Coordinated Blasts:

From H-Bomb Simulations to Numerical Relativity

David Kaiser
“Temple of Relativity”
“Of all physicists, the general relativist has the least social commitment. [...] Let the relativist rejoice in the ivory tower where he has peace to seek understanding of Einstein’s theory as long as the busy world is satisfied to do its jobs without him.”

A Relativist at Livermore

Lagrangian Hydro

Building a Program
From H-Bombs to the Cosmos
From H-Bombs to the Cosmos

Bryce DeWitt
“Owing to the difficult and tedious nature of research in gravitational theory, and also owing to the apparent complete lack of any immediate practical application of its results, I was, until recently, strongly resolved to discontinue further work along these lines and to turn my attention elsewhere.”

DeWitt to Raymond Birge, 11 November 1951
“Owing to the difficult and tedious nature of research in gravitational theory, and also owing to the apparent complete lack of any immediate practical application of its results, I was, until recently, strongly resolved to discontinue further work along these lines and to turn my attention elsewhere.”

DeWitt to Raymond Birge, 11 November 1951
DeWitt arrived at Livermore in September 1952, was sent to the “leper colony” while awaiting clearance, and told to read about radiative transfer and shockwaves.
DeWitt arrived at Livermore in September 1952, was sent to the “leper colony” while awaiting clearance, and told to read about radiative transfer and shockwaves.

Teller-Ulam idea, 1951

M. Zimet in Thorne, *Black Holes & Time Warps*
Simulating Flow

DeWitt arrived at Livermore in September 1952, was sent to the “leper colony” while awaiting clearance, and told to read about radiative transfer and shockwaves.

Teller-Ulam idea, 1951

M. Zimet in Thorne, Black Holes & Time Warps

UNIVAC-1 being delivered to Livermore, March 1953
Teller’s Assignment

Early numerical codes had assumed spherical symmetry (1d), but essential details of H-bomb designs required 2d simulations.

M. Zimet in Thorne, Black Holes & Time Warps
Teller’s Assignment

Early numerical codes had assumed spherical symmetry (1d), but essential details of H-bomb designs required 2d simulations.

Eulerian coordinates: fixed grid
Early numerical codes had assumed spherical symmetry (1d), but essential details of H-bomb designs required 2d simulations.

**Difficulties:** boundary conditions at each time-step, $t$; moving interfaces; radiation and shock waves exited the lattice too quickly.

**Eulerian coordinates:**
- fixed grid
Teller’s Assignment

Early numerical codes had assumed spherical symmetry (1d), but essential details of H-bomb designs required 2d simulations.

Eulerian coordinates: fixed grid

Lagrangian coordinates: flow with fluid elements

M. Zimet in Thorne, *Black Holes & Time Warps*
Teller’s Assignment

Early numerical codes had assumed spherical symmetry (1d), but essential details of H-bomb designs required 2d simulations.

Lagrangian coordinates, with respect to Eulerian grid

M. Zimet in Thorne, *Black Holes & Time Warps*
Teller’s Assignment

Early numerical codes had assumed spherical symmetry (1d), but essential details of H-bomb designs required 2d simulations.

Lagrangian coordinates, with respect to Eulerian grid

Lagrangian coordinate grid
Teller’s Assignment

At Livermore, DeWitt invented the first 2d Lagrangian hydrodynamics numerical code.

“One evening, breaking the rules of the lab, I decided to work on the problem at home, actually writing things down on paper. I took the hydrodynamic equations in two dimensions and differenced them.”

DeWitt at 1982 celebration for Jim Wilson
Teller’s Assignment

At Livermore, DeWitt invented the first 2d Lagrangian hydrodynamics numerical code.
Teller’s Assignment

At Livermore, DeWitt invented the first 2d Lagrangian hydrodynamics numerical code.

A Numerical Method for Two-Dimensional Lagrangian Hydrodynamics

Bryce DeWitt

Radiation Laboratory, University of California, Livermore, California

With the increasing availability of high-speed computing machines having large fast-memory storage it becomes possible to undertake the numerical investigation of hydrodynamic shock problems in two dimensions. Here is presented in outline a simple scheme for setting up the difference equations of such problems in purely Lagrangian form.

