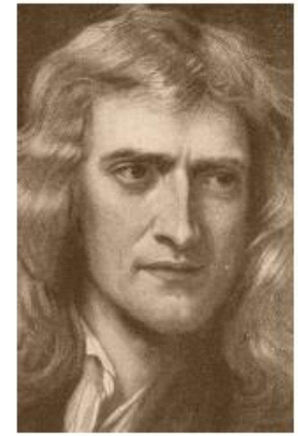
现代物理学概论

1．电、磁、光的统一

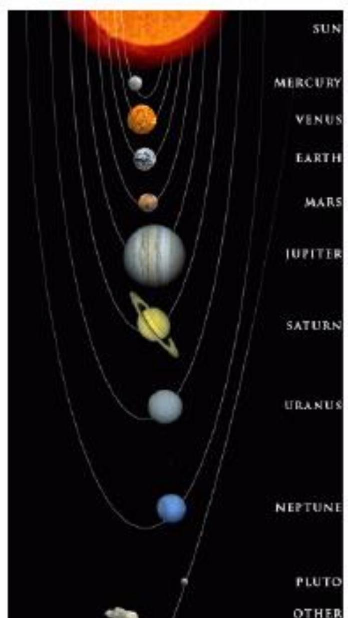
2．黑体辐射、光电效应

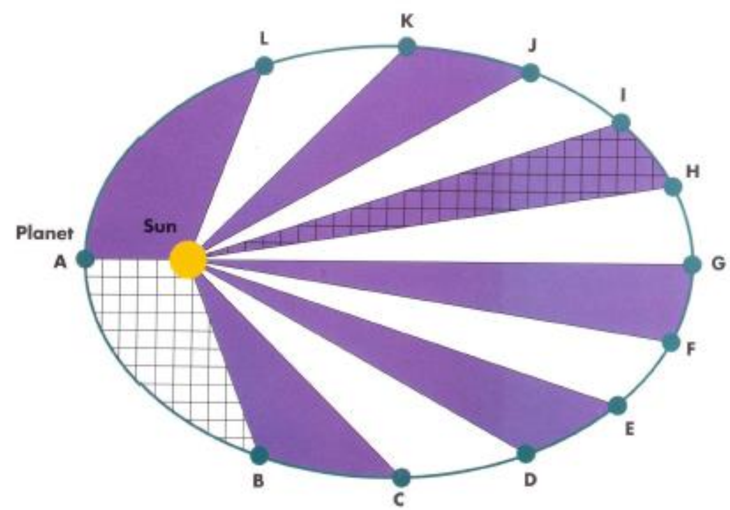
Mechanical revolution



Newton (1687)

- **Unified** falling apples on earth and the planets motions in sky
- **New world view:** All matter are formed by collections of "particles", and their motion is described by the Newton's equation $F = ma$.
- **New math: Calculus**





Isaac Newton

That one body may act upon another at a distance through a vacuum without the mediation of anything else, by and through which their action and force maybe conveyed from one to another, is to me **so great an absurdity (荒谬)** that, I believe, no man who has in philosophic matters a competent faculty of thinking could ever fall into it.

Albert Einstein

During the second half of the nineteenth century new and revolutionary ideas were introduced into physics; they opened the way to a new philosophical view, differing from the mechanical one. The results of the work of Faraday, Maxwell, and Hertz led to the development of modern physics, to the creation of new concepts, forming a new picture of reality.

Albert Einstein

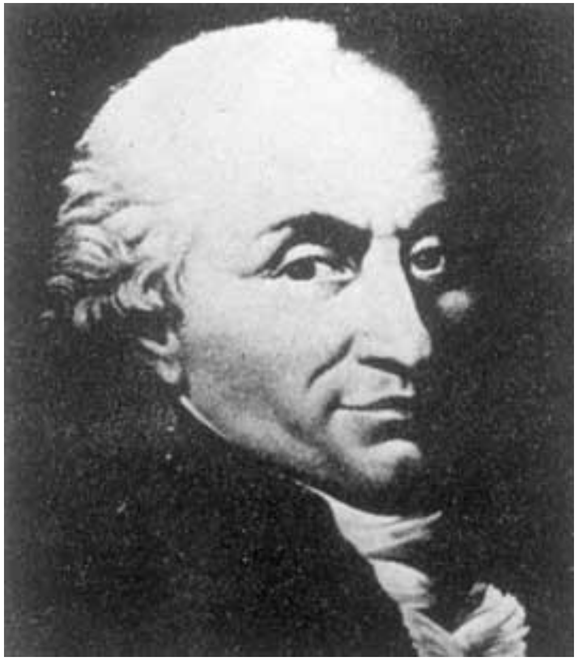
A new reality was created, a new concept for which there was no place in the mechanical description. Slowly and by a struggle the field concept established for itself a leading place in physics and has remained one of the basic physical concepts. The electromagnetic field is, for modern physicist, as real as the chair on which he sit.

Coulomb's law

$$\mathbf{F}_{21} = k\frac{q_1 q_2}{r_{12}^2}\mathbf{r}_{12}^0 = -\mathbf{F}_{12}$$

$$k = \frac{1}{4\pi\varepsilon_0} \approx 9\times10^9\ \frac{\mathrm{N\cdot m^2}}{\mathrm{C^2}}$$

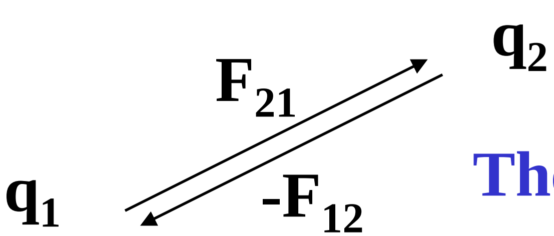
$$\boxed{\varepsilon_0 \approx 8.85\times10^{-12}\ \frac{\mathrm{C^2}}{\mathrm{N\cdot m^2}}}$$



Charles Augustin de Coulomb(1736–1806)

电场

$$\vec{E}_1 = \vec{F}_{21}/q_2$$

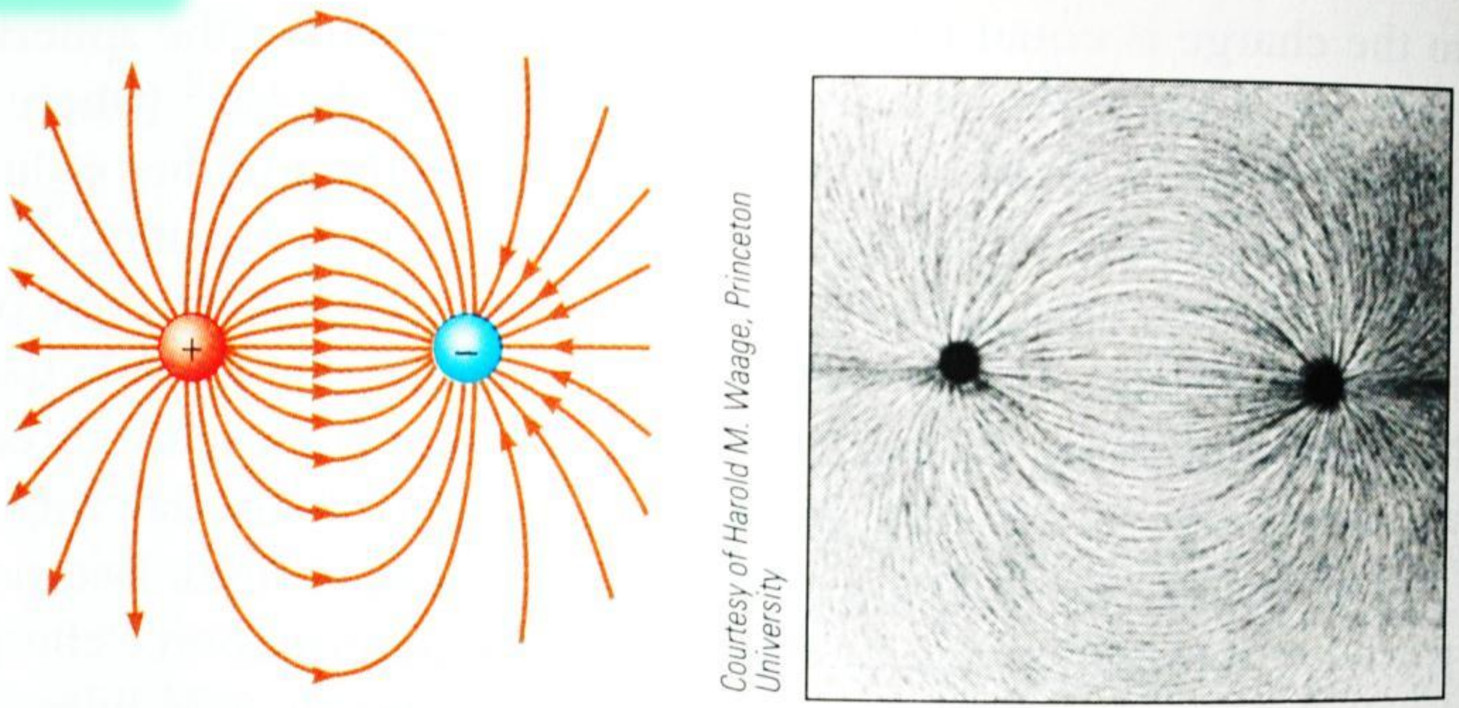


The force by q_1 on q_2

James Clerk Maxwell (1864)

Faraday, in his mind's eye, saw lines of force traversing all space where the mathematicians saw centers of force attracting at a distance; Faraday saw a medium where they saw nothing but distance; Faraday sought the seat of the phenomena in real actions going on in the medium, they were satisfied they had found it in a power of action at a distance.

