

7.2: Magnets, Electromagnets and Magnetic Matter

Learning Objectives

By the end of this section, you will be able to:

- Describe the difference between the north and south poles of a magnet.
- Describe how magnetic poles interact with each other.
- Define ferromagnet.
- Describe the role of magnetic domains in magnetization.
- Explain the significance of the Curie temperature.
- Describe the relationship between electricity and magnetism.

Magnets

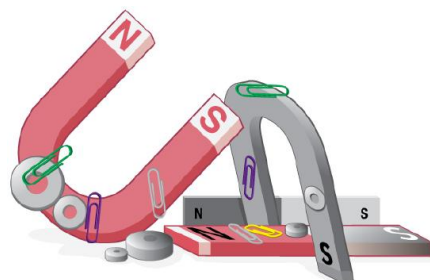


Figure 7.2.1: Magnets come in various shapes, sizes, and strengths. All have both a north pole and a south pole. There is never an isolated pole (a monopole).

All magnets attract iron, such as that in a refrigerator door. However, magnets may attract or repel other magnets. Experimentation shows that all magnets have two poles. If freely suspended, one pole will point toward the north. The two poles are thus named the north magnetic pole and the south magnetic pole (or more properly, north-seeking and south-seeking poles, for the attractions in those directions).

UNIVERSAL CHARACTERISTICS OF MAGNETS AND MAGNET POLES

It is a universal characteristic of all magnets that *like poles repel and unlike poles attract*. (Note the similarity with electrostatics: unlike charges attract and like charges repel.)

Further experimentation shows that it is *impossible to separate north and south poles* in the manner that $+$ and $-$ charges can be separated.

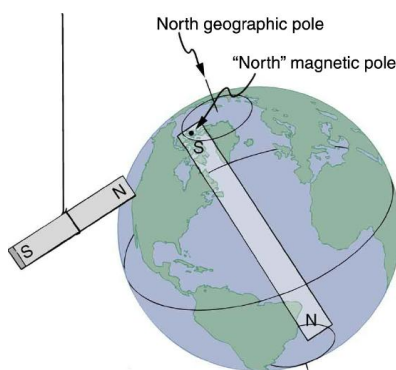


Figure 7.2.2: One end of a bar magnet is suspended from a thread that points toward north. The magnet's two poles are labeled N and S for north-seeking and south-seeking poles, respectively.

MISCONCEPTION ALERT: EARTH'S GEOGRAPHIC NORTH POLE HIDES AN S

The Earth acts like a very large bar magnet with its south-seeking pole near the geographic North Pole. That is why the north pole of your compass is attracted toward the geographic north pole of the Earth—because the magnetic pole that is near the geographic North Pole is actually a south magnetic pole! Confusion arises because the geographic term “North Pole” has come to be used (incorrectly) for the magnetic pole that is near the North Pole. Thus, “North magnetic pole” is actually a misnomer—it should be called the South magnetic pole.

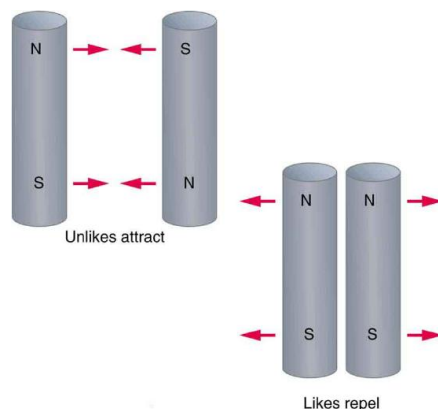


Figure 7.2.3: Unlike poles attract, whereas like poles repel.

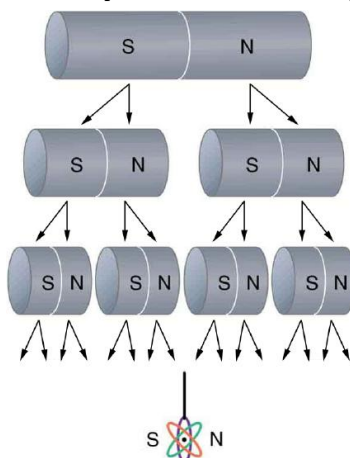


Figure 7.2.4: North and south poles always occur in pairs. Attempts to separate them result in more pairs of poles. If we continue to split the magnet, we will eventually get down to an iron atom with a north pole and a south pole—these, too, cannot be separated.

