Adaptive Mesh Refinement for multi-fluid simulations of the processes in the solar atmosphere

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Outline

1. Overview of Adaptive Mesh Refinement (AMR)

2. Paramesh

3. Paramesh use cases

Description of structured AMR

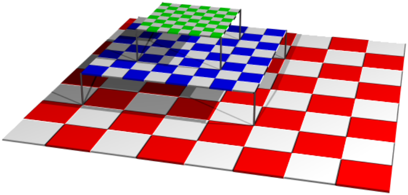

Figure: Graphical representation of AMR refinement levels (from http://www.lsc.phy.cam.ac.uk/research/amr.shtml)

- Method for dynamically (de)refining the grid resolution.
- Allows simulations with large length and time-scales.
- Increased computational savings over a static grid approach.
- Increased storage savings over a static grid approach.
- Eeach mesh can be advanced independently using its own time step.
- Strict conservation by matching fluxes at grid boundaries.
- Easily parallelizable due to the logically rectangular patches.

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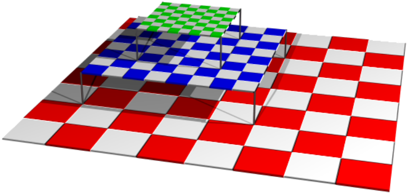

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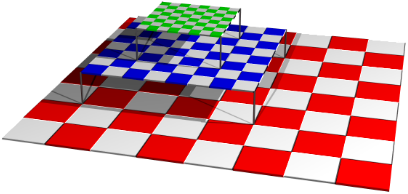

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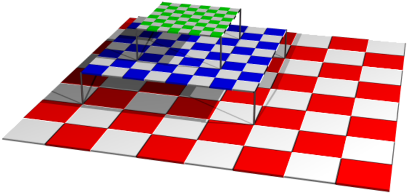

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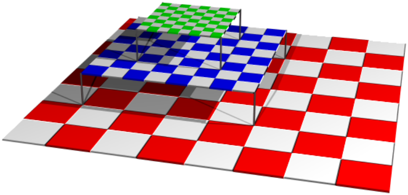

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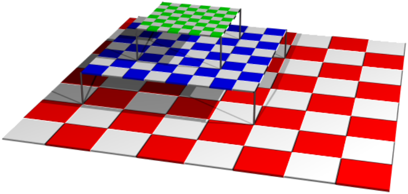

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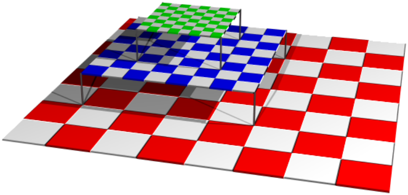

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Some existing AMR packages

- Many non-generic AMR packages: Pluto, Enzo, Uintah, RAMSES, NIRVANA, A-MAZE, FLASH, AstroBEAR, ...
- Some generic structured AMR packages

Table: Generic AMR packages

Package name	Prog. language	Actively developed?
AMRClaw	F77,F90, Python	Last: January 2013 (Part of Clawpack)
ForestClaw	F77,F90, Python, C	In development, not yet available.
AMROC	C++	Last: November 2004
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Chombo	C++	Last: March 2012
Paramesh	Fortran90	Last: March 2008. Support stopped.
SAMRAI	C++	Last: January 2013

  - Freely available (to run and to visualize output)
  - 2D and 3D.
  - Multi-stepping
  - Parallel (OpenMP and/or MPI)

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Paramesh

Main characteristics

- Parallel (MPI) Adaptive Mesh Refinement (Fortran 90 and C)
- Multidimensional
- Structured Grid Blocks
- Portable
- User Tunable Load Balancing
- Support for Conservation Laws
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Paramesh

Basic usage

Define the models dimensionality, properties of each grid block, etc. (amr_runtime_parameters)

```
50                          ! maxblocks
2                           ! ndim
0                           ! l2p5d
124                         ! nxb
124                         ! nyb
1                           ! nzb
164                         ! nvar
[...]
5                           ! nguard
[...]
2                           ! nboundaries
.true.                      ! diagonals
.true.                      ! amr_error_checking
```

Paramesh

Basic usage (2)