电现象



(a) (b)

Figure 23.22 (a) The electric field lines for two point charges of equal magnitude and opposite sign (an electric dipole). The number of lines leaving the positive charge equals the number terminating at the negative charge. (b) The dark lines are small pieces of thread suspended in oil, which align with the electric field of a dipole.

丝线

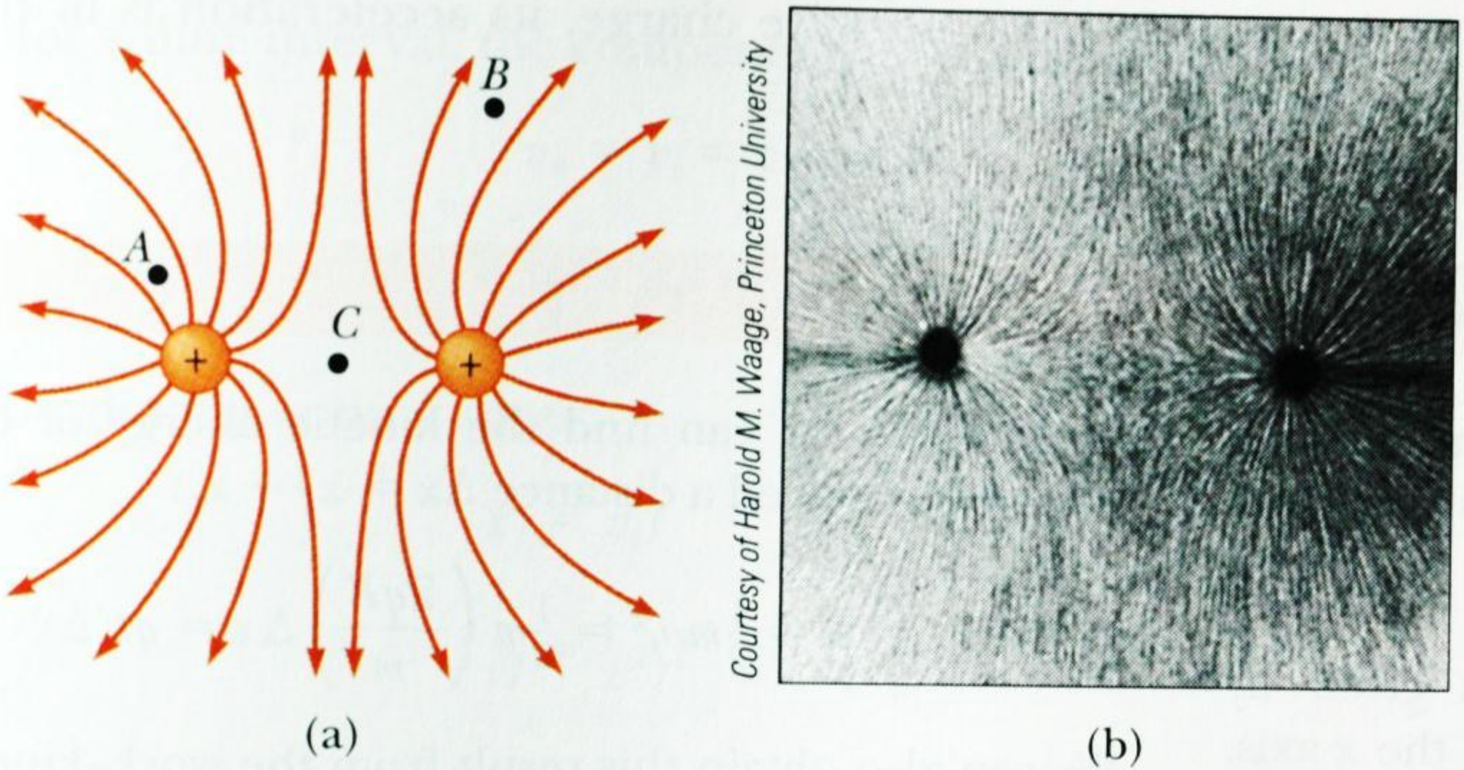
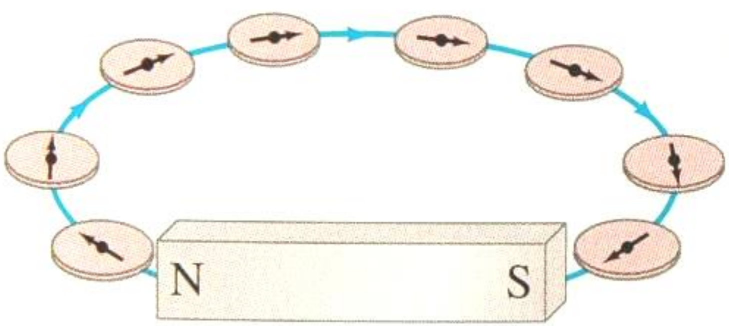


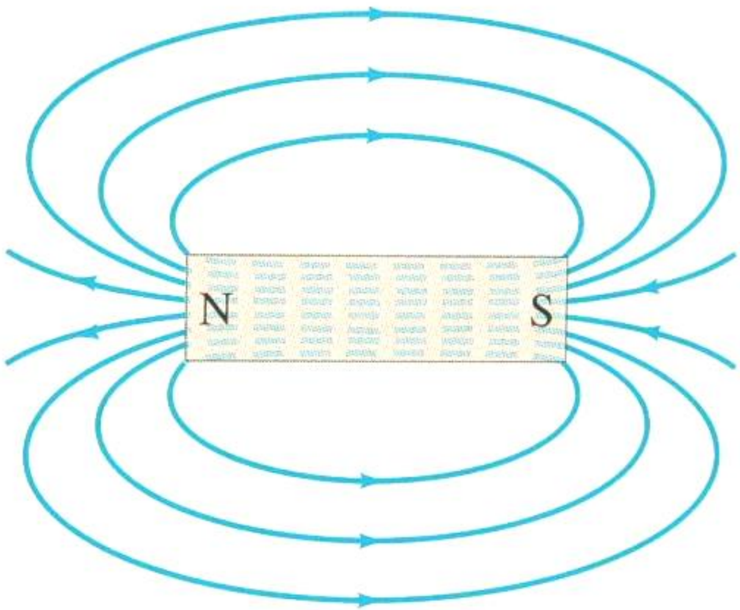
Figure 23.23 (a) The electric field lines for two positive point charges. (The locations A, B, and C are discussed in Quick Quiz 23.7.) (b) Pieces of thread suspended in oil, which align with the electric field created by two equal-magnitude positive charges.

磁现象

FIGURE 27–3 (a) Plotting a magnetic field line of a bar magnet. (b) Magnetic field lines for a bar magnet.

