Chronology of main discoveries

... it is of course necessary to make some supposition respecting the nature of that medium, or ether, the vibrations of which constitute light, ... Now, if we adopt the theory of transverse vibrations, ... we are obligued to suppose the existence of a tangential force in the ether, ... In consequence of the existence of this force, the ether must behave, so far as regards the luminous vibrations, like an elastic solid.

... I have assumed, as applicable to the luminiferous ether in vacuum, the known equations of motion of an elastic medium, such as an elastic solid. These equations contain two arbitrary constants, depending upon the nature of the medium. The argument which Green has employed to shew [show] *that the luminiferous ether must be regarded as sensibly incompressible, in treating of the motions which constitute light (Camb. Phil. Trans., Vol. VII, p. 2) appears to me of great force. The supposition of incompressibility reduces the two arbitrary constants to one; ...*

George Gabriel Stokes (Stokes, 1856)

As early as the 17th century, it was known that light waves and acoustic waves are of a similar nature. Hooke believed light to be a vibratory displacement of a medium (the aether), through which it propagates at a finite speed. Later, in the 19th century, Maxwell and Lord Kelvin made extensive use of physical and mathematical analogies to study wave phenomena in acoustics and electromagnetism. In many cases, this formal analogy becomes a complete mathematical equivalence such that the problems in both fields can be solved by using the same analytical (or numerical) methodology. Green (1842) made the analogy between elastic waves in an incompressible solid (the aether) and light waves. One of the most remarkable analogies is the equivalence between electric displacements and elastic displacements (Hooke law) used by Maxwell to obtain his famous electromagnetic equations. Therefore, the studies of acoustic wave propagation and light propagation are intimately related, and this fact is reflected in the course of scientific research.

The task of describing the principal achievements in the field of wave propagation is a difficult one, since many important scientists have been involved in the subject, contributing from different fields of research. Dates reveal connections and parallels; they furnish us with a basis for comparisons, which make historical studies meaningful and exciting. The following chronological table intends to give a brief glimpse of "evolution" and "causes and results" of the main scientific developments and ideas.[1]

600 BC, ca.	Thales of Miletus discovers that amber (*elektron* in Greek) rubbed with fur attracts light bodies.
580 BC, ca.	Pythagoras makes experiments on harmony and musical intervals. He relates the length of vibrating strings to the pitch.
300 BC, ca.	Euclid describes the law of reflection in his *Optica*. Hellenistic science, with its center at Alexandria, gave rise to advanced technology and scientific discoveries that would not be seen again until the 18th century (sec. Russo, 2004).
45, ca.	Seneca states that earthquakes are caused by water, air, or fire located inside the Earth.
60, ca.	Heron writes his *Catoptrica*, where he states that light rays travel with infinite velocity.
139, ca.	Ptolemy measures angles of incidence and refraction and arranges them in tables. He found those angles to be proportional (for small angles).
990, ca.	al-Haythan writes his *Optics*. He shows that Ptolemy was in error and refers for the first time to the "camera obscura".
1210, ca.	Grosseteste writes *De Natura Locorum* and *De Iride*.
1268, ca.	Bacon writes *The Communia Naturalium* and *The Communia Mathematicae.* He attributes the rainbow to the reflection of sunlight from single raindrops.
1269, ca.	Petrus Peregrinus writes *Epistola de Magnete*.
1270, ca.	John Peckham writes the treatise on optics *Perspectiva Communis*. Witelo writes *Perspectivorum Libri*, where he interprets the rainbow as reflection and refraction of light.
1307, ca	Dietrich of Freiberg gives the first accurate explanation of the rainbow.
1480	Leonardo da Vinci makes the analogy between light waves and sound (da Vinci, 1923).
1558	Della Porta publishes *Magia Naturalis*, where he analyzes magnetism.
1560 ca.	Maurolycus writes *Photismi de Lumine et Umbra* about photometry.

[1] Sources: Cajori (1929); Love (1944); Rayleigh (1945); Asimov (1972); Goldstine (1977); Ben-Menahem and Singh (1981); Cannon and Dostrovsky (1981); Pierce (1981); Ben Menahem (1995); the web site www.britannica.com and the web site of the University of St. Andrews, Scotland (https://mathshistory.st-andrews.ac.uk/).

1581	V. Galilei (Galileo's father) studies sound waves and vibrating strings.
1600	Gilbert writes *De Magnete* and shows that the Earth is a magnet.
1608	Lippershey constructs a telescope with a converging objective lens and a diverging eye lens.
1611	De Dominis explains the decomposition of colors of the rainbow and the tides. Kepler publishes his *Dioptrica*, where he presents an empirical expression of the law of refraction. He discovers total internal reflection.
1620, ca.	Snell obtains the law of refraction experimentally, although the discovery is attributed to Harriot.
1629	Cabeo writes *Philosophia Magnetica* on electrical repulsion.
1636	Mersenne publishes his *Harmonie Universelle*, containing the first correct account of the vibrations of strings, and the first determination of the frequency of an audible tone (84 Hz).
1637	Descartes publishes Snell law in his *La Dioptrique* without citing Snell.
1638	Galileo publishes *Discorsi e Dimostrazioni Matematiche, intorno à due Nuove Scienze*, including a discussion of the vibration of bodies.
1641	Kircher writes *Magnes, De Arte Magnetica*. It contains the first use of the term "electro-magnetism".
1646	Browne introduces the term "electricity".
1646	Leibniz introduces the idea of internal tension.
1656	Borelli and Viviani measure the sound velocity in air and obtain 350 m/s.
1660	Boyle demonstrates from vacuum experiments that sound propagates in air. Hooke states his law: *Ut tensio sic vis* (The Power of any Spring is in the same proportion with the Tension thereof), published in 1678.
1661, ca.	Fermat demonstrates Snell law using the principle of least time.
1665	Hooke publishes his *Micrographia*, where he proposes a theory of light as a transverse vibrational motion, making an analogy with water waves. (Mariotte enunciates the same law independently in 1680.)
1666	Grimaldi discovers the phenomenon of diffraction (in *Physico Mathesis of Lumine*). Newton performs his experiments on the nature of light, separating white light into a band of colors - red, orange, yellow, green, blue, and violet. He uses the corpuscular assumption to explain the phenomenon.

1669	Bartholinus observes double refraction in Iceland spar.
1675	Newton is against the assumption that light is a vibration of the aether. He argues that double refraction rules out light being aether waves and develops the theory of finite differences and interpolation, previously introduced by Harriot and Briggs. Boyle writes *Experiments and Notes about the Mechanical Origin or Production of Electricity*.
1676	Römer measures the speed of light by studying Jupiter's eclipses of its four larger satellites.
1678	Huygens proposes the wave nature of light in his *Traité de la Lumière* (first published in 1690). He assumes the vibrations in the aether to be longitudinal, exposes the principle of wavefront construction, and provides a theoretical basis for double refraction. (A wave theory of light had been proposed earlier by Ango and Pardies.)
1682	Pierre Ango publishes his *L'optique*.
1687	Newton publishes his *Principia*. He provides a theoretical deduction for the velocity of sound in air and finds 298 m/s. The relation wavelength times frequency equal velocity is given.
1700, ca.	Sauveur introduces the terms "nodes", "harmonic tone", "fundamental vibration" and suggests the name "acoustics" for the science of sound.
1704	Newton publishes his *Opticks*.
1713	Taylor obtains a dynamic solution for the vibrating string (*Philosophical Transactions*).
1727	Euler proposes a linear relation between stress and strain.
1728	Bradley discovers the phenomenon of stellar aberration.
1729	Gray shows that electricity can be transferred with conducting wires.
1733	du Fay discovers that electricity comes in two kinds, which he called resinous($-$) and vitreous($+$).
1740	Bianconi shows that the velocity of sound in air increases with temperature.
1743	d'Alembert publishes his *Traité de Dynamique*.
1744	Euler introduces the concept of strain energy per unit length for a beam.
1744-51	D. Bernoulli and Euler obtain the differential equation and the dispersion relation for lateral vibrations of bars.