The fact that magnetic poles always occur in pairs of north and south is true from the very large scale—for example, sunspots always occur in pairs that are north and south magnetic poles—all the way down to the very small scale. Magnetic atoms have both a north pole and a south pole, as do many types of subatomic particles, such as electrons, protons, and neutrons.

MAKING CONNECTIONS: TAKE-HOME EXPERIMENT -- REFRIGERATOR MAGNETS

We know that like magnetic poles repel and unlike poles attract. See if you can show this for two refrigerator magnets. Will the magnets stick if you turn them over? Why do they stick to the door anyway? What can you say about the magnetic properties of the door next to the magnet? Do refrigerator magnets stick to metal or plastic spoons? Do they stick to all types of metal?

Ferromagnets

Only certain materials, such as iron, cobalt, nickel, and gadolinium, exhibit strong magnetic effects. Such materials are called ferromagnetic, after the Latin word for iron, *ferrum*. A group of materials made from the alloys of the rare earth elements are also used as strong and permanent magnets; a popular one is neodymium. Other materials exhibit weak magnetic effects, which are detectable only with sensitive instruments. Not only do ferromagnetic materials respond strongly to magnets (the way iron is attracted to magnets), they can also be magnetized themselves—that is, they can be induced to be magnetic or made into permanent magnets.

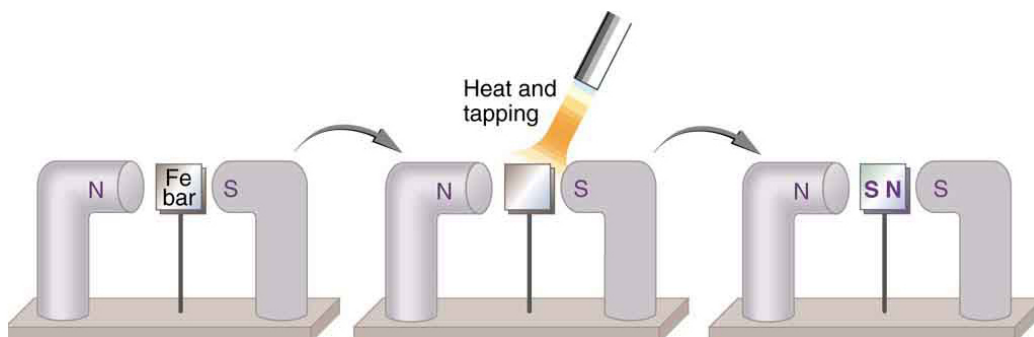


Figure 7.2.1: An unmagnetized piece of iron is placed between two magnets, heated, and then cooled, or simply tapped when cold. The iron becomes a permanent magnet with the poles aligned as shown: its south pole is adjacent to the north pole of the original magnet, and its north pole is adjacent to the south pole of the original magnet. Note that there are attractive forces between the magnets.

When a magnet is brought near a previously unmagnetized ferromagnetic material, it causes local magnetization of the material with unlike poles closest, as in Figure 7.2.1. (This results in the attraction of the previously unmagnetized material to the magnet.) What happens on a microscopic scale is illustrated in Figure 7.2.2. The regions within the material called domains act like small bar magnets. Within domains, the poles of individual atoms are aligned. Each atom acts like a tiny bar magnet. Domains are small and randomly oriented in an unmagnetized ferromagnetic object. In response to an external magnetic field, the domains may grow to millimeter size, aligning themselves as shown in Figure 2b. This induced magnetization can be made permanent if the material is heated and then cooled, or simply tapped in the presence of other magnets.

