The Ontological Demystification of Spacetime: Relationalism, Instrumentalism, and Gravity without Substantial Space or Time

The conceptualization of gravity as the literal "bending of time" or the cosmic expansion of the universe as the literal "expansion of space" has long been a source of debate in the philosophy of physics.[1] To define space as a physical entity capable of being bent, stretched, or expanded is to assign substantial, material properties to what is conceptually defined as an absence.[3] Under rigorous physical and epistemological scrutiny, the literalist reification of spacetime is exposed as a consequence of mistaking coordinate-dependent mathematical shortcuts for physical realities.[4] This analysis evaluates the ontological status of space and time, demonstrating that the apparent physical dynamics of spacetime can be fully accounted for through relational mechanics, kinematic Doppler shifts, alternative flat-space gravitational theories, and emergent quantum entanglement.[6]

The Reification of Mathematics: Mathematical Shortcuts vs. Physical Territories

The ontological dispute over whether space and time possess an independent physical existence or are merely abstract relational frameworks is central to the philosophy of science.[1] Scientific realism asserts that the mathematical entities postured by successful physical theories must reflect the true, underlying structure of the physical world.[10] Conversely, instrumentalism, tracing back to the methodology of Pierre Duhem, argues that scientific theories are merely useful instruments designed to explain and predict observable phenomena.[10] Under an instrumentalist framework, the mathematical success of a model does not imply that its unobservable theoretical terms possess a literal, physical counterpart in reality.[12]

This tension is highly apparent in the standard description of gravity as the curvature of a four-dimensional spacetime continuum.[14] George Berkeley and David Hume argued that abstract primary qualities like absolute space are inconceivable without reference to sensible, material properties.[12] Immanuel Kant expanded this critique through transcendental idealism, asserting that space and time are not external substances, accidents, or physical relations, but rather subjective, ideal a priori forms of human cognition necessary for coordinating sensory experiences.[12]

In modern physics, the tendency to treat the coordinate-dependent language of general relativity as a literal, physical "fabric" represents a fundamental category mistake—the reification of a mathematical map for the physical territory.[4] Spacetime is not a physical object or a material medium; it is a mathematical structure, specifically a differentiable manifold equipped with a metric tensor, designed to calculate the physical distances and intervals between material objects.[13] Confusing the geometric description of particle trajectories with an active physical deformation of space and time itself has led to a century of unnecessary mystification that is neither demanded by physical experiments nor enforced by mathematical consistency.[4]

The Historical Crucible: Substantivalism, Relationalism, and the Hole Argument

The modern debate regarding the ontology of space and time began with the famous confrontation between Isaac Newton's absolute substantivalism and Gottfried Wilhelm Leibniz's relationalism.[1]

Ontological Framework	Core Ontological Status	Physical Interpretation of Motion	View of a Literal Vacuum
Substantivalism (Newton)	Space and time are real, absolute, and exist independently of matter.[1]	True motion is absolute translation through the parts of substantival space.[1]	Empty space is physically real and can exist devoid of any matter.[3]
Relationalism (Leibniz)	Space and time are derivative abstractions representing relations among bodies.[1]	Motion is relative change of situation between material objects.[19]	A literal vacuum is conceptually impossible; the universe is a material plenum.[3]
Transcendental Idealism (Kant)	Space and time are subjective, ideal, and originate from the mind's nature.[16]	Motion is a coordinate representation constructed by cognitive faculties.[12]	Space is a cognitive scheme, making the vacuum a non-entity.[16]

Spacetime Structural Realism (Einstein)	Spacetime has no separate existence; it is a structural quality of the metric field.[23]	Motion is represented by geodesics determined by the local metric field.[13]	An empty space without a gravitational field is physically meaningless.[23]

Newton justified the existence of substantival absolute space through his rotating bucket experiment, arguing that the physical force generating the concave meniscus of the water was caused by rotation relative to absolute space, rather than rotation relative to the vessel.[1] Leibniz countered Clarke, Newton's spokesperson, by arguing that if absolute space existed, a universe shifted by a constant distance or moving at a constant velocity would be a distinct physical state, yet completely indistinguishable from our own.[22] This violated the Principle of Sufficient Reason, as God would have no physical reason to create the universe at one absolute location rather than another.[22]