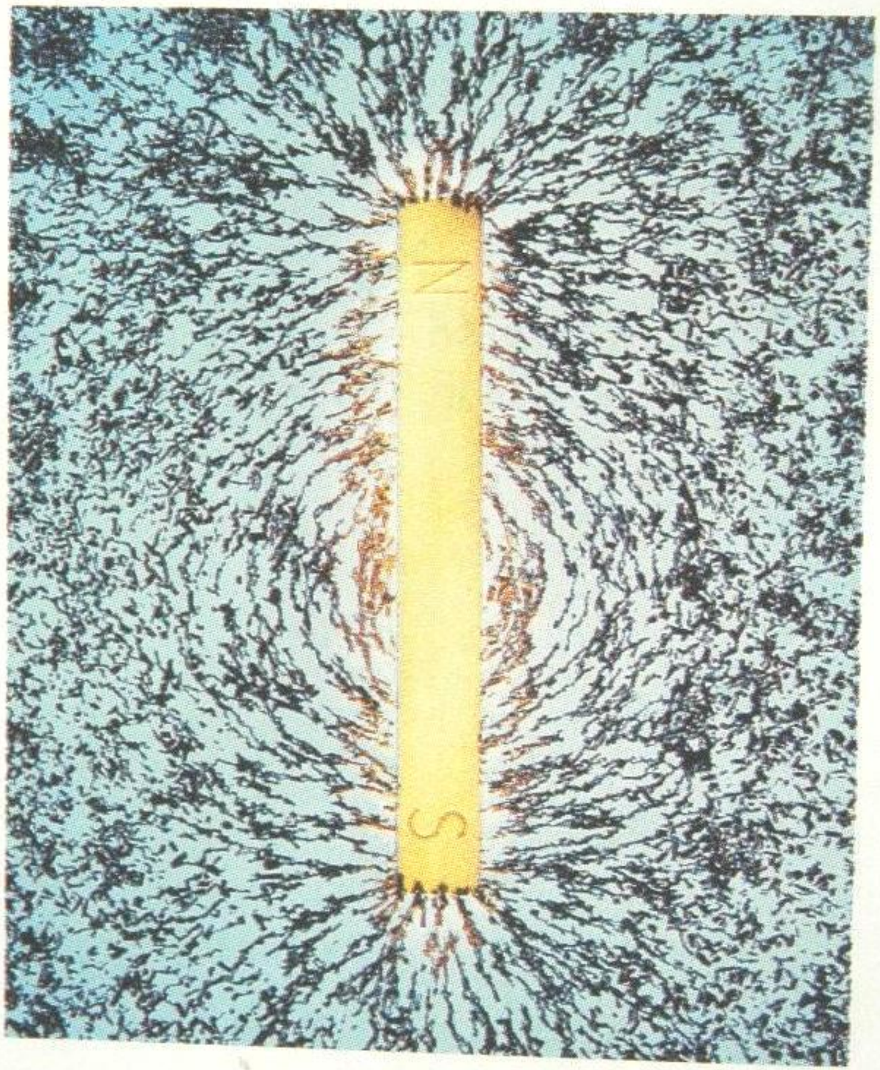


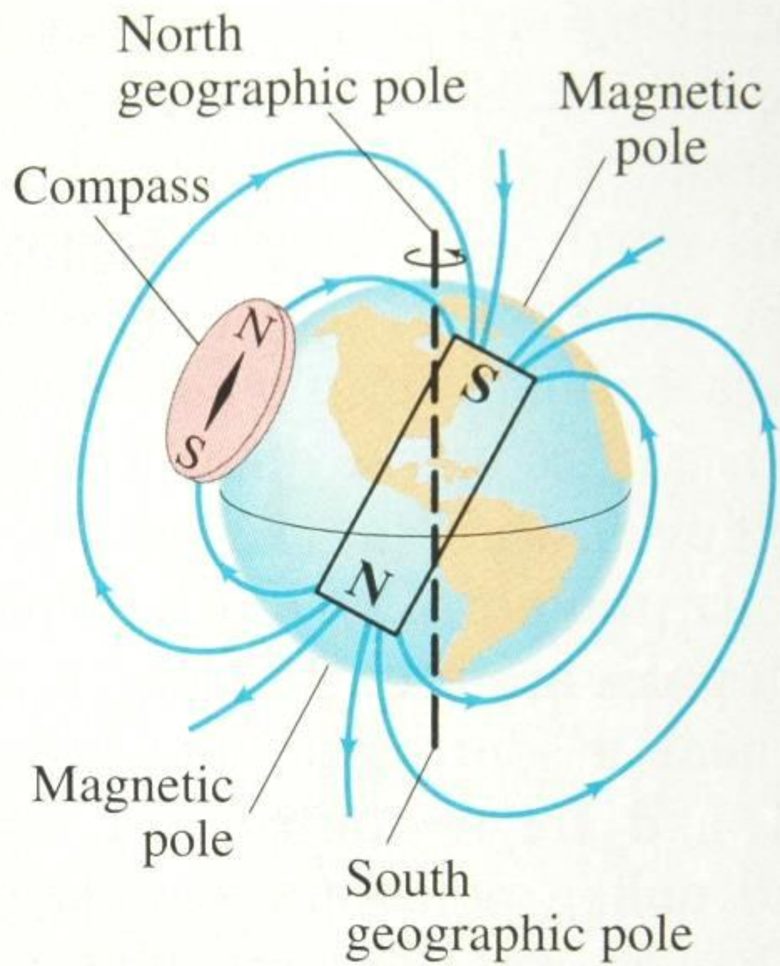
(a)



(b)

FIGURE 27–4 Thin iron filings 铁屑 indicate the magnetic field lines around a bar magnet.





电磁现象

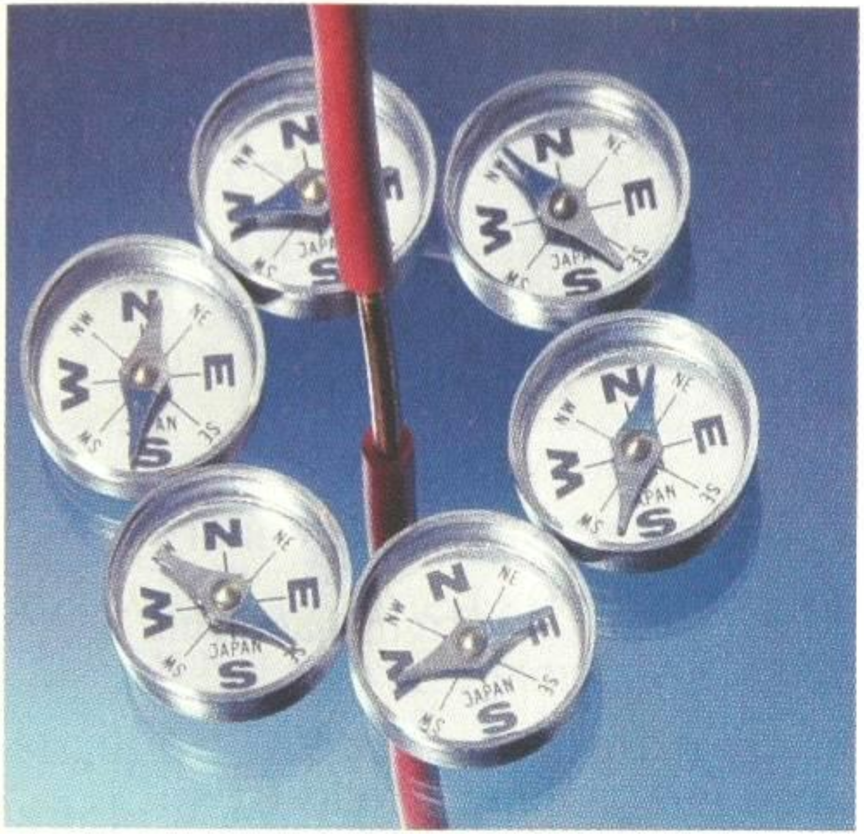


FIGURE 27–8 Deflection of compass needles near a current-carrying wire, showing the presence and direction of the magnetic field.

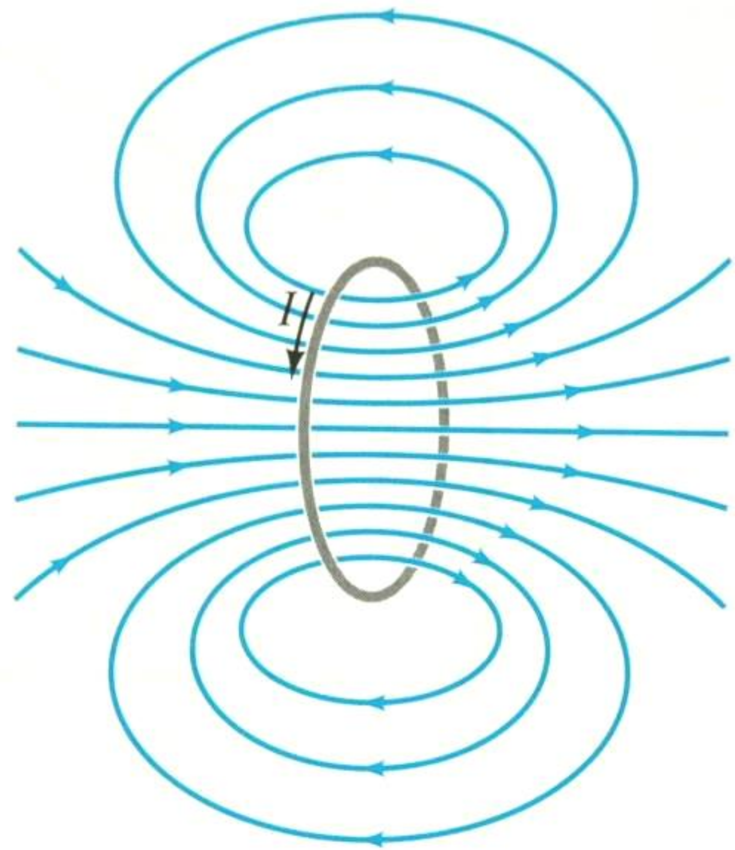


FIGURE 27–10 Magnetic field lines due to a circular loop of wire.

