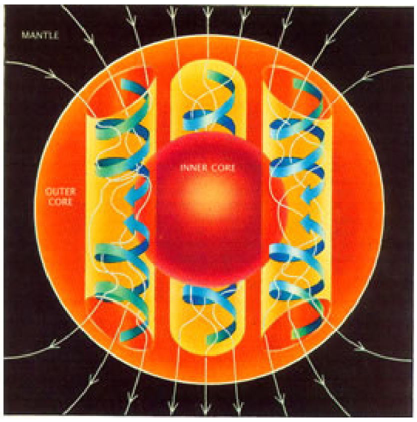
Physical origin

Earth's core and the geodynamo

The Earth's magnetic field is mostly caused by electric currents in the liquid outer core, which is composed of highly conductive molten iron. A magnetic field is generated by a feedback loop: current loops generate magnetic fields (Ampère's circuital law); a changing magnetic field generates an electric field (Faraday's law); and the electric and magnetic fields exert a force on the charges that are flowing in currents (the Lorentz force). These effects can be combined in a partial differential equation for the magnetic field called the *magnetic induction equation*:

$$\frac{\partial \mathbf{B}}{\partial t} = \eta\nabla^2\mathbf{B} + \nabla\times(\mathbf{u}\times\mathbf{B})$$

where **u** is the velocity of the fluid, **B** is the magnetic B-field; and $\eta=1/\sigma\mu$ is the magnetic diffusivity with σ electrical conductivity and μ permeability.[] The term $\partial\mathbf{B}/\partial t$ is the time derivative of the field; ∇^2 is the Laplace operator and $\nabla\times$ is the curl operator.



A schematic illustrating the relationship between motion of conducting fluid, organized into rolls by the Coriolis force, and the magnetic field the motion generates.

The first term on the right hand side of the induction equation is a diffusion term. In a stationary fluid, the magnetic field declines and any concentrations of field spread out. If the Earth's dynamo shut off, the dipole part would disappear in a few tens of thousands of years.[]

In a perfect conductor ($\sigma=\infty$), there would be no diffusion. By Lenz's law, any change in the magnetic field would be immediately opposed by currents, so the flux through a given volume of fluid could not change. As the fluid moved, the magnetic field would go with it. The theorem describing this effect is called the *frozen-in-field theorem*. Even in a fluid with a finite conductivity, new field is generated by stretching field lines as the fluid moves in ways that deform it. This process could go on generating new field indefinitely, were it not that as the magnetic field increases in strength, it resists fluid motion.[]

The motion of the fluid is sustained by convection, motion driven by buoyancy. The temperature increases towards the center of the Earth, and the higher temperature of the fluid lower down makes it buoyant. This buoyancy is enhanced by chemical separation: As the core cools, some of the molten iron solidifies and is plated to the inner core. In the process, lighter elements are left behind in the fluid, making it lighter. This is called *compositional convection*. A Coriolis effect, caused by the overall planetary rotation, tends to organize the flow into rolls aligned along the north-south polar axis.[][21]

The mere convective motion of an electrically conductive fluid is not enough to insure the generation of a magnetic field. The above model assumes the motion of charges (such as electrons with respect to atomic nuclei), which is a requirement for generating a magnetic field. However, it is not clear how this motion of charges arises in the circulating fluid of the outer core. Possible mechanisms may include electrochemical reactions which create the equivalent of a battery generating electrical current in the fluid or, a thermoelectric effect[22] (both mechanisms somehow discredited). More robustly, remnant magnetic fields in magnetic materials in the mantle, which are cooler than their Curie temperature, would provide seed “stator” magnetic fields that would induce the required growing currents in the convectively driven fluid behaving as a dynamo, as analyzed by Dr. Philip William Livermore.[23]

The average magnetic field in the Earth's outer core was calculated to be 25 G, 50 times stronger than the field at the surface.[24]