1745	Nollet writes *Essai sur l'Electricité des Corps*.
1747	d'Alembert derives the one-dimensional wave equation for the case of a vibrating string and its solution for plane waves.
1750	Michell writes *A Treatise on Artificial Magnets.*
1752	Euler introduces the idea of compressive normal stress as the pressure in a fluid.
1755	D. Bernoulli proposes the principle of "coexistence of small oscillations" (the superposition principle).
1759	Euler derives the wave equation for sound. He develops the method of images. Aepinus publishes *An Attempt of a Theory of Electricity and Magnetism.* Lagrange solves the problem of the vibrating string.
1760	Laplace introduces the first version of the "divergence theorem", later enunciated by Gauss in 1813.
1762	Canton demonstrates that water is compressible.
1764	Euler derives the "Bessel equation" when analyzing the vibrations of membranes.
1772	Cavendish writes *An attempt to explain some of the Principal Phenomena of Electricity by means of an Elastic Fluid.*
1773–79	Coulomb applies the concept of shear stress to the failure of soils and frictional slip.
1776	Euler publishes the so-called "Euler equation of motion" in its general form. Soldner calculates the deflection of light by the sun (0.85 arc-seconds), rederived later by Cavendish and Einstein.
1777	Lagrange introduces the concept of scalar potential for gravitational fields.
1782	Laplace derives the so-called "Laplace equation".
1785	Coulomb uses the torsion balance to verify that the electric-force law is inverse square.
1787	Chladni visualizes – experimentally – the nodes of vibrating plates.
1788	Lagrange publishes his *Mécanique Analytique*.
1799	Laplace publishes his *Traité du Mécanique Céleste*. Volta invents the electric battery.
1801	Ritter discovers ultraviolet radiation. Young revives the wave theory of light. He introduces the principle of interference.

1802	Chladni publishes his *Die Akustik*. He investigates longitudinal and torsional vibrations of bars experimentally. Romagnosi is close to discovering the relationship between electric current and magnetism before Oersted.
1806	Young defines the Young modulus and considers shear as an elastic strain.
1808	J. B. Biot measures the velocity of sound in iron. Chladni studies the vibrations of strings and plates and longitudinal and torsional vibrations in rods. Laplace proposes a corpuscular theory of double refraction. Malus discovers polarization of light. Poisson publishes his memoir on the theory of sound.
1809	Young proposes a dynamic (wave) theory of light in crystals.
1811	Poisson publishes his *Traité de Mécanique*. Arago shows that some crystals alter the polarization of light.
1812	J. B. Biot shows that some crystals rotate the plane of polarization of light.
1813	Poisson derives the so-called "Poisson equation" as a relation between gravitational potential and mass density.
1814	Fraunhofer discovers the dark line spectrum. Light waves reveal the presence of some elements in celestial bodies (Kirchhoff and Bunsen's paper, 1859).
1815	Brewster investigates the "Brewster angle" on the basis of his experiments and those of Malus.
1816	Fresnel establishes the basis for the "Fresnel-Kirchhoff theory of diffraction". Laplace shows that the adiabatic elasticity constant should be used to calculate the sound velocity in the air. Young suggests the transversality of the vibrations of light, based on the fact that light of differing polarization cannot interfere. This solves many of the difficulties of the wave theory.
1820	Poisson solves the problem of propagation of compressional waves in a three-dimensional fluid medium. Oersted notes the relation between electricity and magnetism. Ampère models magnets in terms of molecular electric currents (electrodynamics). Biot and Savart deduce the formula for the magnetic strength generated by a segment of wire carrying electric current.
1821	Davy shows that the resistance of a long conductor is proportional to its length and inversely proportional to its cross-sectional area. Fresnel interprets the interference of polarized light in terms of transverse vibrations. Navier derives the differential equations of the theory of elasticity in terms of a single elasticity constant.

1822 Seebeck discovers the thermoelectric effect. Cauchy introduces the notion of stress (strain) by means of six component stresses (strains). He also obtains an equation of motion in terms of the displacements and two elasticity constants. Fourier publishes his *Analytical Theory of Heat*, where he introduces the infinite series of sines and cosines (a mathematical form of the superposition principle).

1823 Fresnel obtains his formulae for reflection and refraction of light.

1824 Hamilton publishes his first paper *On Caustics*. Poisson invents the concept of the magnetic scalar potential and of surface and volume pole densities.

1825 Ampère publishes his law, also known as "Stokes theorem". Nobili invents the astatic galvanometer. Weber publishes his book *Wellenlehre*.

1826 Airy publishes his *Mathematical Tracts on Physical Astronomy*. Colladon and Sturm measure the speed of sound in water, obtaining 1435 m/s. Hamilton publishes his *Theory of Systems of Rays*. He introduces the characteristic function for optics.

1827 Ohm obtains the relation between electric current and resistance.

1828 Cauchy extends his theory to the general case of aeolotropy and finds 21 elasticity constants – 15 of them are true elasticity constants (the "rari-constant" theory). Green introduces the concept of potential in the mathematical theory of electricity and magnetism. He derives "Green theorem".

1828 Poisson predicts the existence of compressional and shear elastic waves. His theory predicts a ratio of the wave velocities equal to $\sqrt{3}/1$, and a Poisson ratio equal to 1/4.

1829 Zantedeschi anticipates Faraday's classical experiments on electromagnetic induction.

1830 Cauchy investigates the propagation of plane waves in crystalline media. Savart measures the minimum and maximum audible frequencies (8 and 24,000 vibrations per second, respectively).

1831 Faraday shows that varying currents in one circuit induce a current in a neighboring circuit.

1832 Henry independently discovers the induced-currents effect. Gauss independently states Green theorem.

1833	Hamilton introduces the concept of "eikonal equation", the term eikonal being introduced into optics by Bruns. Hamilton develops the basic geometric concepts of slowness surfaces for anisotropic media. He predicts conical refraction, which is verified experimentally by Lloyd.
1834	Hamilton publishes his *On a General Method in Dynamics*. The Hamiltonian concept for dynamics is introduced.
1835	Gauss formulates "Gauss law". MacCullagh and Neumann generalize Cauchy's theory to anisotropic media.
1836	Airy calculates the diffraction pattern produced by a circular aperture.
1837	Green discovers the boundary conditions of a solid/solid interface. He derives the equations of elasticity from the principle of conservation of energy and defines the strain energy, finding 21 elasticity constants in the case of aeolotropy (the "multi-constant" theory). Faraday introduces the concept of the dielectric permittivity.
1838	Faraday explains electromagnetic induction, showing that magnetic and electric inductions are analogous. Airy develops the theory of caustics. Green solves the reflection-refraction problems for a fluid/fluid boundary and for a solid/solid boundary (the aether) and applies the results to light waves. Zantedeschi states that light can be an electromagnetic wave.
1839	Cauchy proposes an elastic aether of negative compressibility. Green, like Cauchy in 1830, investigates crystalline media and obtains the equations for the propagation velocities in terms of the propagation direction. MacCullagh proposes an elastic aether without longitudinal waves, based on the rotation of the volume elements. Lord Kelvin finds a mechanical-model analog of MacCullagh's aether.
1841	Forbes devises the first seismograph. Doppler discovers the "Doppler effect". Mayer states that work and heat are equivalent. His paper is rejected in the *Annalen der Physik*. Lord Kelvin uses the theory of heat to obtain the continuity equation of electricity.
1844	Scott Russell discovers the solitary wave.
1845	Faraday discovers the magnetic rotation of light. He introduces the concept of field. Neumann introduces the vector potential. The next year, Lord Kelvin shows that the magnetic field can be obtained from this vector. Stokes identifies the modulus of compression and the modulus of rigidity as corresponding to resistance to compression and resistance to shearing, respectively.

1846 Faraday publishes *Thoughts on Ray Vibrations* in *Philosophical Magazine*. He suggests the electromagnetic nature of light. Weber combines electrostatics, electrodynamics, and induction and proposes an electromagnetic theory.

1847 Helmholtz writes a memoir about the conservation of energy. The paper is rejected for publication in the *Annalen der Physik*.

1848 Kirchhoff generalizes Ohm law to three dimensions.

1849 Meucci invents the telephone. Stokes shows that Poisson's two waves correspond to irrotational dilatation and equivoluminal distortion. Fizeau confirms Fresnel's results using interferometry.

