Coordinated Blasts:
Cold War Roots of Numerical Relativity in the United States*

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Abstract. A significant development in the study of general relativity over the past half century has been the advent of numerical relativity. Some of the central techniques in that field originated in a context rather far from academic research: the top-secret efforts to simulate hydrogen-bomb designs at classified US weapons labs. As a young researcher, Bryce DeWitt first invented a multidimensional Lagrangian hydrodynamic simulation code while working at Lawrence Livermore Laboratory in the early 1950s. Beginning in the early 1970s, when modest computing resources became available for unclassified projects, DeWitt and his students converted insights gained from the H-bomb project for the study of strong-gravitational systems, including the first computations of gravitational waves from colliding black holes. Even then, DeWitt's younger colleagues still had to return to Livermore to access sufficiently powerful computers, and to learn subtleties of high-performance computing techniques from the expert community of weapons designers.

Introduction

Early in the morning of September 14, 2015, two enormous machines wobbled almost imperceptibly, in concert. The machines were huge, L-shaped detectors of the Laser Interferometric Gravitational-Wave Observatory, or LIGO, and they were located more than two thousand miles apart: one near Baton Rouge, Louisiana, and the other in Hanford, Washington. An international team of astrophysicists later announced to great fanfare that on that morning, the LIGO detectors had measured the feeble signal left over from a colossal collision. About a billion years earlier, in a distant galaxy, two massive black holes had spiralled into each other. Their collision and merger had released a

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tremendous burst of energy, roiling the surrounding spacetime and sending tell-tale gravitational waves streaming out in every direction at the speed of light. By the time those waves reached Earth, the once-cosmic roar had attenuated to a barely detectable whimper.[1]

In a remarkable tour de force, the LIGO-Virgo collaboration not only measured the gravitational-wave signal, but extracted considerable information from it. Based on the subtle patterns in the waves, the team could draw inferences, for example, about how massive each black hole had been prior to impact. The team gleaned such details by comparing the measured signal with a large bank of template waveforms, specific patterns for various types of waves that had been pre-computed by sophisticated computer programs. The programs incorporated elements from "numerical relativity": computer codes that simulated the field equations of Albert Einstein's general relativity numerically. Today, experts across gravitation, astrophysics, and cosmology routinely deploy numerical-relativity simulations to yield insights about the cosmos.[2]

The LIGO triumph rightly draws our focus to the stars. Yet critical groundwork for such discoveries was forged more than sixty years earlier, in a top-secret weapons laboratory nestled in the arid hills of northern California. Physicist Bryce DeWitt first learned rudiments of computer simulation techniques as part of a frenzied effort to design hydrogen bombs: nuclear weapons that could release thousands of times more explosive power than the weapons that had devastated the cities of Hiroshima and Nagasaki during the closing days of the Second World War. While working at the Lawrence Livermore Laboratory, DeWitt gained unusual experience with programmable electronic computation, honing specific choices of coordinate systems for efficient calculations.

About two decades later, DeWitt and his Ph.D. students converted insights from DeWitt's weapons-lab experience to help launch the new field of numerical relativity.

Decades after H-bombs had entered the US arsenal, large-scale computing infrastructure and expertise within the United States remained siloed in classified weapons laboratories. Until the early 1980s, researchers who aimed to simulate cosmic phenomena like colliding black holes—including DeWitt's students and collaborators—needed to stay tethered to the nuclear-weapons program. Amid the "Nuclear Freeze" movement of the early 1980s, DeWitt's protégé Larry Smarr made the case that civilian researchers also required dedicated centers for large-scale scientific computing. The subsequent funding by the US National Science Foundation of the National Center for Supercomputing Applications, in turn, enabled major advances in fields like numerical relativity.

The early roots of numerical relativity illustrate starkly the blurred lines and mutual interdependencies among "pure" and "applied" science, or "basic" and "mission-oriented" research within the US during the Cold War. Far beyond fields such as nuclear physics or quantum electronics—which offered researchers deep, open questions and military patrons a clear incentive to sustain generous support—even subjects as abstruse and otherworldly as the collision of extragalactic black holes became enmeshed in the worlds of military classification, high-level national-defense priorities, and hulking infrastructure.[3] As this example illustrates, not only maps, but abstract coordinate systems have a political history.[4] Moreover, the early coalescence of a numerical-relativity community underscores the importance—and also the contingencies—of people in

motion, acquiring esoteric skills in one setting and learning to put them to work in quite different ones.[5]

Livermore: A Second Nuclear Weapons Laboratory

From the first stirrings of the Manhattan Project, physicists had been confident that they would be able to build hydrogen bombs, thermonuclear devices whose destructive power would come from fusing together isotopes of hydrogen, such as deuterium and tritium. During an early, secret planning meeting at the University of California, Berkeley in the summer of 1942—before the Los Alamos laboratory even existed—J. Robert Oppenheimer and a cluster of close colleagues brainstormed about how best to prioritize their upcoming efforts. Members of the group quickly convinced themselves that fission bombs—devices that would explode from the runaway chain reaction of large, unstable nuclei like uranium or plutonium splitting into smaller pieces—would be straightforward to construct. The interesting challenge would be to create a fusion bomb, which they quickly dubbed the "Super": a bomb that would reproduce the nuclear fusion reactions of the stars.[6]

Within months, the physicists discovered just how hasty their early planning sessions had been. Fission bombs weren't so simple to produce, after all; there would be no easy leap from blackboard sketches to physical devices. The challenges of producing sufficiently large stores of fissionable isotopes, and designing ways to force subcritical

chunks together quickly enough to trigger explosive chain reactions, required industrial-scale efforts.[7]

Amid the frenzy to produce fission weapons during the war, the fusion-bomb program slipped to a low priority. Soon after the war, however, advocates like physicist Edward Teller sought to accelerate efforts on the Super. Teller and colleagues focused on the idea of using a fission bomb to trigger fusion reactions among deuterium and tritium. The heat from the fission bomb "primary," they reasoned, might induce fusion among the light nuclei. If they could get a fusion-reaction started, the explosive potential of such a bomb seemed unlimited. Teller quickly convinced himself that an H-bomb could release thousands of times more explosive power than the uranium and plutonium bombs that had only recently been used against Japan.[8]

Others remained skeptical. Teller's proposals were dotted with "ifs": *if* the heat from the fission primary could induce fusion reactions; *if* the group could figure out the optimal mix of deuterium, tritium, and other light nuclei to sustain fusion burning; *if* the resulting device could be kept small enough to be delivered by aircraft, and so on. Moreover, Teller's (unproven) designs for a Super called for large amounts of tritium; pursuing his H-bomb program would require that the nation's nuclear reactors produce tritium at the expense of producing more plutonium. Late in 1949, critics of Teller's proposals calculated that the United States would need to forgo up to 150 plutonium (fission) bombs for each H-bomb; and there still would not be sufficient tritium to fuel a single H-bomb for five years.[9]

Upon reviewing the latest plans for a Super, the Atomic Energy Commission's General Advisory Committee—chaired by Oppenheimer—concluded in October 1949

that "there appears to be no chance of [H-bombs] being an economical alternative to fission weapons," based on "the strict criteria of damage area per dollar." Only in the closing pages of the classified report did two members of the advisory committee, Isidor Rabi and Enrico Fermi, raise moral concerns. The extraordinary power of an H-bomb, if such a weapon could be built, would threaten entire cities, not just military targets. An H-bomb, they wrote, would "necessarily [be] an evil thing considered in any light."[10]

As clear as the arguments may have seemed to the advisors, however, events quickly overshadowed the debate. The advisory committee's recommendation to maintain a low priority for H-bomb work came just one month after the US announced that its nuclear monopoly had been lost: the Soviets had detonated their own fission bomb. (US analysts nicknamed the Soviet bomb "Joe 1," in a nod to Josef Stalin.) That same autumn, Mao Zedong's Communist forces overpowered the US-backed nationalists in China, establishing the People's Republic of China. Then in January 1950 came the shocking revelation that Klaus Fuchs, a German-born member of the British delegation to the wartime Manhattan Project, confessed to having shared top-secret information about the weapons program with the Soviets throughout the war. Days after Fuchs's confession, President Harry Truman announced that the United States would pursue a high-priority, crash-course development of the H-bomb. Six months after that, fighting broke out on the Korean peninsula, and the United States was once again at war.[11]

The American entry into the Korean War thrust the nation's nuclear complex back into emergency mode. Los Alamos shifted to a six-day work week. Teller's arguments for a Super—now backed by presidential directive—began to attract more adherents. Yet Teller continued to clash with leadership at Los Alamos, who, Teller complained, failed

to devote sufficient priority to the H-bomb work. Several times during his heated exchanges with lab managers, Teller announced his resignation, only to rescind it a few hours later—a pattern that became familiar throughout 1950 and 1951. Before long, Teller began to push for a second weapons laboratory, apart from Los Alamos altogether.[12]

By February 1952, Teller and his allies had pitched their proposal for a second weapons laboratory directly to influential members of Congress as well as to the Secretary of the Air Force, each of whom shared Teller's sense of urgency and, like him, had grown frustrated by the measured response of the Atomic Energy Commission (AEC). Berkeley's Ernest Lawrence, whose group had performed critical roles during the Manhattan Project, gave Teller a tour of an auxiliary site that Lawrence's group had recently begun to use, forty miles east of Berkeley at an abandoned naval air station in Livermore, California. Like Teller, Lawrence was eager to speed progress on the H-bomb; he thought the Livermore site might be useful. Given the modest infrastructure already in place at Livermore, and the increasing pressure from Congress and the Air Force to act, the AEC approved the proposal to expand Livermore into a second nuclear-weapons laboratory in late spring 1952.[13]

In September 1952, the Livermore Laboratory officially began operations, with 123 new staff members. The number of technical staff rose quickly: up to 698 within a year of the lab's founding, crossing 3,000 five years later.[14]

A Relativist at Livermore

The young theoretical physicist Bryce DeWitt arrived at Livermore Laboratory the very month that it opened, and was immediately dispatched to an area that had been dubbed the "leper colony." His security clearance had not yet come through, and until he was cleared, he could not handle any classified information, so most of the laboratory was off-limits to him. For nearly three months, DeWitt waited in a special, quarantined area of the lab, along with the other recruits whose security reviews had yet to be completed.[15]

DeWitt's supervisor instructed him to read two textbooks while waiting in the "colony": *Radiative Transfer* (1950), by the famed astrophysicist Subrahmanyan Chandrasekhar, and *Supersonic Flow and Shock Waves* (1948), by the applied mathematicians Richard Courant and Kurt Friedrichs. The selection made sense as soon as DeWitt received his security clearance. That very day, he was brought to his new office deep inside the lab, directly across the hall from Edward Teller's. Teller ushered DeWitt into his office and gave DeWitt a one-man crash-course briefing on all that was then known about hydrogen bombs. "I guess he wanted me to lose my virginity immediately," DeWitt later joked.[16] As Teller and others had only recently hypothesized, scientists might be able to construct a working H-bomb if they channeled the intense radiation pressure from an exploding fission bomb. Their weapon, in other words, might work if it harnessed some of the same processes—nuclear fusion, radiative transfer, and supersonic flows—that powered the stars.