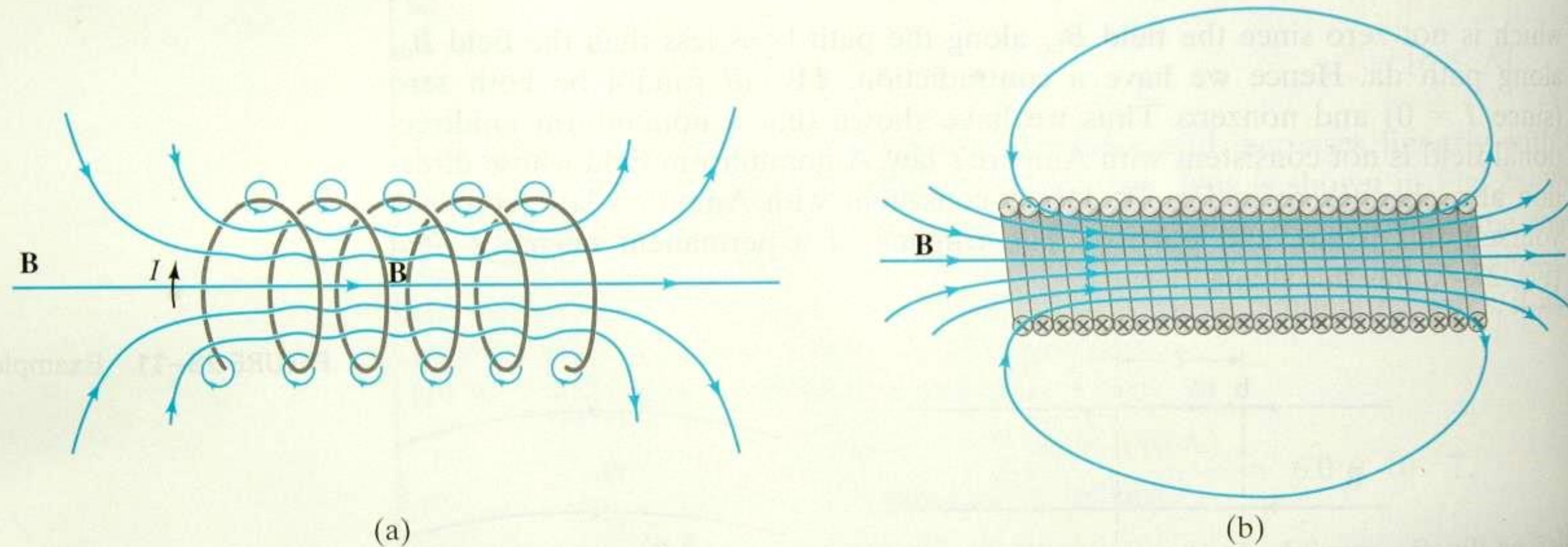
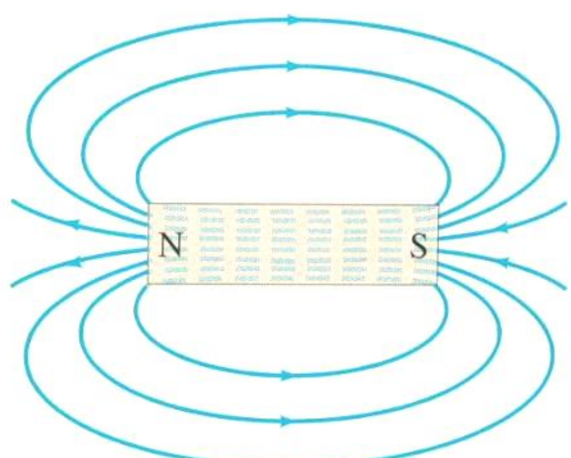
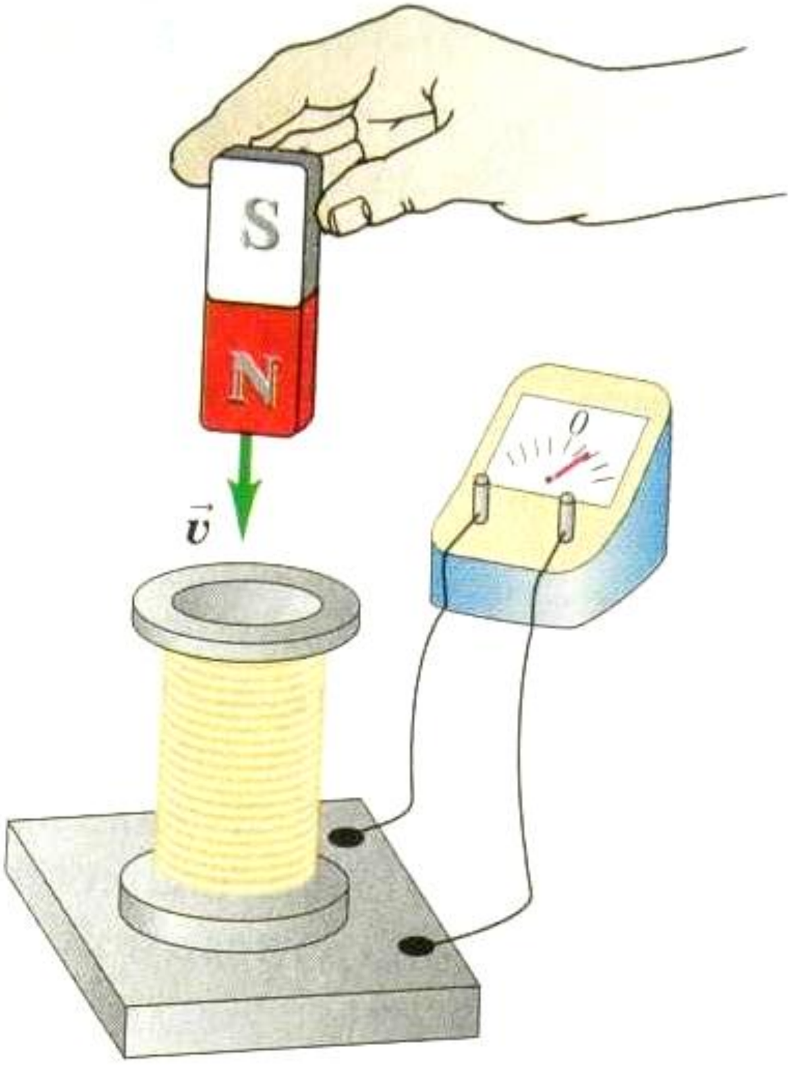


FIGURE 28–12 Magnetic field due to a solenoid: (a) loosely spaced turns, (b) closely spaced turns.



磁感应现象

1831 Fraday



(a)

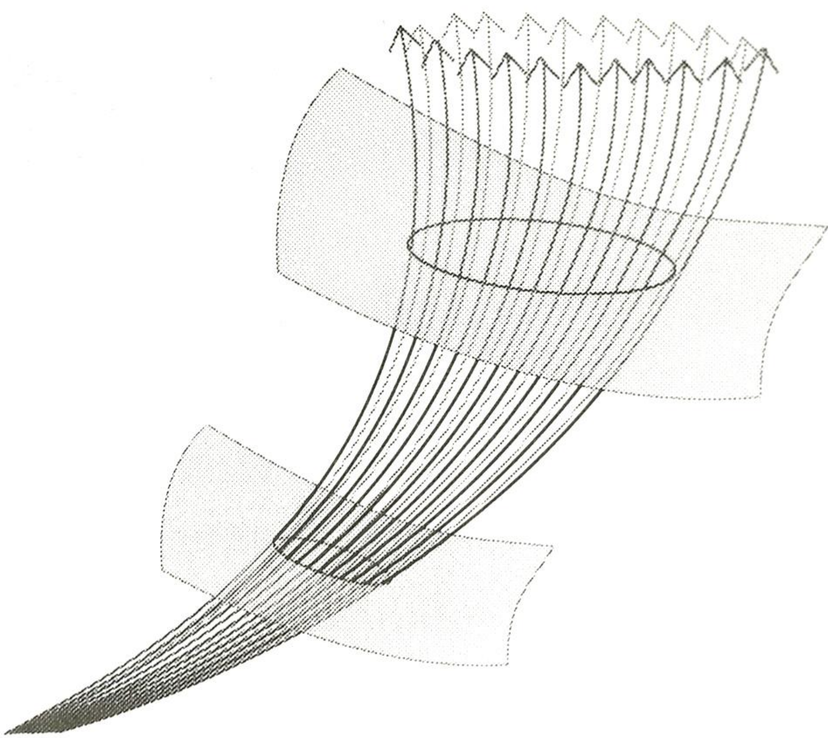
Electromagnetic revolution

Maxwell (1861)

- **Unified** electricity, magnetism, and light
- **New world view:** There is a new form of matter – "wave-like" matter, which causes electromagnetic interaction between the "particle-like" matter. The motion of "wave-like" matter is described by the Maxwell equation $\dot{\boldsymbol{E}} - c\partial \times \boldsymbol{B} = \dot{\boldsymbol{B}} + c\partial \times \boldsymbol{E} = 0.$
- **New math: Fiber bundle (gauge theory)**

The first compass

D ***B***



Maxwell

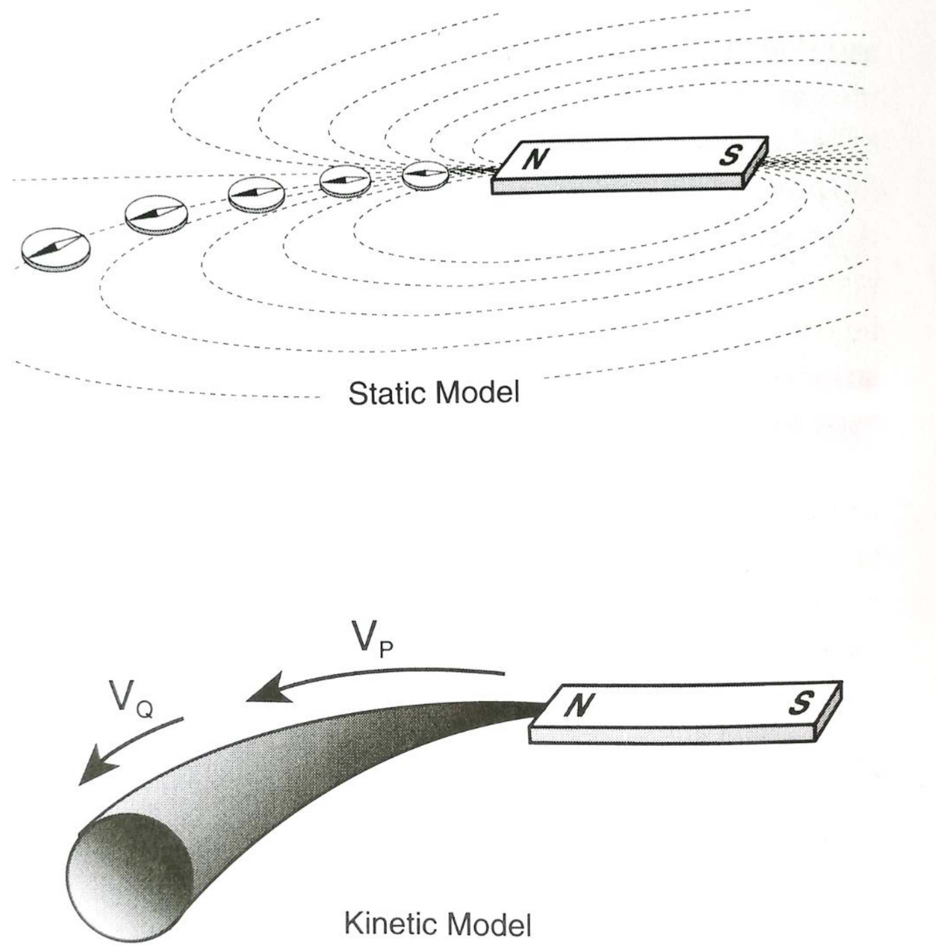
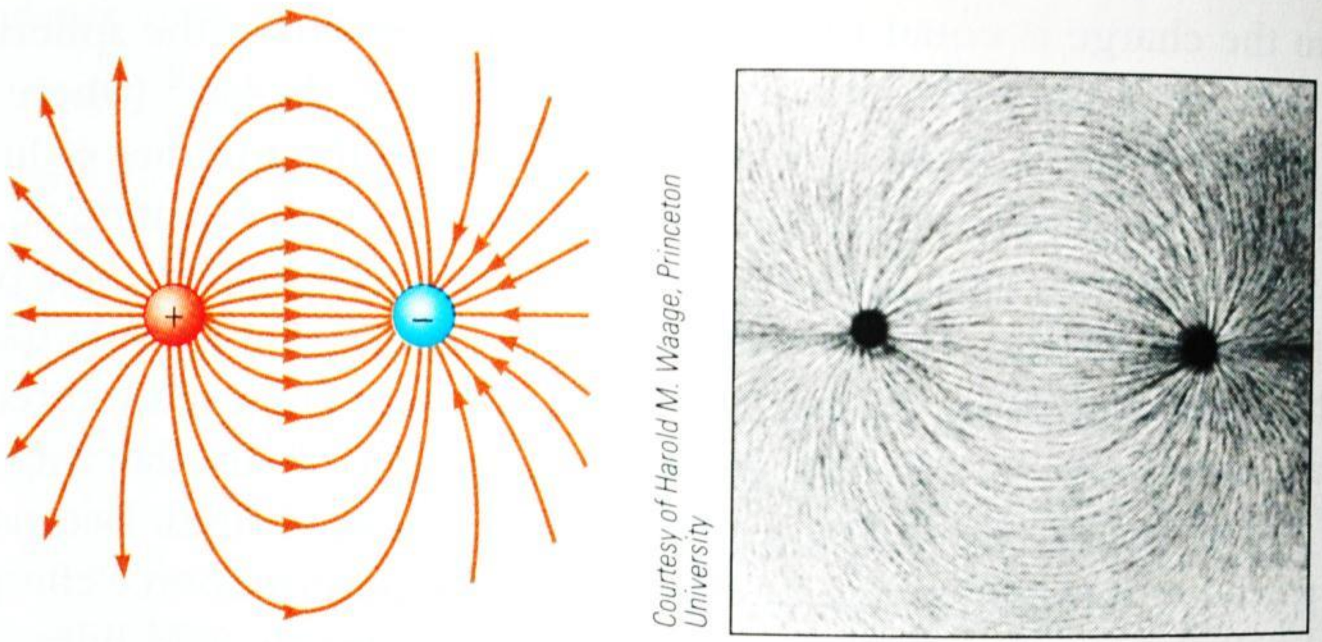