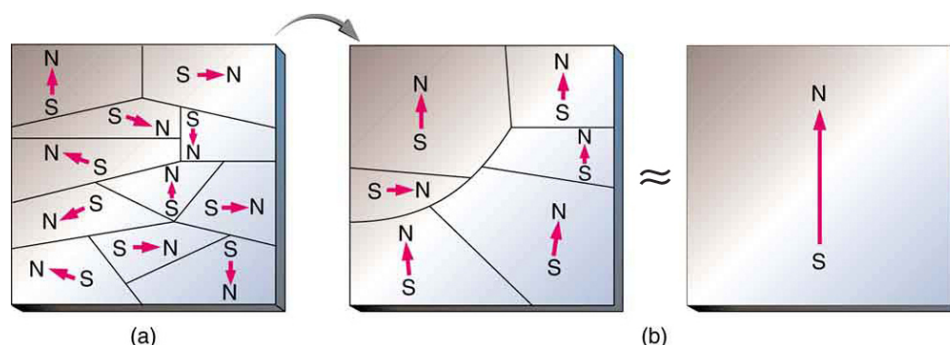


Figure 7.2.2: (a) An unmagnetized piece of iron (or other ferromagnetic material) has randomly oriented domains. (b) When magnetized by an external field, the domains show greater alignment, and some grow at the expense of others. Individual atoms are aligned within domains; each atom acts like a tiny bar magnet.

Conversely, a permanent magnet can be demagnetized by hard blows or by heating it in the absence of another magnet. Increased thermal motion at higher temperature can disrupt and randomize the orientation and the size of the domains. There is a well-defined temperature for ferromagnetic materials, which is called the Curie temperature, above which they cannot be magnetized. The Curie temperature for iron is 1043 K (770°C), which is well above room temperature. There are several elements and alloys that have Curie temperatures much lower than room temperature and are ferromagnetic only below those temperatures.

Electromagnets

Early in the 19th century, it was discovered that electrical currents cause magnetic effects. The first significant observation was by the Danish scientist Hans Christian Oersted (1777–1851), who found that a compass needle was deflected by a current-carrying wire. This was the first significant evidence that the movement of charges had any connection with magnets. Electromagnetism is the use of electric current to make magnets. These temporarily induced magnets are called electromagnets. Electromagnets are employed for everything from a wrecking yard crane that lifts scrapped cars to controlling the beam of a 90-km-circumference particle accelerator to the magnets in medical imaging machines (Figure 7.2.3).



Figure 7.2.3: Instrument for magnetic resonance imaging (MRI). The device uses a superconducting cylindrical coil for the main magnetic field. The patient goes into this “tunnel” on the gurney. (credit: Bill McChesney, Flickr)

Figure 7.2.4 shows that the response of iron filings to a current-carrying coil and to a permanent bar magnet. The patterns are similar. In fact, electromagnets and ferromagnets have the same basic characteristics—for example, they have north and south poles that cannot be separated and for which like poles repel and unlike poles attract.

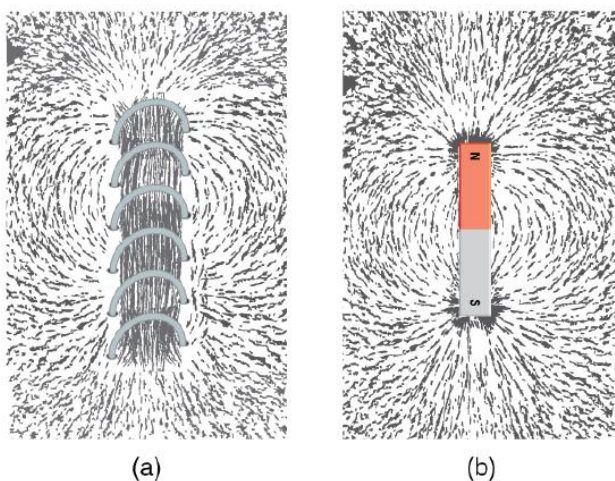


Figure 7.2.4: Iron filings near (a) a current-carrying coil and (b) a magnet act like tiny compass needles, showing the shape of their fields. Their response to a current-carrying coil and a permanent magnet is seen to be very similar, especially near the ends of the coil and the magnet.

Combining a ferromagnet with an electromagnet can produce particularly strong magnetic effects (Figure 7.2.5). Whenever strong magnetic effects are needed, such as lifting scrap metal, or in particle accelerators, electromagnets are enhanced by ferromagnetic materials. Limits to how strong the magnets can be made are imposed by coil resistance (it will overheat and melt at sufficiently high current), and so superconducting magnets may be employed. These are still limited, because superconducting properties are destroyed by too great a magnetic field.

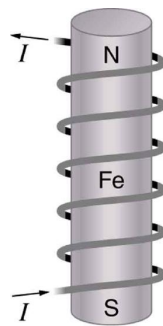


Figure 7.2.5: An electromagnet with a ferromagnetic core can produce very strong magnetic effects. Alignment of domains in the core produces a magnet, the poles of which are aligned with the electromagnet.