DeWitt had traveled a long road to Teller's office. He was born in the tiny, rural town of Dinuba, in California's Central Valley. Once he turned twelve years old, his mother sent him East, to the suburbs of Boston, for boarding school. His academic talents quickly blossomed, and he was admitted to Harvard at age sixteen. DeWitt entered Harvard in September 1939, just as war erupted in Europe. He received a draft deferment to pursue his studies in physics. After college, DeWitt was eager to get back to California; he took a junior position in Berkeley, working with the Calutron accelerator to separate isotopes of uranium for the Manhattan Project. Yet he quickly grew dissatisfied: he was eager to make a more direct contribution to the war effort, now that the US had entered the conflict, and he didn't think his meager efforts at Berkeley would amount to much. He joined the navy and trained to become a naval aviator.[17]

A few months after the war ended, DeWitt returned to Harvard to begin his doctoral studies. He worked with the famous *Wunderkind*, Julian Schwinger, at the time Harvard's youngest tenured professor. Schwinger was just then embarking on the research that would earn him his Nobel Prize (awarded in 1965): conquering the troubling infinities in quantum electrodynamics. DeWitt sought to do his advisor one better. While Schwinger tackled a quantum treatment of electromagnetism, DeWitt would try to craft a quantum-mechanical description of gravity.[18]

Though DeWitt fell somewhat short of his goal with his dissertation, his work clarified several of the underlying subtleties in the quantum-gravitational program. He earned a prestigious postdoctoral fellowship at the Institute for Advanced Study in Princeton, New Jersey, where he moved in 1949. There he met, and began to court, a young French mathematical physicist, Cécile Morette, who was also at the Institute on

fellowship; they married two years later. At the time, Morette was better known in the field than DeWitt; indeed, Wolfgang Pauli delighted in referring to DeWitt as "Mr. Morette."[19]

After his fellowship in Princeton, DeWitt traveled to Mumbai for a second postdoctoral stint, this one at the new Tata Institute for Fundamental Research. Morette joined him there a few months later, in September 1951; their first daughter was born in Mumbai that spring. As Bryce and Cécile raised their young family, however, they found themselves increasingly cut off from the physics community in the United States.[20]

Their isolation stemmed from more than just geography. The research topic to which Bryce DeWitt had devoted his energies—general relativity and prospects for its quantization—lay far outside the core topics on which most American physicists focused at the time. For physicists in the US, the hot topics centered on quantum electrodynamics, nuclear forces, and solid-state physics—topics in which theorists could test their speculations against reams of new experimental data. Gravitation seemed too far removed from these areas, a mathematically elegant bauble off on its own. In fact, the topic had fallen so far out of fashion that in the mid-1950s, the editor of the *Physical Review* considered banning all publications on the topic.[21]

During his two years away from the United States, DeWitt's ties to the local academic networks waned, and his research remained stubbornly out of sync with trends back home. As his fellowship in Mumbai was ending, he grew disheartened about his career prospects. He wrote to various physics departments throughout the United States, asking if there might be any opportunities for a young theoretical physicist. He had wavered in his commitment to the study of gravity, he explained: "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." Freeman Dyson, whom DeWitt had met at the Institute for Advanced Study in Princeton, and who had just been appointed full professor of physics at Cornell University, encouraged DeWitt to stay focused on gravitation. Dyson counseled that the subject needed theorists, like DeWitt, who had solid training in both general relativity and in quantum field theory. Nonetheless, DeWitt received no encouraging replies to his academic job search. Instead, a chance encounter at an American Physical Society meeting in May 1952 led to the only offer DeWitt received: a junior staff position at the Livermore Laboratory, just then being set up to accelerate the nation's efforts to develop hydrogen bombs.[22]

DeWitt's Assignment: Numerical Simulations for H-Bomb Designs

Once DeWitt's security clearance had been approved, Teller set him to work analyzing various designs for a Super. Teller had some specific ideas that needed to be checked. Back in March 1951, while still feuding with Los Alamos management about resources and priorities, Teller had hit upon a new conception for how to jump-start a fusion reaction in a hydrogen bomb, in conversation with mathematician Stanislaw Ulam. (Decades later, the two men and their acolytes clashed bitterly over who deserved credit for the still-classified idea.) The original idea for a Super had relied upon the heat from a

fission-bomb primary to induce fusion reactions. But fission bombs produce more than just heat; they also release intense radiation. (Indeed, more victims of the bombings in Hiroshima and Nagasaki succumbed to radiation sickness than direct blast damage.) Teller and Ulam proposed that the radiation pressure from an exploding fission bomb could be channeled or focused onto light nuclei, like deuterium and tritium. The radiation pressure might then compress the light nuclei to extreme densities and induce nuclear fusion.[23]

The Teller-Ulam idea seemed straightforward enough on paper—so much so that most weapons experts who had clearance to read their 20-page technical report became enthusiastic that the "New Super" design could actually work. (Even Oppenheimer, who had repeatedly urged the Atomic Energy Commission to focus on fission bombs, pronounced the Teller-Ulam idea to be "technically sweet.") But the Teller-Ulam report was really just a sketch of a promising idea. Major questions remained about how the diverse materials inside such a weapon might actually behave under extreme conditions. For months after Teller and Ulam filed their technical report, the Los Alamos director reported to the AEC and advisors that his staff remained hampered in their efforts to convert the Teller-Ulam scheme into a workable design. Their biggest obstacle was limited computing power.[24]

To really understand whether fusion might be triggered by radiation pressure from a fission-bomb primary—let alone to optimize the mix of deuterium, tritium, and related materials that might produce a given explosive yield—required solving a set of coupled, nonlinear differential equations. The bomb would consist of several types of materials, and each would respond to the radiation and shockwaves in distinct ways. During the

war, several experts at Los Alamos, led by Nicholas Metropolis and John von Neumann, had pioneered rudimentary procedures to track such complicated dynamics quantitatively, modeling various bomb designs in terms of hydrodynamics. For each tiny volume of material inside a proposed weapon, they could assign an energy density, average velocity, pressure, shear, viscosity, and so on, and then track how each tiny volume element would interact with its neighbors, jostling and nudging each other over time.[25]

Metropolis, von Neumann, and their colleagues had first undertaken such multi-step calculations armed with handheld Marchant calculating machines; then they had moved to punch-card computation, before getting their crack at a brand-new ENIAC machine—an Electronic Numerical Integrator and Calculator. The first ENIAC had been completed early in 1945 for the US Army, which planned to use the device to calculate ballistics tables. But soon von Neumann had commandeered the machine for Los Alamos. The numerical codes that Metropolis, von Neumann, and their group hammered out during the spring of 1945 were among the earliest programs ever run on an electronic, programmable device—back when "computer" still referred to the human user, rather than the hulking machine.[26]

The ENIAC was certainly a big leap over handheld calculating machines, but it was a far cry from today's computers. The room-sized machine incorporated nearly twenty thousand vacuum tubes as circuit elements, connected by half a million soldered joints; the tubes became so hot that the entire device had to be cooled by a massive refrigeration unit, capable of producing several tons of ice each day. Moreover, the machine could only execute fixed programs: one had to set a given program by hand, physically rewiring components ahead of time, before any results could be calculated.

Changing the program took weeks of physical manipulation—swapping cables, alternating switches, checking and re-checking the resulting combinations.[27]

After the war, the AEC elevated electronic computation to a high priority. Metropolis continued to lead a group at Los Alamos, while von Neumann created a separate group at the Institute for Advanced Study in Princeton, where Oppenheimer had recently become director. Like the ENIAC, the newer machines still relied on vacuum tubes; but unlike the ENIAC, they could store their programs and the resulting data in the same memory, side by side. By the summer of 1951, von Neumann's machine in Princeton could run around the clock for two-month stretches at a time. At full capacity, it boasted 5 kilobytes of usable memory.[28]

As soon as it was operational, von Neumann's machine was set to work on calculations for the H-bomb project. Metropolis's machine at Los Alamos, nicknamed the MANIAC (Mathematical Analyzer, Numerical Integrator, and Computer), took a bit longer to fine-tune, but by spring 1952 it, too, was running hydrodynamic simulations for the H-bomb program. Yet neither set of codes could handle some of the intricacies of a Teller-Ulam device.[29]

Even before the simulations could catch up, weapons scientists from Los Alamos detonated an enormous thermonuclear device—the first of its kind—early in the morning of November 1, 1952. Code-named "Ivy-Mike," the device incorporated the Teller-Ulam principle to ignite nuclear fusion. The resulting explosion vaporized the tiny island of Elugelab, which had been part of the Eniwetok Atoll in the Pacific Ocean. The Ivy-Mike device was not exactly a bomb—it required enormous cryogenic apparatus to keep the deuterium fuel in a liquid state, and was much too large to be delivered to a military

target—but it did demonstrate that the Teller-Ulam principle could work. The test redoubled efforts at both weapons labs to design smaller, deliverable weapons.[30]

Newly ensconced at Livermore, Teller pushed the laboratory to undertake its own H-bomb simulations, rather than rely on Metropolis's or von Neumann's groups. Since the new lab did not have a computer of its own, a shoestring staff from Livermore made several weeks-long visits to Los Alamos—a thousand miles away—to use the rival laboratory's computer between midnight and 8 a.m.[31] By March 1953, however, Livermore had acquired its own computer, a UNIVAC-1. Designed by the duo who had spearheaded the ENIAC effort, the 8-ton UNIVAC machine offered Teller and his colleagues a chance to delve more deeply into numerical simulations.[32] DeWitt, in particular, set to work trying to design a new type of code that could simulate the Teller-Ulam process, and thereby help refine and evaluate various H-bomb designs. (See Figure 1.)



Figure 1. The UNIVAC-1 computer being delivered to the Lawrence Livermore weapons laboratory, March 1953. (Lawrence Livermore National Laboratory.)

Before the Teller-Ulam proposal from 1951, most ideas for a Super had assumed that the bomb would be spherical in shape. If heat from a fission-bomb blast were to be the main catalyst for igniting fusion burning, so the thinking had gone, then the fusion fuel could be placed in the center of a fission bomb. The spherically symmetric arrangement, in turn, suggested that computations to simulate such a device would be relatively straightforward: the computer program would only need to track variations in the materials' behavior along one direction in space (the radial direction). But in the Teller-Ulam scheme, the fission primary would be separated from the fusion fuel, so that the X-ray outburst from the fission explosion could be focused onto the light nuclei. Such a "New Super" bomb would need to be shaped more like a cylinder than a sphere. To tackle the dynamics inside such a device, programmers would need to track the flow of materials in two spatial directions, not just one.[33]

The obvious thing to try would be to adopt "Eulerian" coordinates, that is, to fix a grid of points—$X = 0$, $X = 1$, and so on across the horizontal axis, $Y = 0$, $Y = 1$, and on up the vertical axis—and then try to model how matter would flow through such a grid over time. But the H-bomb coders had quickly stumbled. One challenge was that the different types of materials inside the bomb would flow at different rates, so that at any given time, the boundaries between materials would become highly deformed and irregular. To update the simulation at each time-step, the code would need to track quantities like pressure gradients across the various boundaries; but since the boundaries aligned so poorly with the coordinate grid, calculating each gradient became costly, loading the computer's limited memory with many separate terms. Most challenging of all, the crux of the Teller-Ulam idea involved several fast-moving processes: radiation zooming

through the system at the speed of light, shockwaves rippling through material faster than the speed of sound. Such processes would race across many grid points in the simulation in a small number of time-steps. Given limitations of the available computers, the coders would never be able to run simulations with a large enough number of grid points to effectively capture, and resolve, such fast-moving processes.[34]

DeWitt learned from his office-mate at Livermore, who had been working on the simulation codes, that the programmers knew about a second type of coordinates, so-called "Lagrangian" coordinates, but had made little progress with that approach. In a Lagrangian coordinate system, one assigns coordinates (such as $x = 0$, $y = 1$) to little bits of fluid, so that the coordinates flow with the fluid; from the perspective of the fixed-grid Eulerian coordinates, the Lagrangian coordinate system would change over time, bending and deforming as the various fluid elements moved. The programmers had hesitated to use such a scheme, DeWitt learned, because calculating quantities such as gradients in such curvilinear coordinates required manipulating additional mathematical machinery, such as Jacobians, to keep track of the shifting map between one coordinate system and the other.[35]

These hesitations made little sense to DeWitt. As he later recalled, "Being a relativist, I could never understand why people were so worried. I always thought that curvilinear coordinates were as good as any other."[36] Unlike his colleagues at the lab, DeWitt had absorbed a chief lesson from relativity during his graduate studies: one's choice of coordinate system is merely a matter of convenience. In fact, experts in relativistic cosmology had long since adopted Lagrangian (or "comoving") coordinate systems to study universes that could expand or contract over time. DeWitt had opened

his dissertation with a sophisticated discussion of how to relate various coordinate systems on a given space-time manifold to each other; the Jacobian for relating different sets of curvilinear coordinate systems, which had so intimidated DeWitt's office-mate at Livermore, appeared as the second equation in DeWitt's dissertation.[37]

DeWitt later described what came next: "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." He was indeed breaking the rules of the lab—and very likely violating provisions of the Atomic Energy Act, which required strict handling of any sensitive materials related to the weapons program. All the same, his handwritten notes from that evening in December 1953 survive in his personal papers.[38]

Across the top of his notes he wrote "Detonation Hydrodynamics," and then he proceeded to map out the Lagrangian and Eulerian coordinates with which to describe fluid elements, along with the basic hydrodynamic relations between quantities like pressure, velocity, and viscosity. Next he replaced all (continuum) derivatives with finite differences, as needed to evaluate quantities defined on a coordinate grid with finite mesh spacing.[39]

On an accompanying page, he doodled pictures of how such a system would appear in Eulerian versus Lagrangian coordinates. At the top of the page, he sketched what the curving boundaries between fluid elements would look like at a given moment in time, when mapped with respect to the Eulerian grid. Just below, he drew how such fluid elements would appear in terms of the Lagrangian coordinates. Because the

Lagrangian coordinates flowed with sample fluid elements, the boundaries (when represented in the new coordinates) appeared perfectly rectilinear. (See Figure 2.)

