Let us begin with a summary of how the notions of space and time have changed over the centuries, making full use of the benefit of hindsight and contemporary terminology. For nearly two thousand years, the four books Aristotle wrote on physics provided the foundation for natural sciences in the western world. In modern terms one can say that in Aristotle’s paradigm, there was absolute time, absolute space, and an absolute rest frame, provided by the earth. This was the reigning world-view Isaac Newton was exposed to as a student at Cambridge in the years 1661-65. Some twenty years later, Newton toppled this centuries old dogma. Through his Principia, first published in 1687, he provided a new paradigm. Time was sill represented by a 1-dimensional continuum and was absolute, the same for all observers. All simultaneous events continued to constitute 3-dimensional space. But there was no absolute rest frame. Thanks to the lessons learned from Copernicus, earth was removed from its hitherto privileged status. Galilean relativity was made mathematically precise and all ‘inertial’ observers —moving uniformly with respect to one another— were put on the same physical footing. Already in the beginning of the 1700s, papers began to appear in the Proceedings of the Royal Society, predicting not only the motion of Jupiter but even of its moons! No wonder, then, that the Principia became the new orthodoxy. It reigned supreme in what was then called natural philosophy for over a century and a half.

The first challenge to the Newtonian world view came from totally unexpected quarters: advances in the understanding of electromagnetic phenomena. As is well known, in the middle of the 19th century James Clarke Maxwell achieved a grand synthesis of all the then accumulated knowledge concerning these phenomena in just four vectorial equations. Surprisingly, these equations further provided a specific value $c$ of the speed of light that did not refer to a reference frame. But the notion of an absolute speed blatantly contradicted Galilean relativity, a cornerstone on which the Newtonian model of space-time rested. Since the model had been so enormously successful, the scientific community found it natural to conclude that Maxwell’s value $c$ of the speed of light is relative to a physical, privileged frame (even though the derivation itself made no reference to it). This was identified as the rest frame of ether, a medium permeating space that carries electromagnetic waves. But by doing so, the community in fact reverted back to the Aristotelian view that Nature specifies an absolute rest frame —but now anchored in ether rather than earth.

The first part, *Emergence of the Spacetime Continuum*, of this volume starts at this juncture. It comprises of seven papers by Hendrik Lorentz, Henri Poincaré, Albert Einstein and Hermann Minkowski. By the beginning of the 20th century a series of experiments had been performed with increasing sensitivity, the most influential of which was carried out by Albert Michelson and Edward Morley. The underlying idea was to measure the velocity of earth relative to ether —the so called ‘ether wind’— by analyzing the speed of light in different directions and at different times as earth spins and moves around the sun. However, as Michelson wrote to Lord Rayleigh in 1887, “The Experiments on the relative motion of the earth and ether have been completed and the result decidedly negative.” This null result was confirmed by other even more sensitive experiments carried out between
The first four papers by Lorentz and Poincaré illustrate that leading scientists at the time were sufficiently troubled by the ensuing dilemma as to propose radical new ideas. It is important to note that they both continued to use the notion of ether as a basic ingredient in their reasoning. Poincaré, for example, argued as follows: “Does our aether actually exist? ... If light takes several years to reach us from a distant star, it is no longer on the star, nor is it on the earth. It must be somewhere, and supported, so to speak, by some material agency.” Their analysis was based on Maxwell’s equations, Lorentz’s electron theory, and a shift from Augustin-Jean Fresnel’s ‘mechanical ether’ to an ‘electromagnetic ether,’ whose state was now characterized by the electric and magnetic fields. The goal was to construct a theory which explains the null results of the ‘ether wind’ experiments. Their way out of the quandary can be understood as the introduction of length contraction and time dilation for all phenomena, when described in the reference frame of ether. The result is what we call Lorentz transformations, although one should note that the proof of the desired covariance of electrodynamics was established by Poincaré, who corrected the transformation properties of charge and current density that Lorentz had originally introduced, and also used the group properties of the full set of transformations.

The true paradigm shift came in the celebrated 1905 papers of Einstein’s that follow Lorentz’s an Poincaré’s. Right in the beginning of the first paper, Einstein made a clear, decisive statement: “The introduction of a “luminiferous ether” will prove to be superfluous in as much as the view here to be developed will not require an absolutely stationary space ... ” This insight is a masterpiece of the conceptual breakthrough that accompanies the removal of ‘excess baggage’! Note that even though Poincaré presented the cleanest treatment of Lorentz transformations, he seems to have held the view that clocks resting in the aether show ‘the true time’, and even as late as 1912, he described light as the “luminous vibrations of the aether”. In a single stroke Einstein made Lorentz transformations kinematical statements about spacetime structure, freeing them from ‘properties of matter relative to ether’. In doing so, he not only abolished the absolute rest frame à la Aristotle that had crept back in through ether, but also the Newtonian notion of absolute simultaneity. Spacetime could still be foliated by preferred 3-dimensional spatial sections of simultaneous events but the choice is no longer canonical – there is a 3-parameter family of these foliations, one for each choice of inertial frames that are in uniform motion relative to one another.

