The analogy of a spinning electron with spinning Earth or spinning top, initially drawn by physicists had to be abandoned. How then was the concept of spin evolved and conceptualised in physics?

In the spectrum of hydrogen atom, a series of distinct lines were observed. For many years physicists were puzzled by the discrete nature of the hydrogen spectrum. This was satisfactorily explained by Niels Bohr in 1913 who pointed out that the electrons can only rotate about the nucleus at certain set distances away from it.

Specifically, his postulate meant that the angular momentum of the electron (mass x velocity x radius of the orbit) is \( n \hbar \), where \( n \) is an integer \( (0,1,2,3,\ldots) \) and \( \hbar \) is a constant called Planck’s constant. The Bohr model not only successfully explained the discreteness of the line spectrum of hydrogen atom, but was also able to predict the correct sequence of lines in the Balmer series of hydrogen spectrum. Bohr had thus introduced the concept of ‘quantisation’ of angular momentum and the integer \( n \) is now called principal or total quantum number.

However, in spite of its many successes, Bohr’s theory was inadequate to explain certain lines in the spectrum of hydrogen atom. As instruments acquired more and more resolving power, clear observations revealed that individual spectral lines were not really single. Rather, they consisted of even finer lines packed together. Bohr’s theory was able to explain the coarser splitting of hydrogen spectral lines, not the closely spaced splitting, which was given the name fine structure. For instance, the first line of Balmer series of hydrogen was experimentally observed to consist of two lines that are 0.014 nm apart; whereas prediction based on Bohr’s theory suggested only a single spectral line of wavelength 656.3 nm.

The conspicuous failure of Bohr’s theory was clearly since it assumed only one orbit for each quantum number \( n \) whereas the observed fine structure suggested that for any given quantum number \( n \), there might be several orbits of slightly different energies (electrons have varying rotational energies in different orbits, so the orbits are also referred to as energy levels). Although Sommerfeld modified Bohr’s theory by invoking the idea of the motion of the electron in elliptical orbits and by considering the relativistic variation of the mass of the electron, it met with only partial success as it could not fully explain the fine structure in the spectrum of hydrogen atom.

Another phenomenon with regard to spectral lines was observed by Pieter Zeeman. He found that in the presence of a magnetic field, the individual spectral lines split into separate lines. This phenomenon is known as Zeeman effect. While the normal Zeeman effect suggests splitting of a spectral line into two (longitudinal) or three (transverse) components, anomalous Zeeman effect suggests complex splitting with four, six or even more components. For instance, it has been known that the yellow D line of sodium splits into two components, \( D_1 \) and \( D_2 \). When a discharge tube containing sodium is placed in a magnetic field of moderate strength, the \( D_1 \) line splits into four while the \( D_2 \) line splits into six components.

In order to explain satisfactorily both the observed phenomena of fine structure and anomalous Zeeman effect, Compton in 1921 made the first ever suggestion that the electron might be a spinning particle. Compton’s concept was taken further by two Dutch physicists Samuel Goudsmit and George Uhlenbeck. In fact, what Goudsmit and Uhlenbeck had in mind was a classical picture of an electron as a charged sphere spinning on its axis. Therefore, in Goudsmit and Uhlenbeck scheme of things, the electron could revolve not only in an orbit round the nucleus but also about an axis of its own like a planet in a solar system. In other words, the electron was endowed with a spin motion over and above the orbital motion.

The concept of “spinning electron” introduced by Goudsmit and Uhlenbeck brought in profound modifications in the atomic model. It proved to be successful in explaining not only the fine structure and anomalous Zeeman effect but a wide variety of other atomic effects as well.

It is known that the rotation of a body about an axis gives rise to a mechanical angular momentum. If the rotating body is charged, its rotation about an axis would produce angular momentum as well as a magnetic dipole moment, which for a revolving charge is equivalent to a circulatory current that gives rise to a magnetic dipole moment. Now, if we incorporate the “spinning electron” concept, the electron will be endowed with two angular momenta and two magnetic dipole moments, one due to orbital motion and the other due to spin.