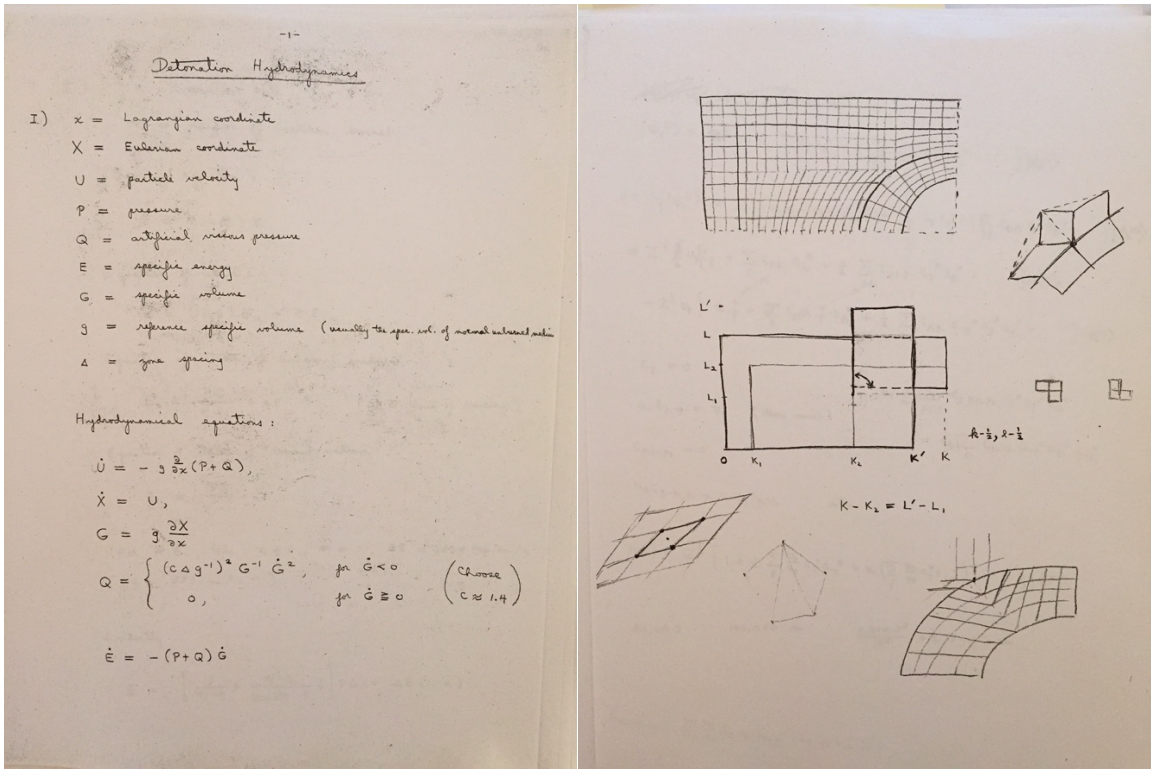


Figure 2. Bryce DeWitt's handwritten notes on "Detonation Hydrodynamics," ca. December 1953. On the left, DeWitt began by writing out familiar hydrodynamic quantities in both Eulerian and Lagrangian coordinates. On the right, he sketched a simple form of flowing material within the original Eulerian grid (the semi-circular wave in the lower right corner), before transforming the same set-up to Lagrangian coordinates, which flowed with fluid elements and hence typically remained rectilinear at each time-step. (Bryce DeWitt papers, University of Texas at Austin.)

Even better, DeWitt soon realized that if one transformed to the Lagrangian coordinates and calculated all gradients in terms of those coordinates, the calculations would simplify considerably. He introduced a "reference specific volume"—modeled closely on the covariant techniques from general relativity that he had mastered in his dissertation—and discovered that if one worked in terms of this new quantity, the Jacobians that had seemed daunting to his office-mate dropped out of the problem altogether. Moreover, because the Lagrangian coordinates flowed with fluid elements,

fast-moving processes involving radiation and shockwaves could be captured with a modest number of grid points.[40]

It all looked so simple. He rushed in to Teller's office the next morning, notes in hand, exclaiming (as he later recalled), "I must be missing something. I don't really understand what the difficulty is." Teller was impressed; that very afternoon, he convened a lab-wide meeting so that DeWitt could explain what he had found. DeWitt had become "the overnight expert on two-dimensional hydrodynamics."[41] He quickly wrote up a brief technical report on his new approach, entitled, "A Numerical Method for Two-Dimensional Lagrangian Hydrodynamics." He needed just a few pages to lay out what he had derived during his evening of scribbling. In case any readers had missed the point, he summarized at the end:

> 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.

Buoyed by what he had found, he closed optimistically: "With modern computing machines it is almost feasible to consider three-dimensional problems."[42]

For now, though, two spatial dimensions would have to do. Teller had been so impressed by DeWitt's calculations that he gave DeWitt a new assignment: he was to work with a programmer to prepare and run an actual code for a specific bomb design. And they had a hard deadline. A new bomb design was scheduled to be tested that June; the lab needed concrete numbers ahead of time. "Well," DeWitt recalled, "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."[43]

One of the new things involved a clever trick that the earliest programmers at wartime Los Alamos had worked out, known as "artificial viscosity." DeWitt learned about the technique from Jim Wilson, who had recently arrived at Livermore. Wilson had been drafted at the outbreak of the Second World War; given his undergraduate training in chemistry, he had been assigned to work at Los Alamos as part of the Army's Special Engineer Detachment, or SED. While there, he gained practical experience in the new art of computing from pioneers like von Neumann and Robert Richtmyer, who were busy inventing numerical tricks like artificial viscosity. Artificial viscosity would prevent certain physical features, like shock waves, from becoming too sharply discontinuous within a numerical simulation. Without the extra "cheat" term, the transition regions surrounding shock waves could become arbitrarily narrow; given a grid with finite spacing, the program would not be able to resolve a too-narrow shock wave, "so the program blows up in your face," as DeWitt later explained. Well into the late 1940s, a group at Los Alamos continued to improve techniques for artificial viscosity; several of their classified technical reports were eventually published in the open scientific literature.[44] DeWitt read their papers, but found that they "lacked a certain gut feeling." Wilson, who had been immersed in such techniques for years, coached DeWitt with more intuitive explanations.[45]

In addition to Wilson, DeWitt gained another partner, a programmer named Tony. At the time, interfacing with the UNIVAC was a full-time job; scientists like DeWitt were assigned to work with dedicated programmers, who actually implemented codes on the computer. DeWitt and Tony began to work closely together. In early March 1954, DeWitt wrote out 38 pages of notes, longhand, identifying every step to be performed in

the iterative computation, looping over grid points for each new time-step. The handwritten notes were classified, their distribution limited to just a few members of the laboratory staff.[46]

On the first page, DeWitt sketched the Lagrangian mesh and identified specific regions of interest, which would represent different types of materials: the fusion fuel, materials that would act as lenses or mirrors for the high-energy radiation from the fission-bomb primary, and so on. Next he stipulated the initial values for quantities like components of the pressure, density, and velocity for each grid point in each region; the loop of variables and gradients to be computed and updated at each time-step of the simulation; and, crucially, tests to perform after the code had run for a certain number of steps. He wrote out instructions like, "*Tests*: If $R^{n+1}{}_{2,0,\,L2\text{-}1} \geq R^{n+1}{}_{2,0,L2}$, *stop* the problem and print out physically interesting quantities. If $R^{n+1}{}_{2,0,L2\text{-}1} < R^{n+1}{}_{2,0,L2}$, proceed with the next test." Intermediate tests like these were meant to check whether material from one region had flowed into a different region, and if so, whether the code itself remained stable enough to continue the computation.[47]

DeWitt and Tony quickly realized that their work together would be even more effective if DeWitt explained more of the ideas behind the series of steps: what the physical motivations or intuitions had been that led to the equations that DeWitt was eager to solve, and how those equations could best be translated into machine form. "So I spent two or three days going step by step and explaining everything," DeWitt later recalled. "Then he [Tony] pointed out to me that one could greatly improve the data input scheme and the way the computations were organized" to streamline the resulting code—lessons that Tony had gleaned from accumulated experience working with the UNIVAC.

Together they improved the routine, and Tony went to work implementing the code on the computer. The code itself required nearly three hundred hours to run; they extracted the numbers that Teller had requested just in time, before the test shot in late spring 1954.[48]

Transition Back to Gravity

DeWitt left the laboratory soon after that. His wife Cécile had been teaching as an adjunct lecturer at Berkeley, and they both were eager to establish more stable academic careers.[49] Around that time, DeWitt saw notice for an annual essay contest, run by the private Gravity Research Foundation; first prize was $1000, at that time comparable to the annual stipend for a Ph.D. student. DeWitt noticed the announcement for the essay contest just before the deadline. Reading the fine print, he saw that essays only needed to be postmarked (not received) by the deadline, and—even better—submissions did not need to be typed. So he sat down at the couple's kitchen table and wrote out, long-hand, a brief essay entitled "New directions for research in the theory of gravitation." He closed by noting that "External stimuli will be urgently needed in the near future to encourage young physicists to embark upon gravitational research in spite of the odds." To Bryce and Cécile's great surprise, Bryce's hasty submission netted first place; he later mused that winning the 1953 Gravity Research Foundation essay prize had been "the easiest $1000 I ever made."[50]

DeWitt's prize—and his earnest call for "external stimuli" to support research on gravity—set some remarkable events in motion. In May 1955, DeWitt received a letter

from industrialist Agnew Bahnson, Jr., based in North Carolina. By that time, Bahnson had befriended Roger Babson, who had established the Gravity Research Foundation in 1948 to try to jumpstart the study of gravity, which—as DeWitt had also found, as he was wrapping up his dissertation and looking for jobs—had fallen to the margins of most physicists' interests. Not only did Bahnson and Babson want to incentivize physicists to study gravity; they both sought *antigravity*. Learning of DeWitt from Babson's essay prize, Bahnson wrote a long letter to DeWitt, emphasizing that antigravity technology "will probably have broad repercussions in international relations." "One fearful note," Bahnson continued, was "that we are undoubtedly not alone in dreaming of such a mechanism, and I believe it is a foregone conclusion that the Communist scientists [in the Soviet Union] are working along these lines already."[51]

Although Bryce and Cécile were tempted to toss Bahnson's note, their senior colleague John Wheeler—an accomplished Princeton physicist who was just then shifting his own research focus to gravitation—counseled Bryce: "Don't say no immediately to this guy." And so, with Wheeler's encouragement, both Bryce and Cécile began a long series of negotiations with Bahnson, resulting in Bahnson underwriting a new "Institute for Field Physics, Incorporated," to be housed at the University of North Carolina in Chapel Hill. Despite the generic name, the DeWitts and Bahnson both remained clear that the Institute would be devoted to the study of gravitation. Bahnson's donations and active fundraising paid for both Bryce DeWitt's and Cécile DeWitt-Morette's salaries, along with resources to hire several Ph.D. students, postdocs, and visiting researchers.[52]

As the Institute's first year was drawing to a close, Bryce DeWitt prepared a progress report for his new patron. He described what he and Cécile had done to date, and

laid out his plans for the next year. Among his highest priorities was to redirect the detailed knowledge he had just acquired at Livermore to simulate other kinds of extreme environments, not just the innards of H-bombs. He aimed to create computer simulations of gravitational systems:

> 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.

Given DeWitt's recent experience with comparable numerical simulations—including his own invention of finite-difference simulation codes for Lagrangian hydrodynamics—he thought this new research program could be accomplished within about a year. He quickly learned, however, that no such progress could happen now that he had left Livermore, since he no longer had access to adequate computing resources.[53]

Instead, the DeWitts turned their focus during their first full year to hosting an international conference on "The Role of Gravitation in Physics" at their new institute. Widely remembered today as "GR1"—the first in what became a long-running series of international conferences on general relativity—the gathering at the Chapel Hill institute in January 1957 proved to be a turning point for the study of general relativity. Forty-five physicists from eleven countries were able to participate, including leading lights like Richard Feynman, who was just then developing an interest in the study of gravitation.[54]

Most often remembered are the now-famous discussions held at the 1957 Chapel Hill meeting that helped convince most of the experts that gravitational waves were a

genuine physical phenomenon predicted by general relativity, rather than a mathematical artifact. Yet the transcribed conference proceedings record some other, fledgling discussions as well. In particular, during one of the discussions at the meeting, Bryce DeWitt spoke up about his interest in numerical computations:

> 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 place. [When applying such techniques to gravitational radiation], you don't want the radiation to move quickly out of the range of your computer.'[55]

These observations seemed obvious to DeWitt; this was, in essence, a succinct summary of why one should adopt Lagrangian coordinates as described in his 1953 technical report at Livermore on "Detonation hydrodynamics," which was still classified at the time. Yet no one else at the meeting had comparable experience, and few followed up on DeWitt's seeming non-sequitur during the meeting.