The last two papers in the first part are by Minkowski. They complete this revolution by genuinely fusing together space and time into a 4-dimensional continuum of events. The role played by the spacetime metric comes to the forefront. In Newtonian theory, given any event, there is a unique 3-dimensional ‘space section’ constituted by all events that are simultaneous with it. This absolute space of Newton’s is now replaced by a 2-sheeted, 3-dimensional cone that separates the region which is causally connected with the given event, from the region which is not. These light cones also dictate the causal propagation

† A century later, experiments using optical resonator have improved the accuracy of the null result and tested the local Lorentz invariance to one part in \(10^{17}!\) See for example Ch. Eisele, A. Yu. Nevsky, and S. Schille, Phys. Rev. Lett. 103, 090401 (2009).
of fields. In the limit in which the velocity of light tends to infinity, the light cone becomes more and more ‘wide-angled’ and, in the limit the two sheets merge and morph into Newton’s absolute space. In the new, spacetime framework, the Poincaré group arises simply as the group of spacetime transformations that preserve the Minkowski metric. Space-time geometry provided by the metric makes the underlying physics transparent. This is the conceptual framework that continues to underlie all of non-gravitational physics even today, including the quantum theory of fields. And it served as the key pointer in Einstein’s efforts that led to general relativity.

The second part, *Gravity is but Geometry*, of the collection contains two papers by Einstein that serve as milestones in this transition. In 1907 while writing a review of special relativity, Einstein realized that while special relativity had successfully reconciled the predictions of Maxwell’s electrodynamics with spacetime kinematics, it was in deep conflict with Newton’s theory of gravity. For, Newton’s law of universal gravitational attraction required absolute time: the gravitational force between two bodies is transmitted instantaneously. Special relativity, on the other hand, had abolished absolute time. So Newton’s law can not even be stated covariantly in Minkowski spacetime. In 1907 then, Einstein set himself the task of finding a new, better theory of gravity by generalizing the Minkowski geometry. The first paper included in this collection was written in 1911 and focuses on the influence of gravity on the propagation of light. It concludes that light rays from distant stars, passing close to the sun, are deflected by its gravitational field and works out the deflection to first approximation. Previous calculations based on Newtonian gravity had used the corpuscular theory of light. Einstein used the equivalence principle, and null rays of a metric, modified from Minkowski’s in its ‘t-t’ part by the gravitational potential of the sun. But the final result reported in this paper is only 1/2 the correct value (i.e. 0.87 rather than 1.75 arcsec), because it ignored the fact that the ‘spatial part’ of the metric is not flat in this approximation. The value he obtained was the same as that from the corpuscular theory of light in Newtonian gravity. In 1912 an Argentinian team was scheduled to measure this light deflection in Brazil and, in 1914, a Russian team planned to carry out the measurement in Crimea, both during solar eclipses. The first mission encountered bad weather and the First World War intervened the second. Had they been fully successful, they would have found that Einstein’s result was incorrect and then Einstein’s views on incorporating gravity in special relativity by modifying the metric would have suffered a major setback. So it is extremely fortunate that Einstein had more time to re-examine the calculation and obtain the correct expression well before Arthur Eddington led the successful mission in 1919!

The second, 1915, paper by Einstein in this part of the collection is the culmination of his 8 years of work. In contrast to Newton’s *Principia*, gravity is no longer a force between two bodies, acting at a distance on one another. Rather, gravity is now encoded in the very geometry of spacetime. Massive bodies like sun bend the spacetime continuum of Minkowski’s and light bodies like planets move in this curved spacetime, following the geodesic motion to first approximation. This is perhaps the most profound paradigm shift that physics has witnessed so far. As Einstein wrote to Arnold Sommerfeld, ‘During the last month, I experienced one of the most exciting and most exacting times of my life, true enough also one of the most
successful.” The nature of the outcome is succinctly summarized by Hermann Weyl: “It is as if a wall which separated us from the truth has collapsed. Wider expanses and greater depths are now exposed to the searching eye of knowledge, regions of which we had not even a pre-sentiment.”

