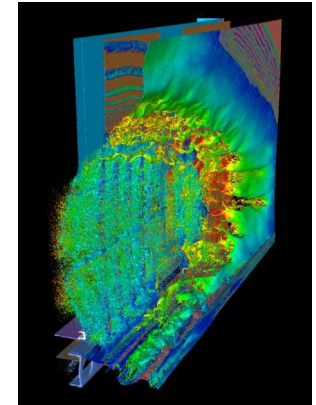
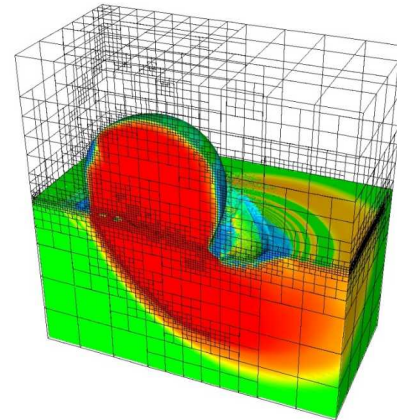
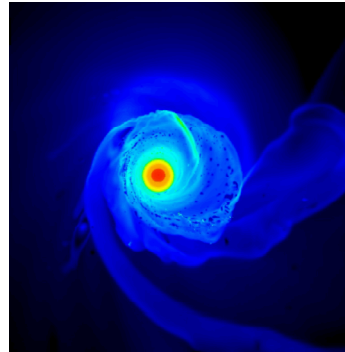
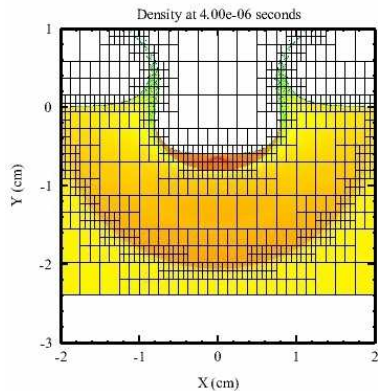


Exceptional service in the national interest



A Decade of Adaptive Mesh Refinement in CTH

New Models and Hydrocodes for Shock Wave Processes

23-27 April, 2012

David Crawford

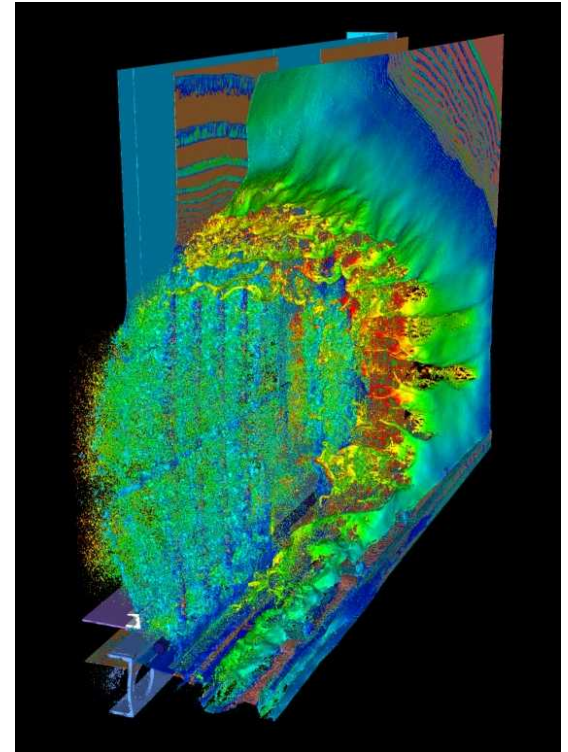


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CTH Overview

CTH is a massively-parallel shock-physics code

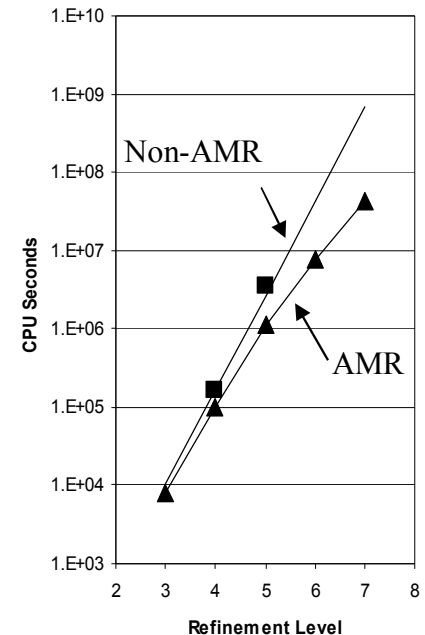
- Explicit Eulerian shock-physics code (hydrocode)
 - Solves conservation equations of mass, momentum, and energy
 - Up to 98 simultaneous materials
 - Gases, fluids, solids, reactive materials
 - Analytic & Tabular Equation-of-State representations
 - Advanced Strength & Fracture models
 - Adaptive Mesh Refinement (AMR)
- Applications (partial list):
 - Armor, Anti-Armor, Conventional Munitions Design, Blast Effects
 - Planetary Science, Asteroid Impact & Planetary Defense
- CTH licensed to U.S. government agencies and their subcontractors and U.S. academic institutions
 - 600+ users
- www.sandia.gov/CTH



32,000 processor
calculation showing
nearby blast on aluminum
and steel structure