Figure 7.2.6 shows a few uses of combinations of electromagnets and ferromagnets. Ferromagnetic materials can act as memory devices, because the orientation of the magnetic fields of small domains can be reversed or erased. Magnetic information storage on videotapes and computer hard drives are among the most common applications. This property is vital in our digital world.

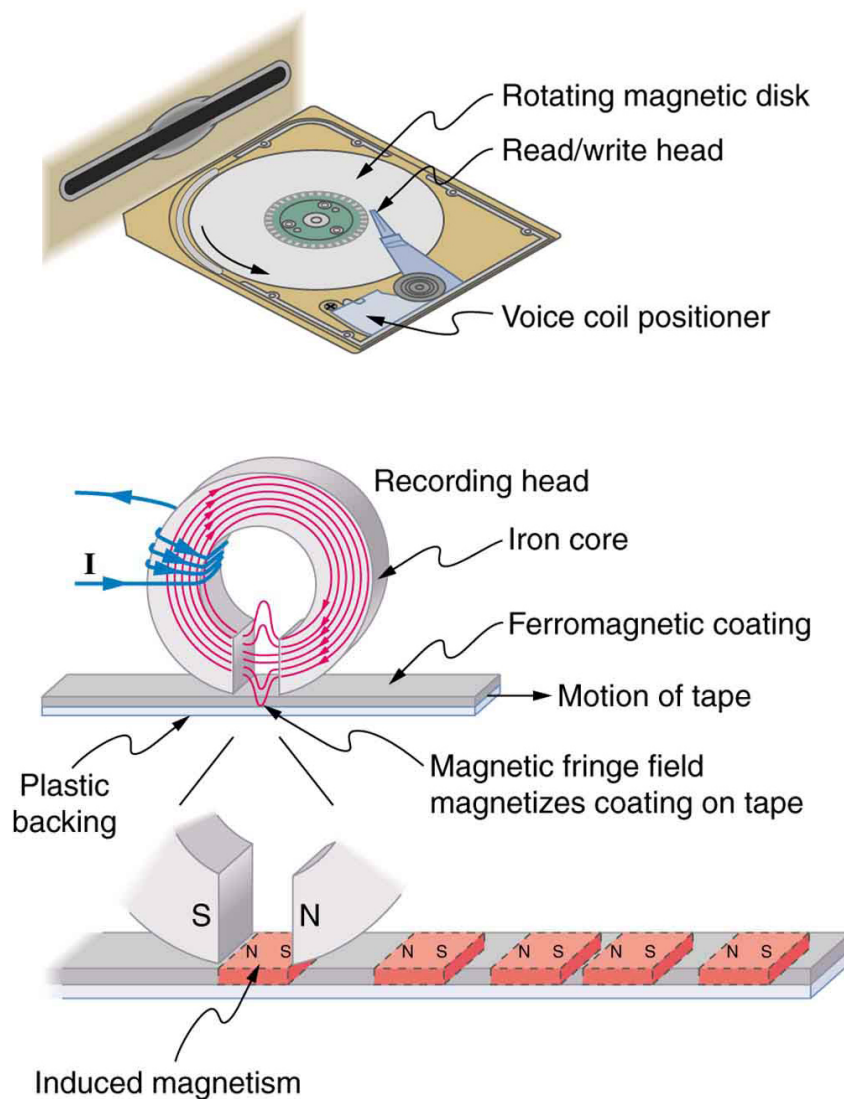


Figure 7.2.6: An electromagnet induces regions of permanent magnetism on a floppy disk coated with a ferromagnetic material. The information stored here is digital (a region is either magnetic or not); in other applications, it can be analog (with a varying strength), such as on audiotapes.

Current: The Source of All Magnetism

An electromagnet creates magnetism with an electric current. In later sections we explore this more quantitatively, finding the strength and direction of magnetic fields created by various currents. But what about ferromagnets? Figure 7.2.7 shows models of how electric currents create magnetism at the submicroscopic level. (Note that we cannot directly observe the paths of individual electrons about atoms, and so a model or visual image, consistent with all direct observations, is made. We can directly observe the electron's orbital angular momentum, its spin momentum, and subsequent magnetic moments, all of which are explained with electric-current-creating subatomic magnetism.) Currents, including those associated with other submicroscopic particles like protons, allow us to explain ferromagnetism and all other magnetic effects. Ferromagnetism, for example, results from an internal cooperative alignment of electron spins, possible in some materials but not in others.