This philosophical dispute was directly integrated into modern physics through Albert Einstein's Hole Argument, formulated between 1913 and 1915.[23] The argument arises when general covariance—the requirement that physical equations retain their mathematical form under arbitrary coordinate transformations—is applied to a region of spacetime devoid of matter: a "hole".[27] If the manifold points inside this hole possess their own substantial identity independent of the fields residing on them, general covariance leads to a failure of physical determinism.[27] By applying an active diffeomorphism (a smooth shifting of the coordinate grid), one can construct a second, mathematically distinct metric field that satisfies the exact same gravitational field equations outside and on the boundary of the hole.[24]

Einstein resolved this dilemma by abandoning the substantivalist interpretation of spacetime points.[23] He concluded that individual spacetime points have no physical significance in themselves.[23] The only physical realities are "point-coincidences," such as the intersection of material worldlines or field values.[27] Consequently, the spacetime manifold cannot be conceptualized as an independent container.[23] Without the metric field, which also acts as the gravitational potential, there is no spacetime at all, confirming that spacetime is merely a structural quality of the gravitational field.[23]

Dismantling "Expanding Space": Coordinate Artifacts and Kinematics

In popular expositions of modern cosmology, the expansion of the universe is frequently described as a physical process in which space itself is swelling up, dragging gravitationally unbound galaxies along with its flow.[2] This literalist physical interpretation is highly misleading and represents an artifact of a specific coordinate choice rather than a coordinate-independent physical phenomenon.[5]

Cosmic expansion is mathematically modeled in general relativity using the Friedmann–

Lemaître–Robertson–Walker (FLRW) metric.[2] This metric employs comoving coordinates where distant, non-interacting galaxies are assigned constant spatial coordinates over time, and the increasing physical distance between them is mathematically accommodated by a time-dependent scale factor, $a(t)$.[2] However, as cosmologists like Steven Weinberg, Martin Rees, and John Peacock have argued, this description is entirely optional.[5] Weinberg notes that the expansion of the universe is locally indistinguishable from any cloud of particles rushing apart in a purely kinematical, Newtonian fashion.[5] The galaxies are simply in motion relative to one another; they are not being pulled apart by a physical stretching of space.[5]

In gravitationally bound systems, such as our Solar System or individual galaxies, the global expansion of the universe does not exert a small, continuous "pulling" force that is constantly being overpowered by gravity or electromagnetism.[5] Explicit mathematical calculations demonstrate that the physical tendency to expand due to the stretching of space in bound systems is non-existent, not merely negligible.[5]

Furthermore, the popular claim that cosmological redshift is caused by the physical stretching of photon wavelengths as they travel through expanding space is a coordinate-dependent interpretation.[5] Theoretical physicists Emory Bunn and David Hogg proved that the cosmological redshift can be decomposed purely as a kinematical Doppler shift.[7] Because general relativity does not possess a single, unique method for comparing velocity vectors at widely separated points, one must parallel-transport the velocity four-vector of a distant galaxy to the observer's position along a chosen path.[7]

- **Transport along a Null Geodesic:** Parallel-transporting the velocity vector of the emitting galaxy along the null geodesic of the incoming photons yields a relation between the transported velocity and the redshift that is given exactly by the standard relativistic Doppler formula.[7] Under this formulation, the redshift is purely kinematic in origin.[7]
- **Transport along a Constant Time Hypersurface:** If the velocity vector is transported along the spatial geodesic on a hypersurface of constant cosmic time, the redshift is decomposed into a kinematic Doppler component (z_D) and a gravitational component (z_G).[7]

The physical recession velocity (v) of a galaxy, when evaluated inside the observer's Local Inertial Frame, is strictly bounded by the hyperbolic tangent function:

$$\beta \equiv \frac{v}{c} = \tanh\left(\frac{\dot{a}x_*}{c}\right)$$

This physical velocity is related to the kinematic component of the redshift by:

$$1 + z_D = \sqrt{\frac{1+\beta}{1-\beta}} = \exp\left(\frac{\dot{a}x_*}{c}\right)$$