1850 Foucault measures the velocity of light in water to be less than in air. Newton's emission theory - which predicts the opposite - is abandoned. Stokes introduces a (wrong) concept of anisotropic inertia to explain wave propagation in crystals. Lord Kelvin states the Stokes theorem without proof, and Stokes provides a demonstration. Lord Kelvin introduces the concept of magnetic permeability.

1852 Lamé defines the elastic parameters.

1853 Lord Kelvin develops the theory of the RLC circuit.

1854 Lord Kelvin derives the telegraphy equation without the inductance (a diffusion equation).

1855 Lord Kelvin justifies the Green strain-energy function on the basis of the first and second laws of thermodynamics. Palmieri devises its seismograph. Weber and Kohlrausch find an electromagnetic velocity equal to $\sqrt{2}$ the light velocity.

1856 Lord Kelvin introduces the concepts of eigenstrain ("principal strain") and eigenstiffness ("principal elasticity").

1857 Kirchhoff derives the telegraphy equation, including the inductance. He finds a velocity close to the velocity of light.

1861 Riemann modifies Weber's electromagnetic theory. Kirchhoff derives the theory of the black body.

1863 Helmholtz introduces the concept of "point source". He publishes his *Lehre von den Tonemfindgungen* about the theory of harmony.

1864 Maxwell obtains the equations of electromagnetism. The electromagnetic nature of light is demonstrated.

1867 Maxwell introduces the "Maxwell model" to describe the dynamics of gases. Lorenz develops the electromagnetic theory in terms of retarded potentials.

1870 Christiansen discovers anomalous dispersion of light in solutions. Helmholtz shows that Weber's theory is not consistent with the conservation of energy. Helmholtz derives the laws of reflection and refraction from Maxwell equations, which were the subject of Lorentz's thesis in 1875.

1871 Rankine publishes equations to describe shock waves (also published by Hugoniot in 1889). Rayleigh publishes the so-called "Rayleigh scattering theory", which provides the first correct explanation of why the sky is blue. William Henry Ward applies for a patent regarding a wireless telegraph.

1872 Bétti states the reciprocity theorem for static fields.

1873 Maxwell publishes his *Treatise on Electricity and Magnetism*. Rayleigh derives the reciprocity theorem for vibrating bodies.

1874 Boltzmann lays the foundations of hereditary mechanics ("Boltzmann superposition principle"). Cornu introduces the "Cornu spiral" for the solution of diffraction problems. Meyer introduces the "Voigt solid". de Rossi sets the first earthquake intensity scale. Umov introduces the vector of the density of energy flux.

1875 Kerr discovers the "Kerr effect". A dielectric medium subject to a strong electric field becomes birefringent.

1876 Bartoli introduces the concept of radiation pressure from thermodynamical considerations. Pochhammer studies the axial vibrations of cylinders.

1877 Christoffel investigates the propagation of surfaces of discontinuity in anisotropic media. Rayleigh publishes *The Theory of Sound*.

1879 Hall discovers the "Hall effect". Stefan discovers the Stefan-Boltzmann law.

1880 Pierre and Jacques Curie discover piezoelectricity. Kundt discovers anomalous dispersion in the vapor of sodium.

1881 Michelson begins his experiments to detect the aether.

1883 Tesla constructs his first model of the induction motor. The father of electricity based on alternating current, he will apply for almost 300 patents during his life, being the first person to patent radio technology in 1897. He will speculate on electric transmission to long distances, loudspeaker, fluorescent lights, X rays, radar, rotary engines, microwaves, diathermy, robotics, missiles, particle beam weaponry (cyclotron), satellites, nuclear fission, tele-geodynamics and relativity.

1884	Poynting establishes from Maxwell equations that energy flows and can be localized.
1885	Lamb and Heaviside discover the concept of skin depth. Somigliana obtains solutions for a wide class of sources and boundary conditions. Lord Rayleigh predicts the existence of the “Rayleigh surface waves”.
1887	Voigt performs experiments on anisotropic samples (beryl and rocksalt). The “multi-constant” theory – based on energy considerations – is confirmed. The “rari-constant” theory – based on the molecular hypothesis – is dismissed. Heaviside writes Maxwell equations in vector form. He invents the modern vector calculus notation, including the gradient, divergence, and curl of a vector. He proposes using induction coils in telephone and telegraph lines to correct the signal distortion. Voigt, investigating the Doppler effect in the aether, obtains a first version of the “Lorentz transformations”.
1888	Hertz generates radio waves, confirming the electromagnetic theory. He discovers the photoelectric effect and predicts a finite gravitational velocity. Fitzgerald suggests that the speed of light is an upper bound. Tesla applies for the alternating current patents.
1889	Heaviside predicts the Cherenkov radiation effect. Reuber-Paschwitz detects P waves in Potsdam generated by an earthquake in Japan. Global seismology is born.
1890	Hertz replaces potential by field vectors and deduces Ohm, Kirchhoff and Coulomb laws.
1893	Pockels discovers the “Pockels effect”, similar to the Kerr effect. Tesla performs experiments to transmit radio waves.
1894	Korteweg and de Vries obtain the equation for the solitary wave. Lodge transmits radio waves between two buildings, demonstrating their potential for communication.
1894-901	Runge and Kutta develop the Runge-Kutta algorithm.
1895	Lorentz gives the “Lorentz transformations” to first order in the normalized velocity. Omori establishes a law for aftershock time series. Popov conducts experiments to transmit radio waves.
1896	Rudzki applies the theory of anisotropy to seismic wave propagation.
1897	Marconi’s first wireless-telegraphy patent. Oldham identifies on seismograms the P, S, and Rayleigh waves.
1899	Knott derives the equations for the reflection and transmission of elastic plane waves at plane interfaces.

1900	Marconi's second wireless-telegraphy patent.
1901	Ricci-Curbastro and Levi-Civita introduce the tensor calculus in the paper "Méthodes de calcul différentiel absolu et leurs applications," which appeared in "Mathematische Annalen". The work attracted little attention until Einstein used it as the mathematical basis of the general theory of relativity.
1902	Mercalli introduces a new intensity scale for earthquakes. Poynting and Thomson introduce the "standard-linear-solid" model, referred to here as the Zener model.
1903	Love develops the theory of point sources in an unbounded elastic space.
1904	Lamb obtains the Green function for surface Rayleigh waves. Volterra publishes his theory of dislocations based on Somigliana's solution. He introduces the integro-differential equations for hereditary problems.
1905	Einstein investigates the photoelectric effect and states that light is discrete electromagnetic radiation.
1906	Milne announces the discovery of the "Moho" discontinuity on the basis of seismic waves. Oldham (1906) discovers the Earth's core by interpreting P-wave amplitudes.
1908	Mie develops the "Mie scattering" theory, describing the scattering of spherical particles.
1909	Cosserat publishes his theory of micropolar elasticity (Cosserat and Cosserat, 1909). Mohorovičić finds more evidence of the "Moho" discontinuity, which defines the base of the crust.
1911	Debye introduces the ray series or "Debye expansion". Love discovers the "Love surface waves".
1912	L. F. Richardson patents the first version of sonar. Sommerfeld introduces the "Sommerfeld radiation condition".
1915	Galerkin publishes his finite-element method.
1919	Mintrop discovers the seismic head wave.
1920-27	The WKBJ (Wentzel, Kramers, Brillouin, Jeffreys) approximation is introduced in several branches of physics.
1921	E. Meissner uses observations of group-velocity dispersion of Rayleigh waves to model the Earth's crust.
1923	de Broglie proposes the model by which tiny particles of matter, such as electrons, display the characteristics of waves. Nakano introduces the theory of seismic radiation from a double-couple source.
1924	Stoneley (1924) publishes his paper about "Stoneley interface waves".