Introduce the following notation: \( x, y \) = Lagrangian coordinates, \( X, Y \) = Eulerian coordinates, \( u, v \) = velocity components, \( P \) = pressure, \( Q \) = artificial longitudinal viscous pressure, and \( \bar{u} \) = specific volume.

Then the basic hydrodynamical equations are

\[
\begin{align*}
\dot{u} &= \frac{1}{2} \left( P + Q \right) / \bar{u} \\
\dot{v} &= \frac{1}{2} \left( P + Q \right) / \bar{u} \\
\dot{\bar{u}} &= u, \quad \dot{\bar{v}} = v \\
\dot{Q} &= Q \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) \\
\end{align*}
\]

Livermore report 4250,
Dec 10, 1953

M. Zimet in Thorne, Black Holes & Time Warps
Teller’s Assignment

At Livermore, DeWitt invented the first 2d Lagrangian hydrodynamics numerical code.

The advantages of a Lagrangian scheme over an Eulerian one are obvious: 1) Boundary conditions are much more easily applied. 2) Moving interfaces as well as boundaries are automatically taken care of. 3) Computations are always confined to the physical region of interest.

\[
\begin{align*}
\dot{\psi} &= \frac{\partial (\psi \cdot \varphi)}{\partial y}, \\
\dot{\varphi} &= \psi, \\
\dot{\xi} &= \nabla \psi, \\
\dot{\xi} &= \Delta \psi / \varphi + \nabla \psi / \varphi,
\end{align*}
\]

Livermore report 4250, Dec 10, 1953
Teller’s Assignment

At Livermore, DeWitt invented the first 2d Lagrangian hydrodynamics numerical code.

“I was told that I had to have a program coded and run before a certain date in June [1954]. There was going to be a test shot and the lab wanted some numbers. Well, it’s one thing to have these simple-looking equations, and another to apply them. I had to sit down and think about things that had never occurred to me before.”

He worked closely with a programmer, who taught him how to improve the data input. DeWitt also learned tricks like inserting “artificial viscosity” to improve numerical stability.

DeWitt at a 1982 celebration for Jim Wilson
Teller's Assignment

At Livermore, DeWitt invented the first 2D Lagrangian hydrodynamics numerical code. M. Zimet in Thorne, Black Holes & Time Warps

DeWitt papers, U. Texas-Austin, n.d., ca. 1953

"I was told that I had to have a program coded and run before a certain date in June [1954]. There was going to be a test shot and the lab wanted some numbers. Well, it's one thing to have these simple-looking equations, and another to apply them. I had to sit down and think about things that had never occurred to me before."

He worked closely with a programmer, who taught him how to improve the data input. DeWitt also learned tricks like inserting "artificial viscosity" to improve numerical stability.

DeWitt at a 1982 celebration for Jim Wilson
Teller’s Assignment

At Livermore, DeWitt invented the first 2D Lagrangian hydrodynamics numerical code. M. Zimet in Thorne, Black Holes & Time Warps DeWitt papers, U. Texas-Austin, n.d., ca. 1953

“I was told that I had to have a program coded and run before a certain date in June [1954]. There was going to be a test shot and the lab wanted some numbers. Well, it’s one thing to have these simple-looking equations, and another to apply them. I had to sit down and think about things that had never occurred to me before.”

He worked closely with a programmer, who taught him how to improve the data input. DeWitt also learned tricks like inserting “artificial viscosity” to improve numerical stability.

DeWitt at a 1982 celebration for Jim Wilson
Teller’s Assignment

At Livermore, DeWitt invented the first 2d Lagrangian hydrodynamics numerical code.

"I was told that I had to have a program coded and run before a certain date in June [1954]. There was going to be a test shot and the lab wanted some numbers. Well, it's one thing to have these simple-looking equations, and another to apply them. I had to sit down and think about things that had never occurred to me before."