Where x_* is the comoving radial coordinate of the emitting galaxy.[31] Because the hyperbolic tangent ensures that $\beta < 1$, physical recession velocities remain strictly subluminal ($v < c$) for all galaxies within our particle horizon.[31] The apparent "superluminal expansion of space" on superhorizon scales is an artifact of utilizing comoving coordinate systems, rather than a real, physical phenomenon, validating the critique that "expanding space" is a mathematical convenience rather than a physical reality.[5]

Gravity Without Curvature: The Flat-Space Paradigm of Teleparallelism

The standard geometric interpretation of gravity as the physical "curvature" of spacetime is further dismantled by alternative, mathematically equivalent formulations of gravitation that operate entirely in flat space.[6] The most prominent of these theories is Teleparallel Gravity, specifically the Teleparallel Equivalent of General Relativity (TEGR).[6]

Theoretical Feature	General Relativity (GR)	Teleparallel Equivalent of GR (TEGR)
Fundamental Connection	Levi-Civita connection ($\mathring{\Gamma}^{\rho}{}_{\mu\nu}$) [6]	Weitzenböck connection ($\Gamma^{\rho}{}_{\mu\nu}$) [6]
Geometric Curvature	Non-vanishing Riemann curvature ($R^{\rho}{}_{\sigma\mu\nu} \neq$) [6]	Vanishing Riemann curvature ($R^{\rho}{}_{\sigma\mu\nu} \equiv 0$) [6]
Geometric Torsion	Vanishing torsion ($T^{\rho}{}_{\mu\nu} \equiv$) [6]	Non-vanishing torsion ($T^{\rho}{}_{\mu\nu} \neq$) [6]
Physical Mechanism	Matter follows curved geodesics on a curved manifold.[13]	Torsion acts as a translational gauge force on a flat manifold.[32]
Mathematical Equivalence	Formulated using the metric tensor $g_{\mu\nu}$.[6]	Formulated using tetrad fields $h^{a}{}_{\mu}$.[6]

While General Relativity relies on the Levi-Civita connection, which is uniquely metric-compatible and torsion-free, Teleparallel Gravity is formulated on a Weitzenböck spacetime.[6] This framework is constructed from a dynamical tetrad field ($h^a{}_\mu$) that defines a flat, linear Weitzenböck connection:

$$\Gamma^\rho{}_{\mu\nu} = h_a{}^\rho \partial_\nu h^a{}_\mu$$

By definition, the Riemann curvature tensor of the Weitzenböck connection vanishes identically everywhere in the spacetime manifold ($R^\rho{}_{\sigma\mu\nu} \equiv 0$).[6] Instead, the gravitational degrees of freedom are fully encoded within the non-vanishing torsion tensor:

$$T^\rho{}_{\mu\nu} = \Gamma^\rho{}_{\nu\mu} - \Gamma^\rho{}_{\mu\nu} = h_a{}^\rho \left(\partial_\mu h^a{}_\nu - \partial_\nu h^a{}_\mu\right)$$

In Teleparallel Gravity, the gravitational interaction is formulated as a gauge theory for the translation group, where the gravitational field is represented by the translational gauge potential ($B^a{}_\mu$).[6] Because the Weitzenböck connection is completely flat, parallel transport is globally path-independent.[6] This absolute parallelism allows vectors at distant points to be compared directly without any geometric ambiguity.[32]

Under this framework, gravity does not act by bending space or time.[32] Rather, the torsion of the flat connection acts as a physical force that deflects material bodies from their straight-line inertial trajectories, behaving conceptually like the electromagnetic force in Newtonian physics.[33] Because TEGR is dynamically equivalent to General Relativity, it produces identical physical predictions for all observable phenomena, including planetary orbits, light deflection, and gravitational wave propagation.[6] The existence of TEGR demonstrates that the geometric "curvature" of spacetime is not a unique, physical property of our universe, but an optional mathematical representational tool.[4]