Introduction

- Adaptive mesh refinement (AMR) was added to CTH in 1998-2001
 - Presented at NMH in Edinburgh (2002)
 - In 2002 we could see ~10x performance gain (vs. non-AMR) on the largest problems
- Today we routinely see 10x performance gains...
 - ...and an extrapolation using Moore's Law suggests we should see 20-30x today on the largest problems.
 - (about a factor of two for every ten years)
- *However, we occasionally see 200-300x on the largest problems...why?*

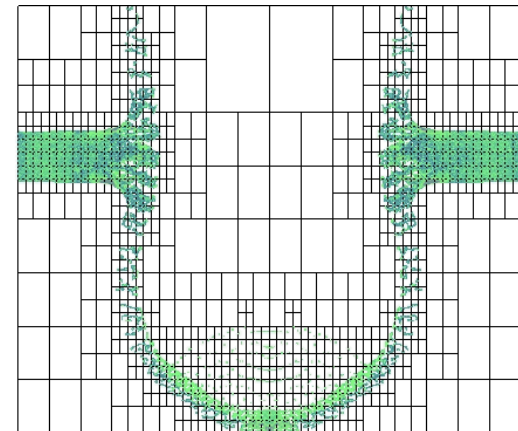
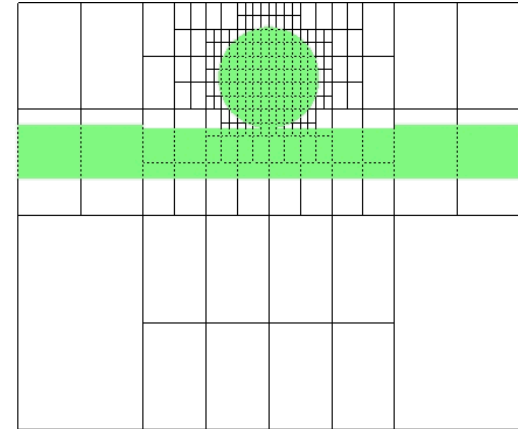


CTH performance
on a heroic problem
in 2001

Adaptive Mesh Refinement in CTH

we use a simple approach

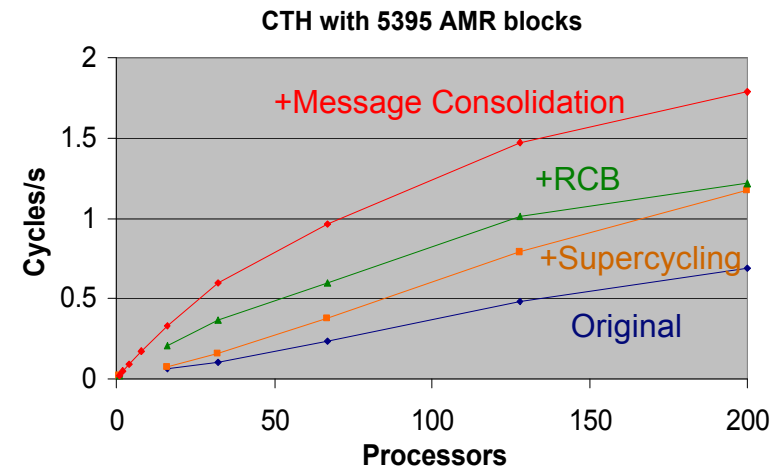
- Block-based
- Identical logical mesh per block
 - 8x8x8 is typical
 - 10x10x10 with ghost cells
- Isotropic 2:1 refinement
- Single time-step for all blocks
- Load balance on per-block basis
- User-definable refinement indicators
- Problem initialized via iterative refinement/load balance step



Achieving Parallel Performance

with our simple approach

- Parallel process block refinement and unrefinement as much as possible by supercycling
 - Every 3 cycles for refinement
 - Every 6 cycles for unrefinement
- Perform load balancing only when disparity is more than 10%.
 - Smaller tolerance when memory resources are tight
- Use Recursive-Coordinate-Bisection (RCB) algorithm to minimize off-processor communications.
- Consolidate message passing to reduce latency



AMR since 2002

- Surprisingly little has changed:
 - Added the ability to refine based on advanced material constitutive properties such as “damage”.
 - Added a spherical region to indicators.
 - Fixed some minor bugs appearing at boundaries
 - Increased number of allowable indicators (to 100 from 10)
- We provided sufficient flexibility in the original design
 - The “style of use” has changed
 - New guidelines for indicator design have evolved
- Flexible, user-defined indicators appear to be the most important aspect of AMR success in CTH

User-Defined Indicators

Where/When Refinement Will Happen

Indicator consists of:

