# 35 ~~25~~ Years of Algorithms for Inertial Confinement Fusion

**Presented to:**

**The Conference on HIGH SPEED COMPUTING**

**Salishan Lodge, Gleneden Beach, OR**

**George B. Zimmerman**

**AX Division, Defense & Nuclear Technologies**

**Lawrence Livermore National Laboratory**

**April 20, 2004**

This work was performed under the auspices of the U.S. Department of Energy by the University of California Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94551-0808

# Algorithms must fit the Applications & Architectures

- APPLIED science always starts with the application
  - Can't just find a problem for the solution at hand
- Real world applications grow increasingly complicated with time
  - At first 1-D scoping studies – does the concept make sense?
  - Then 2-D realistic runs – do symmetry & stability matter?
  - Finally 3-D engineering details – is it worth $2B to build?
- We can influence architectures, but also must use what is here now
  - CDC 7600 serial # 1 to ASCI White & Q
  - Scalar, vector, SMP & distributed parallel

**Boundary conditions on ICF algorithms have changed over 35 years**

# Let's not forget the importance of Language

- **Assembly, Fortran, Stacklib, functional, OO, OpenMP, MPI**

Algorithms
Architecture
Language

*The Conference on*

**HIGH SPEED COMPUTING**

**LANL/LLNL**

**This logo from the '80s held language as a cornerstone**

# CDC 7600 was a cache like machine

- Dual memory architecture
  - LCM – large core (slow) memory
  - SCM – small core (not quite so slow) memory
- Programmer had to determine what data was in each memory
- Memory bank latency was like cache miss latency
  - Never access memory using stride 8
  - Make sure offset between arrays was odd (to use all banks)
  - Best to access sequentially (block copy)
- Efficient coding was riddled with block copy instructions

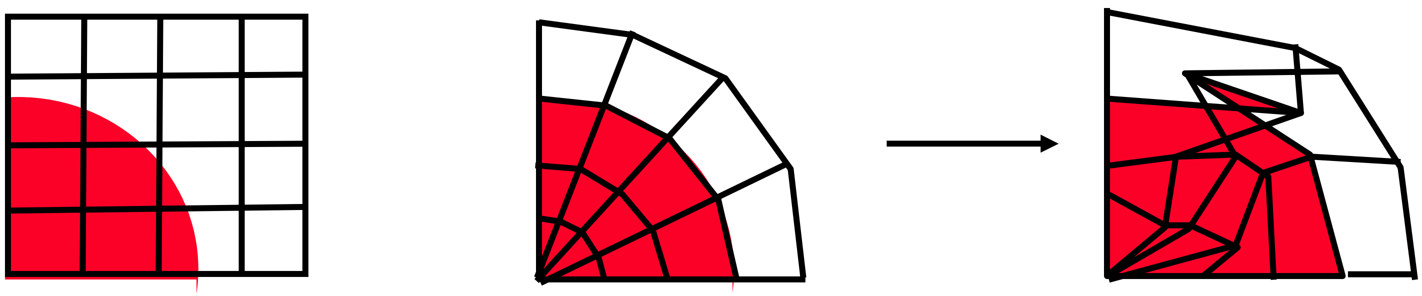
**The cost of ignoring cache today can be large, but at least it doesn't require explicit coding**

# ICF algorithms have changed in every area

- Hydrodynamics
  - Euler, Lagrange, arbitrary connectivity, ALE, AMR
- Laser deposition
  - "1-D", ray trace, Maxwell solver
- Electron transport
  - Conduction, 2 group, multi-group, non-local, Monte Carlo
- Atomic physics (EOS & opacity)
  - LTE tables, non-LTE, hydrogenic, SCA, DCA, response matrix
- X-ray, neutron & alpha particle transport
  - 1 group diffusion, multi-group diffusion, Sn, Monte Carlo
- Steerable user interface
  - Generation, diagnosis, post processing, mesh motion, physics

# Hydrodynamics methods were dictated by the ICF application requirements

- ICF high compressions (1000X) require Lagrange type mesh motion
- 2-D Lagrange mesh tangling
  - Required hand rezones were heroic & inaccurate (1st order)
  - Early SALE methods helped some

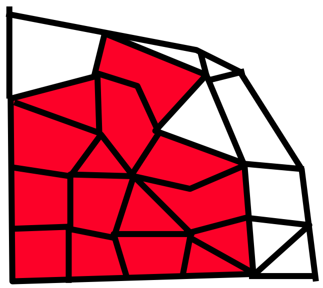


Euler Lagrange

**Lagrange + hand rezoning was not going to work in 3-D**

# The 3-D plan (1990) was Free Lagrange

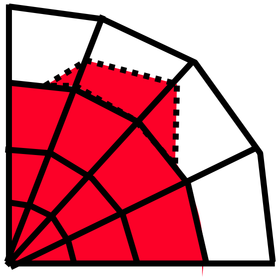
- **Reconnection would allow a Lagrange mesh to conform to complicated flows without tangling**
- **Finite element methods would be used for accuracy on the arbitrary mesh**
- **C++ (or other OO language) would allow us to manage the mesh & its changing connectivity**
- **Complicated initial geometries would be easier with arbitrary connectivity**
- **Dynamic mesh refinement would be possible**