1925	Becker (1925) develops a theory of viscoelasticity with continuous relaxations. Elsasser describes electron diffraction as a wave property of matter.
1926	Born develops the "Born approximation" for the scattering of atomic particles. Jeffreys (1926) establishes that the outer Earth core is liquid by using S waves. Schrödinger works out the mathematical description of the atom called "wave mechanics", based on the Hamilton principle. Klein-Fock-Gordon equation: a relativistic version of the Schrödinger wave equation.
1927	Dirac presents a method to represent the electromagnetic field as quanta.
1928	Nyquist introduces the sampling theorem. Sokolov proposes an ultrasonic technique to detect flaws in metals.
1928–35	Graffi studies hereditary and hysteretic phenomena using Volterra theory.
1929	Reuss derives the isostress stiffness modulus of a composite medium.
1932	Debye and Sears observe the diffraction of light by ultrasonic waves.
1934	Frenzel and Schultes (1934) discover "sonoluminescence" (Born and Wolf, 1964, p. 594).
1935	Richter and Gutenberg introduce the Richter magnitude scale.
1936	Lehmann discovers the Earth's inner core on the basis of P waves generated by the 1929 New-Zealand earthquake.
1937	Bruggeman shows that finely layered media behave as anisotropic media.
1938	S. M. Rytov develops the ray theory for electromagnetic waves.
1939	Elsasser states that eddy currents in the liquid core, due to the Earth's rotation, generate the observed magnetic field. Cagniard (1939) publishes his method for solving transient elastic wave propagation. Graffi extends the reciprocal theorem of Bétti to dynamic fields, although the concept dates back to Helmholtz (1860) and Rayleigh (1973).
1940	Firestone develops an ultrasonic pulse-echo metal-flaw detector.
1941	Biot publishes the theory of consolidation. K. T. Dussik makes the first attempt at medical imaging with ultrasound. Kosten and Zwikker (1941) propose a scalar theory, predicting the existence of two compressional waves. Cole and Cole introduce their model to describe dispersion and absorption in dielectrics which has been implemented in viscoelasticity as the fractional Zener model.

1943	Terzaghi publishes his *Theoretical Soil Mechanics*.
1944	Frenkel publishes his paper on the dynamics of porous media and the seismoelectric effect. The equations are nearly identical to Biot poroelasticity equations. Peshkov observes a second (thermal) sound in liquid helium II.
1947	Scholte identifies the interface wave traveling at liquid-solid interfaces.
1948	Feynman develops the path-integral formulation. Gabor describes the principle of wave-front reconstruction, the basis of holography.
1949	Kyame (1949) publishes his theory about waves in piezoelectric crystals. Mindlin (1949) publishes the Hertz-Mindlin model to obtain the rock moduli as a function of differential pressure.
1950	Lippmann and Schwinger (1950) publish their scattering theory.
1951	Gassmann derives the "Gassmann modulus" for a saturated porous medium.
1952	Lighthill (1952) publishes the aeroacoustics equation. Hill (1952) shows that the Voigt and Reuss averages are upper and lower bounds, respectively.
1953	Haskell (1953) publishes his matrix method for wave propagation. Kornhauser (1953) publishes the ray theory for moving fluids.
1955	Pekeris presents the first computer-generated synthetic seismogram.
1956	Biot publishes the dynamic theory of porous media and predicts the slow compressional wave.
1957	The seminal paper by J. D. Eshelby set the basis for studying the wave fields in media with ellipsoidal inclusions.
1958	de Hoop develops the Cagniard-de Hoop technique. McDonal, Angona, Milss, Sengbush, van Nostrand, and J. E. White publish field experiments indicating constant Q in the seismic frequency band.
1959	The seminal paper by Alterman et al. (1959) on free oscillations starts the low-frequency seismology branch. Knopoff and Gangi develop the reciprocity principle for anisotropic media.
1962	Backus obtain the transversely-isotropic equivalent medium of a finely layered medium.
1963	Deresiewicz and Skalak obtain the boundary conditions at an interface between porous media. Hashin and Shtrikman obtain bounds for the elastic bulk and shear moduli of a composite.

1964	Brutsaert presents a theory for wave propagation in partially saturated soils. The theory predicts three P waves. Hess (1964) provides evidence of the seismic anisotropy of the uppermost mantle.
1965	Shapiro and Rudnik (1965) observe the fourth sound in helium II.
1966	Aki defines the seismic moment. de Hoop develops the reciprocity principle for anisotropic anelastic media. King (1966) performs laboratory experiments on partially-saturated rocks.
1968	Alterman and Karal use finite differences to compute synthetic seismograms. McAllister (1968) invents the Sodar.
1969	Walsh introduces a new model considering penny-shaped cracks, setting the basis for squirt-flow attenuation theories. Waterman (1969) introduces the T-matrix formulation in acoustics.
1971	Buchen investigates the properties of plane waves in viscoelastic media. First observational evidence that the inner core is solid (Dziewonski and Gilbert, 1971). O'Doherty and Anstey obtain a formula to describe stratigraphic filtering.
1972	F. L. Becker and R. L. Richardson explain the "Rayleigh window" phenomenon using viscoelastic waves. Lysmer and Drake simulate seismic surface waves with finite-elements methods.
1975	Brown and Korringa obtain the elasticity tensor for anisotropic porous media. J. E. White develops the theory describing the mesoscopic-loss mechanism.
1977	Currie, Hayes, and O'Leary predict additional Rayleigh waves in viscoelastic media. Domenico (1977) performs laboratory experiments on unconsolidated reservoir sands.
1979	Allan M. Cormack and Godfrey N. Hounsfield receive the Nobel Prize for developing computer axial tomography (CAT). Burridge and Vargas obtain the Green function for poroelasticity.
1980	Plona observes the slow compressional wave in synthetic media. Schoenberg introduces the linear-slip model to describe partially-welded interfaces, such as fractures and cracks.
1981	Gazdag introduces the Fourier pseudospectral method to compute synthetic seismograms. Masters and Gilbert (1981) observe spheroidal mode splitting in the inner code, indicating anisotropy.
1983	Feng and Johnson predict a new surface wave at a fluid/porous medium interface.
1984	Day and Minster use internal variables (memory variables) to model anelastic waves.

1990	Santos, Douglas, Corberó, and Lovera generalize Biot theory to the case of one rock matrix and two saturating fluids. The theory predicts a second slow P wave.
1994	Leclaire, Cohen-Ténoudji, and Aguirre-Puente generalize the Biot theory to the case of two rock matrices and one saturating fluid. The theory predicts two additional slow P waves and a slow S wave. Helbig introduces Kelvin's theory of eigenstrains in seismic applications.
1995	First simulation of the slow Biot mode by Carcione and Quiroga-Goode.
2002	Carcione, Mainardi, Cavallini, Mainardi, and Hanyga apply fractional calculus to geophysics and simulate 2-D wave fields.
2004	Pride, Berryman, and Harris show that mesoscopic loss is the dominant mechanism in fluid-filled rocks at seismic frequencies.
2006	Haines and Pride design a finite-difference algorithm to simulate electric fields caused by seismic waves.
2007	Ciz and S. A. Shapiro generalize the Gassmann equation to an anisotropic frame and solid pore infill.
2010	Gurevich et al. (2010) propose a model for squirt-flow dispersion and attenuation in fluid-saturated granular rocks.
2011	Krzikalla and T. Müller obtain the complex and frequency-dependent stiffnesses of a transversely isotropic porous medium equivalent to fine layering or to a dense set of fractures. The theory combines the mesoscopic-loss and linear-slip models.
2013	Carcione and Poletto implement the Arrhenius equation and Burgers viscoelastic model to describe seismic waves in the crust and mantle.
2019	First simulation of the thermal wave in thermoelastic and thermo-poroelastic media by Carcione and co-workers.

Leonardo's manuscripts

Leonardo da Vinci (1452–1519)[1]

"Leonardo perceived intuitively and used effectively the right experimental method a century before Francis Bacon philosophised about it inadequately, and Galileo put it into practice (Dampier, 1961).

Description of wave propagation, interference and Huygens' principle (1678):

Everything in the cosmos is propagated by means of waves... (Manuscript H, 67r, Institut de France, Paris.) *I say: if you throw two small stones at the same time on a sheet of motionless water at some distance from each other, you will observe that around the two percussions numerous separate circles are formed; these will meet as they increase in size and then penetrate and intersect one another, all the while maintaining as their respective centres the spots struck by the stones. And the reason for this is that water, although apparently moving, does not leave its original position, because the openings made by the stones close again immediately.. Therefore, the motion produced by the quick opening and closing of the water has caused only a shock which may be described as tremor rather than movement. In order to understand better what I mean, watch the blades of straw that because of their lightness float on the water, and observe how they do not depart from their original positions in spite of the waves underneath them caused by the occurrence of the circles. The reaction of the water being in the nature of tremor rather than movement, the circles cannot break one another on meeting, and as the water is of the same quality all the way through, its parts transmit the tremor to one another without changing position.* (Manuscript A, 61r, Institut de France, Paris.)