He worked closely with a programmer, who taught him how to improve the data input. DeWitt also learned tricks like inserting "artificial viscosity" to improve numerical stability.
Teller’s Assignment

At Livermore, DeWitt invented the first 2D Lagrangian hydrodynamics numerical code.

M. Zimet in Thorne, Black Holes & Time Warps

DeWitt papers, U. Texas-Austin, n.d., ca. 1953

"I was told that I had to have a program coded and run before a certain date in June [1954]. There was going to be a test shot and the lab wanted some numbers. Well, it's one thing to have these simple-looking equations, and another to apply them. I had to sit down and think about things that had never occurred to me before."

He worked closely with a programmer, who taught him how to improve the data input. DeWitt also learned tricks like inserting "artificial viscosity" to improve numerical stability.

At a 1982 celebration for Jim Wilson
Teller’s Assignment

DeWitt invented the first 2D Lagrangian hydrodynamics numerical code. He worked closely with a programmer, who taught him how to improve the data input. DeWitt also learned tricks like inserting “artificial viscosity” to improve numerical stability.

DeWitt at a 1982 celebration for Jim Wilson
The Role of Gravitation in Physics
Report from the 1957 Chapel Hill Conference

Cécile M. DeWitt and Dean Rickles (eds.)

Communicated by
Jürgen Renn, Alexander Blum and Peter Damerow

Edition Open Access
2011
Transition (Back) to Gravity

3. Hydrodynamic representation of the gravitational field equations and machine computations of gravitational interactions.
   a. Search for a suitable hydrodynamic representation in a Lagrangian coordinate system in which singularities remain fixed.
   b. Study of how to handle the supplementary conditions in the initial value problem.
   c. Setting up of appropriate difference equations and preparation of a program for machine computation.
   d. Overseeing the actual running of the problem on the machine.
   e. Interpretation of the results.
“Bryce DeWitt pointed out some difficulties encountered in high-speed computational techniques. [...] ‘Any non-linear hydrodynamic calculations are always done in so-called Lagrangian coordinates, so that the mesh points move with the material instead of being fixed in space. [When applying to gravitational radiation], you don’t want the radiation to move quickly out of the range of your computer.”
A Different Path

Adopted Gaussian-normal coordinates, with vanishing shift vector, $\beta^i = 0$. Could only compute 50 time-steps; lattice points bunched up near the singularity.
Building a Program

CADEZ, Andrej, 1942-
COLLIDING BLACK HOLES.

University of North Carolina at Chapel Hill,
Ph.D., 1971
Physics, general

SMARR, Larry Lee, 1948-
THE STRUCTURE OF GENERAL RELATIVITY WITH A
NUMERICAL ILLUSTRATION: THE COLLISION OF
TWO BLACK HOLES.

The University of Texas at Austin, Ph.D., 1975
Physics, general

EPPLLEY, Kenneth Robert, 1948-
THE NUMERICAL EVOLUTION OF THE COLLISION OF
TWO BLACK HOLES.

Princeton University, Ph.D., 1975
Physics, general

CDC 6600, ca. 1970: 3 megaFLOPS
Adopt a nonzero shift vector, $\beta^i$, proportional to the 3-velocity of the new coordinate lines with respect to Eulerian gridlines.
Building a Program

American Scientist, Volume 66

Larry L. Smarr
William H. Press

1978

Our Elastic Spacetime: Black Holes and Gravitational Waves

A new computer program shows that the old analogy of spacetime as a rubber sheet is remarkably valid.

Figure 6. These “straw hats for a horse”—embedding diagrams (analogies of Fig. 2) for two colliding black holes—show the proper distances and angles between grid lines. (a) At the initial instant the two holes are at rest rather close to one another. The open ends are slightly inside of where the surface of the holes were initially. Note that the holes are already curving the surrounding space substantially. (b) After the collision of the two holes, the bag has stretched out much more. The new location of the surface of the last black hole is somewhere on the long neck. The grid squares have been deformed by the motion of the holes.
Our Elastic Spacetime: Black Holes and Gravitational Waves

A new computer program shows that the old analogy of spacetime as a rubber sheet is remarkably valid.

