Chapter 13

Nanoworld

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13.1 Nanoworld Length

1 – 1000 nanometers (nm) 1.0 x 10^{-9} m

Nanometer Sized Objects

Example	Dimension
Width of Razor Blade	1 nm
Diameter of DNA Helix	2 nm
Font Height of IBM Written with Atoms	5 nm
Ridges Detectable by Human Finger	13 nm
Porcine Circovirus	17 nm
Gold Leaf	52 nm
HIV Virus	100 nm
Cosmic Dust Particle	100 nm
SARS-CoV-2 Virus	100 nm
Depth of Pit on CD Surface	125 nm
Human Ear Drum Deflection	200 nm
Ultra-Small Bacteria	300 nm
Mimivirus	750 nm
Pithovirus Sibericum	1500 nm

Table 13.1

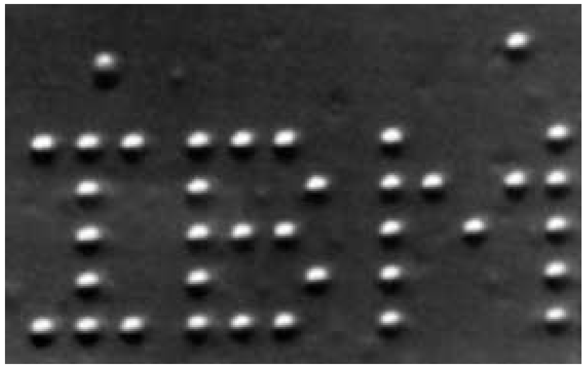

Figure 13.1: Image of the first set of letters written with individual atoms. The letters are 5 nanometers in height. Each dot is a single Xenon atom. (Courtesy of IBM Archives)

The world of nanometer lengths has become glamourous, while at the same time eliciting concern. People see the world of nanometer dimensions as unconventional, and possibly unmoored from conventional physics, yet most people have been using "nanotechnology" every morning for many decades. Common razor blades used each day to remove unwanted hair, have edge widths on the order of 350 to 450 nanometers. It is possible to sharpen the edge of a razor blade down to a 0.5 to 1 nanometer edge width, which straddles the boundary from Nanoworld to Picoworld. The narrow dimension of a very small human hair, which is to be cut using a 400 nanometer cutting edge, is 17 600 nm.

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In 1989, the three letters IBM were written using 35 individual xenon atoms. This was the first time a set of atoms were located precisely on a flat surface, in this case a chilled crystal of nickel. Each glyph is about 5 nanometers tall. The three letters with their spacing take up about 13 nanometers. The entire set of letters would fit nicely on an A_{50} sheet of paper, which, if it existed, would be 35 x 25 nanometers.

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Conductor Sizes in Microprocessors

Year	Transistor Dimensions
1971	10 000 nm
1985	1 000 nm
1995	350 nm
2002	130 nm
2014	14 nm
2022	5 nm

Table 13.2: Process Sizes in Microprocessors

The width of the conductive traces implemented in the first commercial microprocessor was 10 000 nanometers. Table 13.2 lists the steady march toward a one-nanometer integrated circuit (IC). The width dimension of conductive traces in current ICs are smaller than the edges of common razor blades, and they are approaching the widths of laboratory-sharpened razor blades.

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In 1835, Italian entomologist Agostino Bassi asserted in print that a living entity was responsible for a lethal disease that devastated domestic silkworms. Bassi had saved the silkworm industry by introducing measures to isolate infected caterpillars from healthy ones, and eradicating the infected ones. Bassi expanded his idea that diseases were caused by pathogenic organisms to diseases in plants, animals, and human beings. The notion that tiny organisms are responsible for disease became popularly known as "the germ theory of disease."

German scientist Robert Koch (1843–1910) would be the first to link a specific organism to a specific disease. Koch demonstrated that anthrax, a fatal disease, was caused by the presence of the *Bacillus anthracis* bacterium, which can be seen with a microscope.

During this time, it was commonly believed that tuberculosis was an inherited disease. Koch used guinea pigs to demonstrate tuberculosis is caused by a different bacterium. In 1905, this research lead to a Nobel Prize for Koch. Koch went on to identify the microorganism responsible for cholera. The germ theory of disease was placed on solid ground by Koch.