Description of the effect discovered by Doppler in 1842:

[1] Sources: White (2000); http://www.gutenberg.org/.

If a stone is flung into motionless water, its circles will be equidistant from their centre. But if the stream is moving, these circles will be elongated, egg-shaped, and will travel with their centre away from the spot where they were created, following the stream. (Manuscript I, 87, Institut de France, Paris.)

Description of Newton's prism experiment (1666):

If you place a glass full of water on the windowsill so that the sun's rays will strike it from the other side, you will see the aforesaid colours formed in the impression made by the sun's rays that have penetrated through that glass and fallen in the dark at the foot of a window and since the eye is not used here, we may with full certainty say that these colours are not in any way due to the eye. (Codex Leicester, 19149r, Royal Library, Windsor.)

Leonardo's scientific approach to investigate the refraction of light:

Have two trays made parallel to each other... and let one by 4/5 smaller than the other, and of equal height. Then enclose one in the other and paint the outside, and leave uncovered a spot the size of a lentil, and have a ray of sunlight pass there coming from another opening or window. Then see whether or not the ray passing in the water enclosed between the two trays keeps the straightness it had outside. And form your rule from that. (Manuscript F, 33v, Institut de France, Paris.)

Description of atmospheric refraction discovered by Brahe in the 16th century:

To see how the sun's rays penetrate this curvature of the sphere of the air, have two glass spheres made, one twice the size of the other, as round as can be. Then cut them in half and put one inside the other and close the fronts and fill with water and have the ray of sunlight pass as you did above [here he is referring to his earlier simpler refraction experiment]. *And see whether the ray is bent. And thus you can make an infinite number of experiments. And form your rule.* (Manuscript F, 33v, Institut de France, Paris.)

Explanation of the blue sky, before Tyndall's 1869 experiments and Rayleigh's 1871 theory:

I say that the blue which is seen in the atmosphere is not given its own colour, but is caused by the heated moisture having evaporated into the most minute and imperceptible particles, which the beams of the solar rays attract and cause to *seem luminous against the deep, intense darkness of the region of fire that forms a covering among them.* (Codex Leicester, 4r Royal Library, Windsor.)

Statement about light having a finite velocity, before Römer's conclusive measurement in 1676:

It is impossible that the eye should project the visual power from itself by visual rays, since, as soon as it opens, that front [of the eye] *which would give rise to this emanation would have to go forth to the object, and this it could not do without time. And this being so, it could not travel as high as the sun in a month's time when the eye wanted to see it.* (Ashburnham I & II, Biblioathèque Nationale, Paris.)

Description of the principle of the telescope:

It is possible to find means by which the eye shall not see remote objects as much diminished as in natural perspective... (Manuscript E, 15v, Institut de France, Paris.) *The further you place the eyeglass from the eye, the larger the objects appear in them, when they are for persons fifty years old. And if the eye sees two equal objects in comparison, one outside of the glass and the other within the field, the one in the glass will seem large and the other small. But the things seen could be 200 ells* [a little over 200 m] *from the eye...* (Manuscript A, 12v, Institut de France, Paris.) *Construct glasses to see the Moon magnified.* (Codex Atlanticus, 190r,a, Ambrosiana Library, Milan.)

A statement anticipating Newton's third law of motion (1666):

As much pressure is exerted by the object against the air as by the air against the body. (Codex Atlanticus, 381, Ambrosiana Library, Milan.)

The principle of least action stated before Fermat in 1657 and Hamilton in 1834:

Every action in nature takes place in the shortest possible way. (Quaderni, IV, 16r.)

Leonardo described fossil shells as the remains of ancient organisms and put forward a mass/inertia theory to describe seabed and continent up- and down-lifting as mountains eroded elsewhere on the planet. The evolution and age of the Earth and living creatures, preceding George Cuvier (1804) and Charles Lyell (1863), and plate tectonics, anticipating Wegener (1915):

That in the drifts, among one and another, there are still to be found the traces of the worms which crawled upon them when they were not yet dry. And all marine clays still contain shells, and the shells are petrified together with the clay. From their firmness and unity some persons will have it that these animals were carried up to places remote from the sea by the deluge. Another sect of ignorant persons declare that Nature or Heaven created them in these places by celestial influences, as if in these places we did not also find the bones of fishes which have taken a long time to grow; and as if, we could not count, in the shells of cockles and snails, the years and months of their life, as we do in the horns of bulls and oxen, and in the branches of plants that have never been cut in any part...

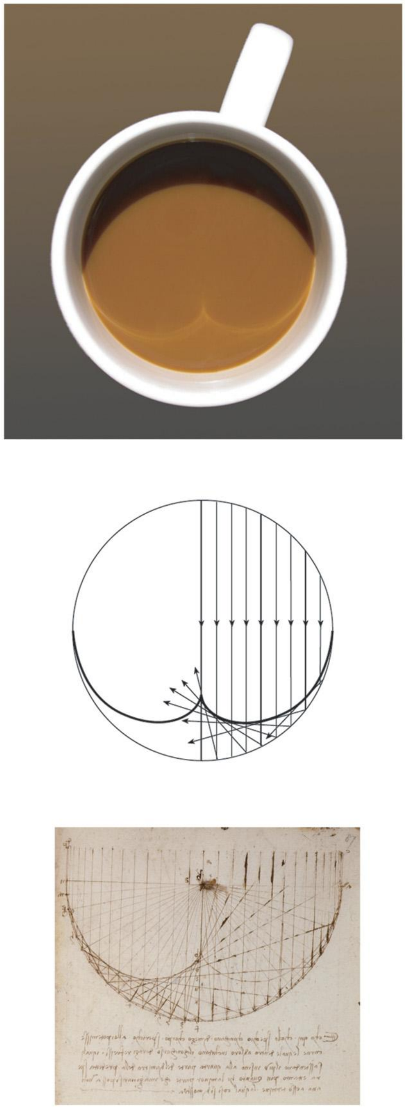
And within the limits of the separate strata of rocks they are found, few in number and in pairs like those which were left by the sea, buried alive in the mud, which subsequently dried up and, in time, was petrified...

Great rivers always run turbid, being coloured by the earth, which is stirred by the friction of their waters at the bottom and on their shores; and this wearing disturbs the face of the strata made by the layers of shells, which lie on the surface of the marine mud, and which were produced there when the salt waters covered them; and these strata were covered over again from time to time, with mud of various thickness, or carried down to the sea by the rivers and floods of more or less extent; and thus these layers of mud became raised to such a height, that they came up from the bottom to the air. At the present time these bottoms are so high that they form hills or high mountains, and the rivers, which wear away the sides of these mountains, uncover the strata of these shells, and thus the softened side of the Earth continually rises and the antipodes sink closer to the centre of the earth, and the ancient bottoms of the seas have become mountain ridges...

The centre of the sphere of waters is the true centre of the globe of our world, which is composed of water and earth, having the shape of a sphere. But, if you want to find the centre of the element of the earth, this is placed at a point equidistant from the surface of the ocean, and not equidistant from the surface of the earth; for it is evident that this globe of Earth has nowhere any perfect rotundity, excepting in places where the sea is, or marshes or other still waters. And every part of the Earth that rises above the water is farther from the centre. (Codex Leicester, Royal Library, Windsor.)

The theory of evolution stated before Maupertuis (1745) and Charles Darwin (1859):

Nature, being inconstant and taking pleasure in creating and making constantly new lives and forms, because she knows that her terrestrial materials become thereby augmented, is more ready and more swift in her creating than time in his destruction... (Codex Leicester, Royal Library, Windsor.)



The coffee cup caustic. The bright line seen in a coffee cup on a sunny day is a caustic. Consider the Sun as a point source of light and constructs rays according to geometrical optics. Parallel rays reflected in the inner surface generate a curved surface (caustic), which is the envelope of the rays. The caustic has a cusp at its center (paraxial focus). Note that the surface is brighter below the caustic (e.g., Nye, 1999). This phenomenon has been described by Bernoulli (1692) and Holditch (1858). Leonardo has predicted the phenomenon. He is arguing that in concave mirrors of equal diameter, the one which has a shallower curve will concentrate the highest number of reflected rays on to a focal point, and *as a consequence, it will kindle a fire with greater rapidity and force* (Codex Arundel, MS 263, f.86v-87, British Library, London). Seismic reflections from a geological syncline produce these types of caustics.