Fig. 2.3. Defining the lines of force (Static Model), and tubes of flow (Kinetic Model).

E ***H***

电场：有源场

$$\nabla \cdot D = \rho$$



(a) (b)

Figure 23.22 (a) The electric field lines for two point charges of equal magnitude and opposite sign (an electric dipole). The number of lines leaving the positive charge equals the number terminating at the negative charge. (b) The dark lines are small pieces of thread suspended in oil, which align with the electric field of a dipole.

电位移矢量：$\mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{P}$ 电极化强度：$\mathbf{P}$

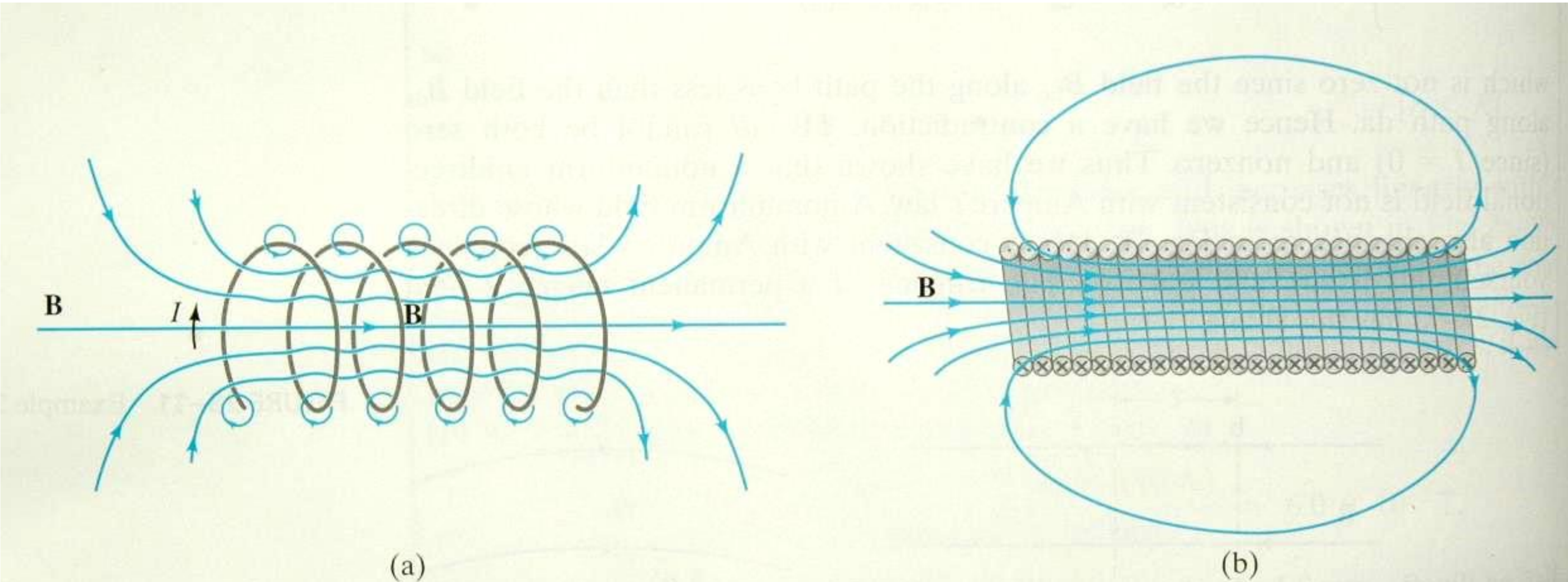
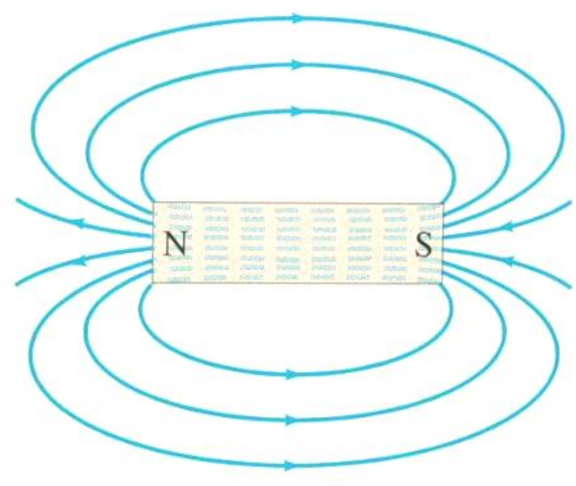


FIGURE 28–12 Magnetic field due to a solenoid: (a) loosely spaced turns, (b) closely spaced turns.

$$\nabla \cdot B = 0$$

磁场：无源场



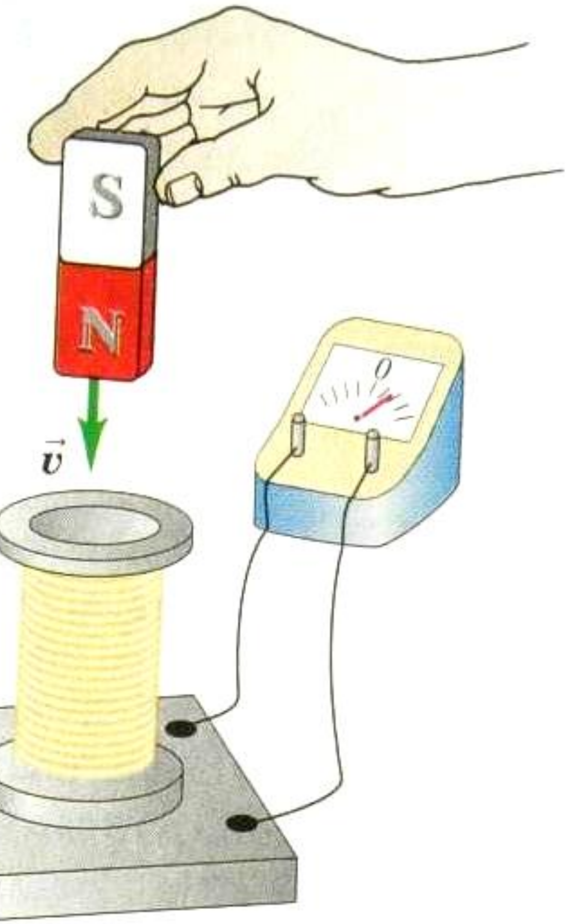
$$\boxed{\nabla \times H = \vec{j}}$$

磁场：有漩场

$$H = B/\mu_0 - M$$

1831 Fraday

$$\nabla \times E = -\frac{\partial \vec{B}}{\partial t}$$



(a)

37.1 The same emf is induced in the coil whether (a) the magnet moves relative to the coil or (b) the coil moves relative to the magnet.