Only Charles Misner—another Wheeler protégé and a leading expert on general relativity—picked up the thread. For any such computations to work, one would have to "assume you have a computing machine better than anything we have now, and many programmers and a lot of money." Even if such resources were available, Misner mused, if one paid insufficient attention to how to specify the initial conditions for such gravitational systems, "then either the programmer will shoot himself or the machine will blow up." DeWitt had similar concerns. Following an elegant mathematical talk by French researcher Yvonne Choquet-Bruhat on the initial-value problem, DeWitt asked if the problem was "understood sufficiently to be put on an electronic computer for actual calculation. 'Do we now know enough about constraints and initial conditions to do this

at least for certain symmetrical cases?'"[56] Neither Choquet-Bruhat nor any other conference participants could engage in questions of actual numerical computations—which was not surprising, given DeWitt's unusual experience at Livermore, and the dearth of any such computing resources outside of weapons work.

After the Chapel Hill meeting, DeWitt set his computational aspirations aside and devoted much of his research time to topics he had first broached in his dissertation. His landmark trilogy of articles on "Quantum Theory of Gravity," published in 1967, capped a decade of intense research on highly formal approaches to quantizing gravity, including what became known as the Wheeler-DeWitt equation.[57]

In the meantime, other researchers made the first attempt to simulate a strong-gravity system on a computer. In 1964, Susan G. Hahn and Richard W. Lindquist published "The two-body problem in geometrodynamics" in *Annals of Physics*, detailing their effort to simulate the collision of two massive bodies in the context of general relativity. Lindquist had completed his Ph.D. under John Wheeler's direction at Princeton and was then teaching at tiny Adelphi University in Garden City, New Jersey. His co-author, Susan Hahn, worked at the International Business Machines Corporation (IBM) after completing her Ph.D. dissertation at New York University on "stability criteria for difference scheme" supervised by the applied mathematician Peter Lax.[58]

Thanks to Hahn, the duo had access to an IBM 7090 electronic computer, one of the earliest computers to use transistors rather than vacuum tubes. The room-filling machine was marketed to government facilities and major corporations; NASA's Goddard Space Flight Center in Maryland acquired a pair in 1960 to help track Mercury capsules during the first US human spaceflight missions, while both Los Alamos and the

Air Force's Ballistic Missile Early Warning System (BMEWS) relied upon IBM 7090s for their classified projects. (The same year that Hahn and Lindquist's article appeared, an IBM 7090 appeared in the film, *Dr. Strangelove*.) The $2.9 million price tag (roughly $32 million in 2026 dollars) kept such machines well outside the reach of most academic researchers.[59]

To set up their computation, Hahn and Lindquist used an initial-data framework that had been worked out analytically by Charles Misner—the relativist who had mused during the 1957 Chapel Hill conference about the distress programmers would face if they paid insufficient attention to such initial conditions. Soon after the 1957 meeting, Misner, along with Richard Arnowitt and Stanley Deser, had introduced a general decomposition of spacetimes, now known as the "ADM" formalism, with which relativists could readily specify equal-time surfaces for arbitrary curved spacetimes.[60] Hahn and Lindquist adopted the ADM formalism for their simulation. Whereas the ADM decomposition could be applied to either Eulerian or Lagrangian coordinate systems, however, Hahn and Lindquist stuck with a (fixed-in-time) Eulerian coordinate system of 51 x 151 grid points. Despite the impressive computing power, with their choice of coordinate system their computation "lost accuracy fairly quickly," as they reported in their article: "the computations were stopped after the 50th time step," long before any relativistic signatures of a collision of such masses could be simulated.[61]

As significant as the Hahn-Lindquist paper remains as a landmark effort in numerical relativity, it also highlights the many ingredients that had to come together for numerical relativity to succeed. The duo drew upon deep knowledge of general relativity as well as access to top-of-the-line electronic computing resources. But they had no direct

experience with classified projects like H-bomb simulations. DeWitt, in contrast, had worked out a decade earlier—in a very different context than Hahn and Lindquist's—that any calculations involving inhomogeneous distributions of masses and fast-propagating phenomena like radiation and shocks were more likely to succeed if one adopted Lagrangian coordinates. In the mid-1960s, DeWitt had expertise in general relativity and extensive experience with practical numerical computations, but (once he left Livermore) no access to sufficient computing resources. That began to change a few years after the Hahn-Lindquist effort.

Building a Program

Agnew Bahnson, Jr., died in early June 1964, when the small airplane he was piloting crashed in bad weather. After Bahnson's widow effectively ended support for the DeWitts' Institute of Field Physics, the University of North Carolina responded by promoting Bryce DeWitt to full professor in the Department of Physics, while demoting Cécile DeWitt-Morette to a lecturer, despite her own significant contributions as an accomplished theoretical physicist. The change rapidly soured both DeWitts on the situation at the University of North Carolina, and within a few years they accepted positions—both as tenured full professors—in the Department of Physics at the University of Texas at Austin. They moved to the University of Texas in 1972, where Bryce became director of the newly founded Center for Relativity.[62]

Just before the move, Bryce DeWitt began to think again about possibilities for simulating gravitational phenomena on a computer. Though he still lacked access to

significant computing resources, other motivations had changed since the mid-1960s. Beginning in 1967, experimental physicist Joseph Weber—who had also attended the 1957 Chapel Hill conference—began reporting that he had successfully detected gravitational waves, phenomena that could only arise from very strong gravitational interactions. Though Weber's claims quickly became controversial within the relativity community, they had the effect of redirecting many people's focus to strong-gravitational systems that could generate such signals. Second, the discovery of quasars in 1963, and novel theoretical developments by a host of experts in general relativity during the next several years, convinced more and more relativists that black holes were legitimate predictions of general relativity, and might even exist in our universe.[63]

At the University of North Carolina, DeWitt advised Ph.D. student Andrej Cadez, who completed a dissertation in 1971 on colliding black holes. Cadez focused on setting up a self-consistent coordinate system for a spacetime including the two black holes, with which one could more readily specify initial data. In the course of that work, Cadez clarified that in the coordinate system used by Hahn and Lindquist in their 1964 computer simulation, they had inadvertently initialized the system such that the two masses had already begun within each other's event horizons.[64] (Such an oversight was not surprising, given that Hahn and Lindquist completed their work before the landmark papers by Stephen Hawking and Roger Penrose on the singularity theorems, which instigated further clarifications between apparent horizons, event horizons, and so on.[65]) Not only did their simulation falter because of their use of non-adaptive (Eulerian) coordinates; their effort to simulate a collision of black holes only began after the collision would have occurred.

The next big jump came once the DeWitts moved to the University of Texas. One of Bryce DeWitt's first Ph.D. students in his new department was Larry Smarr. As an undergraduate at the University of Missouri, Smarr had taken the graduate course in general relativity and was further inspired by John Wheeler's work, including a 1968 article in *American Scientist* in which Wheeler popularized the term "black hole." Smarr began his doctoral studies at Stanford University in the autumn of 1970, working with the renowned relativity researcher Leonard Schiff. After Schiff died unexpectedly following a heart attack in January 1971, Smarr was advised by other faculty in Stanford's department to select a different dissertation topic, since no other faculty in the department worked on general relativity at the time. Having already made significant progress on two articles about black holes, however, Smarr was determined to stick with it. Soon after Schiff died, Smarr called Bryce DeWitt at the University of North Carolina to inquire about transferring to become a graduate student there; Smarr knew some of DeWitt's recent work on approaches to quantum gravity. Rather than accept an unknown student on the spot, DeWitt suggested that Smarr attend the upcoming international conference on gravitation and general relativity—the so-called GR6 meeting, a follow-up to the 1957 Chapel Hill conference—which was to be held in Copenhagen during July 1971. They met there and solidified their working relationship when DeWitt visited Stanford for the Fall 1972 semester to teach advanced topics in gravitation. Soon after the DeWitts got settled at the University of Texas at Austin, Smarr transferred there. He completed his Ph.D. under Bryce DeWitt's direction in January 1975.[66] (See Figure 3.)



Figure 3. Larry Smarr (left) with his Ph.D. advisor Bryce DeWitt at the University of Texas at Austin, 1974. (Photo courtesy of Larry Smarr.)

Ensconced at the University of Texas, DeWitt and Smarr had access to a new acquisition: a Control Data Corporation (CDC) 6600 computer, designed by famed computer engineer Seymour Cray. Often hailed as the first "supercomputer," the CDC 6600 broke all previous computing speed records, managing about 3 million floating-point operations per second. (Such a speed is about one hundred thousand times slower than off-the-shelf laptops today, and one trillion times slower than current state-of-art supercomputers.) The earliest models of the new CDC machine—like the IBM 7090s a few years earlier—went to the nuclear-weapons laboratories at Los Alamos and Livermore, beginning in 1965.[67] But the price of the CDC 6600 was well under that of the IBM 7090, and by the late 1960s, a handful of universities across the US had purchased their own CDC 6600s, including the University of Texas at Austin. At the Austin campus, the new computer was installed underground to help with cooling.[68]

For his dissertation, Smarr returned to the challenge that Hahn and Lindquist had attempted nearly a decade earlier: to numerically simulate the collision of two black holes. Building on Cadez's recent dissertation under DeWitt's supervision, Smarr began by focusing on the initial-data problem, making sure that in his case the two masses began sufficiently far apart. With access to the CDC 6600, Smarr pressed further, scrutinizing how to utilize coordinate systems with which a computer simulation could successfully track the evolution of the system after the initial time. He demonstrated that the type of coordinates that Hahn and Lindquist had used back in 1964—Gaussian-normal coordinates, which functioned effectively like an Eulerian grid—would *necessarily* become inconsistent within a finite time in the presence of nonzero spatial curvature. Little wonder, in other words, that the 1964 simulations had crashed so quickly.[69]

Working closely with DeWitt, Smarr showed that with clever use of coordinates that adapted to the evolving system at each time-step, one could (in principle) follow the evolution even of very strong gravitational systems deep into the nonlinear regime. He described the problem with special flair in his dissertation:

> This is a very difficult problem in general, because one does not know anything about the spacetime one is evolving until it appears slice by slice. Like jungle explorers we must push forward as quickly as possible (our computer funds are finite), but we must try to anticipate whether we are about to run into a snarling physical singularity or a treacherous coordinate crossing. Further, we have to find a way to sift the physics out of the coordinates and piles of computer output, just as a gold miner has to search carefully for nuggets in rock or sand.[70]

As Smarr later recalled, the key insight came from DeWitt, who suggested that Smarr look into a little-known idea that had first been floated—improbably enough—by the French mathematical physicist André Lichnerowicz in 1944, in the midst of the German

occupation of Paris. (Lichnerowicz went on to advise leading relativists like Yvonne Choquet-Bruhat, and both attended the 1957 Chapel Hill conference.) Translated into the new ADM formalism, Lichnerowicz's idea seemed to capture DeWitt's own main insight, developed independently at Livermore in the early 1950s, about adopting coordinates that would flow with fluid elements.[71]

The idea was to exploit a nontrivial "lapse function," $\alpha(x^{\mu})$, which governed how large a step to take in time, at each location on a spatial surface, to move to the next equal-time hypersurface. If one imposed what Smarr, DeWitt, and their colleagues dubbed "maximal slicing" as a condition for their coordinate system, then the lapse function would automatically fall toward zero near a singularity. Rather than expend (literally) endless computing time trying to resolve phenomena near a singularity, such coordinates would simply stop trying to step such regions forward in time—thereby mimicking the behavior of observers' clocks that would suffer extreme gravitational redshift as the observers moved close to a large mass. Smarr wrote that this scheme provided "as good a candidate as any for the 'natural' rest system or 'natural' system of observers"—reflecting DeWitt's older idea of using coordinates that flowed with test bodies in the fluid. Smarr's hand-drawn figure of the coordinate transformation he proposed bore striking resemblance to DeWitt's sketches from his Livermore "Detonation Hydrodynamics" notes.[72] (See Figure 4.)