- 1) Filters for materials,
time, resolution or
space

- 2) Operator

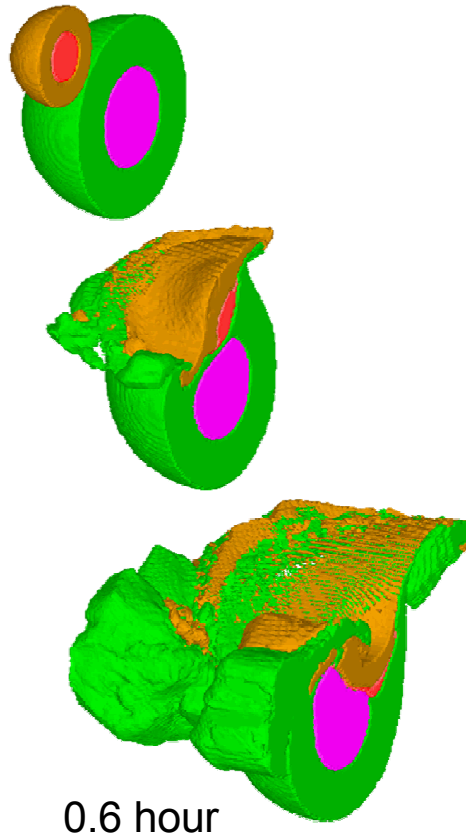
val, abs, diff, grad

- 3) Database Field

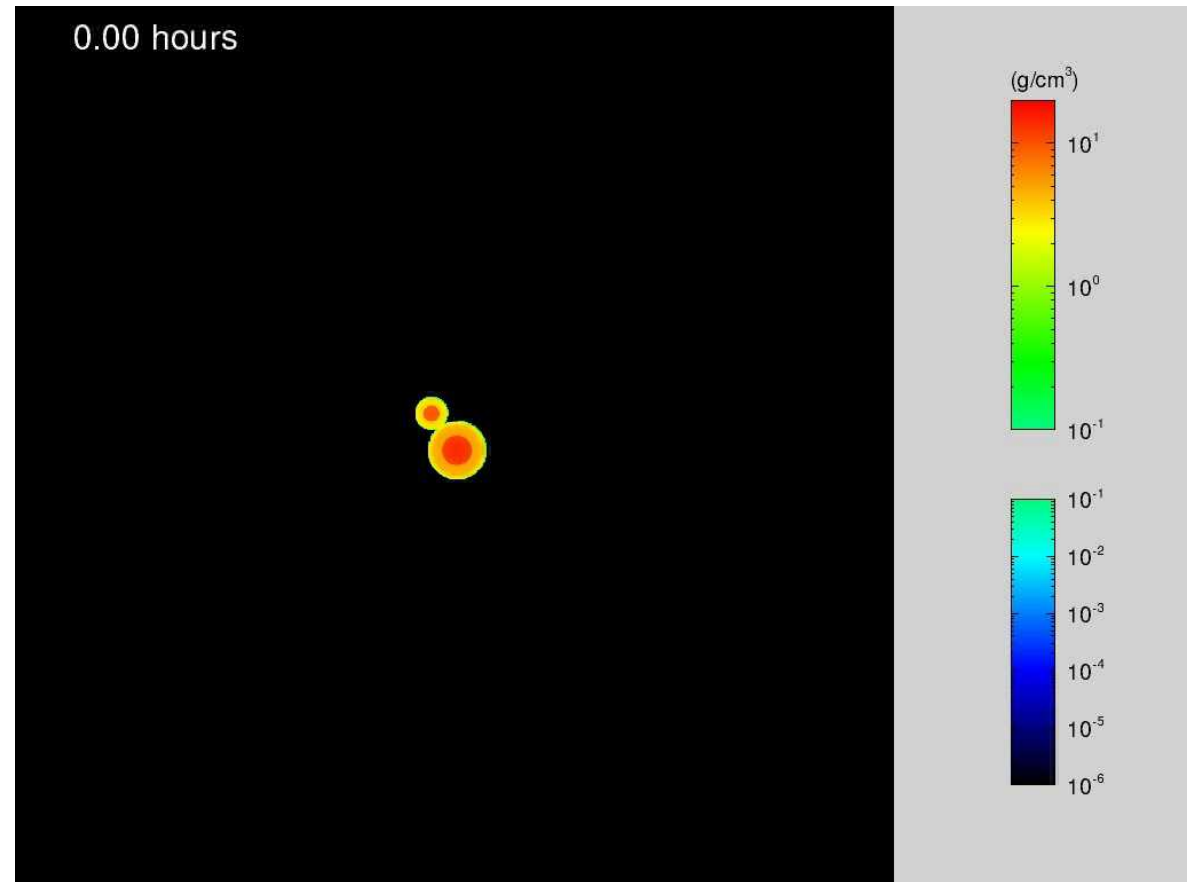
- 4) Threshold(s)

```
indicator
  mat 2
  max1 -3
  p1 = 0, 5, 5
  p2 = 5, 15, 30
  val vmag
  refabove 10
endi
```

Hypothesized Formation of the Moon by Giant Impact early in Earth's history



0.6-hour CTH simulation with central gravity, 3-million zones, Melosh and Kipp (1988)



54-hour, AMR-CTH simulation with self-gravity, 40 million zones, equivalent to 20 billion zones without AMR (2011)