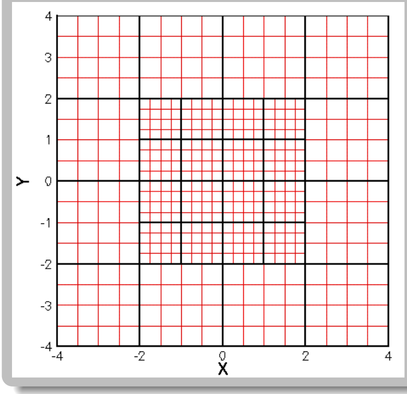
Set up initial grid (sizes, locations, neighbours, boundaries)

```
lrefine_max = 10           ! finest refinement level allowed
lrefine_min = 6            ! coarsest refinement level allowed

if(mype.eq.0.) then
    bnd_box(1,1,1) = 0.    ! lower x bound of block 1
    bsize(1,1) = bnd_box(2,1,1) - bnd_box(1,1,1)
    coord(1,1) = .5*(bnd_box(2,1,1) - bnd_box(1,1,1))
    nodetype(1) = 1        ! identify block 1 as a leaf block
    lrefine(1) = 1         ! set refinement level of block 1
    neigh(1:2,1,1) = -21   ! left boundary condition
    lnblocks = 1           ! no. of blocks on this processor
 endif

! x boundaries
boundary_box(1,2:3,1:2) = -1.e30 ! effectively this is -infinity
boundary_index(1)       = -21
```

Paramesh

Basic usage (3)

Sample mesh



Mesh details

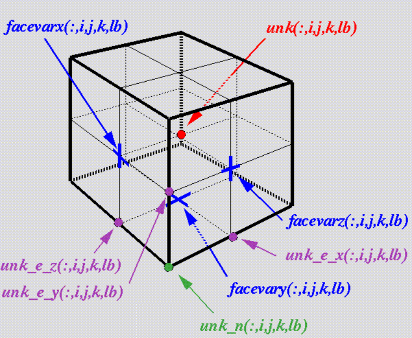
- All grid blocks identical logical structure
- Logically cartesian
- When refined, a block spawns 4 child blocks (2D), same area but twice spatial resolution
- Neighbour leaf blocks differ at most by one refinement level

Paramesh

Basic usage (4)

Use pointers in our code to link to Paramesh data structures

```
REAL(KIND=fp), DIMENSION(:,:), POINTER :: te, pe, rho
[. . .]
te => unk(1,:,:,1,block)
pe => unk(2,:,:,1,block)
rho => unk(3,:,:,1,block)
```



Paramesh

Basic usage (5)

Load initial solution and evolve

```
time = 0.
call initial_soln(mype)

do loop=1,ntsteps
    call amr_guardcell(mype,iopt,nlayers)

    ! advance and amr_test_refinement: user defined
    call advance(mype,dt,time,nprocs,loop)
    call amr_test_refinement(mype,lrefine_min,lrefine_max)

    call amr_refine_derefine
    call amr_prolong(mype,iopt,nlayers)
enddo

call amr_close()
```

Multi-grid example

Whole domain

Detail

Adaptive mesh example: Rayleigh-Taylor instability

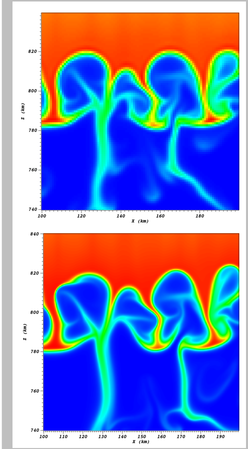
Whole domain

Detail

Adaptive mesh example: RTI

Mesh refinement dynamics

Grid dynamics

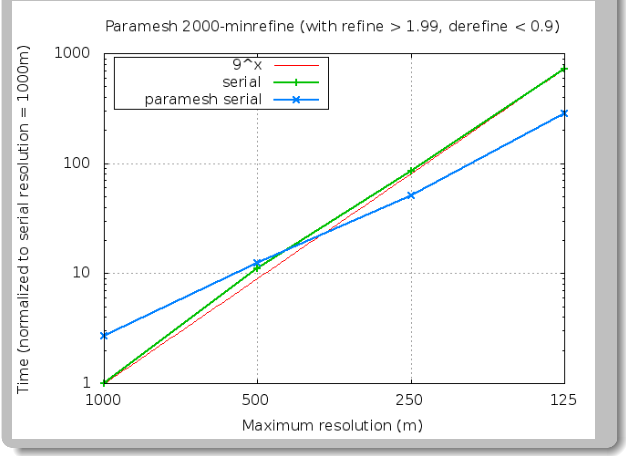


- It works! But is it worth it?