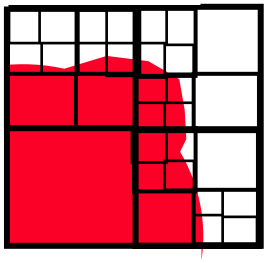
**But Free Lagrange was overtaken by the ALE stampede**

# ALE & AMR provide dynamic resolution

- **ALE moves the zones where they are needed**
  - **Moving nearly with the fluid is usually pretty good**
  - **Simple flows are Lagrange**
  - **Interface reconstruction minimizes numerical diffusion**
- **AMR creates a more refined mesh level when needed**
  - **May require spherical coordinates to obtain good symmetry**
  - **By far the simplest method to initialize**
- **Putting both together is possible**
- **Both can cause load imbalance in domain decomposed parallel runs**



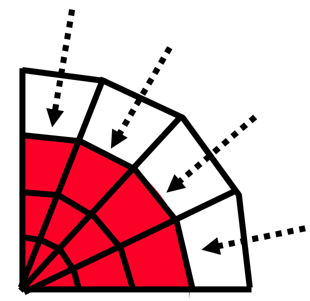
**ALE**



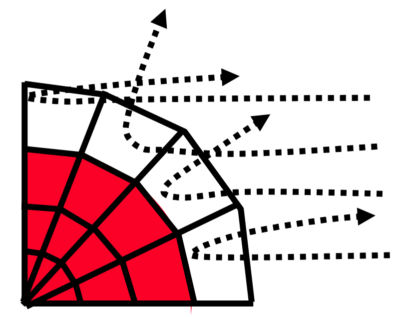
**AMR**

# Laser deposition models respond to application

- Simple ODE solved down each K-line was adequate to launch ICF research
- One sided illumination required 2D ray tracing
  - Geometrical optics requires continuous index of refraction
  - Noisy when rays hit or miss zones
  - “Impossible” to vectorize & difficult to load balance when domain decomposed
- Short pulse lasers (100 fs) required Maxwell solvers
  - No time to expand & make underdense plasma
  - Requires wavelength resolution
- Hybrid methods can use WKB in one region, Maxwell in another



1-D method



ray trace

# Sometimes life gets easier

- Lasers of the early ’70s required more physics modeling
  - High intensity and long wavelength (>1μ)
  - Initiated plasma instabilities => hot non-thermal electrons
  - 2 group & multi-group diffusion provided crude answers
- Fortunately, ½ & 1/3 μ light
  - Were required to achieve high compressions
  - Saved us from having to better model electron transport
- Electron transport with self consistent E & B fields over large ranges in time, space & density scales
  - Needed to explain measured reduction of electron heat flow
  - Models are still being invented -- non-local, Monte Carlo?

**But today’s higher fidelity simulations still require better models**

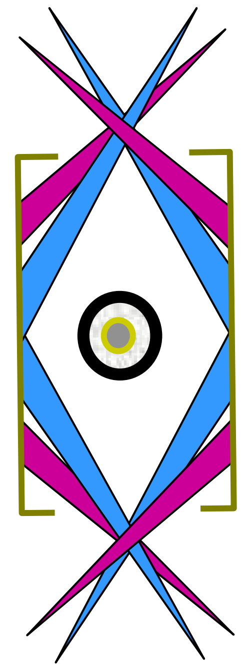
# Atomic physics (EOS & Opacity) are embarrassingly parallel

- In LTE they are just "simple" functions of T, $\rho$ & composition
  - Expensive (non-simple) models can be tabulated
  - Frequency dependent tabulated opacities (1 Mb/composition) are tiny on today's platforms
  - Simple composition variations (Cu doped Be) can be interpolated, but in general it is a high dimensional space
- Can even tabulate "near" LTE systems using response matrix
- Most non-LTE models solve strongly coupled ODE population rate equations ($10\text{-}10^4$) for each material in each cell
  - Accuracy / CPU time tradeoff is very problem dependent
  - Splitting off v*grad term from ALE keeps all cells independent

