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In Pursuit of Gravitational Waves: Solving the Two-Body Problem in General Relativity

by Jean-Philippe Martinez - Max Planck Institute for Gravitational Physics (Albert Einstein Institute)

RFrom 20 to 22 October 2025, the Max Planck Institute for Gravitational Physics (Albert Einstein Institute) in Potsdam hosted the workshop “*In Pursuit of Gravitational Waves: Solving the Two-Body Problem in General Relativity*.” Part of the Balzan Prize Project, the event brought together physicists, historians, and philosophers to reflect on the historical and conceptual development of the relativistic two-body problem and its central role in enabling gravitational-wave detection. Over three days, the workshop provided a rare opportunity to examine not only the technical breakthroughs that underpin gravitational-wave astronomy, but also the institutional, epistemic, and human factors that shaped this achievement.

At the heart of the discussions lay the long-standing challenge of describing two compact objects interacting through Einstein’s theory of gravity. As black holes or neutron stars spiral toward each other, the disturbances they create in spacetime encode a remarkably rich record of the system’s properties. Indeed, the emitted gravitational waves carry signatures of the bodies’ masses, spins, and tidal responses, most prominently during the final orbits, the energetic coalescence, and the subsequent settling of the remnant. To read these signatures reliably, physicists must model the entire evolution of the binary with high precision.

The nonlinear structure of general relativity, however, prevents a closed-form solution for a true binary system, leaving only approximate or special-case solutions. Two complementary strategies have therefore emerged. Analytical treatments—most notably post-Newtonian expansions and other perturbative schemes—provide controlled approximations during the long inspiral, when the motion is slow enough for series methods to remain accurate. Numerical simulations, though computationally intensive, take over in the regime of strong gravity and rapid dynamical change, where only a full solution of Einstein’s equations can capture the plunge, merger, and subsequent ringdown. Over time, these two approaches have become increasingly intertwined, with analytical insights guiding numerical constructions and numerical results feeding back into improved analytical models.

Our current understanding of compact-binary dynamics therefore reflects a long interplay between analytical and numerical traditions, whose combined strengths gradually overcame each other’s limitations. Together, they produced the waveform models that underpin gravitational-wave astronomy and the field’s dramatic expansion after 2015 makes the impact of this synthesis unmistakable. On 14 September 2015, the LIGO detectors recorded GW150914, the first direct observation of gravitational waves, produced by the merger of two unexpectedly massive black holes. That moment condensed decades of effort pursued around the globe—most notably in Europe, Japan, and the United States: without reliable waveforms, shaped by analytic reasoning and honed through numerical simulation, the signal’s interpretation as a binary black-hole merger and the assessment of its statistical significance (exceeding 5σ) would not have been possible. Since then, increasingly sensitive detectors and refined modeling frameworks have made gravitational-wave observation routine, with hundreds of compact-binary coalescences now identified. These observations are reshaping our understanding of stellar evolution, the demographics of compact objects, and the nature of gravity in its most extreme, dynamical regime. The decades-long accumulation of theoretical insight and computational expertise—each shaped by evolving communities, priorities, and

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2025 History Physics Essay Contest Winners

The essay contest winner this year is India Bhalla-Ladd of UC-Irvine for “Introducing the Technical Typists of APS.” Yuxin Fang of the University of Minnesota was named a Runner-Up for “Cold War Echo: Reconstructing the Geopolitical Origins of the 19645 Discovery of Cosmic Microwave Background Radiation.”

History and Philosophy of Physics

NEWSLETTER

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The articles in this issue represent the views of their authors and are not necessarily those of the Forum or APS.

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2026 Global Physics Summit FHPP Sessions

MONDAY 3/16 8:00 AM – 11:00 AM (INVITED SPEAKERS)

80th Anniversary of Operation Crossroads and the Atomic Energy Act

Chair: Ryan Dahn, American Institute of Physics

- Sovereignty at Crossroads, Mary X Mitchell
- Beyond the Threshold: The Regulatory Origins of the Linear Non-Threshold (LNT) Model for Radiation Protection, Toshihiro Higuchi
- Beginning of the US Space Age?, Andrew Ross
- The Medical Section of the Manhattan Project and Radiological Data Collection during Operation Crossroads, Joshua McGuffie
- Modeling Harm in Nuclear Environments after Operation Crossroads, Jacob D Hamblin

MONDAY 3/16 12:00 – 3:00 PM

Black Holes, Quarks, Noise Mitigation, Typists, and Metaphors,

Chair: Kevin Vallego, Idaho National Laboratory

- Introducing the Technical Typists of the American Physical Society, India Bhalla-Ladd
- Shielding Observatories through Legal Constructs: Noise Mitigation for Radio Astronomy, Tiffany Nichols
- The Development of Black Hole Thermodynamics: A Novel Historical Approach, Juan Diego Garcia
- Two Quark Colors of the Cold War: Schism of Narratives, Vitaly Pronskikh
- The Use of Metaphor in and outside the Laboratory: The Story of Science, Kevin Vallejo
- Thomas Henshaw, The Forgotten Alchemist Who Saved the Scientific Journal, Gracie Burrows
- The Strange History of the Doppler Effect and Binary Stars, Paul H Halpern
- The use of metaphor inside and outside the laboratory: the story of science, Kevin Daniel Vallejo

TUESDAY 3/18 10:45–12.33

Damour Pais Prize (Invited Session)

Chair: Kathryn Olesko, Georgetown University

- Building the Cathedral of Quantum Mechanics, Michel Jannsen
- Revisiting the Origins of Schrödinger's Wave Mechanics, Alexander Blum
- Stages in the Conceptual Development of Wave Mechanics, A. Douglas Stone

WEDNESDAY 3/18 2:00 – 3:00 PM

The Crisis in American Science (Invited Session)

Chair: Kathryn Olesko, Georgetown University

- Guiding Physics: The Managerial Ecosystems Supporting US Scientific Research, Michael Riordan
- From the Cold War to the China Initiative: Crisis in American Science in Historical Perspective, Zuoyue Wang
- Peer review: The end of an American institution?, Melinda Baldwin
- A Regime Change and the Scientists' Response, Mitchell G. Ash
- Where Are the Philosophers of Science in the Debates about a Crisis in American Science?, Donald Howard

THURSDAY 3/19 10:30 AM – 12:18 PM

History, Philosophy, Education, & International Engagement

- Empowering Students Through Interactive Physics Simulations: Integrating Replit for Hands-On Computational Learning, Rahmat Rahmat
- A review of Mixed Reality Technologies to Increase Physics Comprehension, Lori A Rebenitsch
- Why are we, the physicists of the modern world, not able to find the theory of everything, Scott S Gordon
- Two Core Organizing Principles Lost in the History of Physics: How it happened and why it matters, Peter Cameron

- Small-scale optical particle counters for actionable air quality data in resource-limited settings, Tchanche F Bertrand
- Astronomy for a Better World: How IAU Office of Astronomy for Development Uses Astronomy to Drive Global Development, Joyful E Mdhuli
- Graduate Teaching Assistant Experiences in Remote Asynchronous and In-Person Introductory Physics Laboratories, Angela Kelly
- Introducing physics students to biophysical reactions, Samuel Safran
- Logic, Human Perception, and Cognition Are at the Heart of the Principle of Relativity, Douglas M Snyder

The Impact and Influence of Academic Genealogies

By Bryan Briones¹, Ronald E. Mickens², and Charmayne Patterson³

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We introduce the concept of an “academic genealogy” (AG) and illustrate how AG charts may be constructed by using Wikipedia as our reference. We then demonstrate how this methodology can be used by applying it to create the partial or full AG charts to two scientists: Paul A. Samuelson and Ronald E. Mickens. For Samuelson we find that not only did he have academic connections to some of the most creative economists of his time, but as his AG chart shows, Josiah W. Gibbs, his academic grandfather, was perhaps the most distinguished scientist to date, from North America. Similarly, the members of Mickens’s AG can be traced back several centuries and include some of the most influential physicists and mathematicians of the 19th and 20th centuries. Thus, our major conclusion is that the AG of a scientist helps us to understand the path of their academic career, why they selected particular research topics, the impact on their discipline, and the success of their academic children.