The Goudsmit-Uhlenbeck concept of spin received support from the experimental findings of Otto Stern.
and Walther Gerlach of the University of Hanburg, Germany. Starting in the 1920s, the two physicists conducted a series of important atomic beam experiments. Knowing that all moving charges produce magnetic field, they proposed to measure the magnetic field produced by the electrons orbiting the nuclei in atoms. In 1922, Stern and Gerlach directed a beam of silver atoms through an inhomogeneous magnetic field. Much to their surprise, they found the beam to split into two beams. This was interpreted by them as due to the electron spinning very rapidly producing tiny magnetic fields independent of those from their orbital motion. This experimental result of Stern and Gerlach was consistent with the possession of an angular momentum and a magnetic moment by the individual electrons.

However, the classical picture of an electron as a spinning charge posed serious problems. Experiments involving scattering of electrons by other electrons at high energy had indicated that the electron must be less than $10^{-17}$ m across i.e. it must almost behave like a point charge. Now, in order to have the observed angular momentum associated with electron spin, so small an object would have to rotate with an equatorial velocity many times greater than the velocity of light. This led to a serious dilemma! The question to ponder was: Is there anything fundamentally wrong with the notion of electron spin?

Actually, the trouble is with the literal meaning of “spin.” The word “spin” means “rotate”. Therefore, taken literally, a spinning electron would mean an electron rotating about its axis. However, the electrons and other subatomic particles are all assumed as point-like; and quantum mechanics tells us that the particles do not have any well-defined axes. So, it really would be misleading to think of an electron as a little top spinning about an axis.

The problem of “spinning electron”, however, gets resolved by regarding spin as an intrinsic (internal) property of electron like its mass and charge. In fact, it has nothing directly to do with the everyday or “classical” concept of spin. The word “spin” as applicable to electron is, therefore, a misnomer which, unfortunately, has stuck. In fact, spin refers to a special property of the electron. It only signifies an intrinsic angular momentum of the electron separate from its orbital angular momentum.

Although spin of an electron like its mass and charge is its intrinsic property, it has an orientation. The magnitude of the spin of an electron is always $\frac{1}{2}$. The orientation of the electron spin is represented by a quantum number which can be either positive or negative; its value is taken as $\pm \frac{1}{2}$. It may be mentioned that before the spin quantum number was introduced, there were three quantum numbers (total quantum number, orbital angular momentum quantum number and magnetic quantum number) in use.

In December 1924, the Viennese physicist Wolfgang Pauli suggested that the complete list of the quantum numbers of an orbiting electron must include its energy, angular momentum and orientation in space. Pauli suggested a fourth quantum number which he called Zweideutigkeit, meaning two-valuedness. This was suggested by Pauli to account for the splitting of the spectral lines due to alkaline-earth metals (caesium, strontium, barium etc.) into two distinct lines; these lines, called doublets, are made of two almost identical frequencies.

It is interesting to note that Ralph de Laer Kronig, an American physicist of Hungarian descent, had suggested that Pauli’s Zweideutigkeit was due to the effects of a spinning electron. However, Pauli had then rejected the idea of Kronig. But, one can see that Kronig was also one of the early originators of the idea of a spinning electron.

Although Pauli’s fourth quantum number was just an add-on, in 1926 Paul Dirac gave his famous relativistic equation for the electron, the Dirac Equation. This equation proved conclusively that electron spin is a natural consequence of quantum physics. Thus, spin was no longer an add-on; it was proved by Dirac to have a quantum mechanical origin.

Spin plays an important role in our understanding of the interactions among subatomic particles, whether in high-energy particle beams, low temperature fluids or the tenuous flow of
particles from the Sun known as the solar wind. Indeed, many if not all physical processes, ranging from the smallest nuclear scale to the largest astrophysical distances, depend greatly on interactions of subatomic particles and the spins of these particles.