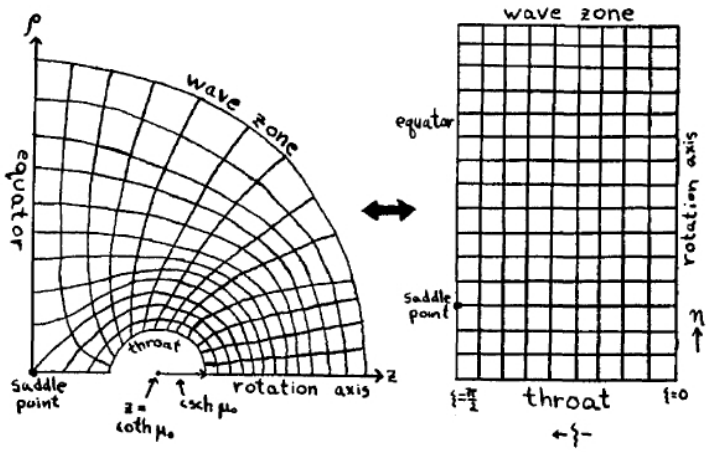


Figure 4. Larry Smarr's hand-drawn mapping between two coordinate systems, taking advantage of coordinates that flowed with accelerated observers (or fluid elements) to yield a rectilinear grid. (Larry Smarr, *The Structure of General Relativity with a Numerical Illustration* [Ph.D. dissertation, University of Texas at Austin, 1975], 126.)

In his dissertation, Smarr demonstrated that if one imposed such "maximal slicing" on a coordinate system, then one might be able to evolve the colliding black hole system far enough in time to begin to capture effects, such as gravitational waves, far from the collision zone. Smarr, DeWitt, and two younger Ph.D. students working with DeWitt (Steven Christensen and Elaine Tsiang) began coding up Smarr's new scheme for the simplified case of a single black hole; hearkening back to his Livermore days, DeWitt even wrote out stretches of Fortran instructions, long-hand, to be fed to the CDC 6600.[73] At that time the computer had a rudimentary display console and no interactive computer graphics, so DeWitt encouraged a more hands-on approach to help his students gain some intuition about the new coordinate system, as Smarr described:

> 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 [of paper] 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.)[74]

Even with these paper constructions and the Texas "supercomputer," however, the team quickly realized that they would need even more powerful computing resources if they were to try to simulate the collision of two black holes and the resulting gravitational-wave output. As Smarr recalls, DeWitt's instructions were clear: "Once I handed in my Ph.D. dissertation Bryce said to me, 'Larry, now that you've shown you can actually solve Einstein's equations, you need more computer power to work out the details. It's time for you to go and work with the Great Ones at Livermore.'"[75]

Smarr followed a circuitous route to Livermore. Upon completing his dissertation, he began a postdoctoral position at Princeton University, where he helped John Wheeler to advise Kenneth Eppley's 1975 Ph.D. dissertation on "The numerical evolution of the collision of two black holes." After that he began a three-year position as a Junior Fellow in the Society of Fellows at Harvard University. As his academic career took him from one prestigious university to another, meanwhile, Smarr began spending each summer at Livermore. One draw: Livermore had recently installed a CDC 7600 supercomputer, which could operate about ten times more quickly than the CDC 6600 at the University of Texas.[76]

After Smarr's first summer at Livermore, he helped arrange for Eppley to join him there as well. As a prerequisite for their summer stays at Livermore, Smarr and Eppley each received Q clearances—the top-secret clearance required to access nuclear secrets—though neither worked on nuclear weapons. Instead, they hunkered down and each put in two eight-hour shifts per day, maximizing their time on the CDC 7600. As Smarr recently recalled, "You're in this fairly small building, and as you walk down the

hall, you get to the office of the guy who was designing the warhead of the Polaris missile. I'd walk down and say, 'there's a weekend coming up, are you going to use your allocation of supercomputer time? Would you mind letting me use some of that allocation if you won't?' We had to work between the cracks."[77]

More than raw computing power was at stake. Just as DeWitt had learned twenty years earlier, part of the draw of spending time at Livermore was to learn directly from "Great Ones" at the lab who had honed state-of-the-art computer simulation techniques. Among the most important for Smarr and Eppley were Jim LeBlanc and Jim Wilson, the latter of whom had coached DeWitt himself in the earliest days of H-bomb simulation codes. As Smarr emphasized when recommending Eppley for the summer position at the lab, "He and I have developed our programs to the point that we very much need the experience on numerical codes which the experts at Livermore possess."[78]

At Livermore, local experts LeBlanc and Wilson coached Smarr and Eppley in several subtleties of high-performance computing. As one concrete example: during one of their first visits to Livermore, Smarr and Eppley experimented with incorporating artificial viscosity to smooth out shocks in their simulations, just as Wilson had first coached DeWitt to do at Livermore in the early 1950s. The trick worked, yielding a stable numerical code. But then Smarr and Eppley realized that for their new quarry—studying outgoing gravitational waves from a black hole collision—the old trick of inserting artificial viscosity would actually add too much dissipation to the system, damping out the waves they were now hoping to focus on. "Following conversations with [Raymond] Chin, LeBlanc, and Wilson at Livermore," Smarr explained in a follow-up article, he and Eppley "turned to the classic staggered-mesh method." Smarr observed

that solving such complicated systems numerically always required what he called "black magic," the kind of know-how learned by hands-on experimentation led by experienced guides. With these twin resources—access to one of the world's most powerful supercomputers plus informal help from experts like LeBlanc and Wilson—Smarr and Eppley succeeded in computing the very first gravitational waveforms from the head-on collision of two equal-mass black holes, in 1977.[79]

Supercomputing Beyond the Weapons Labs

Smarr spent each summer between 1976 and 1985 at Livermore, pursuing his research on numerical relativity. In 1979 he joined the faculty at the University of Illinois at Urbana-Champaign as a tenure-track assistant professor. The need to keep returning to Livermore began to chafe, not least because Smarr—like many US citizens—grew increasingly concerned about nuclear weapons and prospects for nuclear confrontation during the Reagan administration, as détente between the US and Soviet Union waned and Cold War tensions grew. In 1982, Smarr co-founded the Illinois chapter of the Alliance to Prevent Nuclear War, and he quickly became involved with the larger Nuclear Freeze movement. The following year, Smarr appeared on Phil Donahue's popular daytime television show, along with actor Paul Newman, to publicly advocate against the use of nuclear weapons—while still holding his top-secret Q clearance to work at Livermore. (In response to Smarr's television appearance, a divisional director of Livermore fumed at him, "Is that the gratitude you have for all we did for you? We should revoke your clearance.")[80]

Around the time he became involved with the Illinois Alliance to Prevent Nuclear War, Smarr typed up a kind of manifesto, "The supercomputer famine in American universities." Xeroxed copies of the unpublished report began to circulate informally among colleagues. He opened by noting that "The current distribution of supercomputers virtually excludes American universities. As of mid-1982 there are ~50 supercomputers in the world. In this country the national DOE [Department of Energy] weapons labs have the largest concentrations of them. Lawrence Livermore National Laboratory (LLNL) and Los Alamos Scientific Laboratory (LASL) each have four CRAY-1's, or 1/5 of the world supply." Within his own field of expertise, he noted,

> Much of the work in computational astrophysics has been done at LLNL and LASL during the last decade. […] Many scientists from universities who wanted to work on these frontier fields were forced to go to the national labs to gain access to the largest computers. As a result of this limited access, as well as the standard shortcomings of American universities (i.e. low salaries, lack of job openings, etc.), many of these people became lab employees.

Smarr labeled the situation a "flight from the universities." Meanwhile, as supercomputing remained essentially locked up within weapons laboratories in the US, Smarr noted that scientists elsewhere were beginning to acquire their own supercomputers, including his colleagues at the Max Planck Institute for Astrophysics near Munich, who installed a Cray-1 supercomputer around 1980.[81]

His "supercomputer famine" report began to gain traction. For example, mathematician Peter Lax chaired a committee convened by the US Department of Defense (DOD), National Science Foundation (NSF), DOE, and NASA on "large-scale computing in science and engineering." Lax and his colleagues completed their report late in 1982, echoing many of the arguments that Smarr had made, and even reprinting

his "supercomputer famine" report as an appendix.[82] In parallel, Smarr spearheaded a group of faculty at the University of Illinois from across several fields of science and engineering. In 1983 they drafted a proposal—later dubbed the "Black Proposal" because of its black cover—for "A Center for Scientific and Engineering Supercomputing," arguing that many fields of civilian research, beyond relativity, were suffering in similar ways from the lack of adequate computing resources. The proposal called for the US federal government to establish a new coordinated series of supercomputing facilities at universities, available for basic research. To help make the case, they included a "world census of supercomputers," lifted straight from Smarr's "famine" report from the previous year.[83]

Smarr's department chair, Richard Simmons, invited Smarr to accompany him on an upcoming visit to NSF headquarters in Washington, DC, and to bring a copy of the draft proposal with him. Taking advantage of lucky timing—Simmons and Smarr happened to be in an elevator in NSF headquarters with Marcel Bardon, the director of the NSF Division for Mathematical and Physical Sciences—Simmons grabbed the proposal from Smarr and thrust it into Bardon's hands, saying "I think you're going to find this very interesting." Coming quickly on the heels of the Lax Report, NSF officials agreed to begin the review of Smarr's group proposal, even though the NSF had not yet established a program in scientific computing, nor had they posted any call for such proposals.[84]

Remarkably, the unsolicited proposal actually worked: by 1983, the NSF had established the Office of Advanced Scientific Computing, which announced a national competition for university-based supercomputers. Smarr and his team re-submitted their

proposal, and in 1984 the National Center for Supercomputing Applications (NCSA) was announced as one of the four winners; the NSF appropriated more than $40 million to NCSA (roughly $130 million in 2026 dollars). The first NSF supercomputer facilities began to open early in 1986 at the University of Illinois at Urbana-Champaign, Cornell University, Princeton University, and the University of California, San Diego; a fifth facility, at the University of Pittsburgh, was funded soon thereafter.[85]

Within a few years, access to these new civilian supercomputing facilities enabled sustained research on numerical relativity by a growing community, including Smarr's NCSA team, the "Binary Black Hole Grand Challenge Alliance," established in 1993, and the "Simulating eXtreme Spacetimes" (SXS) collaboration, founded in 2002.[86] A few years later, in 2005, Frans Pretorius, a young postdoc at the California Institute of Technology with informal ties to the SXS group, succeeded in developing a novel numerical-relativity scheme that could successfully simulate the inspiral, collision, and merger of two black holes. These new techniques enabled researchers to compute the expected gravitational-wave output from systems much more astrophysically realistic than the pioneering case of a head-on collision of two black holes starting at rest that Smarr and Eppley had shown could be computed back in 1977. Within six months, two other groups developed comparable methods.[87]

From H-Bombs to the Cosmos

The field of numerical relativity is by now well-established, and has become central to efforts across gravitation, astrophysics, and cosmology. Dramatic visualizations

of colliding black holes and roiling gravitational waves, computed via numerical-relativity techniques, adorn T-shirts and coffee mugs as well as lining the walls of many physics and astronomy departments around the world; they even took a star turn in the popular movie *Interstellar* in 2014. Especially since the technical breakthroughs of 2005-2006, experts and enthusiasts alike have learned to "see" such extreme phenomena through the lens of numerical-relativity simulations.[88]

Long before such techniques could advance scientific understanding—let alone dazzle movie audiences—the field required several prerequisites. Among the most important was access to computing resources, which remained largely restricted to the US weapons laboratories from the 1940s into the 1960s. Alongside hardware, physicists also needed to develop expertise in performing simulations, working through various choices of coordinate systems, practicing tricks like adding artificial viscosity for shock-capturing, and learning practicalities of how to organize inputs and outputs of complicated simulation codes. Like the machines themselves, much of this expertise remained siloed within classified weapons laboratories. And finally, the field required infrastructure for convening colleagues and cultivating skills in new generations.

Between the 1950s and the 1970s in the United States, access to these resources was justified by appeal to Cold War priorities—by both public and private patrons. Physicist Bryce DeWitt got his first experience with numerical simulations as a young scientist at the brand-new Livermore Laboratory, beginning in 1952, working around the clock to invent and then implement the first-ever Lagrangian hydrodynamic simulation codes that could compute extreme conditions in two dimensions of space, as materials flowed over time. Stymied by the lack of access to comparable computing facilities—and

to local computing experts, like Livermore's Jim Wilson—DeWitt temporarily abandoned his dream of redirecting those simulation skills to stubborn problems in relativity, such as colliding black holes.

With generous support from industrialist Agnew Bahnson, Jr., Bryce DeWitt and Cécile DeWitt-Morette instead built up a flourishing community of experts in general relativity at their Institute of Field Physics at the University of North Carolina, itself made possible by Bahnson's aim of harnessing the power of (anti)gravity before the Soviets did. Spurred by new questions about the behavior of strong gravitational fields—including early hints of gravitational waves and budding ideas about black holes—Bryce DeWitt redoubled his efforts to simulate such systems on computers, training a new generation of Ph.D. students in the topic, who made the best use they could of the computing resources newly available at the University of Texas at Austin.