Keywords: Genealogy, invisible colleges, research mentorship, success in the academy, Paul A. Samuelson, Ronald E. Mickens

Introduction

An academic genealogy (AG) is a family tree of scholars based on mentoring relationships. In the sciences, these relationships are generally based on dissertation supervision. However, the AG may also be determined by starting with a subject’s undergraduate mentor. A good introduction to this topic can be obtained from Wikipedia (Academic Genealogy, 2025).

In more detail, an AG is determined by finding out who was the mentor/advisor of the subject and continuing this process as far backward in time as available information will allow. If we plot these items in two dimensions, an AG chart is produced and may be used for a variety of purposes:

- To indicate the historical connections between the subject and earlier scientists and their research
- Provide insights into possible future paths for research on future topics.
- Understand why a subject selected a particular topic to investigate for their research.
- Determine the social, academic, and research networks that shaped the career of a specific subject.

In essence, careful examination of the AGs of scientists who are connected by the same research agendas allows us to learn about the history of past achievement, and to determine who pioneered these achievements. For example, the roles played by knowledge of the history of science, particularly physics, is discussed in Reddington (2017) and Stanley (2016).

AGs have also been used to investigate and give insights into a number of related social science issues and behaviors. For instance:

- Investigating the role of faculty advisors in the career pathways of their doctoral students (German, 2018),
- Measuring the impact of medical AG on publication patterns and medical practice (Hirshman, 2016),
- Determining the impact of an individual researcher on their discipline (Ridder, 2025),
- Applying bibliometric methodologies to study scientific AGs (Ruihua, 2021),
- Using AG to understand and predict academic success (Wuestman, 2020),
- Using AG to investigate the influence of coauthorship on researcher affiliation, research topic, productivity, and impact (Xie, 2022).

The construction of an AG can proceed in several ways. In the next section, we mainly focus on how this may be accomplished by using Wikipedia as a reference.

However, one can also use information on the networked digital library of theses and dissertations (Dores, 2016).

Viewing AG within a wider context allows the introduction of the concept of an “invisible college” (Price, 1971; Crane, 1972; Paisley, 1972). Invisible colleges are groups of researchers who work in the same area, forming a network of informal contacts with one another. These groups generally have memberships of the order of 20-50 individuals. The following is a listing of the major characteristics of invisible colleges:

- Membership is not formalized but is strongly dependent on the acceptance of one’s research by other members of the invisible college.
- The membership is generally not in the same or nearby geographical locations.
- The members’ informal contacts and exchange of information, ideas, data, etc., can take place by using a wide variety of mechanisms. For example, in today’s research environment, modes of information exchange generally take place via email, phone correspondence, social media platforms, or video conferencing.
- Members generally assume that researchers who are not in their circle are not doing research of value, as if to establish that their invisible college contains just the important players, making it an exclusive club of sorts.
- Members assume that other members can appreciate and understand each other’s work and provide, if required, the appropriate interpretation.
- Members generally agree on what are the important issues, what methodologies, should be used to resolve them, and can agree on when a suitable resolution has been obtained.

It should be noted that invisible colleges play very important roles in maintaining scientific progress and its administration. For example, members of the invisible college will generally:

- provide peer reviews of other members' manuscripts that are submitted to journals,
- sit on research panels to evaluate research funding proposals,
- serve on committees to make selections for high-value awards and honors,
- determine whether a given member is considered in elite professional organizations,
- influence the opportunities for other members to assume leadership of their discipline,
- provide career guidance,
- shape particular scientific centered social interactions of members who are being mentioned by others in the invisible college

Invisible colleges are dynamic, social, and scientific structures. Their membership changes with time and may dissolve when the initial critical issues or problems have either been "solved" or are no longer considered of any importance.

Finally, the invisible college can play a significant role in determining the value of any member's research and the resulting publications. This occurs because the member of the invisible college can encourage other members to cite other members' papers, and this can have both an immediate and significant impact on the value of these publications within the general scientific research community for that discipline.

With this background in hand, we can now state the main task of this paper, namely, to illustrate how the concepts of academic genealogy and the invisible college can be used to evaluate the careers of scientists. The next section provides a concise summary of our methodology. We then proceed to apply this methodology to first examine the career and influence of the economist, Paul A. Samuelson. This is followed by carrying out a similar analysis for physicist Ronald E. Mickens. Finally, we end the paper with a discussion of our results and a brief list of conclusions.

This paper is also an extension of a presentation made at the 2019 Annual Meeting of the Georgia Academy of Science,

Section VI, History and Philosophy of Science (Mickens and Patterson, 2019).

Methodology

The basic information on all of the persons discussed or presented in this work is obtained from the publicly available, online encyclopedia Wikipedia. For the natural sciences and related disciplines, their professional communities have worked very hard to ensure that data given by Wikipedia is accurate, up to date, and contains few errors or misinformation. These features generally hold for both technical and biographical entries given on their web pages.

Another important feature of Wikipedia's biographical entries is that they give for individuals holding a doctorate the name(s) of their advisor(s) and/or mentor(s), with a direct link to their Wikipedia entry. Consequently, it is rather easy to construct the academic genealogy of any given holder of a Ph.D. in the sciences.

In recent years, many science-based professional societies have become interested in providing data which allows their members and others the opportunity to generate or construct individual academic genealogies. Figure 1 gives a partial listing of several of these websites. Each year additional websites are being constructed for this purpose.

In this work, we do not provide the Wikipedia URLs for most of the persons who we place on the charts related to either the academic genealogies or the associated academic/research connections. This is largely done, as stated above, for the reasons that their information is easily available via their own Wikipedia entries.

The methodology used to construct the several academic genealogies is based on carrying out the following steps:

1. Go to Wikipedia (<https://www.wikipedia.org>) and search the subject by name.
2. Determine the subject's Ph.D. advisor.
3. Click the link to the subject's Ph.D. advisor and then determine that advisor's own Ph.D. advisor.
4. Continue this process for as far in the past as is needed or is possible.
5. From this information, construct the subject's academic genealogy chart.

Note that for the case of more than one Ph.D. advisor, the chart may become complicated as multi- (backward in time) trajectories exist.