Shape Dynamics: Eradicating Ambient Space and Background Time

A radical alternative to standard spacetime physics is Julian Barbour's Shape Dynamics, which seeks to implement Mach's principle by completely eliminating background space and time from the fundamental laws of physics.[8] In classical mechanics and general relativity, the positions and motions of particles are defined relative to a background coordinate grid.[8] Shape Dynamics replaces this picture, asserting that the only physically real data are the observable, relational arrangements of matter.[8]

For a model universe consisting of three particles interacting gravitationally, their spatial arrangement at any instant forms a triangle.[8] To define the physical "size" of this triangle, one would require an external, absolute ruler.[36] Because no such external ruler exists for the entire universe, Barbour argues that absolute size is physically redundant.[8] By identifying all mathematically similar triangular states through coordinate transformations and removing overall scale, Shape Dynamics "removes space," leaving only the dimensionless ratios of the side lengths (angles) to describe the shape of the system.[8]

Pure Shape Dynamics (PSD) extends this relational program to classical gravity.[37] Starting from the canonical Arnowitt-Deser-Misner (ADM) formulation of general relativity, PSD mathematically decouples and eliminates the last remaining non-shape degrees of freedom: the total spatial volume of the universe and York time.[34] This results in an autonomous, decoupled dynamical system that describes an unparameterized trajectory directly in the conformal superspace of metric and matter configurations.[37] The evolution of the universe is encoded in a geometric equation of state of this trajectory, completely independent of any external units of scale or absolute duration.[37]

Time is similarly revealed to be an emergent, relational abstraction.[8] Rather than asking how shape variables change as absolute time passes, Shape Dynamics determines how they change relative to one another.[36] Physical "clocks" are simply localized subsystems (matter marching in step) that provide a convenient method for tracking relational change.[8]

The arrow of time emerges dynamically through the concept of the **Janus point**.[35] In a relational N-body system, the configuration space possesses a central state of minimum structure and complexity.[35] As the system evolves away from this Janus point in either direction, complexity and the accumulation of local records naturally increase.[34] This asymmetry generates an apparent, local arrow of time on both sides of the central point, without requiring an absolute, external time parameter to guide the evolution of the universe.[34]

Reinterpreting Observables: Relational Dilation and Laser Rangefinding

To validate the premise that "bending space" and "expanding space" are coordinate-dependent mathematical shortcuts, one must provide alternative physical explanations for the experimental results typically used to support those concepts.[4] Two key cases are gravitational time dilation and the direct detection of gravitational waves.[38]

[redacted]

[redacted]

Gravitational Time Dilation as an Electromagnetic Interaction

Standard general relativity asserts that clocks in stronger gravitational fields run slower because "time itself" is physically dilated by the curved metric of spacetime.[38] A relationalist, non-relativistic explanation shows that this effect is caused by the direct physical interaction of gravity on local electromagnetic and mechanical systems.[4]

Consider a standard "light clock," consisting of a photon bouncing vertically between two highly reflective surfaces that act as detectors.[40] Every time the photon strikes a surface, the clock ticks.[40] Because light possesses energy ($E = mc^2$), its propagation trajectory is bent by gravitational fields, forcing the photon to travel along a curved, diagonal path rather than a straight, horizontal one.[40] Geometrically, a curved or diagonal trajectory is longer than a straight horizontal path.[40] Because the local speed of light is always measured as a constant (c) in any local frame, the photon takes longer to traverse this extended curved path between the reflecting plates.[38]

Consequently, the clock ticks slower.[40] This slowing is caused by the physical interaction of gravity on electromagnetic wave propagation, not because an abstract, physical dimension called "time itself" has been bent or stretched.[4]

Gravitational Waves as Force-Induced Displacement

In 2015, the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) detected gravitational waves (GW150914) from the merger of two black holes, a discovery popularized as observing "ripples in the fabric of spacetime".[39] However, a precise physical description of the LIGO apparatus reveals that no "fabric" was directly measured.[4]