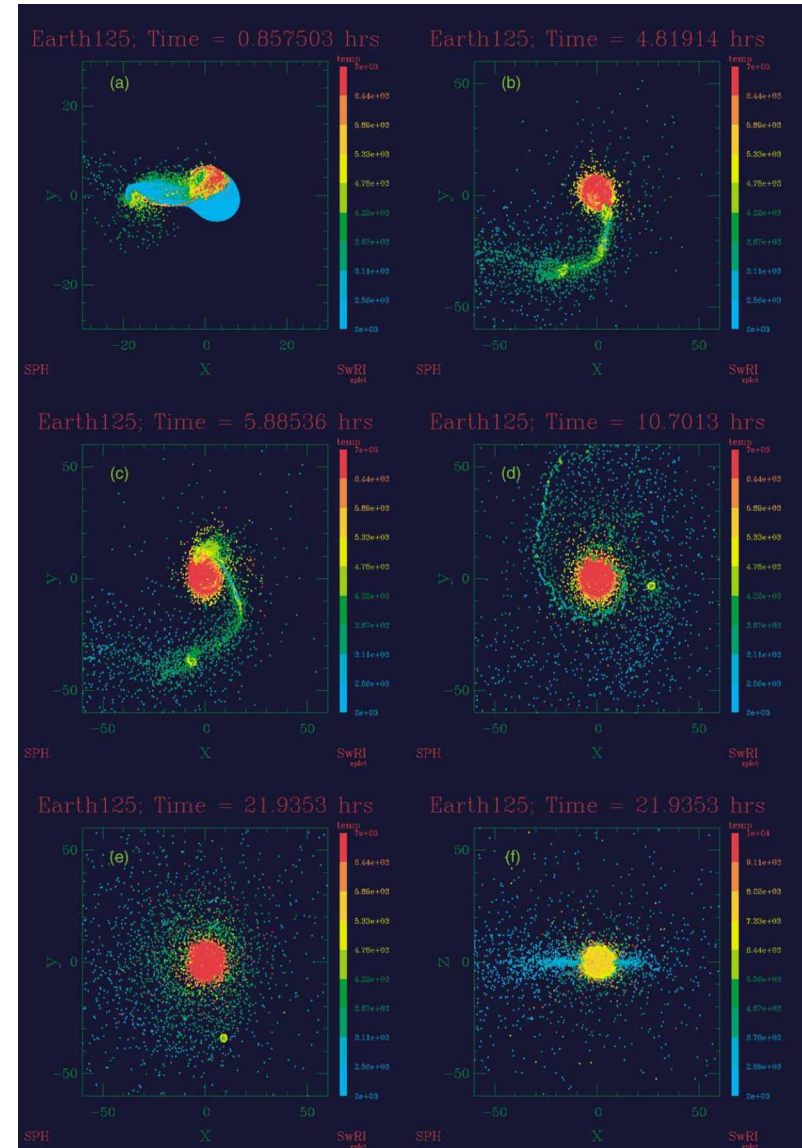
- 500x memory gain, 200-300x performance gain

Giant Impacts

SPH simulations

- SPH has long history for these simulations
- Equal mass per particle
- $10^6 - 10^7$ particles provide adequate resolution

R. M. Canup, *Simulations of a late lunar-forming impact*, **Icarus**: 168 pp. 433–456, 2004.

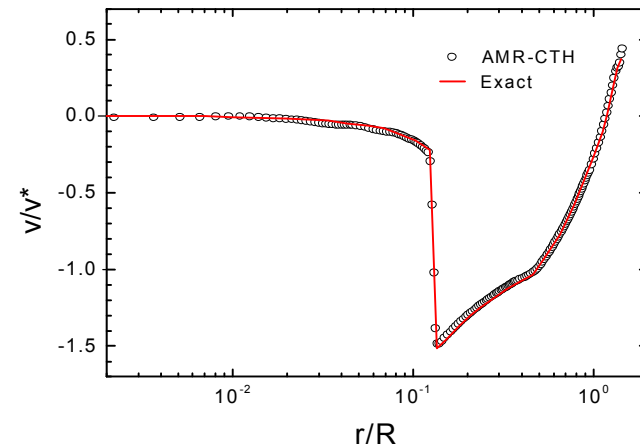


AMR indicators for equal mass approximation

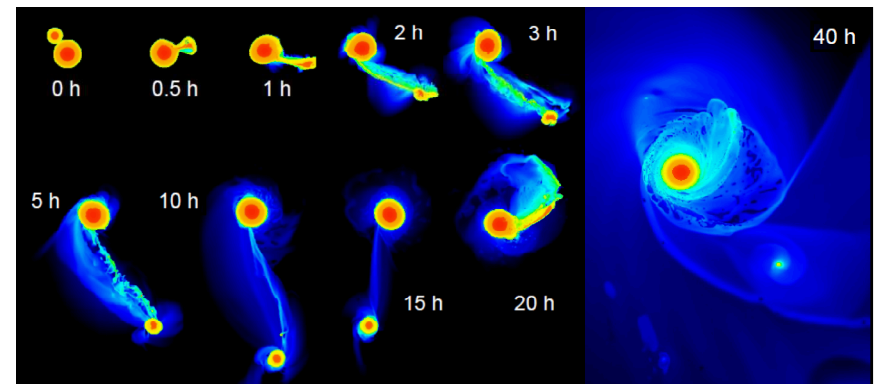
```
indicator
  val density
  refabove 1e-2
endi
```

```
indicator
  maxl -1
  val density
  refabove 1.25e-3
endi
```

...



Verification: adiabatic collapse of an initially isothermal spherical gas cloud.



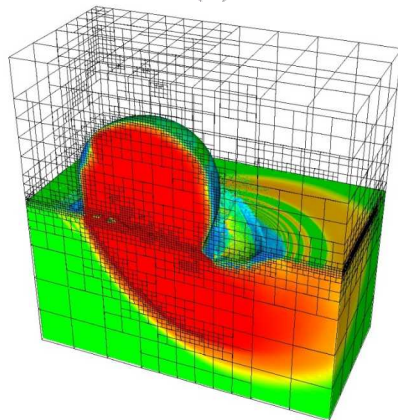
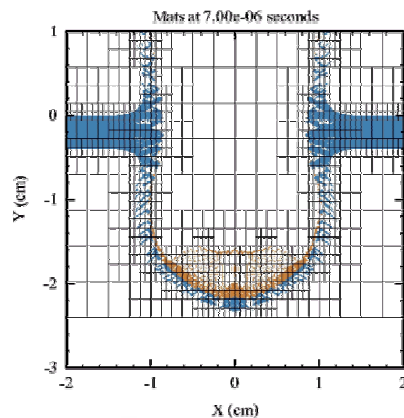
$10^6 - 10^7$ AMR zones provide adequate resolution for giant impact simulations