Finally, Wikipedia provides a wealth of information for those who wish to explore the details of the life and career of the subject. Generally, on the right-hand side of the entry there is a panel of bulleted information as follows (not all of them may be available or known):

- Full name of the subject
- Date of birth and death
- Nationality
- Education and alma mater
- Concise summary of what they are known for
- Names of spouse(s) and child(ren)
- Research fields
- Institutional affiliations
- Title of thesis or dissertation
- Doctoral advisor

There might also be a link to an electronic copy of the subject's thesis or dissertation.

Case Study: Paul A. Samuelson

In this section, we apply the concept of academic genealogy to the case of Paul A. Samuelson, one of the most important and impactful economists of the twentieth century (Samuelson, 2007).

Figure 2 presents a truncated version of Samuelson's academic genealogy chart (AGC), covering his academic fathers and grandfathers and two of his academic children. However, using the procedure given in the section on Methodology, this chart may be expanded in either temporal direction.

Observe that Samuelson descended from a line of very distinguished late 18th and early 19th century economists. The AGC also indicates that two of his academic children, Lawrence Klein and Robert C. Merton, received the Nobel Prize in Economics, an honor bestowed to Samuelson himself in 1970. Samuelson used physical and mathematical concepts, reinterpreted, to raise the level of scientific analysis in economic theory (Samuelson, 2007). For example, he demonstrated mathematically that the existence of an equilibrium point in a supply-demand graph (explained

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in Pinkasovitch, 2024) did not necessarily imply that the equilibrium was stable.

Samuelson's work and writings influenced students worldwide and helped make MIT a premier center for the study and application of economics. Further extensions of this methodology produced what is now called "econophysics" (Farmer et al, 2025; Slanina, 2014; *Wikipedia*, 2025), the generalization of physical concepts from statistical and thermal physics for application to economical phenomena. One consequence of this approach was that economics could be made more logically rigorous. Thus, predictions could be made from the mathematical structures devised to model economic systems and, as a result, economic theories could be tested using actual data.

Figure 3 indicates that Samuelson's views and methodology regarding economics and how it should be thought about and approached were heavily influenced by Josiah Willard Gibbs (*Wikipedia*, 2025) via contact with Edwin Bidwell Wilson (*Wikipedia*, 2024). In a real sense, Gibbs is the most distinguished, impactful, and important American scientist to date; there are more than 23 concepts named after him (*Wikipedia*, 2025). Likewise, similar things can be said for Wilson (*Wikipedia*, 2024), who was a general polymath. Both individuals made major contributions to chemistry, mathematics, and physics. While Wilson was a Ph.D. student of Gibbs at Yale University, Samuelson was a student, and later colleague, of Wilson at Harvard University and MIT. Both believed that complex phenomena, properly analyzed, could be understood if appropriate mathematical models could be constructed to describe their behaviors.

In summary, Paul A. Samuelson's very successful academic and research career was based on the following consequential set of conditions and circumstances:

- Samuelson came from a very distinguished line of elite academics who were involved in important research and scholarship, not just in economics, but also in the natural sciences and mathematics.
- Samuelson continued on this track and himself became the ancestor academic who produced students who tackled some of the most challenging problems and issues in economics.

- Samuelson attended and worked at two of the most elite universities in the world, namely, Harvard and MIT. Consequently, he had ready access to both resources and scientific networks of influence.
- Samuelson's and his students' work were awarded the highest honors in the field of economics. He and several of his students were given Nobel prizes for their contributions.

These factors were a direct result of Samuelson's stellar academic genealogy.

Case Study: Ronald E. Mickens

Ronald E. Mickens is a mathematical scientist whose research centers on the modeling of systems. He has published almost 400 papers in peer-reviewed journals, and authored/co-authored twenty-two books. He grew up in Petersburg, Virginia, attending Peabody High School. After graduating from Fisk University, in 1964, he obtained his doctorate degree in theoretical physics in 1968 from Vanderbilt University and spent two years at the Center for Theoretical Physics at MIT as a National Science Foundation Fellow.

Mickens's research has been very broad in its subject matter and involved topics in areas such as (*Wikipedia*, 2025):

- high energy physics (asymptotic properties of scattering amplitudes),
- difference equations and their applications, and
- nonlinear oscillations in one-dimensional systems (Mickens, 2010).

Mickens's noteworthy accomplishments and contributions to mathematics and physics include (*Wikipedia*, 2025):

- the construction of nonstandard finite difference schemes (NFDS) for the discretization of differential equations (Mickens, 1994),
- construction and analysis of generalized trigonometric functions (Mickens, 2019), and
- writing of biographical essays on the lives, careers, and research of African American scientists.

Mickens was also among the first modern authors to write a book on difference equations and their applications (Mickens, 1987),

The AG charts for Mickens are given in Figures 4 and 5. Figure 4 is the AG which goes through his undergraduate advisor/mentor at Fisk University, Professor/Dr. James Raymond Lawson. Lawson received his BA in Physics at Fisk in 1935 and the Ph.D. from University of Michigan in 1939. Likewise, Figure 5 is the AG that goes through Mickens's Ph.D. advisor/mentor, Professor/Dr. Wendell Gene Holladay. Holladay received his BA (1949) and MS (1950) degrees from Vanderbilt University, and his Ph.D. in Physics from the University of Wisconsin (1954).

A close inspection of Figure 4 shows that one of the connections for the first five levels of academic ancestry is that all of these scientists were involved in the area of infrared spectroscopy. It should also be pointed out that Mickens was heavily grounded in techniques and the methodology of IR-spectroscopy while an undergraduate at Fisk. Furthermore, all of the academic ancestors of Mickens were distinguished scientists who made important contributions to several areas of the physical sciences and scientific administration.

Likewise, Figure 5 includes the names of two individuals who received the highest award in physics, namely, the Nobel Prize. They are Max Born (1954 NP) and Maria Goeppert Mayer (1963 NP). This chart also contains the names of one of the foremost mathematicians of the 19th century, Karl Weierstrass, along with his student Carl Runge. Furthermore, this AG includes Friedrich Bessel and Carl Gauss, who are well known to students and professors in both physics and mathematics.

In summary, Ronald Mickens's AGs are populated by many of the 19th and 20th centuries' most accomplished scientists and mathematicians.

Conclusion

This article has reported on certain aspects of academic genealogies (AG) as it applies (mainly) to scientists. We have not attempted to be complete, but only presented the essential features of how to actually construct an AG. Below we list several of the consequences which flow from having a knowledge of your or some other individual's AG:

- Having an AG chart allows a scientist to acquire a sense of their scientific heritage as it relates to their research.

- AGs of other scientists may be used to help in the selection of collaborators, which can then initiate the formation of an “invisible college.”
- Knowledge of the successes and failures of researchers higher up on the AG trees can inform a scientist on paths to both take and to avoid, and thus eliminating previously made errors and mistakes.
- Knowledge of the AGs of collaborators can help in the recruitment of top level students and allow for the possibility of forming networks with elite scientists.
- Having an “outstanding” AG and membership in the appropriate invisible college enhances opportunities to be nominated and selected for top level awards and honors; it also increases the chances of receiving research funding; and brings the scientist to the attention of the scientific community to which they belong, thus increasing the possibility to be selected to positions of scientific leadership.
- An “outstanding” AG, along with distinguished research outputs, greatly increases the chances of obtaining a position at an elite university or research institute; consequently, in these positions they can reproduce their own research siblings.

