Boolean algebra is a simple system with many applications. In binary arithmetic, numbers have a value of 1 or 0; in logic, a statement is true or false; in set theory, an object is in or out of a set; in circuitry, a switch is on or off. All are subject to the same rules of logic.

SEE ALSO
Computers, History of; Personal Computers; Supercomputers.

BIBLIOGRAPHY


BOSE-EINSTEIN CONDENSATES
When a gas of bosonic particles is cooled below a critical temperature, it undergoes a phase transition and forms a Bose-Einstein condensate. The condensate consists of particles in the ground state of the system. The phase transition to Bose-Einstein condensation (BEC) is based on the indistinguishability and wave nature of particles, and does not depend on specific interactions between the particles in the gas.

This phenomenon is a consequence of Bose-Einstein statistics. The key features of Bose-Einstein statistics are that they describe indistinguishable particles, and allow an arbitrary number of particles to occupy any quantum state. Compared to classical statistics, where particles are distinguishable, this quantum statistics favors multiple occupation of a quantum state and ultimately BEC of particles in a single quantum state. The reason is that if states are sparsely populated, the number of configurations (distribution of particles over quantum states) is larger in classical statistics by N!, the number of possible permutations among N particles. However, if states i have population N_i, this ratio becomes smaller, N!/(N_1 N_2 N_3 N_4 ...), that is, in classical statistics the relative statistical weight of multiply occupied states is smaller than in quantum statistics.

This way of counting configurations was introduced by the Indian mathematician and physicist Satyendra Nath Bose (1894–1974). Bose attended school in Calcutta (now Kolkata), and after being a lecturer in the physics department of the University of Calcutta, he became a reader in the department of physics at the University of Dhaka. He worked there on theoretical physics. In 1924 he wrote his most important paper titled "Planck's Law and the Hypothesis of Light Quanta," in which he derived the Planck Law of Blackbody Radiation in a novel way. The key element was this new way of counting the states occupied by the photons, by treating them as indistinguishable particles.

Bose sent his manuscript to the German physicist Albert Einstein (1879–1955) and asked him to have it published in the German scientific journal Zeitschrift für Physik. Einstein recognized its importance, translated it himself into German and had it published under Bose's name. Almost immediately, Einstein generalized Bose's approach from photons to material particles and derived what we now call Bose-Einstein statistics, a statistical description for the properties of a gas of indistinguishable particles.

There are two different ways in which indistinguishable particles can behave. In the first case, if the number of particles per quantum state can be unlimited, then we call them bosons and they are described by Bose-Einstein statistics. On the other hand, if only one particle per quantum state is allowed—meaning the particles are
subject to the Pauli exclusion principle—then we call the particles fermions and Fermi-Dirac statistics applies.

A simplified description of matter assumes, that all matter consists of protons, neutrons and electrons. Particles that are composed of an even number of constituents are bosons, of an odd number are fermions. More rigorously, the classification is based on the spin (intrinsic angular momentum) of the particles: particles with an integer spin are bosons, while those with half-integer spins are fermions. Since photons and helium 4 both possess zero spin, they are bosons; electrons, on the other hand, have half spin and are therefore fermions.

After working in Paris and Berlin for two years and meeting many of the famous European scientists, Bose returned to India in 1926 and had a distinguished career as a teacher and researcher in physics and other disciplines, and assumed responsibilities as dean and vice chancellor to develop science in India.

For a long time, it was not clear whether the predicted BEC could ever be observed in nature. The prediction was for an almost ideal gas, whereas all material particles interact with each other and, at low temperatures, form liquids and solids before reaching the critical temperature for BEC. The superfluidity of helium which occurs below 2.2 Kelvin (K), has some characteristics of BEC, but occurs in a dense liquid with many properties different from a gas. Only in the 1970s was it realized that gases could be kept in a metastable phase where condensation into a liquid or solid is suppressed, and BEC could occur.