The third part, *Birth of a Dynamical Universe* contains five papers by Einstein, Willem de Sitter, Alexander Friedmann and Georges Lemaître on cosmology. Recall that Newton made a profoundly bold leap and declared that the law of gravitation is universal—the same law that governs the fall of the apple on earth also governs the orbits of planets around sun. Einstein made an even bolder assertion. Equations he derived in order to bring gravitation in harmony with special relativity had received direct support only through small corrections to the orbit of mercury. But he made a giant leap and declared that they also dictate the large scale dynamics of the universe as a whole! This is the birth of modern cosmology.

At the time, the lesson Copernicus taught us was well appreciated and it was natural for Einstein to suppose that, on a sufficiently large scale, there is no preferred place, nor a preferred direction. However, one belief from ancient times still persisted: while change was manifest in our immediate neighborhood, on larger scales the universe as a whole was serene; distant stars unchanging and fixed; havens immutable. Therefore in 1917 Einstein sought a static, spatially homogeneous and isotropic solution of his field equations, assuming that the universe is spatially closed, and stars and nebulae can be modeled as dust particles. He realized that the requirement of staticity could not be satisfied if one uses his originally proposed field equations and therefore, somewhat reluctantly, introduced a positive cosmological constant $\lambda$. The result is the Einstein’s cylindrical universe with topology $S^3 \times R$. In 1918, de Sitter showed that Einstein’s equations with a positive $\lambda$ admit other natural solutions with maximal symmetry in which there is no matter. His view was the presence of the physical matter in the universe contributes very little to the curvature compared to $\lambda$ and could therefore be neglected in the leading order approximation. The topology is again $S^3 \times R$ but there is no matter; curvature is supported entirely by the positive cosmological constant. de Sitter presented this solution as static, conforming to the widely held belief in the unchanging havens (by using certain coordinates that cover only a part of what we now call the global deSitter solution). The solution drew attention because it naturally led to a redshift that seemed compatible with observations of extragalactic nebulae.

In 1922 Friedmann wrote two novel papers, deriving an entirely different class of solutions with matter, and allowing a cosmological constant of either sign. The first followed Einstein and de Sitter and considered closed universes. These solutions were independently rediscovered by Lemaître in 1927, who also allowed non-zero pressure, arguing that it cannot be neglected for radiation. The second Friedmann paper analyzed the ‘open topology’ in detail. In 1925 Lemaître clarified that the widely held belief that de Sitter universe is static was incorrect: apparent staticity was an artifact of the choice of coordinates in which spatial sections fail to be homogeneous and isotropic. Once homogeneity and isotropy are made manifest, the solution resembles the Einstein’s cylindrical universe where, however,
the spatial radius changes in time; it is no longer static.† This reasoning made it clear that the requirement of staticity is not sacrosanct. Once it is dropped, entirely new classes of solutions become available. These are precisely the new solutions that were discovered by Friedmann and Lemaître. These universes are truly dynamical; in contrast to de Sitter spacetime, they do not admit a time-translation symmetry even in patches! The clarity of the Friedmann-Lemaître papers is striking. Indeed, presentations in most contemporary texts on cosmology is the same as Lemaître’s. Friedmann’s papers contain illuminating comments/remarks on the underlying geometry, while Lemaître also comments on the physical implications. In particular, he has a detailed discussion of what we now call the cosmological red-shift, rooted in the expansion of the universe, including numerical values using the then best available data. This paper contains (in Equations (23) and (24)) what was called the Hubble law until 2018, when the International Astronomical Union voted to change the name to the Hubble-Lemaître law. From a contemporary perspective, then, the passage from the Einstein and de Sitter solutions to the truly dynamical universes with matter, discovered by Friedmann and Lemaître, was a huge transition—a truly major step that transformed our view of the large scale structure of the universe we inhabit. Indeed, the title of the Russian biography of Friedmann calls him ‘The man who made the universe expand’.

Surprisingly, this impressive leap was not immediately hailed as an important breakthrough! Einstein first thought that dynamical solutions were not possible and, in a short 1922 note in Zeitschrift für Physik, he argued that Friedmann had made a mistake. He retracted his objection in another, shorter note in 1923 after he received an explanatory letter from Friedmann through his St. Petersburg colleague, Yuri Krutkov. However, he continued to think of these solutions merely as mathematical possibilities, having little relevance to the physical world. Indeed in 1927, while taking a stroll in the park Léopold during a break in the Solvay conference, he complimented Lemaître on his mathematical competence but also said that from a physical point of view he found the idea of an expanding universe “tout à fait abominable” (completely abominable)! It was a true uphill battle for the expanding universe of Friedman and Lemaître to be accepted by the wider community. The 1929 review that Einstein wrote for Encyclopedia Britanica, for example, makes no reference to the possibility of an expanding universe. A push in favor of an expanding universe came from Eddington’s finding in 1930—soon after Lemaître reminded him of his 1927 paper—that Einstein’s universe is unstable: under slightest perturbations, it begins to expand (or contract). As a result, Eddington started to favor the idea of an expanding universe. It was only in 1931 after meeting Edwin Hubble in Pasadena that Einstein fully conceded that his static universe was not viable. However, in the report to the Prussian Academy on his return from the trip, he gave instability as the primary reason.