The real significance of these six items becomes apparent when a comparison is made with the indicators that many use to gauge success in science:

- significant and impactful research;
- producing publications having high impact factors;
- receiving adequate funding for research and student support;
- having a tenured professorship, especially at a prestigious college, university, research institute, or government laboratory;
- collaborating with other highly successful scientists;
- producing successful students;
- being a leader in your discipline;
- holding positions of leadership in the appropriate professional societies;
- being invited to write a review on some technical issue of relevance to your discipline;

- being an active member and leader in your associated “invisible college”; and
- becoming a role model or inspiration for the next generation of scientists.

Finally, based on our experiences in gathering an assortment of materials to write this article, and discussions among ourselves and with others, we conclude that every academic, whether a scientist or not, should construct their own academic genealogical tree and use it to explore its various meanings, interpretations, and evaluations related to one’s research and scholarly career, to date. This will prove to be a task that gives no regrets.

Selected Academic Genealogical Websites

Chemistry

<https://web-genealogy.acs.illinois.edu>

Mathematics

<https://www.genealogy.math.ndsu>

Philosophy

<https://academicstree.org/philosophy>

Neuroscience

<https://neurotree.org/neurtotree>

Linguistics

<https://academicstree.org/linguistics>

General

<https://academicstree.org/>

(This one covers genealogies of more than 38 academic disciplines)

Figure 1. Websites for genealogy searches for selected disciplines.

ECONOMICS: PAUL A. SAMUELSON

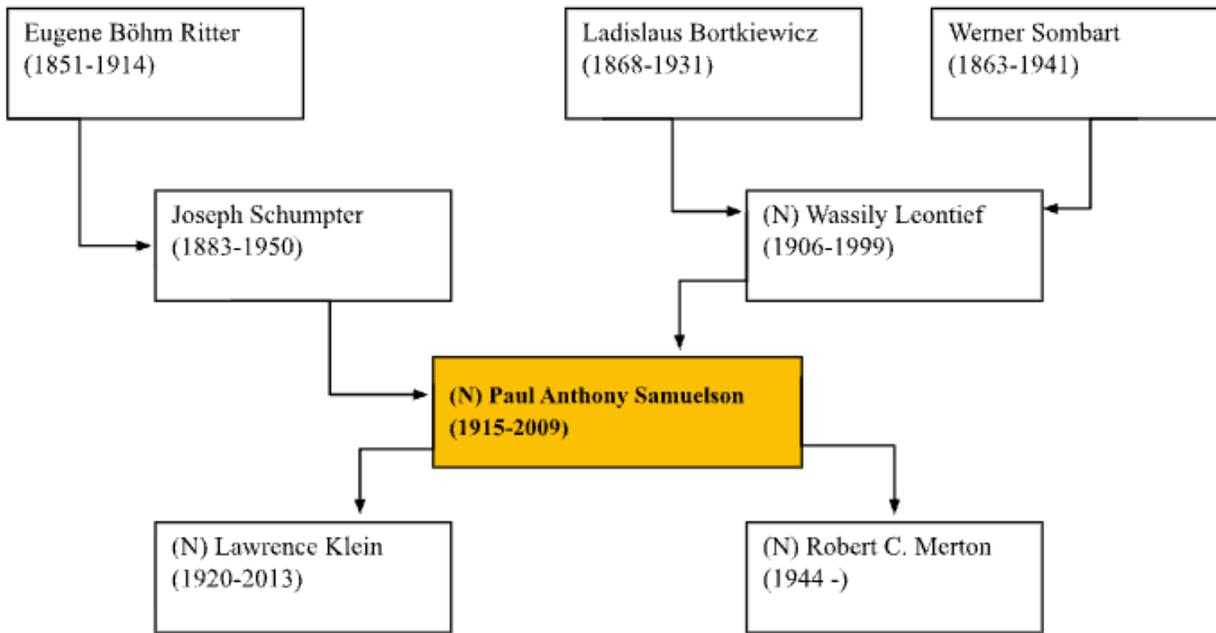


Figure 2. Truncated AG of academic connections for Paul A. Samuelson in the discipline of Economics. (N) denotes Nobel Prize recipient.

MATHEMATICS/PHYSICS: PAUL A. SAMUELSON

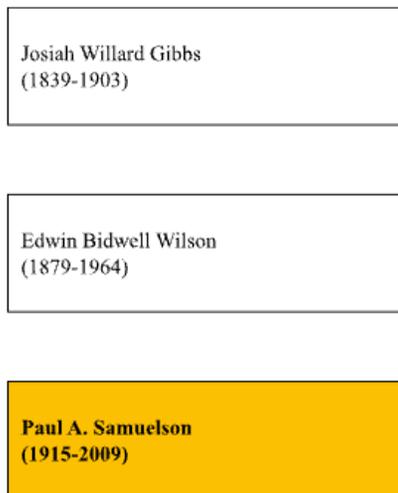


Figure 3. Paul A. Samuelson's academic connections to the discipline of mathematical/theoretical physics. Samuelson transferred physical concepts to the field of economics using mathematics.

ACADEMIC GENEALOGY OF RONALD E. MICKENS VIA JAMES R. LAWSON (FISK UNIVERSITY)

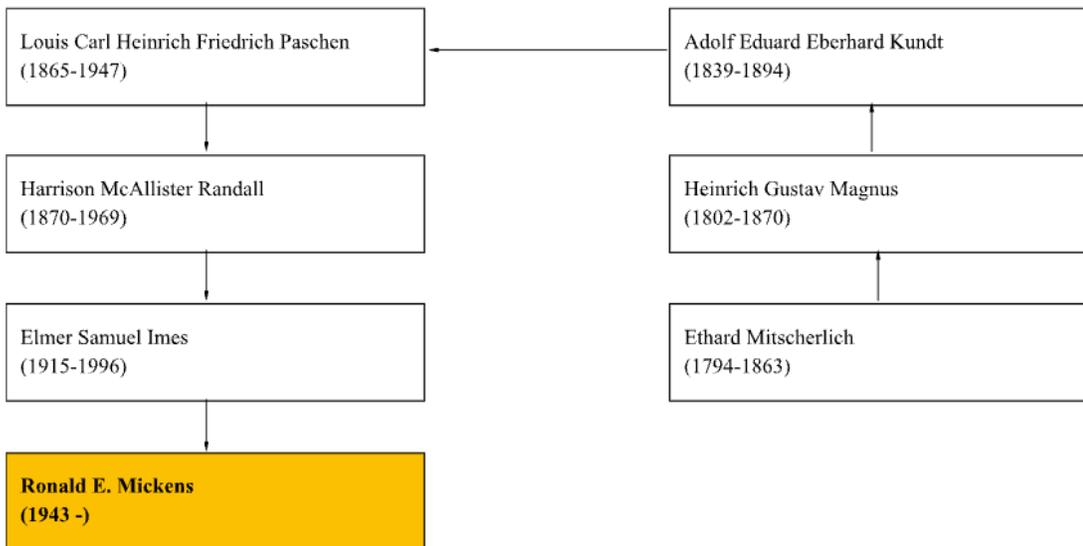


Figure 4. Academic genealogy of Ronald E. Mickens via his undergraduate mentor at Fisk University, James R. Lawson.