Louis Pasteur (1822-1895) used the germ theory of disease to investigate rabies. An animal that contracts rabies becomes savage and mad as the disease attacks its nervous system. Rabid dogs become thoroughly aggressive. The word rabies is derived from a Latin word that means rage, madness and fury. The bite of a rabid dog was clearly responsible for the transmission of rabies to humans. Pasteur procured samples of saliva from rabid dogs, and injected them into rabbits, which contracted the disease. He was able to use rabbits to culture the disease for study. Pasteur dried an infected spinal cord in the presence of moderate warmth, and each following day injected rabbits to see if the effectiveness of the germ would be attenuated. It was. Day after day the germ was less and less lethal. After two weeks, the injections did not produce rabies at all. Pasteur used injections of the deteriorated germ to provide immunity to dogs, and famously cure a young boy.

Unlike Koch's earlier work, Pasteur had not been able to identify any germ within any of his preparations. He found microorganisms, but none that produced rabies. This did not comport with the germ theory of disease, but did not trouble Pasteur. The results of his work made no sense without the framework of the theory. Visible microorganisms ranged in size from those which were just barely discernible with the unaided eye, to those which were at the edge of perceptibility with a microscope. Pasteur was certain the germ which caused rabies was simply too small to see using contemporary microscopes.

Perhaps there was another way to isolate the microorganism without a microscope and visual identification. Suppose one used a filter with holes small enough to allow the germ of interest to pass, but not other organisms. When the filter holes were small enough to allow water molecules to pass, but not the germ, the fluid which passed through the filter would not produce disease, but the fluid left behind would.

In 1884, French bacteriologist Charles Chamberland (1851–1908), while working with Pasteur, developed a filter that would block average sized germs from passing through it. The filter itself is an unglazed permeable porcelain tube. Russian scientist Dmitri Ivanovsky (1864–1920) used a Chamberland Filter* to demonstrate that the infectious agent which caused Tobacco Mosaic disease was so small, it would pass through a filter that would remove bacterial sized agents, but could not bring himself to believe they were so small they could not be viewed with a microscope. Dutch microbiologist Martinus Beijerinck (1851–1931) independently replicated Ivanovsky's experiments in 1898. Unlike Ivanovsky, Beijerinck asserted that the infectious agent was too small to see with a microscope.

Beijerinck called this infectious fluid a "virus" from the Latin word for poison. Because the agent which caused Tobacco Mosaic disease passed through a filter, yet remained a virus, led Beijerinck to call it a "filtrable virus."

British microbiologist William Joseph Elford (1900–1952) used a different type of filter which could be engineered to produce pores of any size. The germs that caused disease were finally trapped with these ultrafilters, showing they had a size between bacteria and water molecules, at about 100 nm in size.[1]

In 1931, German engineers Ernst Ruska (1906–1988) and Max Knoll (1897–1969) invented electron microscopy, which allowed for the creation of the first images of viruses.

But what was a virus? Before that could be answered, a different puzzle would need to be solved, that of how life works. In 1944, Austrian physicist Erwin Schrödinger (1887-1961) published the book *What is Life?*, based on lectures he gave in 1943. Schrödinger introduced the idea of the existence of an "aperiodic crystal" which contained the information needed to create life. This inspired researchers to search for this chemical repository of genetic information. Research involving pneumococci by

*Colloquially called a Chamberland Candle.