Spin has served as the prototype for other, even more abstract notions that seem to have the mathematical properties of angular momentum but do not have a simple classical analogue. For example, isotopic spin is used in nuclear physics to represent the two states of a ‘nucleon’-proton and neutron. Similarly, quarks are paired as isospin ‘up’ and ‘down’, which are the names given to the two quarks that make up ordinary matter.

Like electrons, other elementary particles also have spin-like properties. Electrons belong to a class of particles called fermions (after Enrico Fermi) which have spin that are half-integer multiple of Planck’s constant divided by 2\pi. Another class of particles, called bosons (after S. N. Bose), have integer spin (0, 1, 2, etc.). While bosons obey Bose-Einstein statistics, fermions are governed by Fermi-Dirac statistics.

### Spin and Parity

Spin adds an extra dimension to the symmetry called parity. Like symmetry, parity has a loose general meaning and a much more restricted scientific definition.

Ordinarily, parity means equality; for example, two individuals are on a par or have parity if they are equal in some respect like position or stature. To scientists, however, parity means the kind of equality that results from a particular kind of transformation under which spatial coordinates are reversed and right becomes left, down becomes up and backward becomes forward. This is quite what happens when one looks into a mirror, except that up and down are not reversed in a mirror. This produces a special form of symmetry called reflection symmetry or parity.

It may be remarked that the physical laws were assumed to be indifferent to reflection transformation. What works for left, up and forward works equally well for right, down and backward. However, parity has a different significance in the context of elementary particles.

When physicists speak of the parity of elementary particles, they have in mind what happens when minus signs are placed in front of the spatial coordinates (X’s, Y’s and Z’s) for the wave function of a stationary particle, which is the mathematical description of its physical state. If the wave function is not changed, the particle is said to have even parity.

Bosons with integer spin are particles of even parity. However, if the wave function of the particle reverses sign when its orientation in space is reversed, the particle is said to have odd parity. Fermions, which are particle of half-integer spin, are particles with odd parity. Therefore, the parity of a particle depends on its spin. If the particle has integer spin (boson), it has even parity; and if it has half-integer spin (fermion), it has odd parity.

### Quantum Mechanical Spin

Spin has been regarded as one of the most challenging aspects of quantum mechanics. Mathematically, quantum mechanical spin states are described by vector-like entities known as spinors. There are certain differences between the behaviour of spinors and vectors under coordinate relations. For example, rotating a particle of spin \( \frac{1}{2} \) by 360 degree does not bring it back to the same quantum state, but to the opposite quantum state; this can be detected, in principle, with interference experiments. To return the particle to the exact original state, a 720 degree rotation is needed. Thus, a particle of spin \( \frac{1}{2} \) when turned through two complete revolutions (each revolution amounting to rotation of 360 degree) would look the same.

A particle of spin zero (Higgs Boson) can be imagined as a dot, which would look the same after whatever angle it is turned through. Particle of spin 1 will look the same when turned through 360 degrees, a complete revolution. Particle of spin 2 would look the same when turned through 180 degree (half revolution) while a particle of spin 4 would have to be rotated through 90 degree (one-fourth revolution) to look the same.

The concept of electron spin, and spin of other elementary particles, is not only intricate but intriguing, too. It is a quantum mechanical concept and has no classical analogue. Actually, classical analogy of spin was evolved in the initial stages of its understanding. It is a misnomer which has stuck in physics.

Nonetheless, it is a very significant and important concept of physics and plays a very prominent role in understanding the interactions among subatomic particles. Therefore, the concept of spin needs to be properly understood by shunning the ill-construed idea of a “rotating” electron or particle.

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The electron behaves as if it were spinning about an axis through its center. The two directions of spin correspond to the two possible values for the spin quantum number, ms.