ACADEMIC GENEALOGY OF RONALD E. MICKENS VIA WENDELL G. HOLLADAY (VANDERBILT UNIVERSITY)

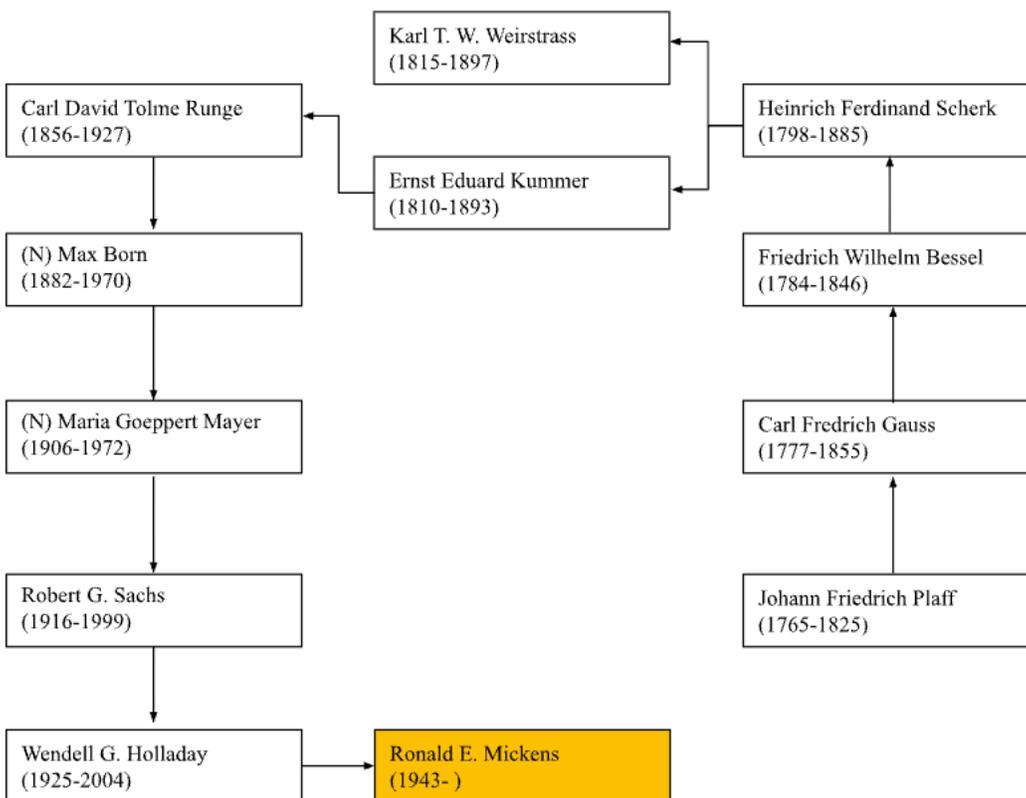


Figure 5. Academic genealogy of Ronald E. Mickens via his Ph.D. advisor, Wendell G. Holladay, at Vanderbilt University. (N) denotes Nobel Prize recipient.

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March 2025 FHPP Pais Prize

2025 Pais Prize Awarded to Michael Riordan – Session Report

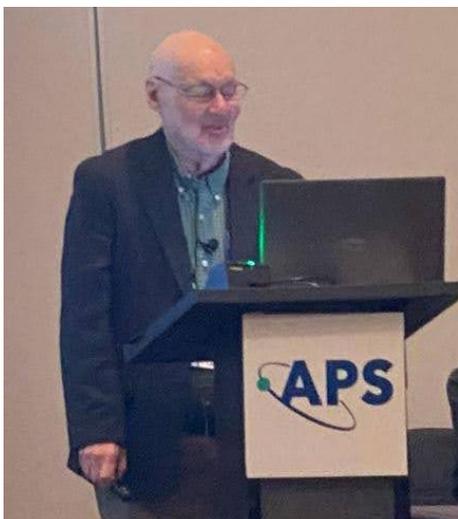
By Donald Salisbury, Department of Physics, Austin College, Sherman, Texas



Michael Riordan



Peter Galison



Allan Franklin

This was a truly memorable session dealing with fascinating chapters in the history of particle physics. The first talk was given by this year's Pais Prize for the History of Physics recipient Michael Riordan. He was followed by the Peter Galison, himself so honored in 2018. His title was *The Photon Ring: An Illumination of Spacetime*. He was followed by Allan Franklin, himself a recipient in 2016. His title was *Once Can Be Enough: Decisive Experiments*. It is remarkable that all three began their careers in experimental particle physics, and this clearly both motivated and assisted them in their historical analysis.

Riordan's talk was entitled *Are Quarks and Gluons Real?* His insights clearly emerged from his own participation, first in 1967 as an MIT senior student, at the Stanford Linear Accelerator. His senior thesis focused on the elastic scattering experiments. He continued five years at SLAC, working under the direction of his thesis advisor Jerome Friedman who was awarded with Henry Kendall and Richard Taylor the 1990 Nobel Prize in physics in recognition of their pioneering work in producing experimental evidence of the quark constituents of protons and neutrons. As he explained in his talk, the original research focus was not on discovering quarks, but rather to measure the electromagnetic structure functions of the proton and neutron. A brief discussion of his collaboration with this extraordinary team appears in his 2003 article.¹ I recommend reading the full overview of the historical emergence of evidence for quark and gluon constituents in his 1983 text.² A full report of his own contribution to the evidence of quark existence can be found in his 1973 PhD thesis.³ As commented in the thesis, the observed inelastic scattering of the electron beam was definitely consistent with there being underlying particle constituents of the proton and neutron. Feynman at SLAC had only recently prior to these experiments proposed the real existence

of constituent partons. Gell-Mann had of course earlier, in 1964, invented what he viewed initially as a useful mathematical model of constituent quarks.

My impression has been that he did not adequately describe his own role in the production of evidence for the existence of quarks. He was of course recognized for his role, and readers would indeed appreciate his more theoretically detailed account of quark evidence in his 1997 *Science* article.⁴ Significant links are to be found there to the 1974 publications of collaborative work he undertook in 1973 on the SLAC synchrotron detection of inelastically scattered electrons.⁶ Initially the results were consistent with the scale independence that had been forecast by James Bjorken in 1968.⁵ There followed wider angle synchrotron detection of electron scattering in which deflection from protons and neutrons could be numerically distinguished. He was the leading author of two resulting highly cited papers. Although he discussed in his lecture and displayed in a slide the evidence they had collected on the breakdown of scale invariance due to the new role of gluons he did not mention the role he had played in these discoveries! These SLAC experiments were labeled E49 and E87, and they played a continuing role in 1975 publications. The latter part of his presentation dealt with Stanford Positron Electron Accelerating Ring (SPEAR), and the so-called November revolution. Evidence arose that each quark could exist in three different "colors". And the detection of the Psi meson confirmed the existence of charm quarks. There followed beginning in 1978 at the Positron-Electron Tandem Ring Accelerator (PETRA) in Hamburg, Germany, the detection of two and then three jet hadron production. This led to a firmer belief in quantum chromodynamics.⁷

Not incidentally, progress in particle physics led to initial funding support for the so-called Superconducting Super

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Collider near Waxahachie, Texas, just south of Dallas. In one of his initial slides Dr. Riordan displayed images of the two individuals he identified as his “principal academic mentors”. One was of course of his thesis advisor Jerry Friedman. And the second identified an even earlier recipient of the Pais prize in 2012. She is Lillian Hoddeson, a renowned science historian. She indeed co-wrote with Riordan and Adrienne Kolb in 2015 a deep historical analysis of the emergence and sudden death of the SSC.⁸

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7. I recommend reading these [recent reflections by Riordan](#) on the strength of experimental evidence. And there is a wonderful photo of him in the group photo on the occasion of Taylor, Friedman and Kendall receiving the Nobel Prize in 1990.