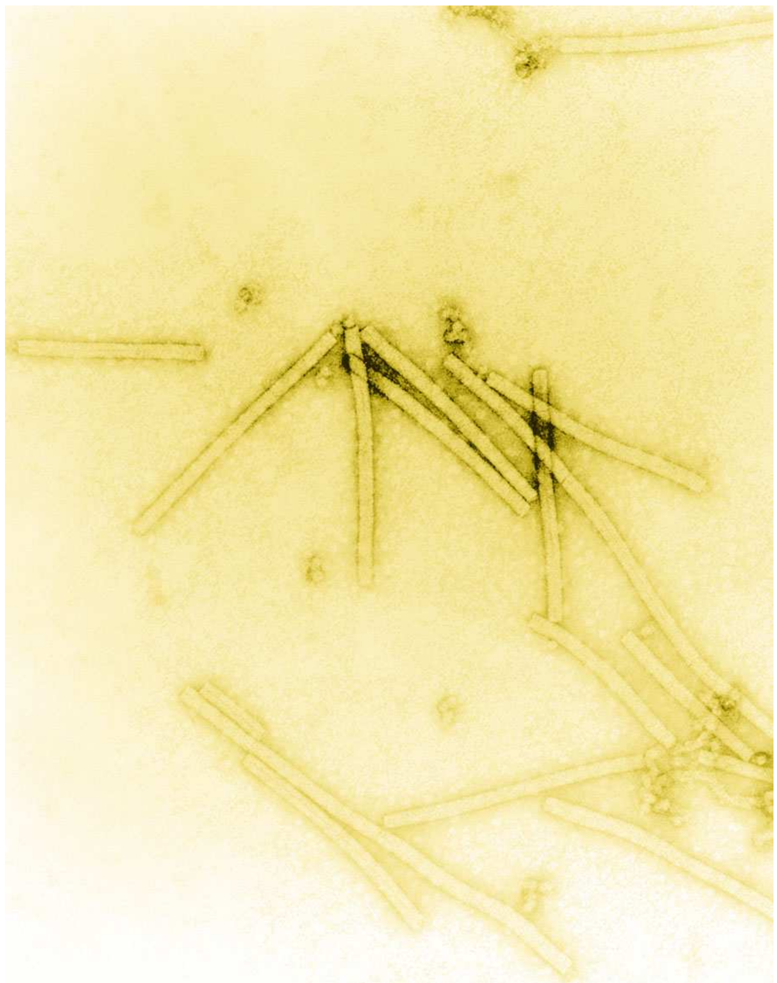

Figure 13.2: Electron Micrograph of Tobacco Mosaic Virus. The virus is approximately 300 nm long and 18 nm across – Wikimedia Commons

English bacteriologist Frederick Griffith (1879–1941), from as far back as 1928, indicated that some type of transformation factor could change one strain of pneumococcus into another. An American team lead by Oswald Theodore Avery (1877–1955), purified this transformation factor, and to their surprise it was not protein, but pure nucleic acid, or DNA.

Bacteriologist and geneticist Alfred Hershey (1908-1997) along with his lone long-time laboratory assistant Martha Chase (1927-2003) set out to determine once and for all if the true genetic material was protein, DNA, or some combination of the two. In 1952, Hershey and Chase published a definitive study, which became colloquially known as the "Waring blender" experiment. This was because they separated the protein and nucleic acid components of bacteria with the same machine that blended milk shakes.[2] They replaced sulfur in bacteriophages with radioactive sulfur in proteins that were *only* found in proteins and not DNA. Phosphorus, found *only* in DNA, was replaced with radioactive phosphorus. They then infected bacteria with the radioactive phages they had created. After cell replication, they could determine if viral DNA or viral protein, or both, were transmitted to the next generation of cells. Phages with radioactive phosphorous passed it on to the next generation of DNA. The protein that was radiotagged with sulfur, produced progeny with non-radioactive proteins. It was clear that DNA alone transfered genetic information.

After James D. Watson (1928–) and Francis Crick (1916–2004) proposed the double helix structure of DNA, with the uncredited guidance of X-ray diffraction images produced by Rosalind Franklin (1920–1958), they both credited Schrödinger's book as the inspiration for their research. It was realized that viruses were not complete protein, and contained a small amount of nucleic acid, but until Crick and Watson's discovery, this had mostly been a curiosity. Both RNA and DNA were each found to be within viruses, and sometimes together.

Viruses consist of a protein capsule which contains a coil of nucleic acid. Crucial experiments demonstrated that a virus was able to inject the coil of nucleic acid into a cell, where it would take over the reproductive machinery of the cell, and produce a number of copies of itself, which would breach the cell's boundary, and infect others. Viruses contain a chemical information payload that instructs the cell to create more viruses.

Nanometer lengths are useful for expressing the dimensions of viruses. Viruses were historically considered to have much much smaller dimensions than bacteria, and were therefore thought to be much much harder to study. But then, in 2003, an organism that at first appeared to be a bacterium, because a common test indicated it was, was instead discovered to be a virus. It was dubbed a *mimivirus*, or microbe-mimicking virus. This virus has a diameter of 750 nanometers. This is just plain gigantic for a virus. Suddenly researchers found "giant" viruses everywhere. Why was this? These viruses are really big—and we have much better microscopes and tools than existed in the 1930s when viruses were first imaged. How could it be only in the 21st century that anyone identified them?