Yet even the presence of a supercomputer on campus was not enough, and soon DeWitt's protégés like Larry Smarr and (via Smarr) Kenneth Eppley found themselves trekking back to Livermore in the 1970s, sneaking time on the far grander supercomputing facilities at the weapons lab while absorbing as much as they could from behind-the-fence gurus like Jim LeBlanc and Jim Wilson. Having demonstrated that even physical systems as complicated as colliding black holes could be simulated numerically while ensconced each summer at Livermore, Smarr championed the need for civilian supercomputing access, combining his scientific prowess with his anti-nuclear activism to build a new coalition, at long last breaking numerical relativists' dependence on Cold War weapons laboratories.

The curvilinear path toward numerical-relativity simulations illustrates in extreme form many of the entanglements between scientific research and military priorities within the US during the Cold War. Even topics as seemingly far removed from national security as black hole collisions and gravitational waves were inescapably bound to the nation's nuclear weapons complex, with its systems of classification that kept both advanced computing infrastructure and expert communities separated from civilian research communities. In the end, the development of numerical relativity turned on explosive events nearly as dramatic as the cosmic cataclysms the relativists learned to simulate.

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Notes

The following abbreviations are used: BDW, Bryce DeWitt papers, University of Texas at Austin; CDWM, Cécile DeWitt-Morette papers, University of Texas at Austin; DWM-AIP, Bryce DeWitt and Cécile DeWitt-Morette, oral history interview with Kenneth Ford, 28 February 1995, transcript available at http://www.aip.org/history/ohilist/23199.html; LLS-OH, Larry L. Smarr, oral history interview with David Zierler, 4 May 2020, transcript available in LLS-personal; LLS-personal, Larry L. Smarr papers, in Professor Smarr's possession, San Diego, California; LLS-UIUC, Larry L. Smarr papers, University of Illinois, Urbana-Champaign.

[1]B. P. Abbott *et al*. (LIGO Scientific Collaboration and Virgo Collaboration), "Observation of gravitational waves from a binary black hole merger," *Physical Review Letters* 116 (2016): 061102. See also Janna Levin, *Black Hole Blues and Other Songs from Outer Space* (New York: Knopf, 2016); Harry Collins, *Gravity's Kiss: The Detection of Gravitational Waves* (Cambridge: MIT Press, 2017).

[2]See, e.g., Thomas W. Baumgarte and Stuart L. Shapiro, *Numerical Relativity: Solving Einstein's Equations on the Computer* (New York: Cambridge University Press, 2010); Matthew W. Choptuik, Luis Lehner, and Frans Pretorius, "Probing strong field gravity through numerical simulations," in *General Relativity and Gravitation: A Centennial Perspective*, ed. Abhay Ashtekar, Beverly K. Berger, James Isenberg, and Malcolm MacCallum (New York: Cambridge University Press, 2015), 361-411; and Josu Aurrekoetxea, Katy Clough, and Eugene A. Lim, "Cosmology using numerical relativity," *Living Reviews of Relativity* 28 (2025): article no. 5. See also Juliusz Doboszewki and Jamee Elder, "How theory-laden are

observations of black holes?," *Philosophy of Science* 92, no. 4 (Oct 2025): 827-49; and Emilie Skulberg, "Imaging the shadow of a black hole," in *Testing Einstein: One Hundred Years of Experimental Relativity*, ed. Brian C. Odom and Daniel Kennefick (Cambridge, MA: MIT Press, 2026), 329–351.

[3]On the porosity of "pure" versus "applied" research in US physical sciences during the Cold War, see especially the classic discussions in Paul Forman, "Behind quantum electronics: National security as basis for physical research in the United States, 1940–1960," *Historical Studies in the Physical and Biological Sciences* 18, no. 1 (1987): 149–229; and Daniel J. Kevles, "Cold War and hot physics: Science, security, and the American state, 1945–56," *Historical Studies in the Physical and Biological Sciences* 20, no. 2 (1990): 239–64; as well as more recent treatments, including Benjamin Wilson, "The consultants: Nonlinear optics and the social world of Cold War science," *Historical Studies in the Natural Sciences* 45, no. 5 (2015): 758–804; Naomi Oreskes, *Science on a Mission: How Military Funding Shaped What We Do and Don't Know about the Ocean* (Chicago: University of Chicago Press, 2021). On comparable developments within the study of general relativity, see Benjamin Wilson and David Kaiser, "Calculating times: Radar, ballistic missiles, and Einstein's relativity," in *Science and Technology in the Global Cold War*, ed. Naomi Oreskes and John Krige (Cambridge, MA: MIT Press, 2014), 273–316; and David Kaiser, "Secret clocks: The US military, Einstein's relativity, and the Global Positioning System," *Historical Studies in the Natural Sciences* 56, no. 3 (2026): 210–251.

[4]William Rankin, *After the Map: Cartography, Navigation, and the Transformation of Territory in the Twentieth Century* (Chicago: University of Chicago Press, 2016).

[5]See, e.g., Alexander Blum, Roberto Lalli, and Jürgen Renn, "The reinvention of general relativity: A historiographical framework for assessing one hundred years of curved space-time," *Isis* 106, no. 5 (2015): 598–620; Blum, Lalli, and Renn, "Gravitational waves and the long relativity revolution," *Nature Astronomy* 2 (2018): 534–543; and Roberto Lalli, *Building the General Relativity and Gravitation Community during the Cold War* (Cham, Switzerland: Springer, 2017). On the importance of "postdoc cascades," see also David Kaiser, *Drawing Theories Apart: The Dispersion of Feynman Diagrams in Postwar Physics* (Chicago: University of Chicago Press, 2005).

[6]Lillian Hoddeson, Paul W. Henriksen, Roger A. Meade, and Catherine Westfall, *Critical Assembly: A Technical History of Los Alamos during the Oppenheimer Years, 1943-1945* (New York: Cambridge University Press, 1993), 42-47.

[7]See esp. Richard G. Hewlett and Oscar E. Anderson, Jr., *The History of the United States Atomic Energy Commission*, vol. 1, *The New World, 1939-1946* (University Park: Pennsylvania State University Press, 1962); Hoddeson et al., *Critical Assembly*; Lillian Hoddeson, "Mission change in the large laboratory: The Los Alamos implosion program, 1943-1945," in *Big Science: The Growth of Large-Scale Research*, ed. Peter Galison and Bruce Hevly (Stanford: Stanford University Press, 1992), 265-89; Peter Galison, *Image and Logic: A Material Culture of Microphysics* (Chicago: University of Chicago Press, 1997), chap. 4; and Anne Fitzpatrick, *Igniting the Light Elements: The Los Alamos Thermonuclear Weapon Project, 1942-1952* (Ph.D. dissertation, Virginia Polytechnic Institute, 1998), chap. 2.

[8]Richard G. Hewlett and Francis Duncan, *A History of the United States Atomic Energy Commission*, vol. 2, *Atomic Shield, 1947-1952* (University Park: Pennsylvania State University Press, 1969), chap. 16; Herbert F. York, *The Advisors: Oppenheimer, Teller, and the Superbomb* (Stanford: Stanford University Press, 1976); Peter Galison and Barton Bernstein, "In any light: Scientists and the decision to build the Superbomb, 1952–1954," *Historical Studies in the Physical Sciences* 19, no. 2 (1989): 267-347; Fitzpatrick, *Igniting the Light Elements*, chap. 3.

[9]Hewlett and Duncan, *Atomic Shield*, chap. 16; York, *The Advisors*, chap. 4; Galison and Bernstein, "In any light."

[10]A declassified copy of the October 1949 report by the General Advisory Committee is available in York, *The Advisors*, 153-62, quotations on 155, 158, 161. See also York, *The Advisors*, chaps. 4, 6; Galison and Bernstein, "In any light"; and Kai Bird and Martin Sherwin, *American Prometheus: The Triumph and Tragedy of J. Robert Oppenheimer* (New York: Knopf, 2005), chap. 30.

[11]See, e.g., Hewlett and Duncan, *Atomic Shield*, chaps. 14, 16; York, *The Advisors*, chaps. 6-7; Galison and Bernstein, "In any light"; David Holloway, *Stalin and the Bomb: The Soviet Union and Atomic Energy, 1939-1956* (New Haven: Yale University Press, 1994); Michael Gordin, *Red Cloud at Dawn: Truman, Stalin, and the End of the Atomic Monopoly* (New York: Farrar, Strauss, and Giroux, 2009). On the Fuchs affair, see Robert C. Williams, *Klaus Fuchs: Atom Spy* (Cambridge: Harvard University Press, 1987); and Michael S. Goodman, "The grandfather of the hydrogen bomb? Anglo-American intelligence and Klaus Fuchs," *Historical Studies in the Physical and Biological Sciences* 34 (2003): 1-22.

[12]Hewlett and Duncan, *Atomic Shield*, chaps. 16-17; Peter J. Westwick, *The National Labs: Science in an American System, 1947-1974* (Cambridge: Harvard University Press, 2003), 120-28.

[13]Hewlett and Duncan, *Atomic Shield*, chap. 18; York, *The Advisors*, 129-33; Westwick, *National Labs*, 126-27.

[14]York, *The Advisors*, 135.

[15]Bryce S. DeWitt, "The early days of Lagrangian hydrodynamics at Lawrence Livermore Laboratory," in *Numerical Astrophysics*, ed. Joan M. Centrella, James M. LeBlanc, and Richard L. Bowers (Boston: Jones and Bartlett, 1984), 474-481, on 474. On weapons work and ways of life at Livermore during the 1980s and early 1990s, see Hugh Gusterson, *Nuclear Rites: A Weapons Laboratory at the End of the Cold War* (Berkeley: University of California Press, 1996).

[16]DeWitt, "Early days of Lagrangian hydrodynamics," 474. See also Subrahmanyan Chandrasekhar, *Radiative Transfer* (New York: Oxford University Press, 1950); Richard Courant and Kurt Friedrichs, *Supersonic Flow and Shock Waves* (New York: Interscience, 1948).

[17]Steven Weinberg, "Bryce Seligman DeWitt," *Biographical Memoirs of the National Academy of Sciences* (Washington, D.C.: National Academies Press, 2009), vol. 90: 55-67, on 56.

[18]Weinberg, "Bryce Seligman DeWitt," 57; Carl Bryce Seligman [Bryce S. DeWitt], *The Theory of Gravitational Interactions, and the Interaction of Gravitation with Light* (Ph.D. dissertation, Harvard University, 1949). See also Cécile DeWitt-Morette, *The Pursuit of Quantum Gravity: Memoirs of Bryce DeWitt from 1946 to 2004* (New York: Springer, 2011). DeWitt formally changed his last name from "Seligman" in 1950: Weinberg, "Bryce Seligman DeWitt," 57.

[19]Weinberg, "Bryce Seligman DeWitt," 57-58; DeWitt and DeWitt-Morette oral history interview with Ford. For the Pauli anecdote, see Toni Feder, "Snapshots from the life of Cécile DeWitt-Morette," *Physics Today* (10 October 2017).

[20]Weinberg, "Bryce Seligman DeWitt," 57-58.

[21]See, e.g., David Kaiser, "A psi is just a psi? Pedagogy, practice, and the reconstitution of general relativity, 1942-1975," *Studies in the History and Philosophy of Modern Physics* 29 (1998): 321-38; Jean Eisenstadt, *The Curious History of Relativity: How Einstein's Theory of Gravity was Lost and Found Again* (Princeton: Princeton University Press, 2006); Alexander Blum, Roberto Lalli, and Jürgen Renn, "The reinvention of general relativity: A historiographical framework for assessing one hundred years of curved space-time," *Isis* 106 (September 2015): 598-620. On Samuel Goudsmit's proposal to ban papers on general relativity from the *Physical Review*, see DeWitt-Morette, *Pursuit of Quantum Gravity*, 6; and Weinberg, "Bryce Seligman DeWitt," 59.

[22]Bryce DeWitt to Raymond Birge, 11 November 1951 ("owing to the difficult and tedious nature"; Freeman Dyson's advice), in University of California, Berkeley, Department of Physics Records, Box 5, Folder 31, call number CU-68, Bancroft Library, Berkeley; DeWitt, "Early days of Lagrangian hydrodynamics," 475; DWM-AIP.

[23]Richard Rhodes, *Dark Sun: The Making of the Hydrogen Bomb* (New York: Simon and Schuster, 1995), chap. 23; McMillan, *Ruin of J. Robert Oppenheimer*, chap. 9. On the priority dispute, see, e.g., Stanislaw Ulam, *Adventures of a Mathematician* (New York: Scribner's, 1976), 149-50; Gary Stix, "Infamy and honor at the Atomic Café: Edward Teller has no regrets about his contentious career," *Scientific American* (October 1999): 42-43. On radiation damage from the Hiroshima and Nagasaki bombs, see M. Susan Lindee, *Suffering Made Real: American Science and the Survivors at Hiroshima* (Chicago: University of Chicago Press, 1994).