8. M. Riordan, L. Hoddeson and A. W. Kolb, *Tunnel Visions – The Rise and Fall of the Superconducting Super Collider* (2015). This tale is especially significant for me. Vigdor Teplitz assumed the role in 1990 as Chair of the Physics Department at Southern Methodist University in Dallas in preparation for long term elementary particle physics at the emerging collider under construction just south of Dallas. We began working together in organizing a North Texas physics group. After the death of the collider in which already two million dollars had been invested he then assumed a leading role in the White House Office of Science and Technology Policy.

In Pursuit of Gravitational Waves: Solving the Two-Body Problem in General Relativity

practices—was itself a central object of historical and philosophical reflection at the Balzan workshop.

Awarded by the International Balzan Prize Foundation in 2021 to Alessandra Buonanno and Thibault Damour for “their leadership in the prediction of the gravitational-wave signals produced when compact objects like neutron stars and black holes spiral together and eventually merge,” the Balzan Prize encourages the development of research programs involving new generations of scholars. Buonanno, director of the Astrophysical and Cosmological Relativity department at the Albert Einstein Institute (AEI), used the award to launch a major interdisciplinary initiative on the history and philosophy of the relativistic two-body problem. The project is carried out in collaboration with Dennis Lehmkuhl, Chair of Natural Philosophy and Philosophy of Science and Lichtenberg Professor for History and Philosophy of Physics at the University of Bonn, and Alexander Blum, initially group leader of the “Historical Epistemology of the Final Theory” research group at the Max Planck Institute for the History of Science in Berlin. They are joined by Jean-Philippe Martinez, a Balzan Fellow at the AEI, in reconstructing the recent history of the relativistic two-body problem by examining how research traditions, institutional contexts, and collaborative dynamics have shaped its development. By tracing the interplay between analytic and numerical methods—and how these approaches ultimately converged to produce the waveforms essential for gravitational-wave detection—the project offers a unique opportunity to illuminate the intellectual and practical foundations of one of contemporary physics’ most remarkable achievements.

This interdisciplinary effort, based at the AEI—a center actively engaged in cutting-edge gravitational-wave research—embodied the spirit of the Balzan workshop. The event built on a rare opportunity: many of the field’s key contributors remain active, yet the implicit decisions shaping the development of the two-body problem

have seldom been examined in a scholarly context. For the first time, the workshop brought together these central figures, alongside historians and philosophers, to revisit landmark developments and reflect on the evolving methods, collaborations, and conceptual challenges that have driven this remarkable scientific journey. Coinciding with the tenth anniversary of the first direct detection of gravitational waves (GW150914), the Potsdam meeting also marked other notable milestones: thirty years since the computation of gravitational radiation damping at second post-Newtonian order, and twenty years since the numerical-relativity breakthroughs of 2005, which produced the first complete simulations of binary black hole mergers. These parallel analytic and numerical traditions formed the structural backbone of the workshop.

Accordingly, the workshop’s first day emphasized the analytic tradition of gravitational-wave theory, the second focused on the development of numerical relativity and the computational innovations enabling stable simulations, and the third explored the growing synergies between these approaches and the epistemic structure of gravitational-wave modeling. Over the three days, participants delivered twelve presentations—both historical and forward-looking—and engaged in three panel discussions at the end of each day addressing institutional, conceptual, and methodological questions:

Why Did Progress in Analytical Relativity Differ in Europe Compared to the U.S., and More Generally Among Countries?

Why Did Progress in Numerical Relativity Differ in Europe Compared to the U.S., and More Generally Among Countries?

Appreciation, Competition, and Synergism Between Analytical and Numerical Relativity Approaches.

On Monday, 20 October, Kip Thorne—2017 Nobel Laureate in Physics and Emeritus Richard P. Feynman Professor of Theoretical Physics at Caltech—opened the workshop with a central lesson for the history of

science: historical accounts must rely on contemporary documentation to avoid the fallibility of memory. Drawing on his work for the *History of LIGO project*, Thorne highlighted pivotal but lesser-known episodes in the development of gravitational-wave detection, showing how personalities, institutional cultures, and political factors shaped the project. He recounted the decisive role of reviews, particularly the 1986 Blue Ribbon Committee, and described the formation of the LIGO Scientific Collaboration, which continues to coordinate thousands of physicists and engineers, organize data analysis, and provide governance. On the theoretical side, he traced the evolving understanding of compact binaries and chronicled key steps in numerical relativity—from the 1990s Grand Challenge Alliance to the initial Caltech-Cornell Simulating eXtreme Spacetimes (SXS) collaboration—emphasizing how accurate waveform models were crucial for guiding and interpreting LIGO’s experiments.

Shifting to the analytical development of the relativistic two-body problem, Thibault Damour—Professor at the *Institut des Hautes Études Scientifiques* (IHES) near Paris—surveyed the evolution of general relativity in France from the mid-1960s to the present. He described a research culture initially marked by strong mathematical rigor and caution toward physical interpretation, particularly regarding black holes and gravitational waves, contrasting it with the more intuitive, physically driven style seen in the United States. Drawing on transnational exchanges, Damour then traced the gradual development of analytic tools for the two-body problem, from early post-Newtonian (PN) and post-Minkowskian (PM) methods to the multipolar post-Minkowskian framework and the effective-one-body (EOB) formalism. He emphasized that these advances were shaped not by a single guiding strategy but by incremental insights, institutional settings, and evolving collaborations across Europe and beyond. His account illustrated

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how intellectual style, methodological choices, and scholarly networks together structured the analytic foundations later essential for gravitational-wave astronomy.

In the afternoon, Zvi Bern—Director of the Mani L. Bhaumik Institute for Theoretical Physics at UCLA—highlighted striking examples of cross-field fertilization in recent advances on the relativistic two-body problem. Rather than the familiar “lone genius” narrative, his talk emphasized how ideas developed over decades in particle physics—effective field theory, scattering amplitudes, generalized unitarity, and double-copy structures—have been repurposed to tackle classical gravitational dynamics. A key turning point, he recalled, came after GW150914. From 2017 onward, gravitational-wave theorists—notably Buonanno and Damour—actively engaged with the amplitudes community and invited it to compute higher-order post-Minkowskian contributions. Drawing on forty years of conceptual and technical advances in quantum field theory, amplitude methods rapidly produced major results, including the 3PM Hamiltonian and its nontrivial agreement with post-Newtonian and numerical-relativity benchmarks. Bern’s account underscored how shared problems, methodological pluralism, and open communication—sustained through personal interaction at workshops and conferences—enabled an unanticipated but transformative convergence between particle physics and gravitational-wave theory.