The Advanced LIGO instrument is essentially an ultra-sensitive laser rangefinder consisting of two perpendicular, 4-kilometer-long optical cavities formed by suspended 40-kilogram mirror test masses.[41] An incident gravitational wave is a transverse wave of spatial strain that carries physical energy and momentum.[43] As the wave passes through the detector, it exerts an oscillating force field that physically displaces the mirrors—shortening one arm while lengthening the other.[41] This tiny displacement, measuring less than one-ten-thousandth the diameter of a proton, is detected by measuring the phase shift of the laser light bouncing between the mirrors.[41]

LIGO did not interact with a physical spacetime fabric; it measured the physical displacement of material mirror test masses caused by an oscillating gravitational force field, analogous to how a buoy moves in response to an ocean wave.[4] The mathematical description of this force as a perturbation of the metric tensor ($h_{\mu\nu}$) is a highly successful coordinate shortcut, but it should not be mistaken for the physical oscillations of an underlying material medium.[4]

The Physical Reality of the Vacuum: Quantum Fields vs. Empty Absence

While classical relationalism often defines space as a mere "absence" or void, modern Quantum Field Theory (QFT) introduces a more complex ontology.[3] In QFT, the vacuum state ($|0\rangle$) is not an empty void, but the lowest energy state of the quantized fields that permeate the universe.[46] Due to the non-commutation of quantized field operators, local field values inevitably exhibit quantum fluctuations [46]:

$$\langle 0|\hat{\Phi}^2(x)|0\rangle - \langle 0|\hat{\Phi}(x)|0\rangle^2 > 0$$

These non-zero variances manifest as a physical Zero-Point Energy (ZPE).[46] This ground-state energy is an unavoidable consequence of the Heisenberg Uncertainty Principle; completely emptying a box of its field energy would require assigning precise values to both the position (field amplitude) and momentum (rate of change) of its field oscillators, which is physically impossible.[48]

However, the popular description of this vacuum energy as a "quantum foam" of virtual particles constantly popping in and out of existence is another mathematical shortcut that has been incorrectly literalized.[49] Virtual particles are not real, independent physical entities.[11] Mathematically, they represent internal lines (propagators) in Feynman diagrams used to perform perturbative calculations of scattering amplitudes.[11] They are mathematical crutches, not physical components of the vacuum.[11]

Vacuum Phenomenon	**Mathematical representation**	**Physical Observable**
Casimir Effect	Boundary conditions cutting off long-wavelength zero-point oscillations.[46]	Attractive physical force between two closely spaced, uncharged plates.[46]
Virtual Particles	Internal propagators in Feynman diagrams.[49]	Strictly unobservable; mathematical tools of

		perturbation theory.[11]
Zero-Point Energy	Infinite sum of ground-state harmonic oscillators.[48]	Physical effects including molecular vibrations and the cosmological constant.[46]
Emergent Spacetime	Holographic boundary entanglement entropy ($S =$).[50]	Macroscopic general relativity and gravitational field equations.[17]

This physical vacuum presents a massive crisis when coupled to gravity.[46] Because all forms of energy must gravitate in general relativity, the sum of the ZPE of all quantum fields should generate a gravitational field so massive that the universe would instantly undergo gravitational collapse or rapid acceleration.[46] The fact that this gargantuan energy remains gravitationally muted (the Cosmological Constant Problem) suggests a fundamental flaw in our understanding of how quantum fields couple to the geometric representation of gravity, highlighting the limitations of treating general relativity's spacetime curvature as a literal physical fact.[46]

Emergent Spacetime from Quantum Information

To resolve these contradictions, modern quantum gravity models increasingly treat spacetime as an emergent, non-fundamental macroscopic description.[9] Andrei Sakharov's induced gravity first demonstrated that general relativity's dynamics can emerge as an effective, low-energy approximation of quantum matter fields, without introducing gravitational dynamics fundamentally.[50]