[24]A redacted version of the Teller-Ulam report is available online, though the report remains classified. See, e.g., Alex Wellerstein, "The infamous Teller-Ulam report (1951)," available at http://blog.nuclearsecrecy.com/2012/02/22/weekly-document-15-the-infamous-teller-ulam-report-1951. See also Alex Wellerstein, "From classified to commonplace: The trajectory of the hydrogen bomb 'secret'," *Endeavor* 32 (2008): 47-52. Oppenheimer pronounced the idea "technically sweet" during his 1954 personnel security board hearings: Richard Polenberg, ed., *In the Matter of J. Robert Oppenheimer: The Security Clearance Hearing* (Ithaca: Cornell University Press, 2002), on 41. On computing limitations at Los Alamos, see Hewlett and Duncan, *Atomic Shield*, 537, 558-59, 571; Fitzgerald, *Igniting the Light Elements*, chap. 3.

[25]N. Metropolis and E. C. Nelson, "Early computing at Los Alamos," *Annals of the History of Computing* 4 (1982): 348-357; Francis H. Harlow and N. Metropolis, "Computing & computer: Weapons simulation leads to the computer era," *Los Alamos Science* (Winter / Spring 1983): 132-141; Richard Feynman and Ralph Leighton, *"Surely You're Joking, Mr. Feynman!" Adventures of a Curious Character*

(New York: W. W. Norton, 1985), 107-136; Galison, *Image and Logic*, chap. 8; and Fitzgerald, *Igniting the Light Elements*, chap. 3.

[26]Metropolis and Nelson, "Early computing at Los Alamos"; Atsushi Akera, *Calculating a Natural World: Scientists, Engineers, and Computers during the Rise of U.S. Cold War Research* (Cambridge: MIT Press, 2007), chap. 2; Jennifer Light, "When computers were women," *Technology and Culture* 40 (1999): 455-483; David Alan Grier, *When Computers were Human* (Princeton: Princeton University Press, 2005).

[27]Metropolis and Nelson, "Early computing at Los Alamos," 352-54; Harlow and Metropolis, "Computing & computers," 134-35; George Dyson, *Turing's Cathedral: The Origins of the Digital Universe* (New York: Pantheon, 2012), chap. 5.

[28]Donald MacKenzie, "The influence of the Los Alamos and Livermore National Laboratories on the development of supercomputing," *Annals of the History of Computing* 13 (1991): 179-201; Seidel, "Mars to Minerva," 34-36; Westwick, *National Labs*, 227-28; Dyson, *Turing's Cathedral*, chaps. 5-6.

[29]Dyson, *Turing's Cathedral*, chap. 6; Fitzpatrick, *Igniting the Light Elements*, 166-67.

[30]Hewlett and Duncan, *Atomic Shield*, chap. 18; York, *The Advisors*, chap. 5; Rhodes, *Dark Sun*, chap. 24.

[31]Tad Kishi, "The 701 at the Lawrence Livermore Laboratory," *Annals of the History of Computing* 5 (1983): 206-210, on 208. Since the MANIAC computer at Los Alamos was not fully operational yet, the laboratory purchased an IBM 701 early in 1953. IBM had stepped up its efforts to produce electronic computers at the urging of the AEC, after the US entered the Korean War. The IBM 701 was modeled closely on von Neumann's machine at Princeton, and developed in close coordination with technical staff from the weapons laboratories and other AEC facilities. See Seidel, "Mars to Minerva," 35-36; MacKenzie, "Influence of Los Alamos," 188-89.

[32]Kishi, "The 701," 206; MacKenzie, "Influence of Los Alamos," 189.

[33]Fitzpatrick, *Igniting the Light Elements*, chap. 3.

[34]Bryce DeWitt, "A numerical method for two-dimensional Lagrangian hydrodynamics," Livermore technical report UCRL-4250, 10 December 1953, on p. 4. Report retrieved from the Lawrence Livermore National Laboratory in response to a Freedom of Information Act Request filed by David Kaiser on 3 Aug 2008.

[35]DeWitt, "Early days of Lagrangian hydrodynamics," 475. On the early efforts, in the mid-eighteenth century, to identify and distinguish between Eulerian and Lagrangian coordinate systems for hydrodynamics, see Olivier Darrigol, *Worlds of Flow: A History of Hydrodynamics from the Bernoullis to Prandtl* (New York: Oxford University Press, 2005), 23-30.

[36]DeWitt, "Early days of Lagrangian hydrodynamics," 475.

[37]Seligman [DeWitt], *The Theory of Gravitational Interactions*, opening section on "The general coordinate formalism," 6-26; see, e.g., Eq. (1.2) on p. 6. On textbook treatments of various coordinate systems used in relativistic physics at the time, see, e.g., Richard C. Tolman, *Relativity, Thermodynamics, and Cosmology* (New York: Oxford University Press, 1934); Peter Bergmann, *Introduction to the Theory of Relativity* (New York: Prentice-Hall, 1942).

[38]DeWitt, "Early days of Lagrangian hydrodynamics," 475. DeWitt's handwritten notes on "Detonation Hydrodynamics," n.d., available in BDW, Series 3, folder, "Early notes." DeWitt's notes are undated, but they are a close match to the material in DeWitt's report, "A numerical method for two-dimensional Lagrangian hydrodynamics," Livermore report UCRL-4250, which is dated 10 December 1953. On prevailing secrecy provisions at the weapons laboratories at the time, see esp. Alex Wellerstein, *Restricted Data: The History of Nuclear Secrecy in the United States* (Chicago: University of Chicago Press, 2021).

[39]See Galison, *Image and Logic*, chap. 8.

[40]DeWitt, "Numerical method," 1-4. It had long become customary in hydrodynamic calculations to define the specific volume (G) as the inverse of the mass density (ρ) for a given fluid: $G = 1/\rho$. That is, G represents the spatial volume of the fluid per unit mass. (See, e.g., Courant and Friedrichs, *Supersonic Flow and Shock Waves*, 4-5.) DeWitt defined the "reference specific volume" as $g = G / J$, where G is the specific volume in the Eulerian coordinates, and J is the Jacobian relating the Eulerian and Lagrangian coordinates. Then the specific volumes obey the relation $dx\, dy / g = dX\, dY / G$, where (x,y) are the Lagrangian coordinates and (X,Y) are the Eulerian coordinates. This is akin to working in terms of the invariant volume elements $d^4x\, [- \det (g_{\mu\nu})]^{1/2}$ in general relativity.

[41]DeWitt, "Early days of Lagrangian hydrodynamics," 476-77.

[42]DeWitt, "Numerical method," 4-5. See also Larry L. Smarr, "The contributions of Bryce DeWitt

to classical general relativity," in *Quantum Theory of Gravity: Essays in Honor of the 60th Birthday of Bryce S. DeWitt*, ed. S. Christensen (Bristol: Adam Hilger, 1983), 1-35, on 21-29.

[43]DeWitt, "Early days of Lagrangian hydrodynamics," 477.

[44]J. von Neumann and R. D. Richmyer, "A method for the numerical calculation of hydrodynamic shocks," *Journal of Applied Physics* 21 (1950): 232-237; Robert D. Richtmyer, "Proposed numerical method for calculation of shocks, II," Los Alamos technical report LA-899 (19 August 1948), declassified in 1993; see also Ann E. Mattson and W. J. Rider, "Artificial viscosity: Back to the basics," *International Journal for Numerical Methods in Fluids* 77 (2015): 400–417; and L. G. Margolin and N. M. Lloyd-Ronning, "Artificial viscosity: Then and now," available at https://arXiv.org/abs/2202.11084 (February 2022). Von Neumann's and Richtmyer's main innovation was to add to the ordinary fluid pressure in the evolution equations a new term $q = \rho c\,(\Delta x)^2\,(\partial u/\partial x)^2$, where ρ is the fluid density, c a dimensionless constant, u the fluid velocity, and Δx the number of finite-difference grid points across which one aims to smooth out the sharp feature. Such a term appears as Q in DeWitt's handwritten notes on "Detonation Hydrodynamics," reproduced in Fig. 2.

[45]DeWitt, "Early days of Lagrangian hydrodynamics," 478-79; J. von Neumann and R. D. Richtmyer, "A method for the numerical calculation of hydrodynamic shocks," *Journal of Applied Physics* 21 (1950): 232; Robert D. Richtmyer, "Proposed numerical method for calculation of shocks, II," Los Alamos Technical Report LA-899, Series A (19 August 1948), declassified in 1993. On wartime SEDs at Los Alamos, see, e.g., Hoddeson et al., *Critical Assembly*, 97-98; and Hales, *Atomic Spaces*, 239, 301. On Wilson's background, see "Memoir of James R. Wilson," available at http://computer-history.info/Page2.dir/pages/Wilson.html (accessed on 6 January 2009); anon., "James Ricker Wilson" (obituary), *San Francisco Chronicle* (16 August 2007); and Daniel Kennefick, "Star crushing: Theoretical practice and the theoreticians' regress," *Social Studies of Science* 30 (2000): 5-40.

[46]Bryce DeWitt, "Difference Equations for Tony," handwritten technical report UCRL 4300, Parts I and II, available from the Lawrence Livermore National Laboratory; declassified on 17 December 2009 in response to a Freedom of Information Act request. See also DeWitt, "Early days of Lagrangian hydrodynamics," 478-79. I assume that "Tony" was the first name of the programmer with whom DeWitt worked, rather than a code-name for the project or program. Program names for other Livermore simulation codes at the time included "Dash," "Coronet," "Slug," "Gravel," "Swordtail," and "Proteus," rather than individuals' first names. Nonetheless, no "Tony" or "Anthony" appears in the (partial) list of programmers who worked at Livermore in that era, nor on the list of individuals to whom DeWitt's classified report was distributed (see distribution lists on Part I, p. 33 and Part II, p. 5), and DeWitt did not name his programmer partner in his later recollections. For a partial list of other Livermore programmers and program code-names at that time, see Kishi, "The 701," 209.

[47]DeWitt, "Difference Equations for Tony," 29; see also 26.

[48]DeWitt, "Early days of Lagrangian hydrodynamics," 479. In DeWitt's reminiscences, he mentions that Teller required the 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." (*Ibid*., 477.) However, no US nuclear tests are listed as having occurred in June 1954; DeWitt might have been referring to test detonations in the "Operation Upshot-Knothole" series, which included several tests of Livermore-based designs in late March and April 1954. See US Department of Energy, Nevada Operations Office, *United States Nuclear Tests: July 1945 through September 1992*, report DOE/NV-209-REV 15 (Oak Ridge, TN: US Department of Energy, 2000), p. 4.

[49]DeWitt, "Early days of Lagrangian hydrodynamics," 479; DWM-AIP, 7.

[50]Bryce DeWitt, "New directions for research in the theory of gravitation" (1953), available in the Gravity Research Foundation records, Box 2, Folder 8, call number 14.20, Special Collections, Babson College, Wellesley, Massachusetts. DeWitt's essay is also reprinted in Cécile DeWitt-Morette, *The Pursuit of Quantum Gravity: Memoirs of Bryce DeWitt from 1946 to 2004* (New York: Springer, 2011), 61-68. Bryce DeWitt, interview with David Kaiser, 9 July 1999 ("easiest $1000"). On the Gravity Research Foundation and its annual essay contest, see David Kaiser and Dean Rickles, "The price of gravity: Private patronage and the transformation of gravitational physics after World War II," *Historical Studies in the Natural Sciences* 48, no. 3 (2018): 338-379, on 343-355.

[51]Agnew Bahnson, Jr., to Bryce DeWitt, 30 May 1955, reproduced in DeWitt-Morette, *Pursuit of Quantum Gravity*, 71-73. On the founding of the Institute of Field Physics, Inc., see Kaiser and Rickles, "The price of gravity," 355-365. See also Bryce DeWitt, handwritten memorandum on "A presently neglected area of physical research, and its potentialities," n.d., ca. August 1955, in CDWM, folder

"IOFP."

[52]Kaiser and Rickles, "Price of gravity," 364-68.

[53]Bryce DeWitt, Progress Report (n.d., 1956) to Agnew Bahnson, Jr., CDWM, folder "IOFP."

[54]Kaiser and Rickles, "Price of gravity," 372-73, 376-77; Daniel Kennefick, *Traveling at the Speed of Thought: Einstein and the Quest for Gravitational Waves* (Princeton: Princeton University Press, 2007), chap. 7.

[55]Bryce DeWitt discussion comments in Cécile M. DeWitt, ed., *Conference on the Role of Gravitation in Physics*, WADC Technical Report 57-216 (Wright-Patterson Air Force Base, Ohio: Air Force Research and Development Command, March 1957), 26; see also Cécile M. DeWitt and Dean Rickles, eds., *The Role of Gravitation in Physics: Report from the 1957 Chapel Hill Conference* (Berlin: Max Planck Research Library, 2011), 83.