AMR-CTH vs. SPH for Giant Impacts

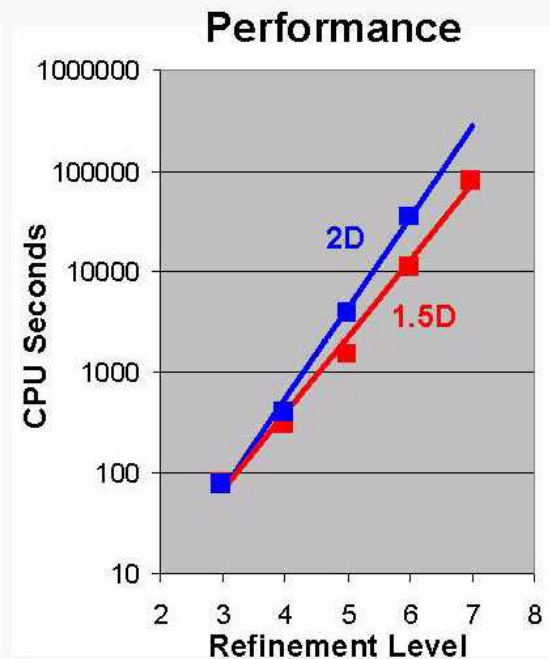
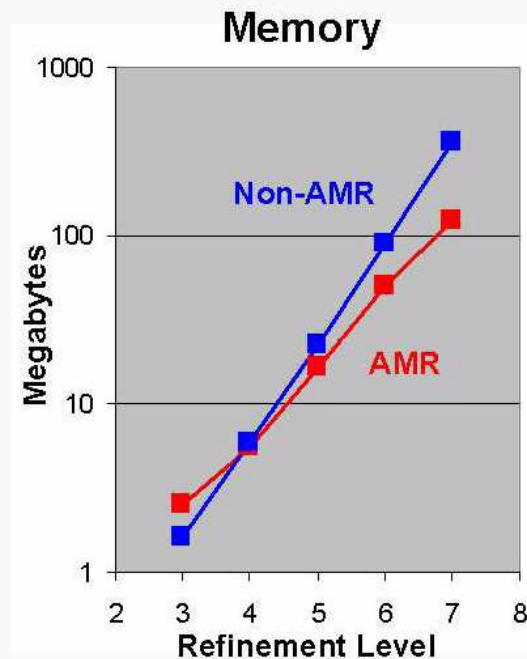
- We're seeing good agreement in answers
- *...and comparable performance...*
- R. M. Canup, A. C. Barr and D. A. Crawford, *Lunar-forming impacts: High-resolution SPH and AMR-CTH simulations, Icarus* (submitted)

An overlooked AMR scaling paradigm?

- Our 2002 view of AMR scaling:
 - High resolution mesh concentrated along sub-dimensional regions (curves in 2-D, surfaces in 3-D)

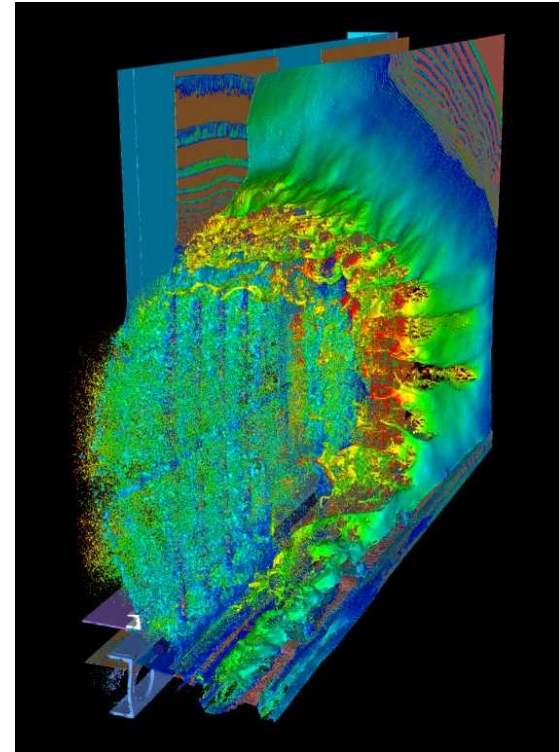


2D AMR CTH (bumper shield calculation)



An overlooked AMR scaling paradigm (cont)?