Adaptive mesh example: RTI

Paramesh computation overhead

Serial code vs. Paramesh (serial)



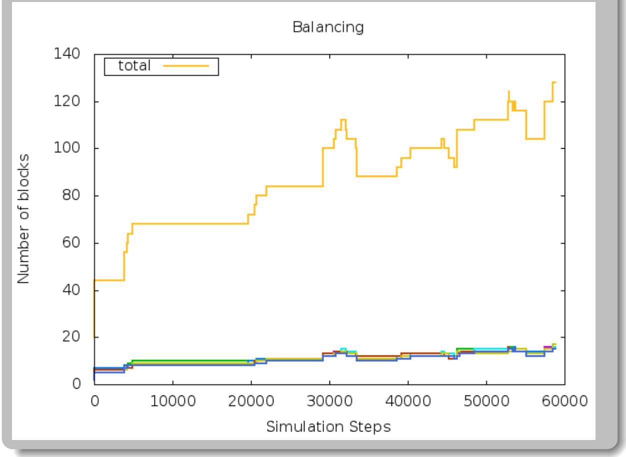
Notes

- Paramesh minimum levels of refinement: 2
- Performance will greatly depend on refinement details.

Adaptive mesh example: RTI

Grid blocks distribution

Blocks balance across 8 processors



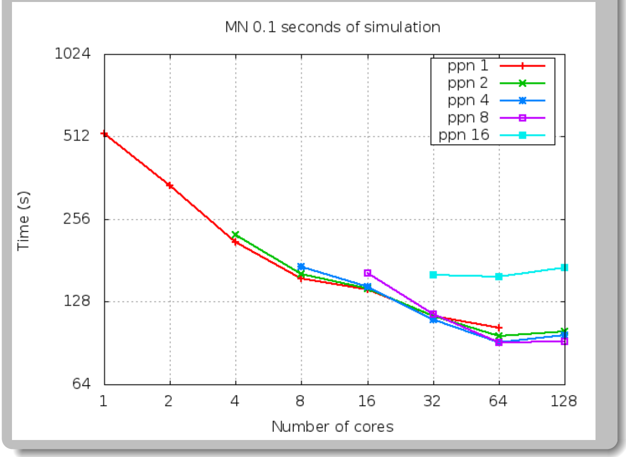
Notes

- Blocks are being created and destroyed dinamycally
- Number of blocks in each processor well balanced throughout

Adaptive mesh example: RTI

Parallel performance

Scalability in MN



Notes

- Poor scalability in single node due to cache misses (also present in serial and MPI versions)
- Poor scalability across nodes due to high communication requirements
- Cache misses have even bigger impact than network communication
- Parallel performance similar to that of own MPI version

On-going work

Variable Timestep

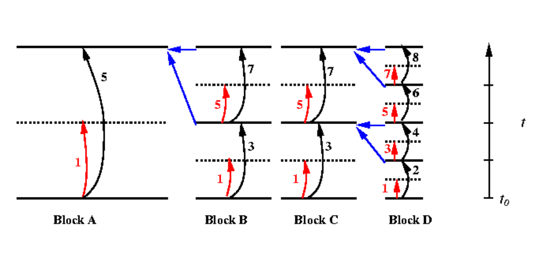


Figure: Variable timestep flow-chart (from http://www.physics.drexel.edu/~olson/paramesh-doc/Users_manual/amr_variable_dt.html)

Notes

- Need loads of extra storage
- Flow-chart can get quite complex
- Now not all blocks do the same work: block balance?

Conclusions

- Adding Paramesh not too difficult (specially if starting from scratch)
- CPU overhead quite large, so we need to be carefull when defining the refinement function if we are to get performance gains
- Memory overhead not too large for constant timestep, but quite large for variable timestep
- Minor drawback: blocks are not dinamycally allocated, but rather fixed in amr_runtime_parameters
- Paramesh has other features that we didn't discuss: divergenceless prolongation, conservation laws, checkpointing, ...

References

- Adaptive mesh refinement for hyperbolic partial differential equations - M. Berger, J. Oliger - J. Comp. Phy. 1984 http://www.sciencedirect.com/science/article/pii/0021999184900731
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- Paramesh V4.1 webpage: http://www.physics.drexel.edu/õlson/paramesh-doc/Users_manual/amr.html