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A list of scientists

L'ère nouvelle commence à Galilèe, Boyle et Descartes, les fondateurs de la Philosophie expérimentale; tous trois consacrent leur vie à méditer sur la nature de la lumière, des couleurs et des forces. Galilèe jette les bases de la Mécanique, et, avec le télescope à réfraction, celles de l'Astronomie physique; Boyle perfectionne l'expérimentation; quant à Descartes, il embrasse d'une vue pénétrante l'ensemble de la Philosophie naturelle.

Alfred Cornu (Cornu, 1899)

The following 376 scientists have contributed to the understanding of wave propagation from different fields – optics, music, rheology, electromagnetism, acoustics, ray and field theory, differential calculus, seismology, etc. The list includes scientists born prior to year 1901.[1]

Thales of Miletus	ca. 634 BC	ca. 546 BC	Greece
Anaximander	ca. 610 BC	ca. 546 BC	Greece
Pythagoras	ca. 560 BC	ca. 480 BC	Greece
Aristotle	ca. 384 BC	ca. 322 BC	Greece
Euclid of Alexandria	ca. 325 BC	ca. 265 BC	Egypt
Archimedes of Syracuse	ca. 287 BC	ca. 212 BC	Greece
Chrysippus of Soli	ca. 279 BC	ca. 207 BC	Greece
Eratosthenes of Cyrene	ca. 276 BC	ca. BC 194	Greece
Lucretius	ca. 99 BC	ca. 55 BC	Rome
Vitruvius, Marcus	ca. 70 BC	ca. 15 BC	Rome
Seneca, Lucius Annaeus	ca. 4 BC	ca. 65	Rome

[1] The sources are the Dictionary of Scientific Biography, Gillispie, C. C., Ed., Charles Scribner's Sons (1972), the web site of the University of St. Andrews, Scotland (https://mathshistory.st-andrews.ac.uk/), the web site of Eric Weisstein's World of Scientific Biography (https://scienceworld.wolfram.com/biography/), the web site of the University of Florence, Italy (https://php.math.unifi.it/archimede/matematicaitaliana/), the web site of the University of Göttingen, Germany (https://www.uni-goettingen.de/), www.asap.unimelb.edu.au (Bright Sparcs), www.encyclopedia.com, www.bookrags.com, www.univie.ac.at, and www.sparkmuseum.com. Names in bold font appear in the chronology. The place of birth is indicated.

Heron of Alexandria	ca. 10	ca. 75	Egypt
Ptolemy, Claudius	ca. 85	ca. 165	Egypt
Theon of Alexandria	ca. 335	ca. 405	Egypt
Hypatia of Alexandria	ca. 355	ca. 415	Egypt
Philoponos, John	ca. 450	ca. 570	Egypt
Boethius, Anicius Manlius Severinus	ca. 480	ca. 525	Rome
Ibn al-Haythan	ca. 965	ca. 1040	Iraq
al–Ghazzali, Abu Hamid Muhammad	1058	1111	Iran
Grosseteste, Robert	1168	1253	England
Bacon, Roger	1214	1294	England
Petrus Peregrinus	ca. 1220	ca. 1270	France
Peckham, John	ca. 1230	1292	England
Witelo	ca. 1230	ca. 1275	Poland
Dietrich of Freiberg	1250	1310	England
Buridan, Jean	ca. 1295	1358	England
Pacioli, Luca	1445	1514	Italy
Leonardo da Vinci	1452	1519	Italy
Agricola, Georgius Bauer	1490	1555	Germany
Maurolycus, Franciscus	1494	1575	Italy
Cardano, Girolamo	1501	1576	Italy
Galilei, Vincenzo	1520	1591	Italy
Risner, Friedrich	ca. 1533	ca. 1580	Germany
Della Porta, Giambattista	1535	1615	Italy
Gilbert, William	1544	1603	England
Brahe, Tycho	1546	1601	Sweden
De Dominis, Marco Antonio	1560	1624	Italy
Harriot, Thomas	1560	1621	England
Bacon, Francis	1561	1626	England
Briggs, Henry	1561	1630	England
Galilei, Galileo	1564	1642	Italy
Lippershey, Hans	1570	1619	The Netherlands
Kepler, Johannes	1571	1630	Germany
Scheiner, Christoph	ca. 1573	1650	Germany
Snel van Royen (**Snellius**) Willebrord	1580	1626	The Netherlands
Cabeo, Nicolo	1585	1650	Italy
Mersenne, Marin	1588	1648	France
Gassendi, Pierre	1592	1655	France
Descartes, René	1596	1650	France
Cavalieri, Bonaventura	1598	1647	Italy

Fermat, Pierre de	1601	1665	France
Guericke, Otto von	1602	1686	Germany
Kircher, Athanasius	ca. 1602	1680	Germany
Browne, Thomas	1605	1682	England
Borelli, Giovanni	1608	1677	Italy
Divini, Eustachio	1610	1685	Italy
Wallis, John	1616	1703	England
Grimaldi, Francesco María	1618	1663	Italy
Mariotte, Edme	ca. 1620	1684	France
Picard, Jean	ca. 1620	1682	France
Viviani, Vincenzo	1622	1703	Italy
Bartholinus, Erasmus	1625	1698	Denmark
Cassini, Giovanni Domenico	1625	1712	Italy
Morland, Samuel	1625	1695	England
Boyle, Robert	1627	1691	Ireland
Huygens, Christiaan	1629	1695	The Netherlands
Hooke, Robert	1635	1702	England
Pardies, Ignace Gaston	1636	1673	France
Gregory, James	1638	1675	England
Ango, Pierre	1640	1694	France
Newton, Isaac	1642	1727	England
Römer, Olaf	1644	1710	Denmark
Flamsteed, John	1646	1719	England
Leibniz, Gottfried Wilhelm	1646	1716	Germany
Tschirnhausen, Ehrenfried Walther	1651	1708	Germany
Sauveur, Joseph	1653	1716	France
Halley, Edmund	1656	1742	England
Hauksbee, Francis	1666	1736	England
Bernoulli, Johann	1667	1748	Switzerland
Gray, Stephen	1670	1736	England
Hermann, Jakob	1678	1733	Switzerland
Taylor, Brook	1685	1731	England
Musschenbroek, Pieter van	1692	1791	The Netherlands
Bevis, John	1693	1771	England
Bradley, James	1693	1762	England
Bouguer, Pierre	1698	1758	France
du Fay, Charles-François de Cisternay	1698	1739	France
Maupertuis, Pierre Louis Moreau	1698	1759	France
Bernoulli, Daniel	1700	1782	The Netherlands

Kleist, Ewald Jürgen von	1700	1748	Germany
Nollet, Jean Antoine	1700	1770	France
Celsius, Anders	1701	1744	Sweden
La Condamine, Charles Marie de	1701	1774	France
Cramer, Grabriel	1704	1752	Switzerland
Franklin, Benjamin	1706	1790	USA
Euler, Leonard	1707	1783	Switzerland
Boscovich, Ruggiero Giuseppe	1711	1787	Italy
Lomonosov, Mikhail	1711	1765	Russia
Watson, William	1715	1787	England
Bianconi, Giovanni Ludovico	1717	1781	Italy
d'Alembert, Jean le Rond	1717	1783	France
Canton, John	1718	1772	England
Mayer, Johann Tobías	1723	1762	Germany
Michell, John	1724	1793	England
Aepinus, Franz María Theodosius	1724	1802	Germany
Lamberts, Johann Heinrich	1728	1777	Germany
Spallanzani, Lazzaro	1729	1799	Italy
Cavendish, Henry	1731	1810	England
Wilcke, Johannes	1732	1796	Sweden
Priestley, Joseph	1733	1804	England
Coulomb, Charles Augustin de	1736	1806	France
Lagrange, Joseph-Louis	1736	1813	Italy
Galvani, Luigi	1737	1798	Italy
Herschel, Frederick William	1738	1822	England
Volta, Alessandro Giuseppe Antonio Anastasio	1745	1827	Italy
Laplace, Pierre Simon	1749	1827	France
Herschel, Caroline Lucretia	1750	1848	England
Legendre, Adrien Marie	1752	1833	France
Rumford, Benjamin Thompson	1753	1814	USA
Chladni, Ernst Florens Friedrich	1756	1827	Germany
Olbers, Heinrich Wilhelm Matthäus	1758	1840	Germany
Romagnosi, Gian Domenico	1761	1835	Italy
Fourier, Jean Baptiste Joseph	1768	1830	France
Nicol, William	1768	1851	Scotland
Seebeck, Thomas	1770	1831	Estonia
Young, Thomas	1773	1829	England
Biot, Jean Baptiste	1774	1862	France
Ampère, André Marie	1775	1836	France