Viruses were *assumed* to be exceptionally small, and in order to separate them from other undesired biological entities, a filter was used. The standard filter employed has 200 nanometer pores. Viruses were essentially defined as replicating particulates which made it through this filter, so larger viruses went undetected over many generations of virology research. The mimivirus was noticed only because it was large enough to be visible under a microscope.

In 2014, researchers resurrected a 30 000 year old virus from Siberian permafrost. It is the largest virus thus far discovered. It is called *pithovirus sibericum*, and measures 1500 nm in length, and 500 nm in width, which approaches the dimensions of Typhoid and Scarlet Fever bacteria.

The lower limit dimensions of bacteria entered the Nanoworld realm in 2015, when filtered groundwater from Rifle Colorado revealed the existence of 300 nanometer sized bacteria. It is currently thought that bacteria of this size may represent the lower limit for life to exist. They are formally called ultra-small bacterial cells.

It is estimated that 4 x 10^{30} viruses exist in the Earth's oceans, with land based viruses included, we have a total of 1 x 10^{31} viruses on Earth.[4] [5]. Each virus is about 100 nanometers in length. If they were laided end-to-end, the viruses would stretch out over 1 Yottameter! Our Milky Way Galaxy is about 1 Zettameter in length. We would need to place 1000 copies of our Galaxy end-to-end to achieve the same length.

In December of 2019, a new coronavirus was identified in Wuhan, China, which spread globally, causing deaths and infections at approximately the same rate as the 1918 influenza pandemic. It is officially called the SARS-CoV-2 virus. Science writer Debora Mackenzie states:

> The virus is officially called SARS-CoV-2, a name chosen by a committee of virologists expressedly to underscore how novel it isn't and how similar it is to the virus that caused the disease SARS in 2003. That virus was renamed SARS-CoV-1.[6]

We barely escaped the SARS-CoV-1 virus in 2003. The world was not so fortunate with the SARS-CoV-2 in 2019. The World Health Organization (WHO) refers to the virus as COVID-19, but many call it the coronavirus.

Coronaviruses were first discovered in domestic chickens in the 1930s. Human coronaviruses were first detected in the 1960s and identified as producing colds. Corona viruses are composed of a sphere that is approximately 80 nm in diameter, with spikes which are about 20 nm in length.

The current COVID-19 virus is about 100 nm in diameter. A typical human cell is about 100 000 nm. This means the virus is about 1000 times smaller than the cell it infects. If a human cell is thought of as approximately 1 meter in length, the COVID-19 virus is about 1 mm by comparison. This miniscule payload of non-living biological information has disrupted the entire human population of the Earth, and is changing the course of history.

The history altering COVID-19 virus is a mere 100 nanometers across, has a volume of about 1 attoliter, and a mass of but a single femtogram.[7]

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Gold is so malleable, one gram of it can be spread over a one square meter area. This may not sound impressive when stated this way, but a single gram of gold has a volume of 52 μL, so when spread over a one meter square area it has a thickness of approximately 52 nanometers. A 52 nm layer of gold is only about 400 atoms thick. Gold has been beaten into thicknesses so thin they allow light to pass through. These translucent gold films are greenish-blue in color.

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Cosmic dust ranges in size from a few molecules, in the realm of picometers, to about 100 nanometers for the largest particles. Cosmic dust is much smaller than micrometeoroids, which are on the order of 50 000 to 500 000 nm.

Perceived Colors vs. Wavelengths of Visible Light

Color	**Wavelength Band**
Violet	400-450 nm
Blue	450-490 nm
Green	490-560 nm
Yellow	560-590 nm
Orange	590-635 nm
Red	635-700 nm

Table 13.3

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It is in the Nanoworld of length where visible light is described. Visible light is an electromagnetic wave with an electric field which reverses direction around 500 x 10^{12} times per second. An oscillation per second is called a Hertz. Visible light has frequencies which range from about 430-750 Terahertz. Generally, light waves are described in terms of how far they travel during one complete oscillation. This is called their wavelength, and for visible light it is in the range of 400-700 nanometers.