Crucial to the statement that electric current is the source of all magnetism is the fact that it is impossible to separate north and south magnetic poles. (This is far different from the case of positive and negative charges, which are easily separated.) A current loop always produces a magnetic dipole—that is, a magnetic field that acts like a north pole and south pole pair. Since isolated north and south magnetic poles, called magnetic monopoles, are not observed, currents are used to explain all magnetic effects. If magnetic monopoles did exist, then we would have to modify this underlying connection that all magnetism is due to electrical current. There is no known reason that magnetic monopoles should not exist—they are simply never observed—and so searches at the subnuclear level continue. If they do *not* exist, we would like to find out why not. If they *do* exist, we would like to see evidence of them.

ELECTRIC CURRENTS AND MAGNETISM

Electric current is the source of all magnetism.

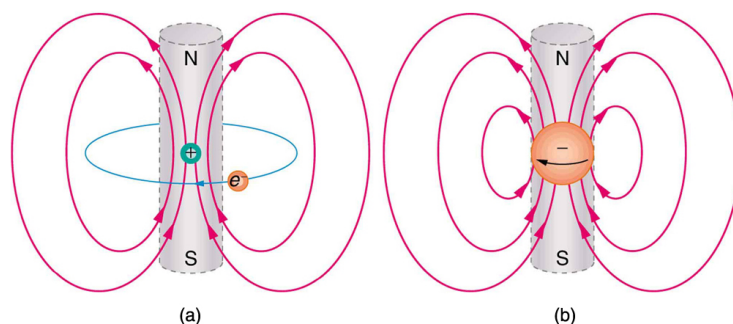


Figure 7.2.7: (a) In the planetary model of the atom, an electron orbits a nucleus, forming a closed-current loop and producing a magnetic field with a north pole and a south pole. (b) Electrons have spin and can be crudely pictured as rotating charge, forming a current that produces a magnetic field with a north pole and a south pole. Neither the planetary model nor the image of a spinning electron is completely consistent with modern physics. However, they do provide a useful way of understanding phenomena.

PHET EXPLORATIONS: MAGNETS AND ELECTROMAGNETS

Explore the interactions between a [compass and bar magnet](#). Discover how you can use a battery and wire to make a magnet! Can you make it a stronger magnet? Can you make the magnetic field reverse?

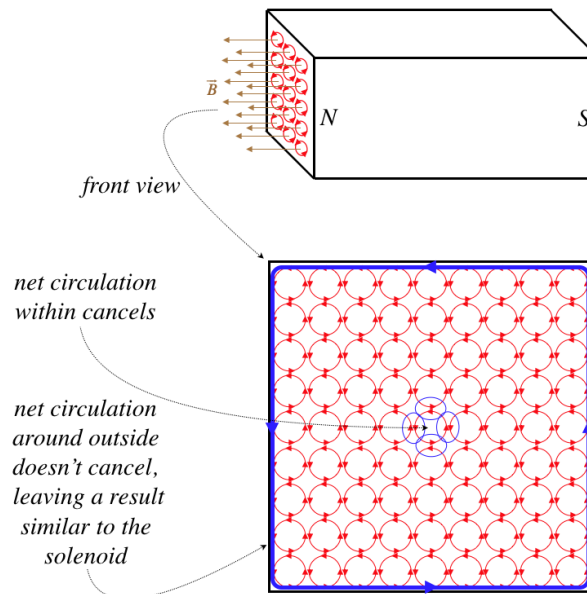
Magnetic Materials

At last we can discuss elements of magnetism that we have been aware of since we were young kids – the properties and behavior of bar magnets. As with any phenomenon that requires an understanding of what is going on at a microscopic level, magnetism inside of materials like bar magnets is very complicated. We'll look at a greatly-simplified version of it here, but keep in mind that a fuller understanding can only be achieved through quantum theory.