Dennis Lehmkuhl—Chair of Natural Philosophy and Philosophy of Science and Lichtenberg Professor for History and Philosophy of Physics at the University of Bonn—examined the early conceptual history of the relativistic two-body problem, revisiting debates in the 1920s over whether the motion of gravitating bodies could be derived directly from Einstein’s field equations. Drawing on Einstein’s exchanges with Yuri Rainich and a reassessment of Hermann Weyl’s attempted two-body solution, he showed how issues of singularities, nonlinearity, and physical admissibility shaped the emergence of the problem of motion. These discussions culminated in the 1927 work of Einstein and Jakob Grommer, who argued that the field equations themselves determine a body’s motion, strengthening the conceptual link between spacetime geometry and



Kip Thorne (left) and Thibault Damour (right).
Credit to @sevens+Jmaltry

dynamics. Lehmkuhl concluded by tracing how this reasoning influenced later post-Newtonian methods and the shift from point particles to black holes, highlighting how foundational debates over interpretation and idealization quietly guided much of the later development of the relativistic two-body problem.

The first day concluded with a panel discussion chaired by Alexander Blum (Munich Center for Mathematical Philosophy). Luc Blanchet (*Institut d’Astrophysique de Paris*), Leor Barack (University of Southampton), Gerhard Schäfer (University of Jena), and Clifford Will (University of Florida & *Institut*

d’Astrophysique de Paris) explored differing approaches to analytical relativity and the influence of institutional contexts. Panelists highlighted contrasts between U.S. and European traditions: U.S. approaches often favor problem-driven, physically intuitive methods shaped by shorter-term funding and teaching obligations, while European research emphasizes formal techniques rooted in long-standing mathematical traditions and supported by stable, long-term positions. These factors—worth considering also for Japan—shape both methodological choices and the framing of key problems, from post-Newtonian expansions to radiation-reaction calculations. The discussion also emphasized the social dynamics of the analytical community: progress relied on a delicate balance of collaboration and competition, fostered through informal networks and specialized gatherings. Mentorship, funding stability, and shared traditions guided which questions were pursued and how. The panel underscored that analytical relativity’s evolution is not merely a sequence of technical achievements but a product of the intellectual, cultural, and institutional ecosystems that enabled theorists to develop the precision models essential for gravitational-wave astronomy.

On Tuesday, 21 October, the focus shifted to numerical relativity, with Frans Pretorius—Professor of Physics at Princeton University—opening the day by revisiting the 2005 breakthrough in binary black hole simulations. Reflecting on whether the problem had truly been “as hard as it seemed,” he emphasized how hindsight, survivor bias, and two decades of accumulated understanding can obscure the genuine difficulty of the task. Pretorius outlined the intertwined technical obstacles that long hindered progress: the nonlinear coupling of gauge, constraints, and boundary conditions; the tendency of constraint violations to grow uncontrollably; and the lack, in the early 2000s, of a clear strategy for handling coordinate singularities. He described how a series of conceptual shifts—including harmonic formulations for simplicity and the introduction of constraint damping—gradually enabled his 2005 simulations. Pretorius also highlighted social and institutional factors, such as fellowship funding, informal discussions



Conference Group Photo. Credit to @sevens[+]maltry

with colleagues, and the advantages and limitations of pursuing an unconventional approach outside large collaborations, which were crucial for this landmark achievement.

Manuela Campanelli—John Vouros Professor and Director of the Center for Computational Relativity and Gravitation at the Rochester Institute of Technology—offered a historical perspective on numerical relativity, tracing its evolution from early, unstable attempts to the robust simulations underpinning today’s gravitational-wave astronomy. She reviewed key advances in Europe, Japan and the U.S. during the 1990s and early 2000s—most notably the Baumgarte–Shapiro–Shibata–Nakamura (BSSN) formulation, puncture initial data, and hybrid “Lazarus” approaches—that laid the groundwork for the 2005 breakthrough. Campanelli highlighted how, within weeks, independently developed ideas—Pretorius’s generalized-harmonic scheme and the moving-punctures method developed by her team and by the NASA Goddard group—enabled long, stable binary-black-hole evolutions. These simulations produced new physical insights, including large gravitational-recoil velocities and early studies of black-hole environments. Today, numerical relativity supports dense parameter-space campaigns, high-spin and high-mass-ratio systems, tests of relativistic gravity beyond Einstein’s theory, and multi-messenger applications. Campanelli emphasized that future detectors will require substantial improvements in waveform accuracy and

astrophysical realism, ensuring numerical relativity remains a central, evolving tool for gravitational-wave science.

After lunch, David Kaiser—Germeshausen Professor of the History of Science and Professor of Physics at MIT—led a discussion on the Cold War origins of numerical relativity in the United States. He traced how early expertise in large-scale computation, developed for simulating thermonuclear weapons, later seeded techniques for modeling strong-field gravitational systems. Central to this story was Bryce DeWitt, who in the early 1950s was recruited to the newly created Livermore Laboratory and developed one of the first two-dimensional Lagrangian hydrodynamics codes—expertise that he and others later applied to gravitational research. Kaiser emphasized how access to computing resources, numerical know-how (from coordinate choices to methods like artificial viscosity), and institutional infrastructures for training and collaboration were all shaped by Cold War priorities. He then followed the community’s transition back to gravity, from early meetings such as GR1 (Chapell Hill, 1957) to the emergence of university programs supported in part by unconventional private patrons. The result was a distinctive American pathway into numerical relativity—rooted not primarily in general relativity itself, but in the weapons laboratories and funding structures that enabled advanced computation before supercomputers reached universities.

Roberto Lalli—Associate Professor at *Politecnico di Torino*—offered a socio-historical analysis of how general relativity, and particularly the two-body problem, coalesced into a modern research community. Using co-authorship and co-citation networks, he traced the transition from the “low-water mark” period (1925–1955) to the subsequent “Renaissance” of general relativity. This revival was driven by both astrophysical discoveries—quasars, the cosmic microwave background, and pulsars—and new institutional structures, including the “GR” conferences (Bern 1955, Chapel Hill 1957, Royaumont 1959) and the founding of the International Committee on General Relativity and Gravitation, which linked previously isolated researchers and centers. Then focusing on the relativistic two-body problem, Lalli showed how collaboration networks expanded in the 1990s and 2000s, integrating analytical relativists, numerical relativists, and astrophysicists. By the mid-2000s, network analysis revealed a dense “giant component,” reflecting both conceptual convergence and institutional maturation. His account highlighted that progress toward gravitational-wave astronomy relied not only on theoretical advances but also on evolving social and institutional structures connecting previously separate research traditions.

The second day concluded with a panel discussion on numerical relativity, chaired by Daniel Kennefick (University of Arkansas) and featuring Miguel Alcubierre (*Universidad Nacional Autónoma de México*),

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Bernd Brügmann (Friedrich-Schiller University, Jena), Edward Seidel (University of Wyoming), and Larry Smarr (University of California, San Diego). Panelists reflected on the field's evolution, the role of computational infrastructure, and the development of collaborative networks. Smarr highlighted the late 1970s and early 1980s as a period of rapid change, when access to supercomputers and interactions with leading groups in the U.S. and Europe were decisive. Seidel emphasized the vision behind building large groups and shared tools, such as the Cactus framework, which facilitated collaboration and community-building across Europe. Brügmann noted the transformative impact of GW150914, showing how waveforms became a tangible part of the scientific method, while Alcubierre traced the methodological timeline from early formulations to grazing collisions and the adoption of moving punctures. The discussion underscored that numerical relativity's advances rely as much on social and institutional ecosystems—mentorship, mobility, and coordinated groups—as on technical breakthroughs. Structured collaboration, open communication, and computational resources proved essential for achieving robust, physically meaningful simulations and preparing the field for the era of gravitational-wave astronomy.

