The laws of electromagnetism are invariant under the Lorentz transformation of space and time coordinates (unlike Newtonian mechanics, which is invariant under the conceptually simpler Galileo transformation), and are thus the origin of Albert Einstein's *special theory of relativity* (1905). Einstein's theory brought about a unification of the concepts of space and time into a four-dimensional *spacetime continuum*, and also of energy and mass through the relation $E = mc^2$, where c is the speed of light *in vacuo*.

To address problems involving many particles (many degrees of freedom), Rudolf Clausius, James Clerk Maxwell, Ludwig Boltzmann, Josiah Willard Gibbs and others developed *statistical physics*. The concept of probability was introduced by Boltzmann to explain the apparent irreversibility of the macroscopic world. For instance, it was found that the second law of thermodynamics does not have an absolute validity, but rather an extremely high probability:

> *In any isolated macroscopic system the only allowed processes are those evolving from a less probable to a more probable macrostate, i.e., those involving no entropy decrease.*

This law results from the fact that there are always many more disordered states than there are ordered ones.

The *kinetic theory of gases* was another great accomplishment of Maxwell. It explained the concept of temperature in terms of a chaotic motion of molecules, thus bridging the gap between mechanics and thermodynamics.

The existence of *discrete energy levels* was conjectured by Boltzmann in 1872. Unlike Max Planck, who believed that light is emitted discontinously but travels through space as a classical electromagnetic wave, Einstein assumed that the energy in a light beam propagates as *field quanta*, called *photons*. The photon energy, E, and momentum, p, are related to the wave frequency of light, ν, through $E = h\nu$ and $p = h\nu/c$ (h is Planck's constant).

A momentous step – although not fully appreciated for almost a century – towards a unified theory of particles and waves was made by a mathematician, William Rowan Hamilton. In 1834, he realized that there was a similarity between the Hamilton–Jacobi equation in mechanics and the Fermat principle in optics:

> *The propagation of a particle in a variable potential is formally equivalent to the propagation of light in a medium with a changing index of refraction.*

Hamilton's insight bore fruit in 1923 when Louis de Broglie suggested that the wave-particle duality of radiation should have its counterpart in a *particle–wave duality* of matter. According to de Broglie, a wave with wavelength λ that propagates in an infinite medium has associated with it a particle, or *quantum*, of momentum $p = h/\lambda$. This concept is at the heart of Erwin Schrödinger's wave mechanics and its probabilistic view of physical phenomena, which was introduced into

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