电磁场方程组

- **Gauss' law**

$$\boxed{\nabla \cdot D = \rho}$$

- **Gauss' law for magnetic field**

$$\boxed{\nabla \cdot B = 0}$$

- **Faraday's law**

$$\boxed{\nabla \times E = -\frac{\partial \vec{\mathrm{B}}}{\partial \mathrm{t}}}$$

- **Ampere's law**

$$\boxed{\nabla \times H = \vec{\mathrm{j}}}$$

$$\boxed{\nabla \times H = \vec{\mathrm{j}}}$$

$$\nabla \times \boldsymbol{B} = \mu_0 j$$

$$\boxed{\mu_0 \approx 1.26 \times 10^{-6} \frac{\mathrm{T \cdot m}}{\mathrm{A}}}$$

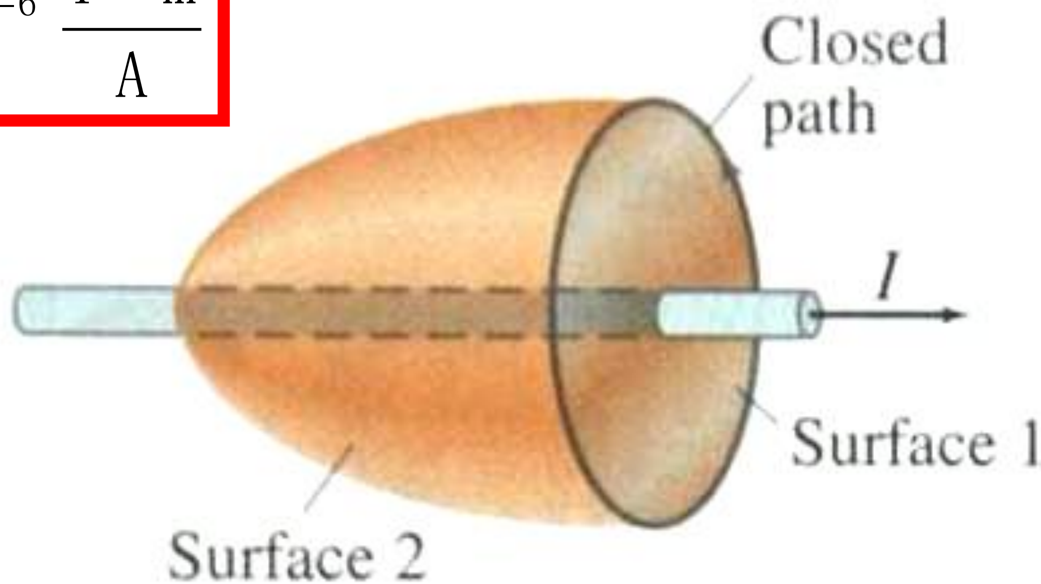
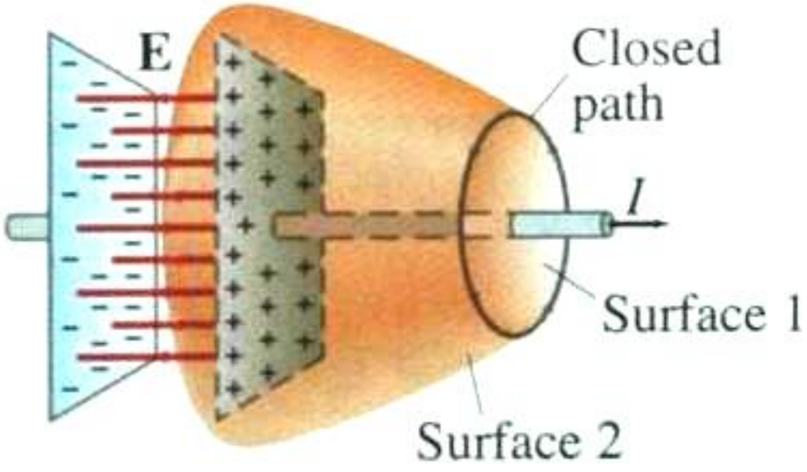


FIGURE 32–2 Ampère's law applied to two different surfaces bounded by the same closed path.

$$\nabla \times H = \frac{\partial \vec{\mathrm{D}}}{\partial \mathrm{t}}$$

位移电流

FIGURE 32–3 A capacitor discharging. No conduction current passes through surface 2. An extra term is needed in Ampère's law.



Maxwell's equations:

- **Gauss' law** $$\boxed{\nabla \cdot D = \rho}$$

- **Gauss' law for magnetic fields** $$\boxed{\nabla \cdot B = 0}$$

- **Faraday's law of induction** $$\boxed{\nabla \times E = -\frac{\partial \vec{\mathrm{B}}}{\partial \mathrm{t}}}$$

- **Ampere's circuital law** $$\boxed{\nabla \times H = \vec{\mathrm{j}} + \frac{\partial \vec{\mathrm{D}}}{\partial \mathrm{t}}}$$

Maxwell's equations in vacuum

- **Gauss' law**

$$\nabla \cdot E = 0$$

- **Gauss' law for magnetic fields**

$$\nabla \cdot B = 0$$

- **Faraday's law of induction**

$$\nabla \times E = -\frac{\partial \vec{\mathrm{B}}}{\partial \mathrm{t}}$$

- **Ampere's circuital law**

$$\nabla \times B = \mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial \mathrm{t}}$$

Maxwell's equations in vacuum

$$\nabla \cdot E = 0$$

$$\nabla \cdot B = 0$$

$$\nabla \times$$

$$\nabla \times E = -\frac{\partial \vec{B}}{\partial t}$$

$$\frac{\partial}{\partial t}$$

$$\nabla \times B = \mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t}$$

For free space, we have

$$\nabla^2 \boldsymbol{E} - \mu_0 \varepsilon_0 \frac{\partial^2}{\partial t^2} \boldsymbol{E} = 0$$

$$\nabla^2 \boldsymbol{B} - \mu_0 \varepsilon_0 \frac{\partial^2}{\partial t^2} \boldsymbol{B} = 0$$

$$\nabla^2 X - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} X = 0$$

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$$

James Clerk Maxwell (1864)

This velocity is so nearly that of light [when the comparison is made to more decimal places] that it seems we have strong reason to conclude that light itself (including radiant heat and other radiations, if any) is an electromagnetic disturbance in the form of waves propagated through the electromagnetic field according to electromagnetic laws.

Light is an electromagnetic wave

Heinrich Hertz (1888)

The experiments described appear to me, at any rate, eminently adapted to remove any doubt as to the identity of light, radiant heat, and electromagnetic wave motion. I believe that from now on we shall have greater confidence in making use of the advantages which this identity enable us to derive both in the study of optics and of electricity.

Light as an Electromagnetic Wave and the Electromagnetic Spectrum

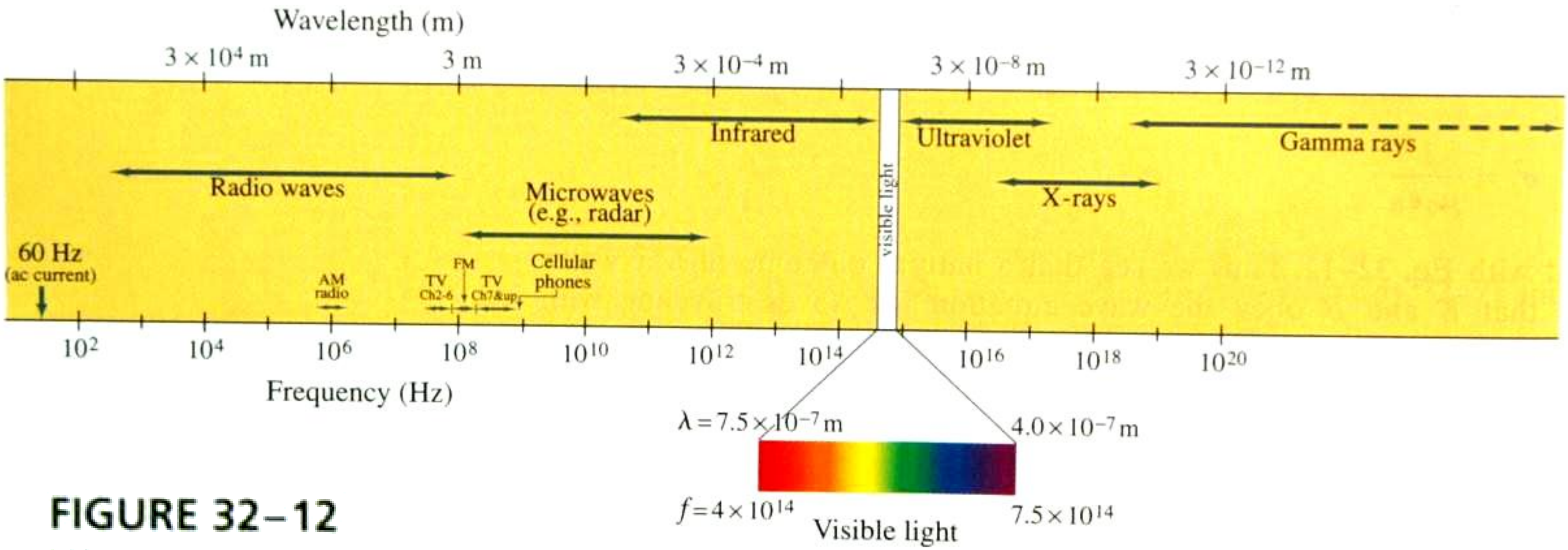


FIGURE 32–12
Electromagnetic spectrum.

Radio and Television

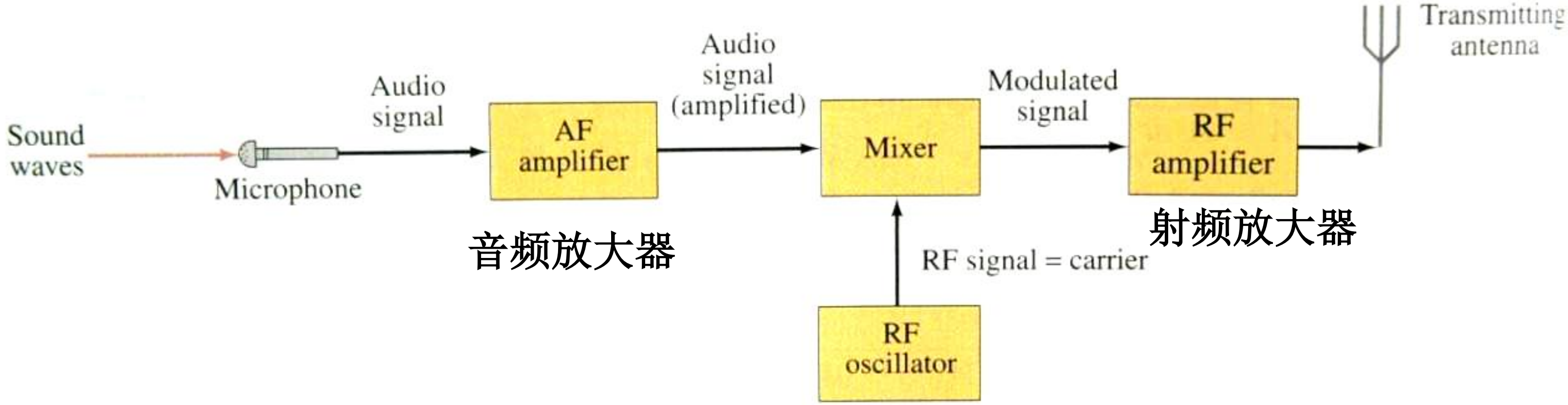


FIGURE 32–15 Block diagram of a radio transmitter.