On Wednesday, 22 October, Abhay Ashtekar—Atherton Professor and Evan Pugh Professor Emeritus at Pennsylvania State University—offered a broad reflection on the conceptual and sociological history of gravitational-wave research. He revisited early confusion over gravitational radiation, when certain solutions blurred the distinction between genuine waves and coordinate artifacts, and described how work by Hermann Bondi, Rainer K. Sachs, Roger Penrose, and Ezra T. Newman in the 1960s established a clean, invariant framework for radiation at null infinity. The discovery of the Hulse–Taylor binary pulsar in 1974 marked a turning point, stimulating renewed debate over the quadrupole formula and fostering collaborations between theorists and observers. Ashtekar traced the field's evolution from loosely connected subcommunities to the integrated landscape shaped by LIGO–Virgo, waveform modeling, and exchanges across general relativity, quantum field theory, and numerical relativity. He also noted

ongoing challenges—communication gaps, divergent conceptual approaches, and tensions between large collaborations and individual initiatives—and emphasized that future detectors will demand highly accurate and conceptually robust waveform models, making sustained interdisciplinary cooperation essential.

As the final day emphasized the synergies of methods in waveform modeling, Alessandra Buonanno—Director at the Max Planck Institute for Gravitational Physics (Albert Einstein Institute)—presented a historical overview of how inspiral–merger–ringdown models developed from the late 1990s onward. Buonanno notably described how the effective-one-body (EOB) framework provided a new analytical route to predict binary-black-hole signals, relying on bold extensions of the test-mass limit and insights into the plunge and ringdown. She reflected on contrasting research cultures at IHES and Caltech and the initial challenge of convincing the LIGO Scientific Collaboration to adopt EOB waveforms which included an analytical approximated merger signal. The 2005 breakthroughs in numerical relativity transformed the field, enabling calibration of EOB models to long SXS simulations and supporting phenomenological inspiral-merger-ringdown (IMR) models. Large collaborative efforts, including the Numerical INjection Analysis (NINJA) project and the Numerical–Relativity–Analytical–Relativity (NRAR) collaboration, strengthened ties between numerical relativists, analytical modelers, and data analysts. Buonanno concluded that modern waveform modeling relies on sustained interdisciplinary collaboration to meet the accuracy demands of current and future detectors.

Turning to gravitational-wave phenomenology and data analysis, Bangalore S. Sathyaprakash—Elsbach Professor of Physics and Professor of Astronomy and Astrophysics at Pennsylvania State University—reflected on the parallel evolution of waveform modeling and detection strategies from the early 1990s onward. Early work on black holes and gravitational waves led to the development of matched filtering, a method for identifying faint signals buried in noise, and the importance of representing waveforms in the frequency domain for efficient searches. A key innovation,

the stationary-phase approximation, made large template-bank searches computationally feasible. Sathyaprakash showed how this Fourier-based framework became central for detection, parameter estimation, and tests of general relativity, evolving from early binary-neutron-star searches to methods capable of capturing subtle features of inspiral, merger, and ringdown. His account emphasized the often-invisible methodological infrastructure—the careful integration of theory, computation, and data analysis—that enabled gravitational-wave astronomy to become a precise, reliable, and predictive science.

Concluding the sequence of presentations, David Shoemaker—Senior Research Scientist at The Kavli Institute for Astrophysics and Space Research at MIT—offered a reflective account of the evolution of gravitational-wave detectors and collaborations in the United States and Europe. Drawing on his long involvement with LIGO, he traced the field's development from small, largely isolated prototype experiments in the 1970s and 1980s to the large-scale observatories and collaborations that made detection possible. Shoemaker emphasized the decisive role of Rainer Weiss's early conceptual roadmap, the consolidation of experimental groups, and the emergence of distinct organizational models for LIGO and Virgo, shaped by differing institutional cultures and funding structures. He highlighted how project management, sustained engineering efforts, and carefully staged demonstrations were as crucial as scientific ideas, while also noting tensions introduced by scale, bureaucracy, and competing priorities. Looking ahead, he discussed the challenges posed by next-generation observatories such as the Einstein Telescope and Cosmic Explorer, stressing that future progress will depend as much on governance, collaboration, and long-term planning as on technological innovation.

The final panel discussion was chaired by Adele La Rana (Sapienza University of Rome) and featured Patrick Brady (University of Wisconsin-Milwaukee), Sascha Husa (University of the Balearic Islands), Lawrence Kidder (Cornell University), and Adam Pound (University of Southampton). Patrick Brady emphasized the interaction between observation, data analysis, and theory, highlighting

how improvements in models and the importance of detector calibration are driven by new challenging detections. Sascha Husa reflected on the value of cross-disciplinary communication and informal interactions, explaining how intensive and daily conversations were crucial for generating new ideas and advancing waveform modeling. Lawrence Kidder recounted episodes of intense competition within numerical relativity and data analysis, including blind injections and competing searches for spinning binaries, illustrating how rivalry can accelerate progress while emphasizing the importance of reproducibility. Adam Pound highlighted the complementary nature of different approaches to the two-body problem, noting that competition occurs primarily within methods rather than between them, and describing how synergies between self-force, post-Newtonian, and numerical relativity calculations have historically driven advances. The ensuing general discussion explored the balance of competition and collaboration across the community, debated open data policies, and considered challenges in cross-code comparisons, collectively showing how shared goals, communication, and methodological rigor continue to shape progress in gravitational-wave science.

The conference concluded with an overarching synthesis which highlighted the complementary strengths across traditions, nations, and generations that have shaped approaches to the two-body problem. Participants observed how progress in the field has been guided not only by funding initiatives, computational infrastructures, and personal networks, but also by key results that reshaped research communities. While robust leadership, clear structures, and collaborative frameworks are essential for technically ambitious projects, individual initiative—marked by risk-taking, timing, and cross-field contributions—often proved decisive. Across the workshop, a recurring theme was the non-linear nature of scientific progress: documenting dead ends alongside successes remains crucial; foundational questions retain their relevance even as applications to astrophysical systems expand; community dynamics—trust, mentorship, mobility of postdocs, openness, and balanced competition—were recognized as vital for sustaining

innovation and transmitting ideas across groups and continents; interdisciplinary interplay, particularly among analytical theory, numerical simulation, and experimental practice, was celebrated as a key driver of breakthroughs. Overall, the conference also reinforced the global nature of the endeavor: no single nation, discipline, or individual can claim ownership of gravitational-wave research.

Attendees were encouraged to build on the enthusiasm and rich collaborations observed during the workshop, to continue pursuing joint research, exchange ideas, and foster long-term partnerships. Preserving public access to talks, maintaining primary sources, and sustaining interdisciplinary spaces were recognized as crucial for supporting future scholarship and inspiring the next generation of researchers. This is why all materials from the workshop are available at <https://workshops.aei.mpg.de/in-pursuit-of-gravitational-waves>, ensuring that the conversation and collaboration sparked in Potsdam will continue to resonate.