Under the AdS/CFT correspondence, the higher-dimensional bulk spacetime geometry and its gravitational dynamics emerge as a holographic projection of quantum entanglement in a lower-dimensional boundary theory.[9] Researchers have shown that the physical distance between points in the bulk is mathematically determined by the entanglement entropy of the boundary states.[9] If spacetime is constructed from quantum entanglement patterns, it cannot be considered a fundamental, independently existing physical entity.[9] This supports the relationalist perspective, revealing spacetime to be an effective macroscopic description of quantum information, rather than a physical canvas.[9]

Conclusions: The Map is Not the Territory

The rigorous analysis of spacetime ontology, alternative gravitational theories, and modern cosmology confirms that the concepts of "bending time" and "expanding space" are coordinate-dependent mathematical models rather than literal, physical processes.[4]
confusions have arisen because the elegant geometric language of general relativity has been

mistaken for an active, physical substance.[4]

1. **Space is Not a Material Fabric:** General relativity does not require space to be a physical substance.[23] Spacetime is a mathematical manifold designed to model the geometric relationships between physical objects and fields.[13]
2. **Expansion is Kinematic, Not Spatial:** The physical expansion of the universe is a kinematic drift of galaxies moving apart through space, not a physical stretching of space itself.[5] Redshift is fundamentally a kinematic Doppler shift, and the apparent superluminal expansion at superhorizon scales is an artifact of comoving coordinates.[7]
3. **Curvature is an Optional Language:** The mathematical equivalence of Teleparallel Gravity (which uses a flat connection with torsion) and General Relativity demonstrates that spacetime curvature is a representational choice.[6] Gravity can be fully described as a translational gauge force operating in flat space.[6]
4. **Time is Relational:** Gravitational time dilation is a physical result of gravity altering the propagation of electromagnetic waves and atomic oscillations inside clocks, rather than a literal warping of a metaphysical dimension called "time".[4] Shape Dynamics proves that absolute scale and time can be completely eradicated, leaving only the relational evolution of shapes.[8]

While quantum field theory demonstrates that empty space is not a absolute, inactive "absence" due to the physical fields and zero-point fluctuations of the vacuum, these fields are quantum mechanical in nature.[46] At the fundamental Planck scale, continuous spacetime is hypothesized to emerge as a macroscopic approximation of discrete causal sets or quantum entanglement networks.[9] A sophisticated understanding of physics must maintain a strict separation between mathematical models and physical reality: spacetime is a highly successful coordinate map, but the map must never be mistaken for the physical territory.[4]

Works cited

1. Substantivalist and Relationalist Approaches to Spacetime - PhilSci-Archive, accessed May 28, 2026, https://philsci-archive.pitt.edu/9055/1/srapproaches.pdf
2. Expansion of the universe - Wikipedia, accessed May 28, 2026, https://en.wikipedia.org/wiki/Expansion_of_the_universe
3. Newton's views on space, time, and motion - Stanford Encyclopedia of Philosophy, accessed May 28, 2026, https://plato.stanford.edu/archives/fall2021/entries/newton-stm/
4. Spacetime Curvature: A Description, Not Reality | by Drmanojgrg - Medium, accessed May 28, 2026, https://medium.com/@drmanojgrg/gravity-does-not-bend-spacetime-it-bends-light-ff6d76fdbd20
5. Do objects in space grow with the expansion of space? : r/Physics - Reddit, accessed May 28, 2026, https://www.reddit.com/r/Physics/comments/1pb6wj7/do_objects_in_space_gro