Malus, Étienne Louis	1775	1812	France
Germain, Sophie	1776	1831	France
Ritter, Johann Wilhelm	1776	1810	Germany
Soldner, Johann Georg von	1776	1833	Germany
Gauss, Carl Friedrich	1777	1855	Germany
Oersted, Hans Christian	1777	1851	Denmark
Davy, Humprhy	1778	1829	England
Brewster, David	1781	1868	Scotland
Poisson, Simón Denis	1781	1840	France
Sturgeon, William	1783	1850	England
Bessel, Friedrich Wilhelm	1784	1846	Germany
Hansteen, Christopher	1784	1873	Norway
Nobili, Leopoldo	1784	1835	Italy
Navier, Claude Louis Marie Henri	1785	1836	France
Peltier, Jean Charles Athanase	1785	1845	France
Arago, Dominique François	1786	1853	France
Fraunhofer, Joseph von	1787	1826	Germany
Fresnel, Augustin Jean	1788	1827	France
Cauchy, Augustin Louis	1789	1857	France
Ohm, Georg Simon	1789	1854	Germany
Faraday, Michael	1791	1867	England
Mossotti, Ottaviano Fabrizio	1791	1863	Italy
Piola, Gabrio	1791	1850	Italy
Savart, Félix	1791	1841	France
Herschel, John Frederik William	1792	1871	England
Green, George	1793	1841	England
Babinet, Jacques	1794	1872	France
Lamé, Gabriel	1795	1870	France
Henry, Joseph	1797	1878	USA
Poiseuille, Jean Léonard Marie	1797	1869	France
Saint Venant, Adhémar Jean Claude Barré de	1797	1886	France
Zantedeschi, Francesco	1797	1873	Italy
Melloni, Macedonio	1798	1854	Italy
Neumann, Franz Ernst	1798	1895	Czech Republic
Clayperon, Benoit Paul Emile	1799	1864	France
Lloyd, Humphrey	1800	1881	Ireland
Airy, George Biddell	1801	1892	England
Fechner, Gustav Theodor	1801	1887	Germany
Colladon, Jean Daniel	1802	1893	Switzerland

Sturm, Jacques Charles	1802	1855	Switzerland
Doppler, Christian Andreas	1803	1853	Austria
Jacobi, Carl Gustav Jacob	1804	1851	Germany
Lenz, Heinrich Friedrich Emil	1804	1865	Germany
Weber, Wilhelm Edward	1804	1891	Germany
Bancalari, Michele	1805	1864	Italy
Dirichlet, Gustav Peter	1805	1859	Germany
Hamilton, William Rowan	1805	1865	Ireland
Mohr, Friedrich	1806	1879	Germany
Palmieri, Luigi	1807	1896	Italy
Meucci, Antonio	1808	1896	Italy
Scott Russell, John	1808	1882	Scotland
Forbes, James David	1809	1868	Scotland
Liouville, Joseph	1809	1882	France
MacCullagh, James	1809	1847	Ireland
Menabrea, Federigo	1809	1896	Italy
Mallet, Robert	1810	1881	Ireland
Bunsen, Robert Wilhelm Eberhard von	1811	1899	Germany
Grove, William Robert	1811	1896	Wales
Angström, Anders Jöns	1814	1874	Sweden
Mayer, Julius Robert	1814	1878	Germany
Sylvester, James Joseph	1814	1897	England
Joule, James Prescott	1818	1889	England
Fizeau, Armand	1819	1896	France
Foucault, Jean Léon	1819	1868	France
Stokes, George Gabriel	1819	1903	Ireland
Rankine, William John Macquorn	1820	1872	Scotland
Tyndall, John	1820	1893	Ireland
Chebyshev, Pafnuty Lvovich	1821	1894	Russia
Helmholtz, Hermann von	1821	1894	Germany
Cecchi, Filippo	1822	1887	Italy
Clausius, Rudolf Julius Emmanuel	1822	1888	Germany
Galton, Francis	1822	1911	England
Hermite, Charles	1822	1901	France
Krönig, A. K.	1822	1879	Germany
Lissajous, Jules Antoine	1822	1880	France
Bétti, Enrico	1823	1892	Italy
Kronecker, Leopold	1823	1891	Poland
Kirchhoff, Gustav Robert	1824	1887	Russia

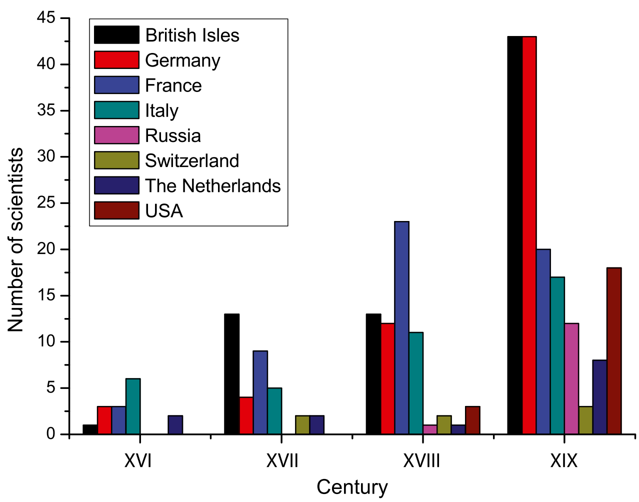
Kerr, John	1824	1907	Scotland
Thomson, William (Baron Kelvin of Largs)	1824	1907	Ireland
Beer, August	1825	1863	Germany
Riemann, Georg Friedrich Bernhard	1826	1866	Germany
Christoffel, Elwin Bruno	1829	1900	Germany
Lorenz, Ludwig	1829	1891	Denmark
Maxwell, James Clerk	1831	1879	Scotland
Tait, Peter Guthrie	1831	1901	Scotland
Crookes, William	1832	1919	England
Lipschizt, Rudolf Otto	1832	1903	Germany
Neumann, Carl Gottfried	1832	1925	Russia
Clebsch, Rudolf Friedrich Alfred	1833	1872	Germany
de Rossi, Michele Stefano	1834	1898	Italy
Beltrami, Eugenio	1835	1900	Italy
Newcomb, Simon	1835	1909	USA
Stefan, Josef	1835	1893	Austria
Mascart, Élèuthere, Élie Nicolas	1837	1908	France
van der Waals, Johannes Diderik	1837	1923	The Netherlands
Mach, Ernst	1838	1956	Slovakia
Morley, Edward William	1838	1923	USA
Hankel, Hermann	1839	1873	Germany
Kundt, August Adolf	1839	1894	Germany
Abbe, Ernst Karl	1840	1905	Germany
Kohlrausch, Friedrich	1840	1910	Germany
Cornu, Marie Alfred	1841	1902	Ireland
Pochhammer, Leo August	1841	1920	Germany
Boussinesq, Valentin Joseph	1842	1929	France
Lie, Marius Sophus	1842	1899	Norway
Reynolds, Osborne	1842	1912	England
Strutt, John William (Third Baron Rayleigh)	1842	1919	England
Christiansen, Christian	1843	1917	Austria
Nippoldt, Wilhem August	1843	1904	Germany
Boltzmann, Ludwig	1844	1906	Austria
Branly, Edouard Eugène Désiré	1844	1940	France
Lippmann, Gabriel	1845	1921	France
Röngten, Whilhem Conrad	1845	1923	Germany
Mittag-Leffler, Gösta Magnus	1846	1927	Sweden
Umov, Nikolai Alekseevich	1846	1915	Russia
Castigliano, Carlo Alberto	1847	1884	Italy