We now know that there are no “magnetic particles” comprising a bar magnet – its magnetic field can only be created by moving charges. But unlike an electromagnet, bar magnets are not plugged into some emf source, so where does the moving charge come from? The atoms that comprise the material of course include lots of charges, and these charges are moving in manners that resemble magnetic dipoles – electrons are orbiting nuclei in more-or-less circular loops, and electrons also have a quantum-mechanical property called “spin” that gives them their own magnetic moments as well.

We will not concern ourselves too much with the specific source of the magnetic moments of these particles, but we will instead just focus on the fact that each particle has its own magnetic moment. In the case of a bar magnet, these dipoles tend to be permanently aligned. This property is called **ferromagnetism**. Only a few materials have this property: iron (thus “ferro”), nickel, cobalt, many of their alloys, and some of the rare earth metals. [Technically, these alignments occur in chunks, called “domains,” within the magnet, and the degree to which the magnet is magnetized is determined by how much certain domains “swallow-up” others, creating more broadly-coordinated alignments of dipoles.]

Figure 4.4.7 – Dipoles in a Bar Magnet



It should be clear how two bar magnets attract each other. One is a magnetic field source, and the other is a magnetic dipole that experiences the non-uniform field of the other. The field diverges as it emerges from one magnet, and the dipole of the other magnet, if the poles are aligned, reacts by feeling a force in the direction where the field gets stronger, following the mechanism depicted in [Figure 4.2.6](#).

But this doesn't explain why a magnet sticks to a refrigerator when the refrigerator metal is not itself magnetized. The answer is that some metals, while their particle dipole moments are not permanently aligned, have the property that their particles are free to rotate their magnetic moments. When an external field is applied, their particles then align, making them magnetized. When the field is removed, the random alignments return. This property is known as **paramagnetism**.

A few general comments to close this subject:

- Ferromagnetism relies primarily upon the spin source of magnetic moment, and very little on the orbital source, while paramagnetism relies upon both.
- Ferromagnetic materials remain magnetized after a strong applied magnetic field aligns the domains, which remain aligned thanks to anomalies in the crystal structure which “snag” the domains and hold them in an aligned orientation.
- Ferromagnets can be demagnetized (“degaussed”) by relieving these snags. This is most easily done by raising the temperature to a critical temperature known as the **Curie temperature**, at which magnetic domain “snags” are no longer possible and the substance has zero ferromagnetism. Other methods for degaussing include applying rapidly-changing magnetic fields (which “shake” the domains into random orientations) and pounding on the magnet so that vibrations cause the domains to un-snap.

Summary

- Magnetic poles always occur in pairs of north and south—it is not possible to isolate north and south poles.
- All magnetism is created by electric current.
- Ferromagnetic materials, such as iron, are those that exhibit strong magnetic effects.
- The atoms in ferromagnetic materials act like small magnets (due to currents within the atoms) and can be aligned, usually in millimeter-sized regions called domains.

- Domains can grow and align on a larger scale, producing permanent magnets. Such a material is magnetized, or induced to be magnetic.
- Above a material's Curie temperature, thermal agitation destroys the alignment of atoms, and ferromagnetism disappears.
- Electromagnets employ electric currents to make magnetic fields, often aided by induced fields in ferromagnetic materials.

Glossary

ferromagnetic

materials, such as iron, cobalt, nickel, and gadolinium, that exhibit strong magnetic effects

magnetized

to be turned into a magnet; to be induced to be magnetic

domains

regions within a material that behave like small bar magnets

Curie temperature

the temperature above which a ferromagnetic material cannot be magnetized

electromagnetism

the use of electrical currents to induce magnetism

electromagnet

an object that is temporarily magnetic when an electrical current is passed through it

magnetic monopoles

an isolated magnetic pole; a south pole without a north pole, or vice versa (no magnetic monopole has ever been observed)

Summary

- Magnetism is a subject that includes the properties of magnets, the effect of the magnetic force on moving charges and currents, and the creation of magnetic fields by currents.
- There are two types of magnetic poles, called the north magnetic pole and south magnetic pole.
- North magnetic poles are those that are attracted toward the Earth's geographic north pole.
- Like poles repel and unlike poles attract.
- Magnetic poles always occur in pairs of north and south—it is not possible to isolate north and south poles.

Glossary

north magnetic pole

the end or the side of a magnet that is attracted toward Earth's geographic north pole

south magnetic pole

the end or the side of a magnet that is attracted toward Earth's geographic south pole

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