName           = GridDensity
CosmologySimulationVelocity1Name         = GridVelocities
CosmologySimulationVelocity2Name         = GridVelocities
CosmologySimulationVelocity3Name         = GridVelocities
CosmologySimulationParticlePositionName = ParticlePositions
CosmologySimulationParticleVelocityName = ParticleVelocities
CosmologySimulationNumberOfInitialGrids = 1
CosmologySimulationUseMetallicityField  = 1
```

$$T_i = 550\ K * [(1 + z_i) / (1 + 200)]^2$$

Cosmology Parameters

http://lca.ucsd.edu/projects/enzo/wiki/UserGuide/EnzoParameters#CosmologyParameters

```
ComovingCoordinates            = 1
CosmologyOmegaMatterNow        = 0.268
CosmologyOmegaLambdaNow        = 0.732
CosmologyHubbleConstantNow     = 0.704
CosmologyComovingBoxSize       = 32.0
CosmologyMaxExpansionRate      = 0.02
CosmologyInitialRedshift       = 50
CosmologyFinalRedshift         = 0
GravitationalConstant          = 1
```

Output Parameters

```
dtDataDump              = 2.5
RedshiftDumpName = RD
RedshiftDumpDir = RD
DataDumpName = DD
DataDumpDir = DD

CosmologyOutputRedshift[0] = 50
CosmologyOutputRedshift[1] = 40
CosmologyOutputRedshift[2] = 35
CosmologyOutputRedshift[3] = 30
CosmologyOutputRedshift[4] = 25
CosmologyOutputRedshift[5] = 20
CosmologyOutputRedshift[6] = 15
CosmologyOutputRedshift[7] = 10
```

Refinement Parameters

http://lca.ucsd.edu/projects/enzo/wiki/UserGuide/EnzoParameters#HierarchyControlParameters

```
StaticHierarchy              = 0
MaximumRefinementLevel       = 3
MaximumGravityRefinementLevel = 3
MaximumParticleRefinementLevel = 3
RefineBy                     = 2
CellFlaggingMethod           = 2 4
MinimumEfficiency            = 0.35
MinimumOverDensityForRefinement = 8.0 8.0
MinimumMassForRefinementLevelExponent = 0.0 0.0
```

Refinement Parameters

CellFlaggingMethod: 2, 4 (baryon, dark matter mass)
Use with:
MinimumOverdensityForRefinement
MinimumMassForRefinementLevelExponent (α)

$M_{ref} = M_{min} * r^{L*\alpha}$ r = RefineBy, L = level

*MinimumOverdensityForRefinement = 8 with RefineBy = 2 gives equal mass on each grid cell.

Refinement Parameters

CellFlaggingMethod: 6 (refine by Jeans Length)
Use with:
RefineByJeansLengthSafetyFactor ($\geq$ 4)

CellFlaggingMethod: 7 (refine when dt > t_{cool})
Use with:
RadiativeCooling = 1
(+ other chemistry/cooling parameters)

Big Sim Parameters

```
ParallelRootGridIO = 1
ParallelParticleIO = 1
Unigrid = 1
```

- ParallelRootGridIO: each processor reads in section of top grid.
- ParallelParticleIO: each processor reads in a subset of all particles. Must run ring.exe!
- Unigrid: needed for large top grids ($>512^3$).

Simple Star Formation and Feedback

http://lca.ucsd.edu/projects/enzo/wiki/UserGuide/EnzoParameters#ParametersforAdditionalPhysics

Cen & Ostriker (1992)

1. density > some critical density
2. dynamical time < cooling time
3. $M_{cell} > M_J$

```
StarParticleCreation             = 2
StarParticleFeedback             = 2
StarMakerOverDensityThreshold    = 100
StarMakerMinimumMass             = 8e6
StarMakerMinimumDynamicalTime    = 1e6
StarMakerMassEfficiency          = 0.1
StarMassEjectionFraction         = 0.25
StarMetalYield                   = 0.1
StarEnergyToThermalFeedback      = 1e-5
```

1, 1 ← Enzo 2.0

*The StarParticleCreation values are different in Enzo 2.0!

*Keep in Mind

With the Cen & Ostriker (1992) star formation/feedback method, the entire star formation history can be calculated from the last data output.

Make it go!

```
mpirun -np $NPROCS ./ring.exe pv ParticlePositions ParticleVelocities

mpirun -np $NPROCS ./enzo.exe -d my_sim.par >& estd.out
```

piping stdout and
stderr to “estd.out”

See it go!

np - available at barn.enzotools.org

```
+------------------------------------------------------------------------------+
| Mon Jun 28 12:26:17 2010                    Status: 21.38% complete.         |
+---------------- Time ------------------+ +------------- Output -----+--------+
|  Initial  |  Current  |   Final   | Units | |      |   Time    | Redshift |  Name  |
+-----------+-----------+-----------+-------+ +------+-----------+----------+--------+
| 8.163e-01 | 4.973e+01 | 2.297e+02 | code  | | Last | 4.832e+01 | 2.331244 | DD0019 |
| 4.911e+07 | 2.992e+09 | 1.382e+10 | years | | Next | 5.082e+01 | 2.218345 | DD0020 |
+-------------------------------------------+ +----------------------------------+
+--------------- Hierarchy -----------------+ +--------- Redshift ---------+
| Level | Grids |  Volume   |  Sub  |  Iter |R| | Initial | Current |  Final  |
+-------+-------+-----------+-------+-------+-+ +---------+---------+---------+
|     0 |     1 | 1.000e+00 |  ---  |   156 |<| | 50.0000 | 2.26617 | 0.00000 |
|     1 |    37 | 1.127e-01 |  ---  |    57 | | +---------------------------+
|     2 |     9 | 2.182e-03 |  ---  |    58 | |
+---------------------------------------------+
+------------------------------------------
| RebuildHierarchy[2]: Flagged 0/9 grids. 0 flagged cells
| Level[2]: dt = 0.136964  0.330137 (0.793495/0.793495)
| EvolveLevel[2]: NumberOfSubCycles = 3 (57 total)
| RebuildHierarchy: level = 1
| TransferSubgridParticles[1]: Moved 11 particles, 0 stars.
| RebuildHierarchy[1]: Flagged 9/37 grids. 378 flagged cells
| RebuildHierarchy[2]: Flagged 0/9 grids. 0 flagged cells
| Level[1]: dt = 0.290888  0.785707 (1.08438/1.08438)
| Level[2]: dt = 0.290888  0.325863 (0.290888/0.290888)
| EvolveLevel[2]: NumberOfSubCycles = 1 (58 total)
+------------------------------------------
```

Warning: do not stare!

Enzo Cosmology Units

- Length: ComovingBoxSize/HubbleConstantNow / (1+z)
- Density: ρ_0 * $(1+z)^3$
- Time: 1 / sqrt(4 * Pi * G * ρ_0 * $(1 + z_i)^3$)
- Temperature: K
- Velocity: (Length/Time) * (1 + z) / (1 + z_i)

(z independent)