Human eyes have two types of photoreceptors: rods and cones. Their names refer to their respective geometry. Rods are much more sensitive to light than cones. The eye has about 120 million rods, but only 6 million cones. Rods are sensitive to only one wavelength of light, 498 nanometers, and are responsible for black and white night vision. Cones are the color receptors of the eyes. Cones which absorb 420 nanometer light, are perceived as blue by the brain, 534 nanometer cones see green, and 564 nanometer cones appear to the mind as red. The combination of these three receptors produces our perception of color. The associated wavelengths of our color perception are given in Table 13.3. Incidentally, light with a wavelength of 632.991 212 58 nanometers is used to define the length of a meter.

The human eye can distinguish about 10 million different colors. A small percentage of women are thought to have a genetic variation which produces an ability to perceive four wavelengths of light, which allows them to see up to 100 million colors. These new colors do not include the ultraviolet wavelengths of light, about 300-400 nanometers, because the lens of the eye blocks this range of electromagnetic waves. On the other hand, some birds and insects can see light in the 300-700 nm range—well into the ultraviolet. The Mantis Shrimp has twelve photoreceptors, yet does not appear to combine them to distinguish colors, instead using them only to aid in the detection of prey.

While the wavelengths of light detected by our eyes are in the 600 nanometer range, our ear drums are only deflected by about 200 nanometers when listening to sounds. The amount of volume displacement is on the order of 120-700 nanoliters. Our eyes and ears are quite impressive at detecting nanolength effects, but our sense of touch is able to distinguish surface ridges more than a magnitude smaller than this. Swedish researchers have demonstrated our fingers can sense ridges on a surface as small as 13 nanometers in height, with a separation of 760 nanometers.[3]

13.2 Nanoworld Area

1 – 1 000 000 square nanometers (nm^2) 1 x 10^{-18} m^2

An object which has dimensions ranging from 1 to 100 nanometers is considered a nanoparticle. Nanoparticles are of great scientific interest, as their dimensions are such they are not quite bulk materials, nor discreet-sized atomic or molecular ones. Sometimes the region from 1 nanometer to 1000 nanometers is called the *mesoscale* region.[8] The word mesoscale is derived from the Greek word "mesos" which means middle.

The properties of some nanoparticles can be strongly dependent on their size. When the number of atoms forming the surface of a nanoparticle approaches the number of atoms contained within the volume, unexpected properties can occur. But when a particle has a dimension *larger* than one micrometer, the total number of atoms inside is much larger than the number of atoms on the surface, and its properties will remain constant as its size is increased further. In other words, the properties of the particles remain stable, no matter how much larger you make them, after they are larger than a micrometer. These size-independent stable properties are called the bulk properties of a material.

Examples of Square Nanometer Objects

Example	Surface Area
Quantum Dot (2 nm diameter)	3 nm^2
Quantum Dot (10 nm diameter)	78 nm^2

Table 13.4

When these nanoparticles are placed into a solvent they can become a suspension. The jiggling of atoms in the solvent (i.e.

Brownian motion) will keep the small particles from settling out of the fluid. The nanometer-sized particles distribute themselves throughout the fluid and have optical properties dependent on their size. Because the nanoparticles are of nanometer dimensions, and the wavelengths of visible light are in the nanometer range, this is consistent with expectations. When excited with fluorescent (ultraviolet) light, nanoparticles can emit visible light of a color dependent on their size. Larger nanoparticles emit red light, and as their dimension is decreased, the light shifts toward the blue end of the spectrum.

When a nanoparticle is made from a semiconducting material, it is often called a *quantum dot*. Quantum dots can confine between 100 to 100 000 atoms within their volume, and have a dot diameter of 10 to 50 atoms. These dots have a physical diameter of around 2 to 10 nanometers, which corresponds to a 3 to 78 square nanometer area. Quantum dots, which are generally below 10 nanometers in size, produce quantized electronic energy levels. What this means is quantum dots will have electron configurations determined by the geometry of the quantum dots, in energy levels analogous to how electrons arrange themselves within electron shells. Because of this, quantum dots are sometimes referred to as *artificial atoms*.

Quantum dots within a solid glass matrix were discovered in 1981 by Russian physicist Alexei Ekimov (1945 –). Later, American chemist Louis Brus (1943 –) prepared colloidal suspensions of quantum dots.

When they were discovered, it was thought quantum dots were first created by modern science, but their use by artisans has a considerable history. Nanoparticles were used to create a glittering effect on the surface of pots at least as far back as the ninth century. Potters in the Middle Ages and Renaissance, produced pots with gold and copper colored metallic glitter. Ceramic glazes with silver and copper nanoparticles dispersed themselves throughout the matrix. When the pottery was fired, a chemical process produced nanoparticles at the surface, which produced the decorative luster. The process was completely empirical in nature.

