A unit for nothing

The way that we understand free space has varied wildly since our first conception of the vacuum. And how we measure the void has proven just as changeable, as Karl Jousten explains.

Ancient Greek philosophers debated whether a void space could exist at all. Among the most famous denying the existence of vacuum was Aristotle, and he was joined by most philosophers in the Middle Ages. The prevailing argument was that space cannot be defined in a region where nothing exists. In 1644, however, the Italian mathematician Evangelista Torricelli proved the sceptics wrong. His experiment was rather simple: Torricelli filled a glass tube of about 1 m in length with mercury and sealed the open end with his fingertip. He then immersed this end in a mercury reservoir before removing his fingertip. The outflowing mercury caused the column in the tube to sink to a depth of 76 cm, measured from the liquid surface of the reservoir. In this way, Torricelli demonstrated that the space void of mercury in the tube was in fact a vacuum because it could also be completely filled with water from below and the mercury level was independent of the volume above. Torricelli had effectively invented the first barometer.

Only four years later, in 1648, the French scientist and philosopher Blaise Pascal (pictured) showed that the mercury height varied with air pressure, which itself depends on altitude[1] and weather conditions. In the 1650s, Otto von Guericke, mayor of the German city of Magdeburg, was the first to generate a large-scale vacuum. He ordered members of the city's fire brigade to drain the water from a water-filled vessel with one of their pumps. This is why 'vacuum pumps' are still named pumps, even though — from an engineering point of view — these instruments are in fact gas compressors.

To measure a vacuum, the original Torricelli tube was formed into a U-shape with a connecting tube to the vacuum vessel. This laid the groundwork for the definition of the measure of vacuum with mm Hg, equivalent to one millimetre of a mercury column, identical to 1 torr at 0 °C. The 'torr' and 'mm Hg' as a quantity for pressure suffered from several drawbacks. First, the value depends on the density of mercury and hence on its isotopic composition,

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purity and temperature. Second, the unit could not be expressed by the base units of the international system (SI) newly introduced between 1948 and 1960. And third, new ways of vacuum measurement, unrelated to mercury, were developed.

For these reasons, at the 14th Conférence Générale des Poids et Mesures (CGPM) in 1971, the name pascal (Pa, 133.22 Pa = 1 torr) for the unit of pressure expressed as kg m^{-1} s^{-2} was introduced. The mbar, equal to 100 Pa, was also a widely used unit for vacuum pressures. Now, the most commonly used vacuum range spans 15 orders of magnitude from 10^{-10} Pa for extremely high vacuum, which is required in surface physics and elementary particle research, up to 10^5 Pa, corresponding to atmospheric pressure. Several National Metrological Institutes provide fundamental measurement standards to realize this huge scale and calibrate vacuum gauges[2].

There is a new trend in the way we define the pascal[3,4], moving away from a mechanical measurement as force per area towards an optical measurement of gas density times the product of Boltzmann constant and temperature. The Boltzmann constant is one of the recently redefined fixed constants of the SI with zero uncertainty. A priori, quantum-electrodynamical calculations of the dynamic polarizability of helium enable determination of molecular density from a measurement of refractive index in a fundamental manner. To measure the gas density of a vacuum makes sense[5], because vacuum pressures do not exert significant forces and most applications of vacuum need either a long enough mean free path of the gas molecule or a well-defined gas density: 10^{-10} Pa corresponds to 10^4 molecules per cm^3, 10^5 Pa to 10^{19} molecules per cm^3. Perhaps, at some point in the future, molecular density instead of the pascal will serve as a measure of the nothing.

Without any doubt, there are macroscopic areas, for example, small volumes of a few dm^3 between galaxies, in which not a single molecule is present. For such a volume, the term 'absolute vacuum' was introduced. We know today, however, that even absolute vacuum is not empty in terms of energy. The nature of the energy of a vacuum is yet to be determined, and may be related to the cosmological constant introduced by Einstein, but we do know that it permits particles to be generated spontaneously by fluctuating quantum fields for short time intervals, even in absolute vacuum. In this sense, there is no space in the world that is truly empty. ❐

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