FIGURE 32–16 In amplitude modulation (AM), the amplitude of the carrier signal is made to vary in proportion to the audio signal's amplitude.

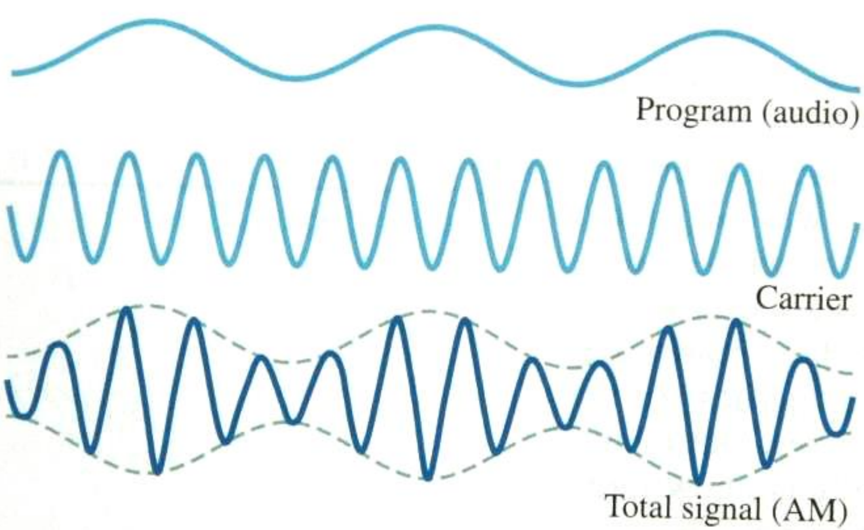
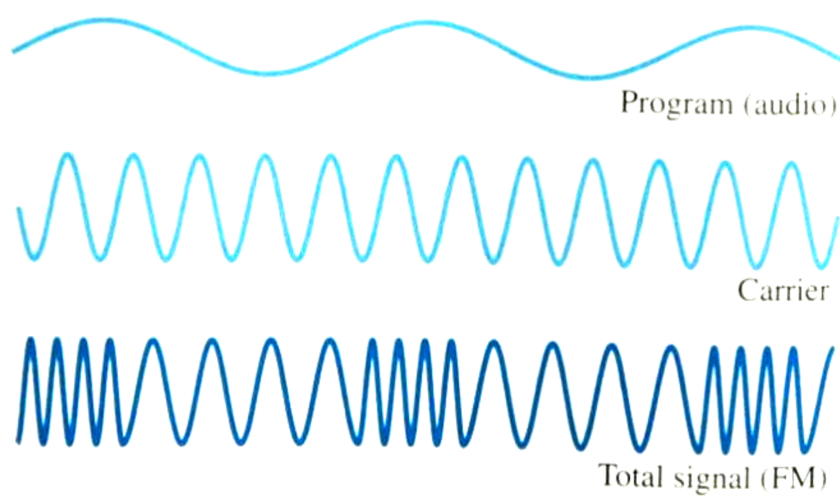


FIGURE 32–17 In frequency modulation (FM), the frequency of the carrier signal is made to change in proportion to the audio signal's amplitude. This method is used by FM radio and television.



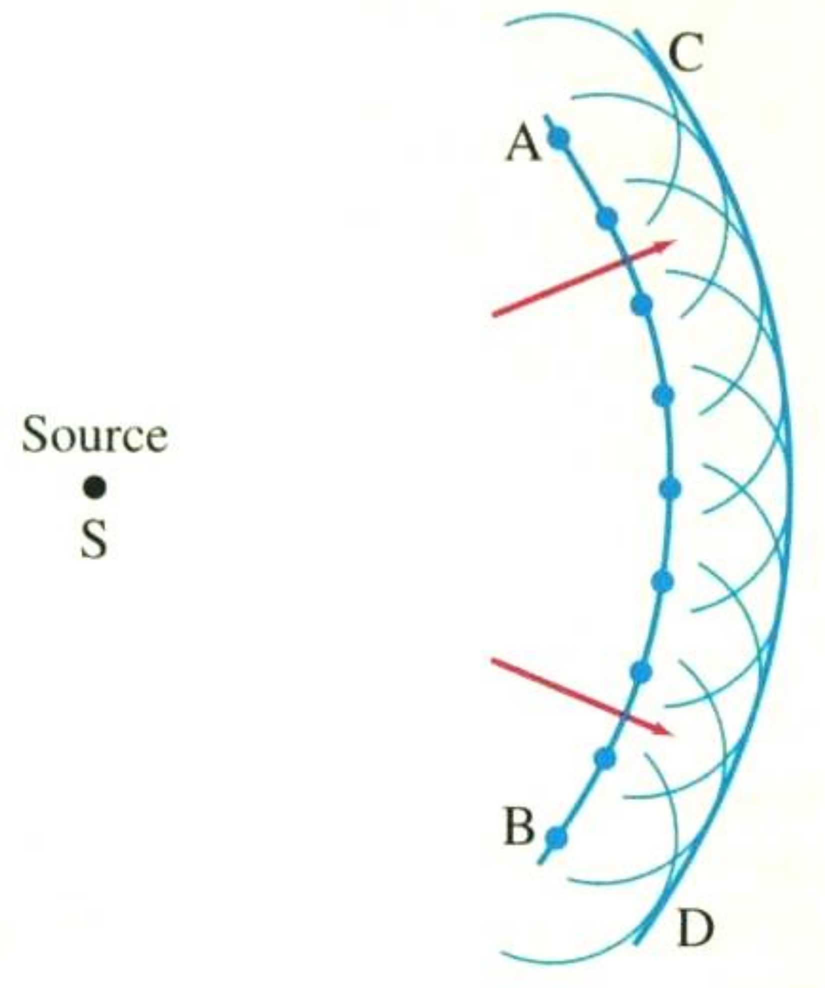
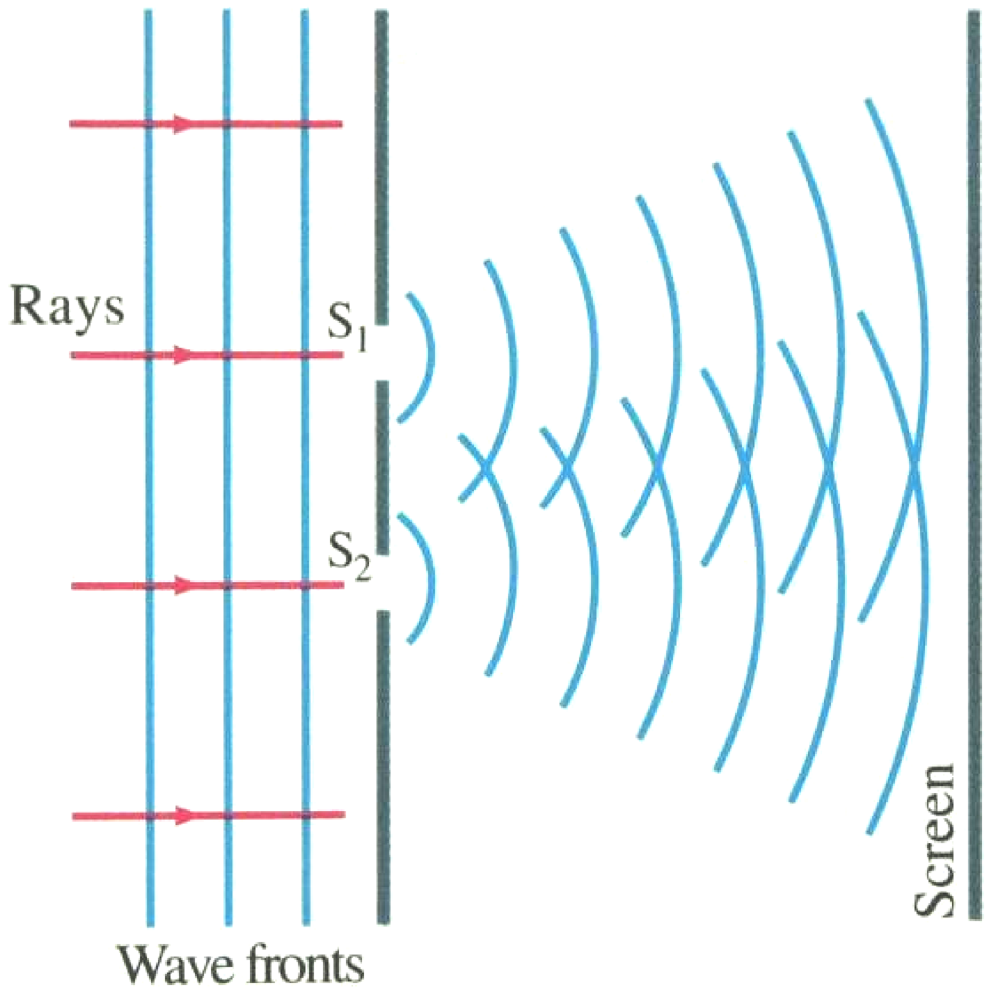


FIGURE 34–1 Huygens' principle, used to determine wave front CD when wave front AB is given.

FIGURE 34–6 If light is a wave, light passing through one of two slits should interfere with light passing through the other slit.



