

## 1.6: The 20th Century Revolution in Physics

The two greatest achievements of modern physics occurred in the beginning of the 20th century. The first was Einstein's development of the Theory of Relativity; the Special Theory of Relativity in 1905 and the General Theory of Relativity in 1915. This was followed in 1925 by the development of quantum mechanics.

**Albert Einstein (1879-1955)** developed the Special Theory of Relativity in 1905 and the General Theory of Relativity in 1915; both of these revolutionary theories had a profound impact on classical mechanics and the underlying philosophy of physics. The Newtonian formulation of mechanics was shown to be an approximation that applies only at low velocities while the General Theory of Relativity superseded Newton's Law of Gravitation and explained the Equivalence Principle. The Newtonian concepts of an absolute frame of reference, plus the assumption of the separation of time and space were shown to be invalid at relativistic velocities. Einstein's postulate that the laws of physics are the same in all inertial frames requires a revolutionary change in the philosophy of time, space and reference frames which leads to a breakdown in the Newtonian formalism of classical mechanics. By contrast, the Lagrange and Hamiltonian variational formalisms of mechanics, plus the principle of least action, remain intact using a relativistically invariant Lagrangian. The independence of the variational approach to reference frames is precisely the formalism necessary for relativistic mechanics. The invariance to coordinate frames of the basic field equations also must remain invariant for the General Theory of Relativity. Thus the development of the Theory of Relativity unambiguously demonstrated the superiority of the variational formulation of classical mechanics over the vectorial Newtonian formulation, and thus the considerable effort made by Euler, Lagrange, Hamilton, Jacobi, and others in developing the analytical variational formalism of classical mechanics finally came to fruition at the start of the 20th century. Newton's two crowning achievements, the Laws of Motion and the Laws of Gravitation, that had reigned supreme since published in the Principia in 1687, were toppled from the throne by Einstein.

**Emmy Noether (1882-1935)** has been described as "the greatest ever woman mathematician". In 1915 she proposed a theorem that a conservation law is associated with any differentiable symmetry of a physical system. Noether's theorem evolves naturally from Lagrangian and Hamiltonian mechanics and she applied it to the four-dimensional world of general relativity. Noether's theorem has had an important impact in guiding the development of modern physics.

Other profound developments that had revolutionary impacts on classical mechanics were quantum physics and quantum field theory. The 1913 model of atomic structure by **Niels Bohr (1885-1962)** and the subsequent enhancements by **Arnold Sommerfeld (1868-1951)**, were based completely on classical Hamiltonian mechanics. The proposal of wave-particle duality by **Louis de Broglie (1892-1987)**, made in his 1924 thesis, was the catalyst leading to the development of quantum mechanics. In 1925 **Werner Heisenberg (1901-1976)**, and **Max Born (1882-1970)** developed a matrix representation of quantum mechanics using non-commuting conjugate position and momenta variables.

**Paul Dirac (1902-1984)** showed in his Ph.D. thesis that Heisenberg's matrix representation is based on the Poisson Bracket generalization of Hamiltonian mechanics, which, in contrast to Hamilton's canonical equations, allows for non-commuting conjugate variables. In 1926 **Erwin Schrödinger (1887-1961)** independently introduced the operational viewpoint and reinterpreted the partial differential equation of Hamilton-Jacobi as a wave equation. His starting point was the optical-mechanical analogy of Hamilton that is a built-in feature of the Hamilton-Jacobi theory. Schrödinger then showed that the wave mechanics he developed, and the Heisenberg matrix mechanics, are equivalent representations of quantum mechanics. In 1928 Dirac developed his relativistic equation of motion for the electron and pioneered the field of quantum electrodynamics. Dirac also introduced the Lagrangian and the principle of least action to quantum mechanics and these ideas were developed into the path-integral formulation of quantum mechanics and the theory of electrodynamics by **Richard Feynman (1918-1988)**.

The concepts of wave-particle duality, and quantization of observables, both are beyond the classical notions of infinite subdivisions in classical physics. In spite of the radical departure of quantum mechanics from earlier classical concepts, the basic feature of the differential equations of quantal physics is their selfadjoint character which means that they are derivable from a variational principle. Thus both the Theory of Relativity, and quantum physics are consistent with the variational principle of mechanics, and inconsistent with Newtonian mechanics. As a consequence Newtonian mechanics has been dislodged from the throne it occupied since 1687, and the intellectually beautiful and powerful variational principles of analytical mechanics have been validated.

The 2015 observation of gravitational waves is a remarkable recent confirmation of Einstein's General Theory of Relativity and the validity of the underlying variational principles in physics. Another advance in physics is the understanding of the evolution of chaos in non-linear systems that have been made during the past four decades. This advance is due to the availability of computers which has reopened this interesting branch of classical mechanics, that was pioneered by Henri Poincaré about a century ago.

Although classical mechanics is the oldest and most mature branch of physics, there still remain new research opportunities in this field of physics.

The focus of this book is to introduce the general principles of the mathematical variational principle approach, and its applications to classical mechanics. It will be shown that the variational principles, that were developed in classical mechanics, now play a crucial role in modern physics and mathematics, plus many other fields of science and technology.

## References

Excellent sources of information regarding the history of major players in the field of classical mechanics can be found on Wikipedia, and the book “Variational Principle of Mechanics” by Lanczos.[La49]

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