† In this 1925 ‘Note on de Sitter Universe’ published in the Journal of Mathematics and Physics, he also obtained spatially flat solutions but, unfortunately, rejected them on philosophical grounds. Note also that Lemaître’s 1927 paper appeared in French in a rather obscure Belgian journal. The version included in this collection is the English translation that appeared in Monthly Notices of the Royal Astronomical Society at Eddington’s initiative. Unfortunately, this translation omits an important para on red-shifts.
for his change of heart, “quite apart from Hubble’s observational results”. And Einstein begins this discussion by paying a tribute to Friedmann: “The first who, uninfluenced by observations, tried this way was A. Friedmann, on whose mathematical results the following remarks will be based.” Eddington and de Sitter came to fully appreciate Lemaitre’s work and, starting from 1930, emphasized its importance in interpreting Hubble’s redshift observations as the discovery of an expanding universe. Einstein also embraced the expanding universe in a paper he wrote with de Sitter in 1932, where they considered the spatially flat expanding universe with zero $\lambda$; zero because Einstein believed and emphasized that, once the requirement of staticity is abandoned, the presence of a cosmological constant served no purpose, and its introduction in 1917 was a mistake.

In spite of these endorsements, the notion of expanding universe did not blossom in the subsequent years as one might have expected. Friedmann passed away in 1925 –just three years after making his seminal discovery. Lemaitre continued to develop the notion further and arrived at the conclusion that a universe that expands in the future must start with, what Fred Hoyle later called, a Big Bang. Lemaitre pursued the theme of a finite beginning systematically, starting with an article in Nature entitled ‘The Beginning of the World from the Point of View of Quantum Theory.’ However, leading figures were put off by it. Eddington, for example, publicly called the idea of a finite beginning “repugnant.” In the 1940s the British school put forward ‘Steady State Cosmology’ as an alternative to the Big Bang and the expanding universe, returning, once again, to the age-old view that on a large scale the universe is unchanging, without a beginning or an end. In the mainstream cosmology, acceptance of the notion of an expanding universe –with an early hot phase– came only after the cosmic microwave background was discovered, and understanding of nuclear abundances matured. However, for several subsequent decades, the community continued to follow Einstein and set the cosmological constant $\lambda$ to zero. Lemaitre, on the other hand, remained committed to a positive $\lambda$ throughout his life and tried to convince Einstein that a cosmological constant was necessary to solve what was then called the “time scale dilemma.” In 1934, he clearly understood that, in its essence, $\lambda$ “corresponds to a negative density of vacuum $\rho_0$ according to $\rho_0 = (\lambda c^2)/4G$” and that “in order that motion relative to vacuum may not be detected, we must associate a pressure $p = \rho c^2$ to the vacuum.” He had interesting correspondence with Einstein on the issue of $\lambda$. In a 1947 letter, Einstein admitted that his preference for a zero value was based on aesthetics and added “I am unable to think that such an ugly thing should be realized in Nature.” Some 45 years later, the supernovae observations showed that Nature is not easily swayed by aesthetic considerations of humans –even of the deepest thinkers among them! Ultimately, Lemaitre’s view did triumph, but he had already passed away in 1966.

The three parts of this collection, spanning the first quarter of the 20th century, highlight the critical transitions that profoundly altered our view of spacetime. They led us to a conceptual framework that underlies all of fundamental physics –from quarks to the cosmos– even today, almost a century later!

Abhay Ashtekar
State College, PA, USA
Additional References

Papers included in this collection led to three major paradigm shifts in our understanding of the structure of spacetime. The first set culminated in a fusion of space and time into a 4-dimensional spacetime continuum; the second led us to abandon the notion that gravity as a force exerted by massive bodies and to encode it, instead, in the very geometry of spacetime; and the third forced us to renounce the age-old notion that the universe is serene and time-unchanging on large scales. There are several other papers that have had significant impact on the contemporary notion of spacetime as it pertains to the large scale structure of our universe. We include a partial list of these early papers that readers may also want to consult.