w_with_the_expansion_of/
6. Teleparallel Gravity: Torsion & Gauge Theory - Emergent Mind, accessed May 28, 2026, https://www.emergentmind.com/topics/teleparallel-gravity
7. The kinematic component of the cosmological redshift, accessed May 28, 2026, https://academic.oup.com/mnras/article-pdf/413/1/585/18591185/mnras0413-0585.pdf
8. An Introduction to Shape Dynamics - Digital Commons @ Cal Poly, accessed May 28, 2026, https://digitalcommons.calpoly.edu/cgi/viewcontent.cgi?article=1192&context=physsp
9. Quantum Entanglement and the Emergence of Spacetime: A Deep Dive - konstantinos.kourentzes.com, accessed May 28, 2026, https://kourentzes.com/konstantinos/index.php/2025/02/02/quantum-entanglement-emergent-spacetime-explained/
10. Do you tend toward the scientific realist end of the spectrum or the instrumentalist side? : r/PhilosophyofScience - Reddit, accessed May 28, 2026, https://www.reddit.com/r/PhilosophyofScience/comments/cuyhr/do_you_tend_toward_the_scientific_realist_end_of/
11. Is "curvature" of spacetime a mathematical abstract (a tool) or a real physical process?, accessed May 28, 2026, https://www.reddit.com/r/AskPhysics/comments/1mb0ck0/is_curvature_of_spacetime_a_mathematical_abstract/
12. Instrumentalism - Wikipedia, accessed May 28, 2026, https://en.wikipedia.org/wiki/Instrumentalism
13. general relativity - Has spacetime some physical properties?, accessed May 28, 2026, https://physics.stackexchange.com/questions/717433/has-spacetime-some-physical-properties
14. Spacetime - Wikipedia, accessed May 28, 2026, https://en.wikipedia.org/wiki/Spacetime
15. Is spacetime literally curved? Or is that a metaphor/model we use to describe the gravitational concepts that we don't yet understand? - Reddit, accessed May 28, 2026, https://www.reddit.com/r/askscience/comments/2szhjt/is_spacetime_literally_curved_or_is_that_a/
16. Kant's views on space and time - Stanford Encyclopedia of Philosophy, accessed May 28, 2026, https://plato.stanford.edu/archives/fall2014/entries/kant-spacetime/
17. What does it mean that space-time is emergent? - Physics Stack Exchange, accessed May 28, 2026, https://physics.stackexchange.com/questions/390058/what-does-it-mean-that-space-time-is-emergent
18. accessed May 28, 2026, https://medium.com/@drmanojgrg/gravity-does-not-bend-spacetime-it-bends-light-ff6d76fdbd20#:~:text=Spacetime%20curvature%20is%20a%20mathematical,to

%20space%20or%20time%20themselves.
19. Space, Time, and Theology in the Leibniz-Newton Controversy | Reviews, accessed May 28, 2026, https://ndpr.nd.edu/reviews/space-time-and-theology-in-the-leibniz-newton-controversy/
20. 20th WCP: Leibniz's Theory of Space in the Correspondence with Clarke and the Existence of Vacuums, accessed May 28, 2026, https://www.bu.edu/wcp/Papers/Mode/ModeMalz.htm
21. Time - Stanford Encyclopedia of Philosophy, accessed May 28, 2026, https://plato.stanford.edu/entries/time/
22. 09. The Leibniz-Clarke Correspondence - Research, accessed May 28, 2026, https://research.engineering.nyu.edu/~jbain/spacetime/lectures/09.Leibniz_Clarke.pdf
23. The Hole Argument and Some Physical and Philosophical Implications - PMC, accessed May 28, 2026, https://pmc.ncbi.nlm.nih.gov/articles/PMC5253803/
24. Einstein's Hole Argument - Luther College, accessed May 28, 2026, https://www.faculty.luther.edu/~macdonal/HoleArgument.pdf
25. Curved spacetime - Wikipedia, accessed May 28, 2026, https://en.wikipedia.org/wiki/Curved_spacetime
26. Leibniz–Clarke correspondence - Wikipedia, accessed May 28, 2026, https://en.wikipedia.org/wiki/Leibniz%E2%80%93Clarke_correspondence
27. Hole argument - Wikipedia, accessed May 28, 2026, https://en.wikipedia.org/wiki/Hole_argument
28. accessed May 28, 2026, https://pmc.ncbi.nlm.nih.gov/articles/PMC5253803/#:~:text=The%20hole%20argument%20purports%20to,the%20interior%20of%20the%20hole.
29. Hole Argument | Encyclopedia.com, accessed May 28, 2026, https://www.encyclopedia.com/humanities/encyclopedias-almanacs-transcripts-and-maps/hole-argument
30. The Hole Argument (Stanford Encyclopedia of Philosophy), accessed May 28, 2026, https://plato.stanford.edu/entries/spacetime-holearg/
31. The kinematic component of the cosmological redshift, accessed May 28, 2026, https://arxiv.org/abs/0911.3536
32. Teleparallelism - Wikipedia, accessed May 28, 2026, https://en.wikipedia.org/wiki/Teleparallelism
33. teleparallel gravity in nLab, accessed May 28, 2026, https://ncatlab.org/nlab/show/teleparallel+gravity
34. Shape dynamics - Wikipedia, accessed May 28, 2026, https://en.wikipedia.org/wiki/Shape_dynamics
35. A Universe Without Time - Nikos Papadopoulos, accessed May 28, 2026, https://www.4rknova.com/blog/2026/01/25/barbour-timeless-universe
36. From Einstein to Barbour: A Brief History of Shape Dynamics - Furkan Semih Dündar, accessed May 28, 2026, https://fsemih.org/files/jb-original.pdf
37. arXiv:2503.00996v1 [gr-qc] 2 Mar 2025 Pure Shape Dynamics: Relational General