Floquet, Gaston	1847	1920	France
Bruns, Ernst Heinrich	1848	1919	Germany
Korteweg, Diederik Johannes,	1848	1941	The Netherlands
Rowland, Henry Augustus	1848	1901	USA
Hopkinson, John	1849	1898	England
Lamb, Horace	1849	1934	England
Cerruti, Valentino	1850	1909	Italy
Goldstein, Eugen	1850	1939	Poland
Gray, Thomas	1850	1908	Scotland
Heaviside, Olivier	1850	1925	England
Mercalli, Giuseppe	1850	1814	Italy
Milne, John	1850	1913	England
Voigt, Woldemar	1850	1919	Germany
Bartoli, Adolfo	1851	1896	Italy
Fitzgerald, George Francis	1851	1901	Ireland
Hugoniot, Pierre Henri	1851	1887	France
Lodge, Oliver Joseph	1851	1940	England
Michelson, Albert	1852	1931	Germany
Poynting, John	1852	1914	England
Lorentz, Hendrik Antoon	1853	1928	The Netherlands
Ricci-Curbastro, Gregorio	1853	1925	Italy
Glazebrook, Richard Tetley	1854	1935	England
Poincaré, Jules Henri	1854	1912	France
Curie, Jacques	1855	1941	France
Ewing, James Alfred	1855	1935	Scotland
Hall, Edwin Herbert	1855	1938	USA
Sekiya, Seiki	1855	1896	Japan
Knott, Cargill Gilston	1856	1922	Scotland
Runge, Carl David Tolmé	1856	1927	Germany
Tesla, Nikola	1856	1943	Serbia
Thomson, Joseph John,	1856	1940	England
Hertz, Heinrich Rudolf	1857	1894	Germany
Larmor, Joseph	1857	1842	Ireland
Mohorovičić, Andrija	1857	1936	Croatia
Bose, Jagadish Chandra	1858	1937	Bengal
Oldham, Richard Dixon	1858	1936	Ireland
Planck, Max	1858	1947	Germany
Cesàro, Ernesto	1859	1906	Italy
Curie, Pierre	1859	1906	France
Popov Alexander	1859	1906	Russia

Reid, Harry Fielding	1859	1944	USA
Chree, Charles	1860	1928	England
Somigliana, Carlo	1860	1955	Italy
Volterra, Vito	1860	1940	Italy
Kennelly, Arthur Edwin	1861	1939	India
Reuber-Paschwitz, Ernst von	1861	1895	Lithuania
Wiechert, Emil	1861	1928	Lithuania
Galitzine, Boris	1862	1911	Russia
Hilbert, David	1862	1943	Germany
Lenard, Phillipp	1862	1947	Hungary
Rudzki, Maurycy Pius	1862	1916	Poland
Wiener, Otto Heinrich	1862	1927	Germany
Love, Augustus Edward Hough	1863	1940	England
Michell, John Henry	1863	1940	Australia
Pérot, Jean-Baptiste Alfred	1863	1925	France
Minkowski, Hermann	1864	1909	Germany
Wien, Wilhem Carl Werner Otto Fritz Franz	1864	1928	Germany
Hadamard, Jacques Salomon	1865	1963	France
Pockels, Friedrich Carl Alwin	1865	1963	Italy
Zeeman, Pieter	1865	1943	The Netherlands
Cosserat, Eugène Maurice Pierre	1866	1931	France
de Vries, Gustav	1866	1934	The Netherlands
Fabry, Marie Paul Auguste Charles	1867	1945	France
Kolosov, Gury	1867	1936	Russia
Kutta, Wilhelm	1867	1944	Germany
Hale, George Ellery	1868	1938	USA
Mie, Gustav	1868	1957	Germany
Millikan, Robert Andrews	1868	1953	USA
Omori, Fusakichi	1868	1923	Japan
Sabine, Wallace Clement	1868	1919	USA
Sommerfeld, Arnold Johannes	1868	1951	Russia
Galerkin, Boris Grigorievich	1871	1945	Russia
Rutherford, Ernest	1871	1937	New Zealand
Langévin, Paul	1872	1946	France
Levi-Civita, Tullio	1873	1941	Italy
Whittaker, Edmund Taylor	1873	1956	England
Marconi, Guglielmo	1874	1937	Italy
Prandtl, Ludwig	1875	1953	Germany
Angenheister, Gustav	1878	1945	Germany

Frechét, Maurice René	1878	1973	France
Timoshenko, Stephen	1878	1972	Ucraina
Mintrop, Ludger	1880	1956	Germany
Wegener, Alfred	1880	1930	Germany
Einstein, Albert	1879	1955	Germany
Herglotz, Gustav	1881	1953	Austria
Zoeppritz, Karl	1881	1908	Germany
Bateman, Harry	1882	1946	England
Born, Max	1882	1970	Poland
Geiger, Ludwig Carl	1882	1966	Switzerland
Macelwane, James Bernard	1883	1956	USA
Mises, Richard von	1883	1953	USA
Terzaghi, Karl von	1883	1963	Czech Republic
Wagner, Karl Willy	1883	1953	Germany
Debye, Peter Joseph William	1884	1966	The Netherlands
Weyl, Hermann Klaus Hugo	1885	1955	Germany
Colonnetti, Gustavo	1886	1968	Italy
Taylor, Geoffrey Ingram	1886	1975	England
Loomis, Alfred Lee	1887	1975	USA
Radon, Johann	1887	1956	Czech Republic
Schrödinger, Erwin	1887	1961	Austria
Courant, Richard	1888	1972	Poland
Lehmann, Inge	1888	1993	Denmark
Raman, Chandrasekhara Venkata	1888	1970	India
Brillouin, Léon	1889	1969	Russia
Gutenberg, Beno	1889	1960	Germany
Hubble, Edwin Powell	1889	1953	USA
Nyquist, Harry	1889	1976	Sweden
Jeffreys, Harold	1891	1989	England
de Broglie, Louis Victor	1892	1987	France
Watson-Watt, Robert	1892	1973	France
Gordon, Walter	1893	1940	Germany
Knudsen, Vern Oliver	1893	1974	USA
Lanczos, Cornelius	1893	1974	Hungary
Frenkel, Yacov Il’ich	1894	1952	Russia
Klein, Oskar	1894	1977	Sweden
Kramers, Hendrik Anthony	1894	1952	The Netherlands
Nakano, Hiroshi	1894	1929	Japan
Stoneley, Robert	1894	1976	England

Wiener, Norbert	1894	1964	USA
Burgers, Johannes Martinus	1895	1981	The Netherlands
Sezawa, Katsutada	1895	1944	Japan
Hund, Friedrich	1896	1997	Germany
Blackett, Patrick Maynard Stuart	1897	1974	England
Sokolov, Sergei	1897	1971	Russia
Firestone, Floyd	1898	1986	USA
Fock, Vladimir Aleksandrovich	1898	1974	Russia
Sears, Francis Weston	1898	1975	USA
Wentzel, Gregor	1898	1978	Germany
Benioff, Victor Hugo	1899	1968	USA
Richter, Charles Frances	1900	1985	USA



This histogram shows the number of scientists of the modern age per country based on the previous list. The eight main countries are considered, taking into account the birth date of the scientists.

Italy opens the way in the 16th century leading to the creation of the *Accademia Nazionale dei Lincei* in 1603, following England and France when the Royal Society and *Académie des sciences* are founded in 1660 and 1666, respectively. Notably, France makes a significant contribution in the 18th century (the age of Enlightenment), while Germany and the British Isles clearly have a major influence in the 19th century, with USA emerging in the 20th century as the main contributor of present times.

Man cannot have an effect on nature, cannot adapt any of her forces, if he does not know the natural laws in terms of measurement and numerical relations. Here also lies the strength of the national intelligence, which increases and decreases *according to such knowledge. Knowledge and comprehension are the joy and justification of humanity; they are parts of the national wealth, often a replacement for those materials that nature has all too sparsely dispensed. Those very peoples who are behind in general industrial activity, in application of mechanics and technical chemistry, in careful selection and processing of natural materials, such that regard for such enterprise does not permeate all classes, will inevitably decline in prosperity; all the more so where neighboring states, in which science and the industrial arts have an active interrelationship, progress with youthful vigor.*

Alexander von Humboldt (Kosmos, I 1845, 36).