Figure 6. These "straw hats for a horse"—embedding diagrams (analogies of Fig. 2) for two colliding black holes—show the proper distances and angles between grid lines. (a) At the initial instant the two holes are at rest rather close to one another. The open ends are slightly inside of where the surface of the holes were initially. Note that the holes are already curving the surrounding space substantially. (b) After the collision of the two holes, the bag has stretched out much more. The new location of the surface of the last black hole is somewhere on the long neck. The grid squares have been deformed by the motion of the holes.
"On sufficient advance notice, a large quantity of beer, food, scissors, scotch tape, and graduate students are assembled. The graduate students cut the squares out and tape them into strips. Other students then weave the strips together, basket fashion, into a final embedding diagram. [...] (Incidentally, the DeWitt technique for constructing embedding diagrams lends some credence to the complaint that graduate school these days is only so much advanced basketweaving.)"
Coda

Larry Smarr, 1983
Coda

### NOTICE OF RESEARCH PROJECT

**SCIENCE INFORMATION EXCHANGE**

**SMITHSONIAN INSTITUTION**
**NATIONAL SCIENCE FOUNDATION**

**PROJECT SUMMARY**

<table>
<thead>
<tr>
<th>FOR NSF USE ONLY</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DIRECTORATE/DIVISION</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NAME OF INSTITUTION (INCLUDE BRANCH/CAMPUS AND SCHOOL OR DIVISION)</th>
</tr>
</thead>
<tbody>
<tr>
<td>University of Illinois at Urbana-Champaign</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ADDRESS (INCLUDE DEPARTMENT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Board of Trustees</td>
</tr>
<tr>
<td>506 South Wright Street, Urbana, IL 61801</td>
</tr>
<tr>
<td>(for the Departments of Astronomy, Physics, Computer Science, Atmospheric Sciences, Chemistry, Electrical Engineering, Chemical Engineering, Theoretical and Applied Mechanics)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PRINCIPAL INVESTIGATORS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Larry L. Smarr, John Kogut, David Kuck, Robert Wilhelmson, Peter Wolynes, Karl Hess, Thomas Hanratty, Robert McMeeking</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TITLE OF PROJECT</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Center for Scientific and Engineering Supercomputing</td>
</tr>
</tbody>
</table>

PROPOSAL

A Center for Scientific and Engineering Supercomputing
# WORLD CENSUS OF SUPERCOMPUTERS

<table>
<thead>
<tr>
<th>Country</th>
<th>Site</th>
<th>Number</th>
<th>Purpose</th>
<th>Computer</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.S.</td>
<td>Los Alamos Nat. Lab.</td>
<td>5</td>
<td>Weapons Research</td>
<td>Cray-1</td>
</tr>
<tr>
<td></td>
<td>Lawrence Livermore</td>
<td>4</td>
<td>Weapons Research</td>
<td>Cray-1</td>
</tr>
<tr>
<td></td>
<td>Nat. Lab</td>
<td>2</td>
<td>Magnetic Fusion Energy Research</td>
<td>Cray-1</td>
</tr>
<tr>
<td></td>
<td>Sandia Nat. Lab</td>
<td>2</td>
<td>Weapons Research</td>
<td>Cray-1</td>
</tr>
<tr>
<td></td>
<td>KAPL</td>
<td>1</td>
<td>Reactor Research</td>
<td>Cyber 205</td>
</tr>
<tr>
<td></td>
<td>Bettis</td>
<td>1</td>
<td>Reactor Research</td>
<td>Cyber 205</td>
</tr>
<tr>
<td></td>
<td>Kirtland Air Force Base</td>
<td>1</td>
<td>Military</td>
<td>Cray-1</td>
</tr>
<tr>
<td></td>
<td>National Center for Atmospheric Research</td>
<td>1</td>
<td>Atmospheric Science</td>
<td>Cray-1</td>
</tr>
<tr>
<td></td>
<td>NSA</td>
<td>2</td>
<td>Intelligence</td>
<td>Cray-1</td>
</tr>
<tr>
<td></td>
<td>NASA-Ames</td>
<td>1</td>
<td>Aerodynamics</td>
<td>Cray-1</td>
</tr>
<tr>
<td></td>
<td>NASA-Goddard</td>
<td>1</td>
<td>Atmospheric Science</td>
<td>Cyber 205</td>
</tr>
<tr>
<td></td>
<td>NASA-Lewis</td>
<td>1</td>
<td>Fluid Dynamics</td>
<td>Cray-1</td>
</tr>
<tr>
<td></td>
<td>FNOCS Monterey</td>
<td>1</td>
<td>Oceanography</td>
<td>Cyber 205</td>
</tr>
<tr>
<td></td>
<td>National Environmental Service</td>
<td>1</td>
<td>Research</td>
<td>Cyber 205</td>
</tr>
<tr>
<td></td>
<td>Satellite Service (NOAA)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**WORLD CENSUS OF SUPERCOMPUTERS**