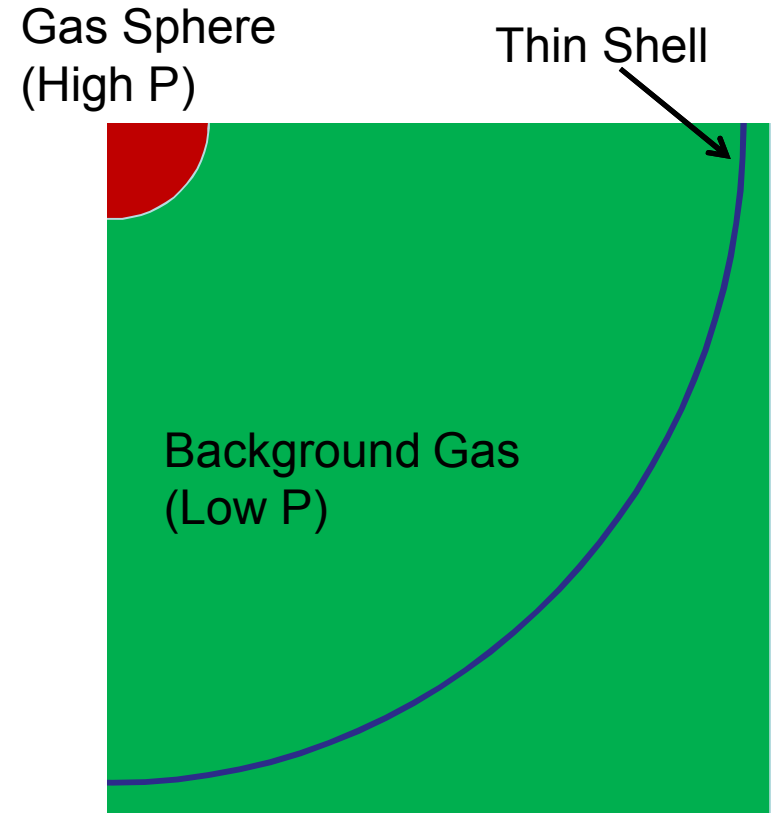
- Indicators based on:
 - density or
 - presence of particular materials or
 - with spatial or temporal filters
- Can provide dramatic performance gains in many circumstances
- Without requiring detailed understanding of indicators tied to the underlying physics
- Many users apply the above strategy...*but how accurate is it?*



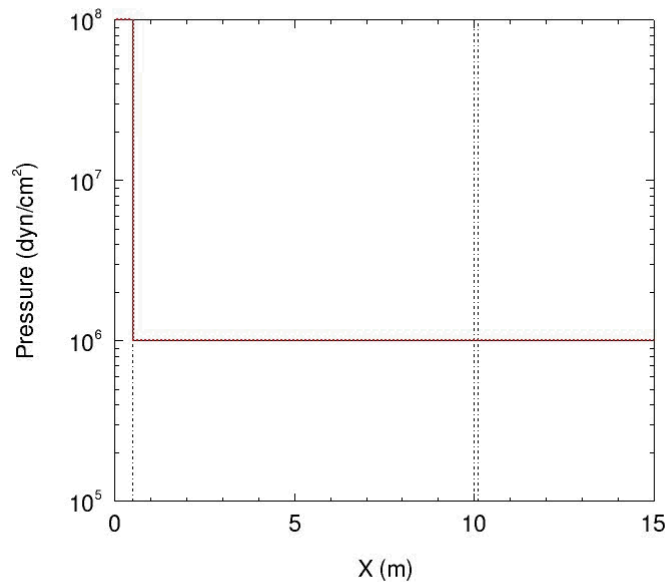
32,000 processor
calculation showing
nearby blast on aluminum
and steel structure

Modified Sedov Blast Wave

- Approximation of blast/structure problem
 - High P gas sphere
 - Low P background gas
 - Modified to impinge shock on a thin spherical shell
 - Measure momentum of shell
- Use AMR to resolve different regions of the problem:
 - High P gas
 - Background gas
 - Thin shell

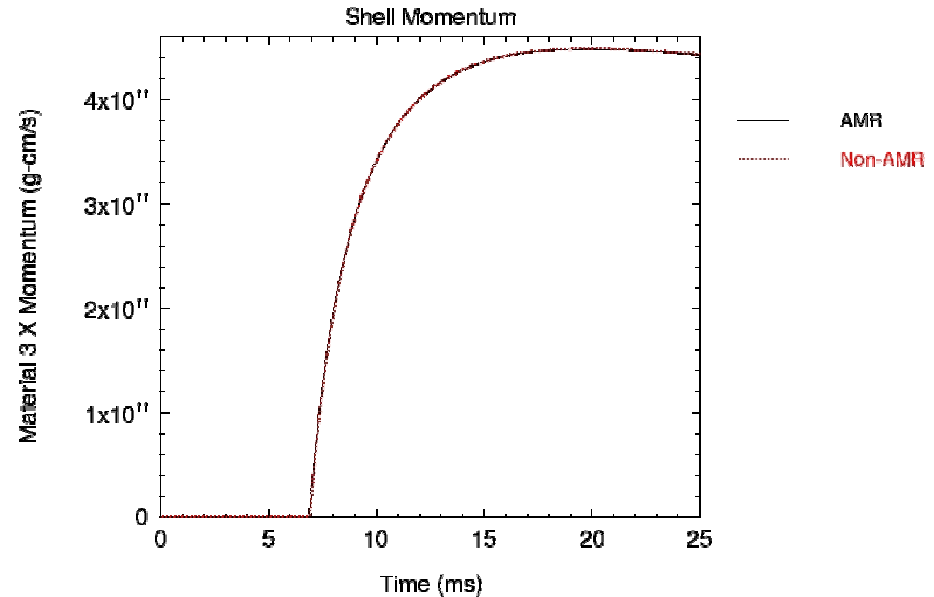


Modified Sedov Blast Wave (cont.)