[56]Charles Misner and Bryce DeWitt comments in DeWitt, *Conference on the Role of Gravitation in Physics*, 25, 29; DeWitt and Rickles, *Role of Gravitation in Physics*, 83, 87. At the time, Prof. Yvonne Choquet-Bruhat presented her work under the name Yvonne Fourès.

[57]See, e.g., Weinberg, "Bryce Seligman DeWitt," 62-63; DeWitt-Morette, *Pursuit of Quantum Gravity*, 57-61.

[58]Susan G. Hahn and Richard W. Lindquist, "The two-body problem in geometrodynamics," *Annals of Physics* 29 (1964): 304-331. See also Susan G. Hahn, "Stability criteria for difference schemes," *Communications on Pure and Applied Mathematics*, 11 (1958): 243–255; and James Barron, "The mathematicians who ended the kidnapping of an NYU computer," *New York Times* (7 December 2015): A18.

[59]Anon., "Project Mercury," available at https://www.ibm.com/history/mercury (accessed 22 April 2026); anon., "IBM 7090," Wikipedia (accessed 22 April 2026). On the Air Force BMEWS system, see also Wilson and Kaiser, "Calculating times: Radar, ballistic missiles, and Einstein's relativity," 277-79.

[60]R. Arnowitt, S. Deser, and C. W. Misner, "Canonical variables for general relativity," *Physical Review* 117 (15 March 1960): 1595-1602; Arnowitt, Deser, and Misner, "Gravitational-electromagnetic coupling and the classical self-energy problem," *Physical Review* 120 (1 October 1960): 313-320. See also Charles W. Misner, "Wormhole initial conditions," *Physical Review* 118 (15 May 1960): 1110-1111.

[61]Hahn and Lindquist, "Two-body problem," 320. In particular, Hahn and Lindquist adopted Gaussian-normal coordinates with trivial lapse function ($\alpha = 1$) and vanishing shift vector ($\beta^i = 0$). See also Michael Holst, Olivier Sarbach, Manuel Tiglio, and Michele Vallisneri, "The emergence of gravitational wave science: 100 years of development of mathematical theory, detectors, numerical algorithms, and data analysis tools," *Bulletin of the American Mathematical Society* 53, no. 4 (October 2016): 513–554, on 531–32. My thanks to Larry Smarr for bringing the Holst *et al*. article to my attention.

[62]Kaiser and Rickles, "Price of gravity," 374, 377-78.

[63]On Weber's detection claims (soon contested), see, e.g., Harry Collins, *Gravity's Shadow: The Search for Gravitational Waves* (Chicago: University of Chicago Press, 2004), Part I. On the resurgence of interest in black holes, see, e.g., Eisenstaedt, *Curious History of Relativity*, chaps. 12, 14; and Marcia Bartusiak, *Black Hole: How an Idea Abandoned by Newtonians, Hated by Einstein, and Gambled on by Hawking Became Loved* (New Haven: Yale University Press, 2015).

[64]Andrej Cadez, *Colliding Black Holes* (Ph.D. dissertation, University of North Carolina at Chapel Hill, 1971).

[65]Roger Penrose, "Gravitational collapse and space-time singularities," *Physical Review Letters* 14 (1965): 57-59; Stephen W. Hawking, "Singularities in the universe," *Physical Review Letters* 17 (1966): 444-45x; Stephen W. Hawking and George F. R. Ellis, *The Large-Scale Structure of Space-Time* (New York: Cambridge University Press, 1973).

[66]LLS-OH, 9-12, 18; see also the correspondence between Larry Smarr, Bryce DeWitt, and Abdus Salam (who was helping to organize the GR6 meeting in Copenhagen, held in July 1971), in LLS-UIUC, Box 1, Folder "DeWitt, Bryce, 1971-72." See also Larry Smarr, "Mass formula for Kerr black holes," *Physical Review Letters* 30 (8 January 1973): 71-73; Smarr, "Surface geometry of charged rotating black holes," *Physical Review D* 7 (15 January 1973): 289-295; and John Wheeler, "Our universe: The known and the unknown," *American Scientist* 56, no. 1 (spring 1968): 1-20.

[67]Nicholas Lewis, "Purchasing power: Rivalry, dissent, and computing strategy in supercomputer selection at Los Alamos," *IEEE Annals of the History of Computing* 39, no. 3 (2017): 25-40. According to *Encyclopedia Brittanica*, the term "supercomputer" was introduced to describe the CDC 6600: https://www.britannica.com/technology/CDC-6600.

[68]"CDC 6600's five year reign," *Computer History Museum*, available at https://www.computerhistory.org/revolution/supercomputers/10/33; "UT Computation Center Records, ca. 1966-1974," Briscoe Center for American History, University of Texas at Austin, https://txarchives.org/utcah/finding_aids/03434.xml.

[69]Larry L. Smarr, *The Structure of General Relativity with a Numerical Illustration: The Collision of Two Black Holes* (Ph.D. dissertation, University of Texas at Austin 1975), 81-83. In terms of the ADM decomposition, the Hahn-Lindquist analysis had fixed the lapse function to be trivial, $\alpha(x^{\mu}) = 1$, and the shift vector to vanish, $\beta^{i}(x^{\mu}) = 0$.

[70]Smarr, *Structure of General Relativity*, 79-80.

[71]André Lichnerowicz, "L'intégration des équations de la gravitation relativiste et le problème des *n* corps," *Journal de mathématiques pures et appliquées* 23 (1944): 37-63; LLS-OH, 29-30.

[72]Smarr, *Structure of General Relativity*, 83-86 ("'natural' system of observers" on 86), figure on 126; compare with DeWitt, "Detonation Hydrodynamics" notes, ca. Dec. 1953. "Maximal slicing" was imposed, in practice, by requiring the trace of the extrinsic curvature (K) to vanish at the initial time. If $K = 0$ on the initial-time hypersurface, then Einstein's equations guaranteed that it would vanish at future times as well. For accessible descriptions of maximal slicing, see Larry L. Smarr and William H. Press, "Our elastic spacetime: Black holes and gravitational waves," *American Scientist* 66 (Jan-Feb 1978), 72-79; and Thomas W. Baumgarte and Stuart L. Shapiro, *Numerical Relativity: Starting from Scratch* (New York: Cambridge University Press, 2021), 117-19.

[73]Frank Estabrook, Hugo Wahlquist, Steven Christensen, Bryce DeWitt, Larry Smarr, and Elaine Tsiang, "Maximally slicing a black hole," *Physical Review D* 7, no. 10 (15 May 1973): 2814-17; Larry Smarr, Andrej Cadez, Bryce DeWitt, and Kenneth Eppley, "Collision of two black holes: Theoretical framework," *Physical Review D* 14, no. 10 (15 Nov 1976): 2443-52. Smarr reproduced a page of DeWitt's handwritten Fortran code, ca. 1972, in Smarr, "Contributions of Bryce DeWitt to classical general relativity," 17.

[74]Smarr and Press, "Our elastic spacetime," 79.

[75]LLS-OH, 33 ("Great Ones at Livermore");

[76]Kenneth R. Eppley, *The Numerical Evolution of the Collision of Two Black Holes* (Ph.D. dissertation, Princeton University, 1975); LLS-OH, 35-36.

[77]Larry Smarr, interview by David Kaiser, 10 Oct 2025; see also LLS-OH, 38.

[78]Larry L. Smarr to Arthur L. Henry (personnel department, Lawrence Livermore Laboratory), 2 Feb 1976, in LLS-UIUC, Box 1, folder "Eppley, Ken, 1974-76." A comparable group at Los Alamos, led by Stirling Colgate, carried out research on simulating related phenomena, such as stellar collapse into supernovae, by building on their weapons-work expertise with numerical simulations. See Arthur I. Miller, *Empire of the Stars* (Boston: Houghton-Mifflin, 2005), chap. 12.

[79]Larry Smarr, "Space-times generated by computers: Black holes with gravitational radiation," *Annals of the New York Academy of Sciences* 302 (Dec 1977): 569-604, quotations on 575–76. See also Smarr and Press, "Our elastic spacetime"; and Holst *et al*., "The emergence of gravitational wave science," 532.

[80]The episode of the 1983 Phil Donahue show with Smarr and Newman is available at https://www.youtube.com/watch?v=dwFe6iGU1NA; Smarr interview with Kaiser ("we should revoke your clearance"). On the 1980s Nuclear Freeze movement, see also Gusterson, *Nuclear Rites*, chaps. 7-9.

[81]Larry L. Smarr, "The supercomputer famine in American universities," on 1-2, unpublished (ca. 1982), copy in LLS-personal and available at https://lsmarr.net/the-supercomputer-famine-in-american-universities. On scientific computing at the Max Planck Institute for Astrophysics, see also https://www.mpcdf.mpg.de/history.

[82] Peter D. Lax *et al.*, "Report of the Panel on Large Scale Computing in Science and Engineering" (26 December 1982), available at https://science.osti.gov/-/media/ascr/pdf/program-documents/archive/Lax_report.pdf.

[83]Smarr interview with Kaiser. The unsolicited 1983 NSF proposal was submitted as Larry L. Smarr *et al*., "A Center for Scientific and Engineering Supercomputing," a copy of which is available at https://lsmarr.net/a-center-for-scientific-and-engineering-supercomputing. A separate unsolicited proposal, which led to the San Diego Supercomputer being funded, was submitted from General Atomics by Sid Karen in 1984, that one based on Lawrence Livermore National Laboratory's Magnetic Fusion Energy Computer Network (MFENET). While Smarr and Karen made the case for federal support with unsolicited NSF proposals, physicist Kenneth Wilson worked hard to build novel industrial support for civilian-based

supercomputing facilities, often framing his case in terms of Reagan-era supply-side economics. See Julia Menzel, *American Physics from the Cold War to Neoliberal Order, 1962-1991* (Ph.D. dissertation, Massachusetts Institute of Technology, 2025), chap. 5.

[84]Smarr interview with Kaiser. See also Lawrence E. Brandt, "Centers of supercomputing: A history and prospectus for the NSF supercomputer centers," *International Journal of Supercomputer Applications* 5, no. 4 (Winter 1991): 4–9. My thanks to Larry Smarr for bringing the Brandt article to my attention.

[85]"Statement of Dr. Mary L. Good, Chairperson, Programs and Plans Committee, National Science Board," *Federal Supercomputer Programs and Policies*, US House of Representatives, Hearing of the Committee on Science and Technology, June 10, 1985 (Washington, DC: US Government Printing Office, 1985), 35-38, on 36; Brandt, "Centers of supercomputing."

[86]Larry Smarr, "Numerical, theoretical, and astrophysical relativity" (1983), available at https://lsmarr.net/research/general-relativity/numerical-black-hole-dynamics; Richard A. Matzner et al., "Geometry of a black hole collision," *Science* 270 (10 Nov 1995): 941-47; Kip S. Thorne, "LIGO and the discovery of gravitational waves," Nobel Prize Lecture (8 Dec 2017), available at https://www.nobelprize.org/uploads/2017/12/thorne-lecture.pdf.

[87]Frans Pretorius, "Evolution of binary black-hole spacetimes," *Physical Review Letters* 95 (16 Sep 2005): 121101. See also M. Campanelli, O. Lousto, P. Marronetti, and Y. Zlochower, "Accurate evolutions of orbiting black-hole binaries without excision," *Physical Review Letters* 96 (22 March 2006): 111101; and J. G. Baker, J. Centrella, D.-I. Choi, M. Koppitz, and J. van Meter, "Gravitational-wave extraction from an inspiralling configuration of merging black holes," *Physical Review Letters* 96 (22 March 2006): 111102. In his landmark 2005 article, Pretorius acknowledged support from a Richard C. Tolman postdoctoral fellowship as well as from each of the large NSF grants that were then funding the Caltech-based SXS group. He also acknowledged helpful discussions with Lee Lindblom, then one of the SXS directors. See also Daniel Kennefick, "The wagers of science," in *Einstein Was Right: The Science and History of Gravitational Waves*, ed. Jed Z. Buchwald (Princeton, NJ: Princeton University Press, 2020), 62-75; and Ulrich Sperhake, "The era of precision in computational models of gravitational waves," arXiv:2607.06728, available at https://arXiv.org/abs/2607.06728.

[88]Oliver James, Eugenie von Tunzelmann, Paul Franklin, and Kip S. Thorne, "Gravitational lensing by spinning black holes in astrophysics, and in the movie *Interstellar*," *Classical and Quantum Gravity* 32, no. 6 (2015): 065001; *idem*., "Visualizing *Interstellar's* wormhole," *American Journal of Physics* 83 (June 2015): 486-499.