<table>
<thead>
<tr>
<th>Country</th>
<th>Site</th>
<th>Number</th>
<th>Purpose</th>
<th>Computer</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.S.</td>
<td>Los Alamos Nat. Lab.</td>
<td>5</td>
<td>Weapons Research</td>
<td>Cray-1</td>
</tr>
<tr>
<td></td>
<td>Lawrence Livermore</td>
<td>4</td>
<td>Weapons Research</td>
<td>Cray-1</td>
</tr>
<tr>
<td></td>
<td>Nat. Lab</td>
<td>2</td>
<td>Magnetic Fusion Energy Research</td>
<td>Cray-1</td>
</tr>
<tr>
<td></td>
<td>Sandia Nat. Lab</td>
<td>2</td>
<td>Weapons Research</td>
<td>Cray-1</td>
</tr>
<tr>
<td></td>
<td>KAPL</td>
<td>1</td>
<td>Reactor Research</td>
<td>Cyber 205</td>
</tr>
<tr>
<td></td>
<td>Bettis</td>
<td>1</td>
<td>Reactor Research</td>
<td>Cyber 205</td>
</tr>
<tr>
<td></td>
<td>Kirtland Air Force Base</td>
<td>1</td>
<td>Military</td>
<td>Cray-1</td>
</tr>
<tr>
<td></td>
<td>National Center for Atmospheric Research</td>
<td>1</td>
<td>Atmospheric Science</td>
<td>Cray-1</td>
</tr>
<tr>
<td></td>
<td>NSA</td>
<td>2</td>
<td>Intellligence</td>
<td>Cray-1</td>
</tr>
<tr>
<td></td>
<td>NASA-Ames</td>
<td>1</td>
<td>Aerodynamics</td>
<td>Cray-1</td>
</tr>
<tr>
<td></td>
<td>NASA-Goddard</td>
<td>1</td>
<td>Atmospheric Science</td>
<td>Cyber 205</td>
</tr>
<tr>
<td></td>
<td>NASA-Lewis</td>
<td>1</td>
<td>Fluid Dynamics</td>
<td>Cray-1</td>
</tr>
<tr>
<td></td>
<td>FNOC-Monterey</td>
<td>1</td>
<td>Oceanography</td>
<td>Cyber 205</td>
</tr>
<tr>
<td></td>
<td>National Environmental Service</td>
<td>1</td>
<td>Research</td>
<td>Cyber 205</td>
</tr>
</tbody>
</table>

**NSF**

**NCSA**
Evolution of Binary Black-Hole Spacetimes

Frans Pretorius\textsuperscript{1,2,}\textsuperscript{*}

\textsuperscript{1}Theoretical Astrophysics, California Institute of Technology, Pasadena, California 91125, USA
\textsuperscript{2}Department of Physics, University of Alberta, Edmonton, AB T6G 2J1 Canada

(Received 6 July 2005; published 14 September 2005)

---

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott et al.\textsuperscript{7}

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)
From Bombs to the Cosmos
From Bombs to the Cosmos

Access, Resources, and Infrastructure