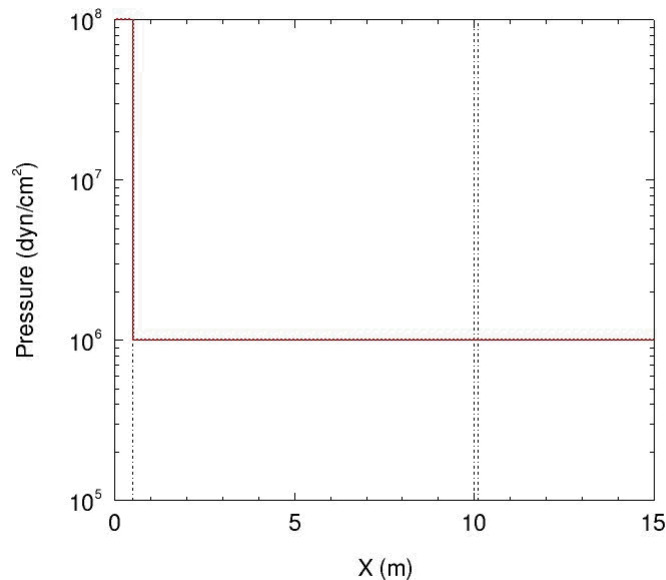
AMR at 0.000e+00 s.

Non-AMR at 0.000e+00 s.



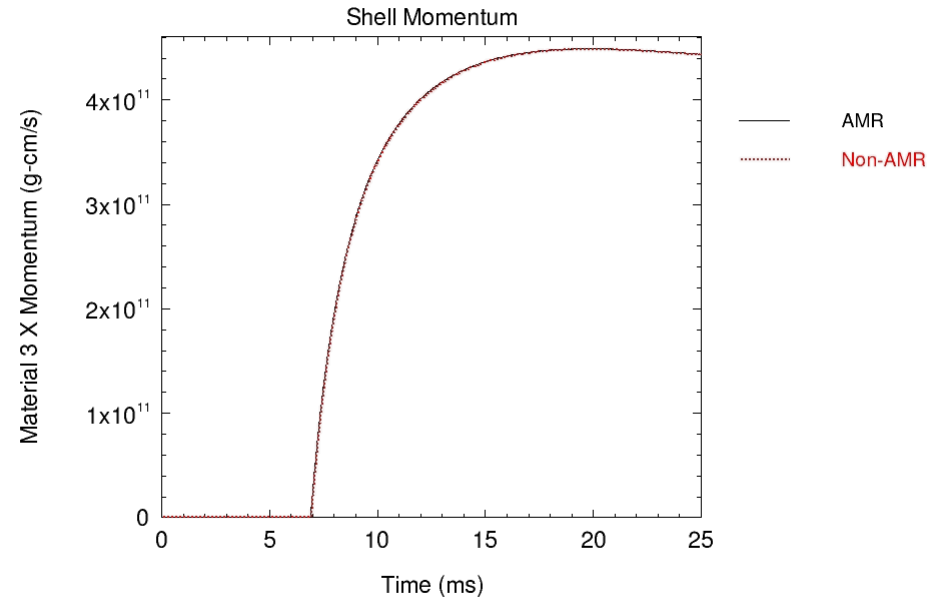
- 1 m sphere
- 10 cm shell
- 10 m standoff
- Uniform Resolution
- AMR & Non-AMR using same effective grid (1 cm)

Modified Sedov Blast Wave (cont.)



AMR at 0.000e+00 s.

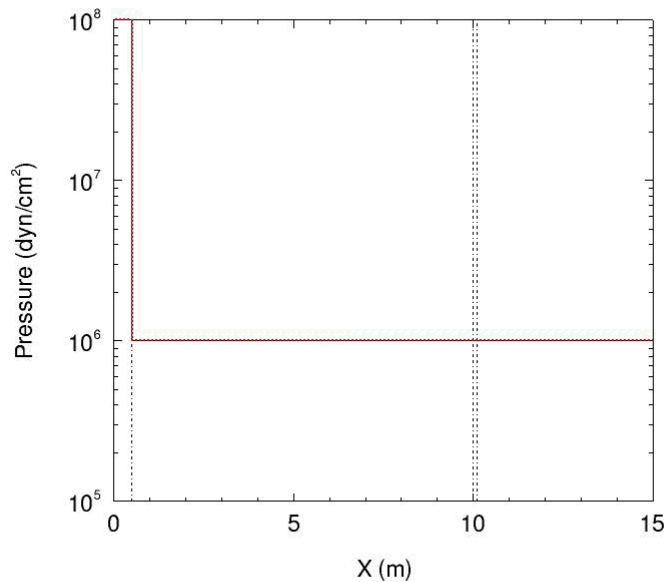
Non-AMR at 0.000e+00 s.



- 1 m sphere
- 10 cm shell
- 10 m standoff

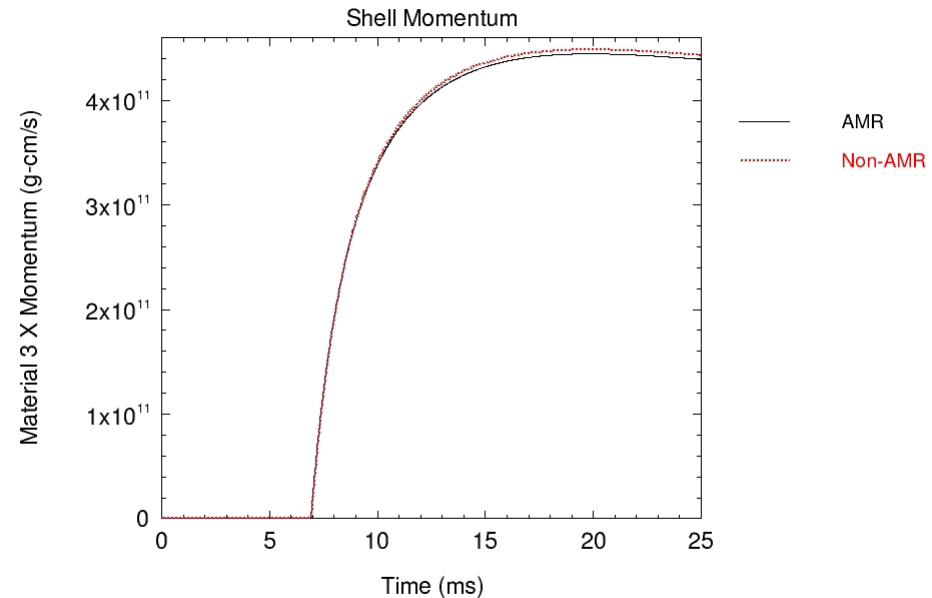
- Non-AMR using uniform 1-cm grid
- AMR:
 - 0.5 cm grid on sphere
 - 1-cm grid on shell and background