Small groups of atoms with Nanoworld dimensions can also produce interesting properties. Aluminum atoms will cluster together and macroscopically adopt chemical properties similar to single atoms of other chemical elements. Clusters of seven aluminum atoms (Al_7) are similar to individual germanium atoms. Aluminum clusters composed of thirteen (Al_{13}) atoms are chemically similar to the highly reactive halogen elements, but most closely resemble chlorine. Groups of atoms which appear to possess the properties of elemental (single) atoms are called *superatoms.*

13.3 Nanoworld Volume

1 – 1000 Nanoliters (nL) 1 x 10^{-9} L

Examples of Nanoliter Objects

Example	**Volume**
Microsphere (124 μm diameter)	1 nL
Human Egg Cell	1.2 nL
Microsphere (1000 μm diameter)	523 nL

Table 13.5

A hollow microsphere with an inside diameter of 124 micrometers encloses a volume of one nanoliter, and one with 1000 micrometers encloses a volume of 523 nanoliters. A human egg cell has a volume of approximately 1.15 nanoliters so over 400 of them would fit inside of a 1000 μm diameter microsphere.

13.4 Nanoworld Mass

1 – 1000 nanograms (ng) 1 x 10^{-9} g

The mass of an average human blood cell is around one nanogram.

Nanogram Objects

Item	Mass
Average Human Cell	1 ng
Colloidal Suspension Particle	1 ng
Droplet of Fog	1.8 ng
Birch Tree Pollen Grain	8 ng
Fine Dust	100 ng
Fairyfly (smallest insect)	100 ng
Magnetic Monopole (hypothetical)	180 ng
Corn Pollen Grain	247 ng
Sand (63 μm diameter)	350 ng

Table 13.6

The mass of particles which make up a colloidal suspension are on the order of one nanogram.

A droplet of fog has a mass of approximately 2 nanograms.

Nanograms are quite useful for describing the mass of pollen grains. A Birch Tree pollen grain is about 8 nanograms, and a grain of corn pollen is 247 nanograms. Fine dust falls between these two values at about 100 nanograms per dust particle. Sand with a 63 μm diameter has a mass of about 350 nanograms.

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The smallest known insect is a fairyfly, which is a member of the wasp family. They are on the order of 150 micrometers in length, and have a mass of about 100 nanograms, similar to that of a piece of fine dust. Fairyflies are rather common insects, but are seldom noticed by humans because of their extremely small size. Fairyflies can have strikingly attractive wings and features, which made them a popular subject for study with microscopes in the 19th and 20th centuries.

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In the 19th century, physicist James Clerk Maxwell developed a set of equations which describe electromagnetic radiation. Examples of electromagnetic radiation are visible light and radio waves. Maxwell's equations, as they are known, have a mathematical asymmetry to them. Engineers and scientists like symmetrical equations. If one postulates a particle with magnetic charge, Maxwell's Equations become symmetric. There is one problem with a magnetic particle, it would have only a single north or south pole in isolation. Every physical magnet has a north *and* south pole. If a magnet is broken in half, it only produces two magnets, each possessing both a north and south pole. This postulated magnetic particle, with a single magnetic pole, is known as a *magnetic monopole*.

The non-symmetry of Maxwell's equations may violate our aesthetic sense, but was of little scientific consequence until 1931. That year, Paul A. M. Dirac (1902–1984) published a paper which showed if *any* magnetic monopoles exist, anywhere in the universe, even a single one, then all electric charge in the universe must be quantized. In other words, the charge on an electron or proton must have exact discreet values, which matches all scientific observations and current theory. The existence of a magnetic monopole then became of great interest to the scientific community, and they have searched for it ever since.

The remarkable property of a magnetic monopole is its incredibly large mass. Science writer Isaac Asimov called it a "subatomic monster." [9] The largest possible mass expected for a magnetic monopole is about 180 nanograms. A proton has a mass of 1.67 yoctograms, which is five metric worlds smaller! In other words, the mass of a magnetic monopole is predicted to be over 1 000 000 000 000 000 times more massive than a proton. The predicted mass of a magnetic monopole is on the order of a fine dust particle or possibly as low as a fog droplet. It is definitely outside expected values for the subatomic realm.

References

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