Relativity, accessed May 28, 2026, https://arxiv.org/pdf/2503.00996
38. Gravitational time dilation - Wikipedia, accessed May 28, 2026, https://en.wikipedia.org/wiki/Gravitational_time_dilation
39. Gravitational Waves Detected 100 Years After Einstein's Prediction - LIGO Caltech, accessed May 28, 2026, https://www.ligo.caltech.edu/news/ligo20160211
40. GRAVITATIONAL TIME DILATION EXPLAINED FOR BEGINNERS - viXra.org, accessed May 28, 2026, https://vixra.org/pdf/1407.0092v2.pdf
41. For the first time, scientists have observed ripples in the fabric of spacetime called gravitational waves, arriving at the eart, accessed May 28, 2026, https://en.uw.edu.pl/wp-content/uploads/2016/02/detection-of-gravitational-waves.pdf
42. Time Dilation - Stem Fellowship, accessed May 28, 2026, https://live.stemfellowship.org/time-dilation/
43. First direct detection of gravitational waves | National Science Review - Oxford Academic, accessed May 28, 2026, https://academic.oup.com/nsr/article/4/5/681/4081679
44. Scientists make first direct detection of gravitational waves | MIT News, accessed May 28, 2026, https://news.mit.edu/2016/ligo-first-detection-gravitational-waves-0211
45. New technology enhances gravitational-wave detection - UCR News - UC Riverside, accessed May 28, 2026, https://news.ucr.edu/articles/2025/02/14/new-technology-enhances-gravitational-wave-detection
46. Quantum vacuum state - Wikipedia, accessed May 28, 2026, https://en.wikipedia.org/wiki/Quantum_vacuum_state
47. Quantum Field Theory For Beginners - Quantum Zeitgeist, accessed May 28, 2026, https://quantumzeitgeist.com/quantum-field-theory-for-beginners-how-empty-space-is-actually-full-2/
48. In Quantum Mechanics, Nothingness Is the Potential To Be Anything ..., accessed May 28, 2026, https://www.quantamagazine.org/in-quantum-mechanics-nothingness-is-the-potential-to-be-anything-20260105/
49. Is the vacuum empty? Are virtual particles in the vacuum? Is the vacuum non-zero? [duplicate] - Physics Stack Exchange, accessed May 28, 2026, https://physics.stackexchange.com/questions/207990/is-the-vacuum-empty-are-virtual-particles-in-the-vacuum-is-the-vacuum-non-zero
50. Induced gravity - Wikipedia, accessed May 28, 2026, https://en.wikipedia.org/wiki/Induced_gravity
51. Unifying Quantum Gravity with Emergent Spacetime in the Dual Sheet Model: A Step-by-Step Educational Deep Dive | by Matthew Hodgkins | Medium, accessed May 28, 2026, https://medium.com/@mattygh01/unifying-quantum-gravity-with-emergent-spacetime-in-the-dual-sheet-model-a-step-by-step-dca28b7db844