Modified Sedov Blast Wave (cont.)



AMR at 0.000e+00 s.

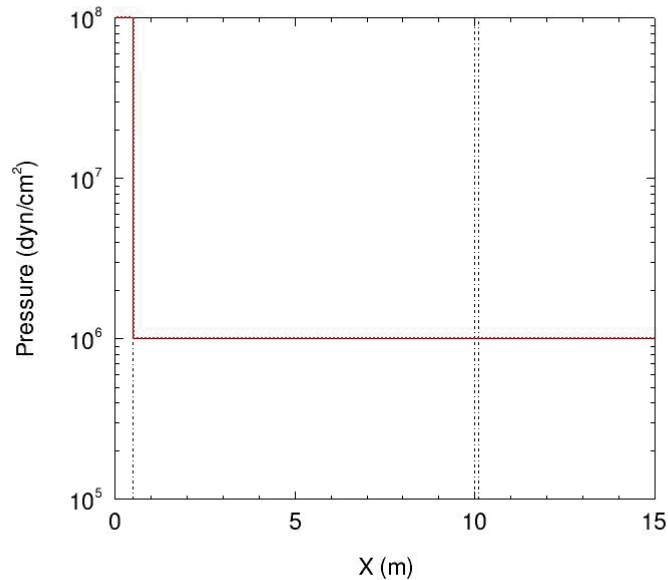
Non-AMR at 0.000e+00 s.



- 1 m sphere
- 10 cm shell
- 10 m standoff

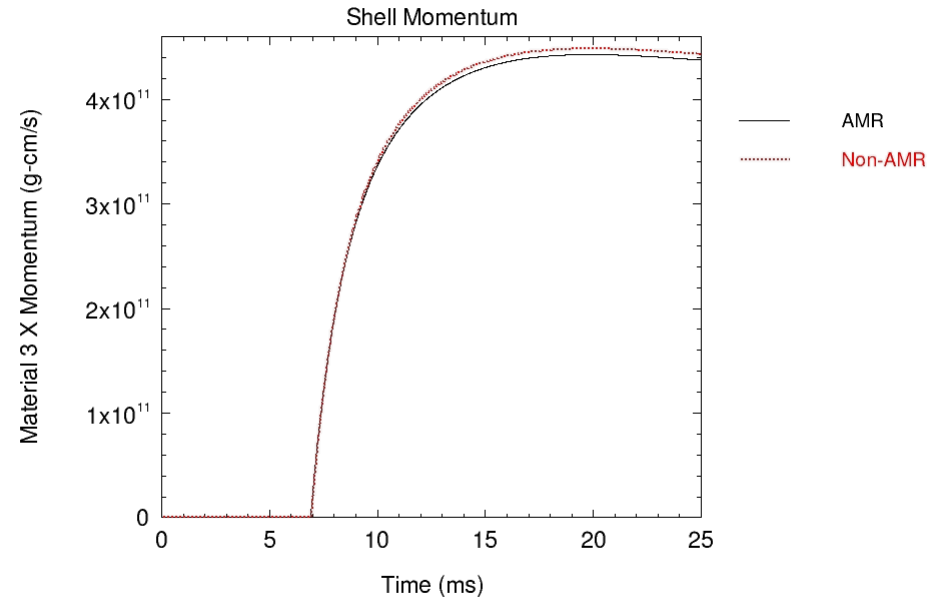
- Non-AMR using uniform 1-cm grid
- AMR:
 - 0.5 cm grid on sphere and shell
 - 1-cm grid on background

Modified Sedov Blast Wave (cont.)



AMR at 0.000e+00 s.

Non-AMR at 0.000e+00 s.



- 1 m sphere
- 10 cm shell
- 10 m standoff

- Non-AMR using uniform 1-cm grid
- AMR:
 - 0.25 cm grid on sphere and shell
 - 1-cm grid on background

Modified Sedov Blast Wave

conclusions

- Shock reflections occur when transitioning from low to high resolution mesh
 - Typical error of momentum *delivered to the plate* is less than 3%
 - Provided background mesh is well resolved to begin with
- Active area of research
 - Higher order refinement schemes
- Problem dependent
 - Importance of user validation

Conclusions

- AMR-CTH has had a successful decade
 - Increasingly used for production computing on large 3-D problems
- Order of magnitude performance advantage is routinely seen
 - In some cases 200-300x performance advantage is seen
- User-defined indicators are an important aspect of AMR-CTH
 - Our users helped us find some of these dramatic performance gains
 - Accuracy can be an issue if naïve indicators used
 - We've always known propagating shocks across resolution boundaries can cause reflections
 - Improving accuracy across resolution boundaries is an ongoing area of research