**But splitting off v*grad is inaccurate for stiff systems**

# Full multi-dimensional transport of X-rays is required for Indirect Drive ICF

- Multi-group diffusion
  - Is adequate for preheat of capsule, but cannot simulate hohlraum symmetry
  - Requires stiff matrix solve both in space and frequency
  - Most outer iteration accelerators (like Grey DSA) can SMP parallelize over groups
  - Inner iteration of single group diffusion vectorizes (ICCG with cyclic reduction or analytic multi-grid)
  - Domain decomposed codes might want to invert the iterations
- Sn methods
  - Require some fix for ray effects to handle symmetry of capsule implosions
  - Can parallelize in several ways in its high dimensional space



# In the past we have talked about the virtues of various parallelization strategies

**NONREPRODUCIBILITY**

**George B. Zimmerman**

**High Speed Computing Conference**

**March 10-13, 1986**

**Gleneden Beach, Oregon**

**Experience has shown reproducibility is required for debugging**

# Monte Carlo methods for X-rays, neutrons & $\alpha$ particles have similar architecture constraints

- SIMD much harder than MIMD
  - Each particle does its own thing
  - Vectorization required many no-ops & particle data transfers
  - Parallelization over particles on a complete domain is easy
- Hard reproducibility (bit for bit) is required for debugging
- Soft reproducibility (random order of sums) is not of much value
  - Errors in real*8 cause random number changes in a few cycles
  - Enforce sum order or “fix” it with 50 year old (integer) arithmetic
- Domain decomposition is required for 3D by memory limitations
  - Big load balance challenge, especially with biasing
  - Adaptive domain movement & replication may save the day
  - Decomposition can be different for each physics package

# Interpreted user interface increases productivity

- Empowers the code user to explore new applications & models
- “Use Once” features can stay out of the code
- Rapid prototyping of new methods can be tested while fully integrated with the rest of the code
- Interface can insulate user from domain decomposed data
- Problem generation and output can be highly tuned to the particular application
- Examples of things done without recompilation
  - Mesh motion algorithms & marker particles for ALE
  - Material strength models including any required ODEs

**But use of this power is hard to document**

# ICF algorithms have changed in every area

- Hydrodynamics
  - Euler, Lagrange, arbitrary connectivity, ALE, AMR
- Laser deposition
  - “1-D”, ray trace, Maxwell solver
- Electron transport
  - Conduction, 2 group, multi-group, non-local, Monte Carlo
- Atomic physics (EOS & opacity)
  - LTE tables, non-LTE, hydrogenic, SCA, DCA, response matrix
- X-ray, neutron & alpha particle transport
  - 1 group diffusion, multi-group diffusion, Sn, Monte Carlo
- Steerable user interface
  - Generation, diagnosis, post processing, mesh motion, physics

# High Speed Computing Conferences have remained a valuable bargain for 23 years

George B. Zimmerman Trip # 69026 —— 0362-02

1981

A TRAVEL EXPENSE VOUCHER SHOULD BE SUBMITTED WITHIN 15 DAYS OF YOUR RETURN

| Year Month & Date | ITINERARY | | MISCELLANEOUS TRANSPORTATION | | | | LODGING | MISCELLANEOUS EXPENSES Telephone, Telegraph, Registration Fees, Etc. | | PER DIEM | TOTAL DAILY EXPENSE |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | TIME | PLACE | PRIVATE AUTO | TAXI | AUTO RENT | OTHER | | DESCRIBE | AMOUNT | | |
| 3/30 | LV 6$^{30}$ A | Lafayette, CA | FR | | | FR | $ 32.00 | | | $ | $ |
| | AR 6$^{30}$ P | Gleneden, Ore | TO | | | TO / TYPE | | | | | |
| | Type of Trans. PA | | AMT.$ | AMT.$ | AMT.$ | AMT.$ | | | | | |
| # 3/31 – 4/2 | LV | | FR | | | FR | $ 3x 32.00 | | | $ | $ |
| | AR | | TO | | | TO / TYPE | | | | | |
| | Type of Trans. | | AMT.$ | AMT.$ | AMT.$ | AMT.$ | | | | | |
| 4/3 | LV 1$^{00}$ P | Gleneden, Ore | FR | | | FR | $ | | | $ | $ |
| | AR 8$^{30}$ P | Sequim, Wa | TO | | | TO / TYPE | | | | | |
| | Type of Trans. PA | | AMT.$ | AMT.$ | AMT.$ | AMT.$ | | | | | |
| 4/6 – 4/7 | LV 11$^{00}$ A | Sequim, Wa | FR | | | FR | $ | | | $ | $ |
| | AR 6$^{30}$ P | Lafayette CA | TO | | | TO / TYPE | | | | | |
| | Type of Trans. PA | | AMT.$ | AMT.$ | AMT.$ | AMT.$ | | | | | |

Vacation on 4/6 & 4/7 / $50 Reg fee bought lunch on 3/31, 4/1, 4/2 & dinner on 3/31

**Reg Fee was $50**