The experimental realization in 1995 was based on the new technique of laser cooling developed in the 1980s which provided clouds of atoms at micro-Kelvin temperatures (i.e., a few millionths of a degree Kelvin above absolute zero). The last step was combining laser cooling with evaporative cooling. This seemed at first very challenging, since laser cooling works only at low atomic densities and evaporative cooling requires high densities. But innovative techniques bridged this gap and led to spectacular observations of Bose-Einstein condensates at nano-Kelvin temperatures, first of rubidium atoms at the University of

Figure 1. Observation of Bose-Einstein condensation by absorption imaging. In absorption imaging, the atom cloud is illuminated with a laser beam, and its shadow is imaged onto a digital camera. Pictures taken for expanding ultracold atom clouds reveal the onset of Bose-Einstein condensation below a critical temperature $T_c$. The Bose-Einstein condensate is characterized by its slow expansion observed after 6 milliseconds time of flight. The left picture shows an expanding cloud cooled to just above the transition point; middle: just after the condensate appeared; right: after further evaporative cooling has left an almost pure condensate. The width of the images is 1.0 millimeters. The total number of atoms at the phase transition is about $7 \times 10^5$, the temperature at the transition point is $2 \mu$K (micro-Kelvin). The bottom picture is a 3-D plot where the height of the peak represents the darkness of the shadow. The Bose-Einstein condensate appears as a sharp peak.
Colorado, and then for sodium atoms at the Massachusetts Institute of Technology (MIT).

The Bose-Einstein condensate is for matter what the laser is for light. Bose-condensed atoms have several properties in common with laser light: many atoms occupy one quantum state similar to single-mode photons. They are described by a macroscopic matter wave field, similar to the coherent electric field characterizing the radiation of a laser. This property of the Bose-Einstein condensate was verified at MIT in 1997 by interfering two Bose-Einstein condensates and observing high contrast interference fringes, similar to the interference pattern of two laser beams.

These experimental breakthroughs triggered a revolution in atomic physics. Laboratories all over the world pursued research on BEC, and theoretical studies made numerous predictions about the properties of this new form of matter. Even more importantly, researchers could use the Bose-Einstein condensate as a starting point and modify it (with additional laser beams and other methods) to create other new interesting forms of matter. This flurry of activity led to an early recognition of the accomplishment of BEC by the award of a Nobel Prize in 2001, only six years after its experimental demonstration. The Nobel Prize in Physics for 2001 was awarded jointly to three physicists: the Americans Eric A. Cornell (1961– ) and Carl E. Wieman (1951– ), and the German Wolfgang Ketterle (1957– ) “for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates” (Nobel Prize citation 2001).

BEC is a fundamental phenomenon occurring for bosonic particles at sufficiently low temperature. The condensate is the way in which nature maximizes entropy below the critical temperature. However, this does not apply to photons that can be absorbed and emitted, that is, their number is not conserved. Photons in thermal equilibrium are described by the Planck law for blackbody radiation (which Bose re-derived using his new way of counting photon states), which does not feature a photon condensate. One can easily see why: if there were a condensate of photons in the lowest frequency mode of the system, an increase in total entropy would be possible by absorbing the condensate (thus heating up the walls of the blackbody cavity). However, situations can be created where the number of photons in the system is constant (e.g., by replenishing lost photons). In such a situation, a condensate of photons has been observed at the University of Bonn in 2010, where photons in a cavity were in thermal equilibrium with a dye solution.
Research on BEC has elucidated important aspects of quantum mechanics, and has allowed quantitative comparisons with first-principle calculations for static properties and dynamic behavior, including fluctuations, vortices, and the nature of the phase transition to the superfluid state. Studies of Bose-Einstein condensates of fermionic atom pairs—a situation wherein the individual atoms themselves cannot form a Bose-Einstein condensate, but pairs of the atoms can—realized the simplest model system for Cooper pairing and superconductivity of an electron gas. The list of novel possibilities seems endless and includes studies of magnetism and novel exotic materials.

SEE ALSO Blackbody Radiation; Lasers; Quantum Mechanics; Standard Model of Elementary Particle Physics; Superfluidity; Wave Nature of Particles.

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BRAIN CONNECTOMICS, HUMAN

The human cerebral cortex consists on the order of 100 billion neurons that interconnect to form a core set of functional neural networks that underlie complex behavior and cognition. The fundamental elegance of this system was detailed in the late 1800s and early 1900s through the pioneering work of researchers from various nations: the Spaniard Santiago Ramón y Cajal (1852–1934), Italian Camillo Golgi (1843–1926), the Germans Theodor Schwann (1810–1882) and Franz Nissl (1860–1919), and many others. Considerable effort has been devoted since that time toward elucidating the structure and function of neural systems. Yet, even now, we do not currently have a comprehensive