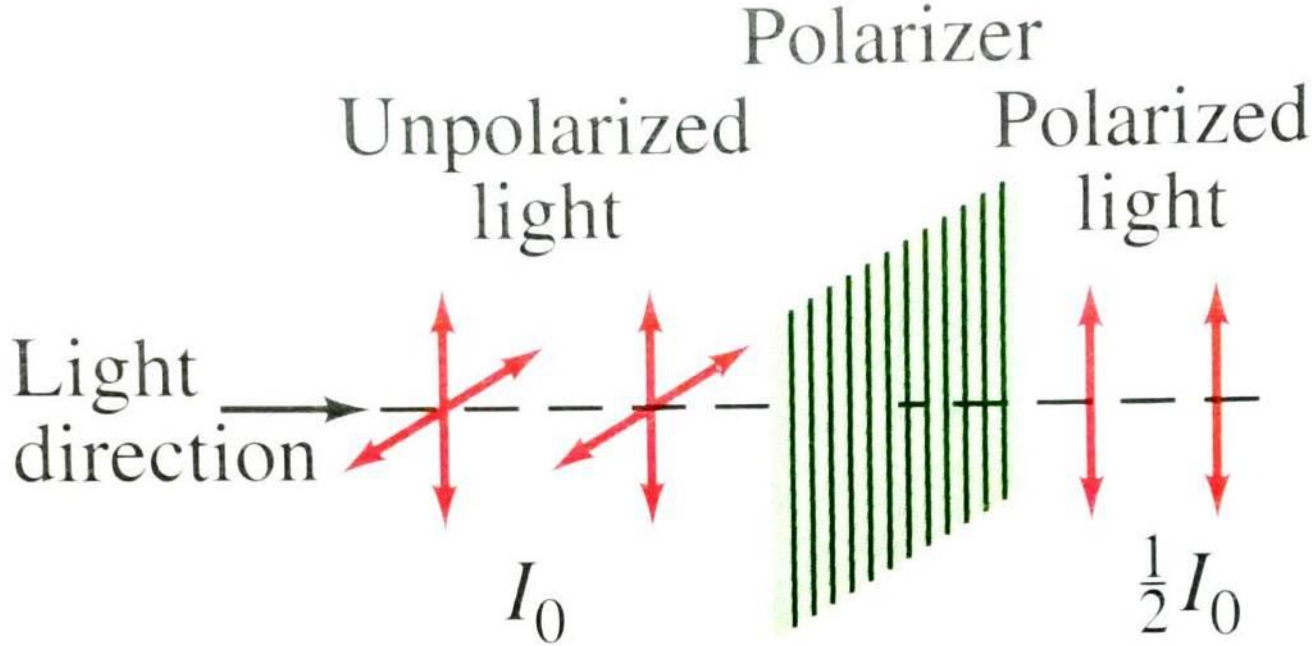


FIGURE 35–35 Unpolarized light has equal intensity vertical and horizontal components. After passing through a polarizer, one of these components is eliminated. The intensity of the light is reduced to half.

Electromagnetic revolution

Maxwell (1861)

- **Unified** electricity, magnetism, and light
- **New world view:** There is a new form of matter – "wave-like" matter, which causes electromagnetic interaction between the "particle-like" matter. The motion of "wave-like" matter is described by the Maxwell equation $\dot{\boldsymbol{E}} - c\partial \times \boldsymbol{B} = \dot{\boldsymbol{B}} + c\partial \times \boldsymbol{E} = 0$.
- **New math: Fiber bundle (gauge theory)**

The first compass

Albert Einstein

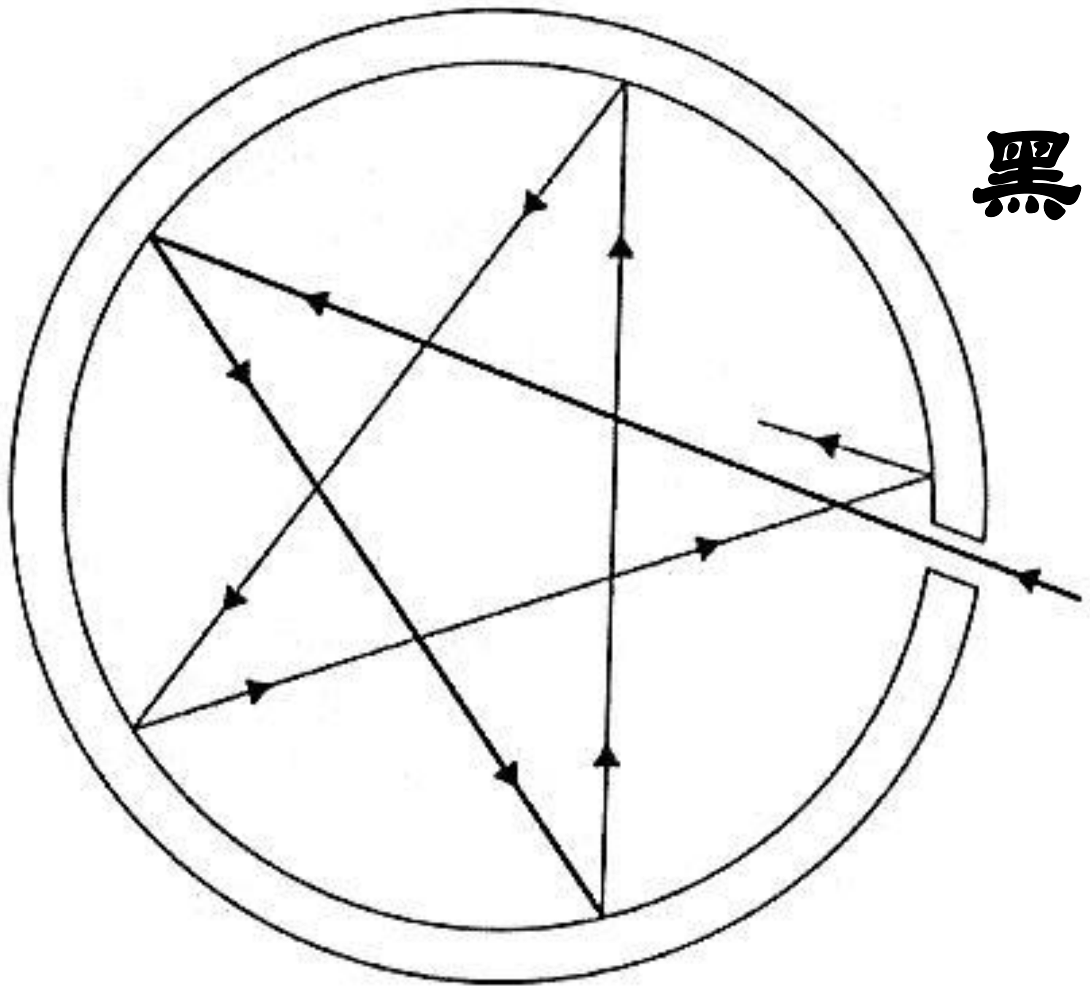
In the new field language it is the description of the field between the two charges, and not the charges themselves, which is essential for an understanding of their action. The recognition of the new concepts grew steadily, until substance was overshadowed by the field.

A. Einstein

"Since Maxwell's time, physical reality has been thought of as represented by continuous field… This change in the conception of reality is the most profound and the most fruitful that physics has experienced since the time of Newton."

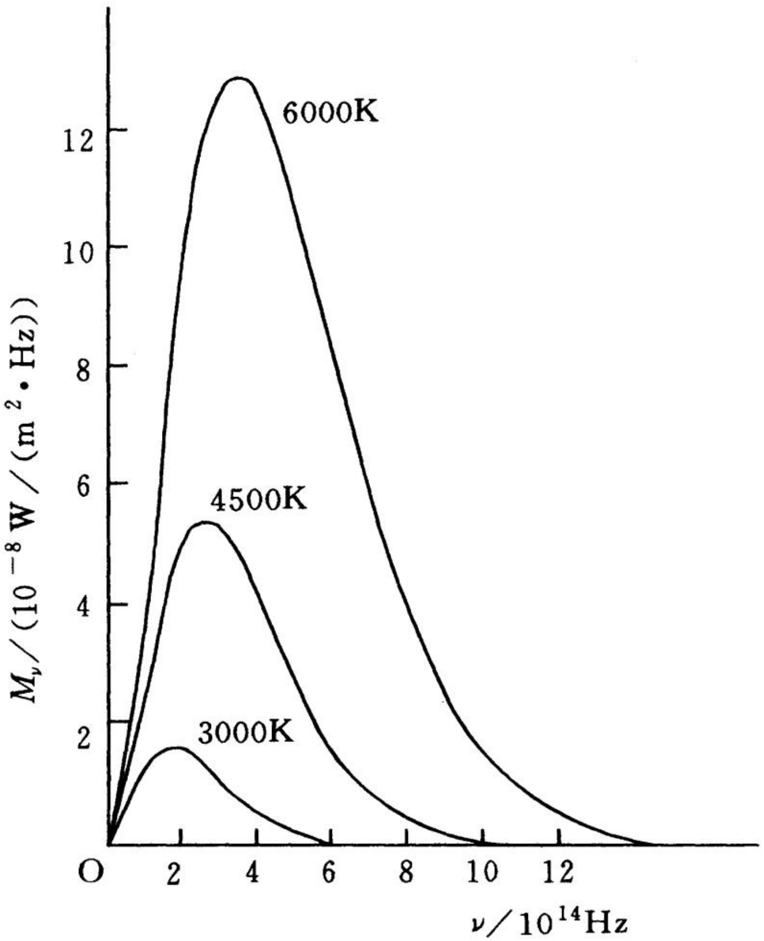
"Imagine his feelings when the differential equations he had formulated proved to him that electromagnetic fields spread in the form of polarized waves and with the speed of light!"

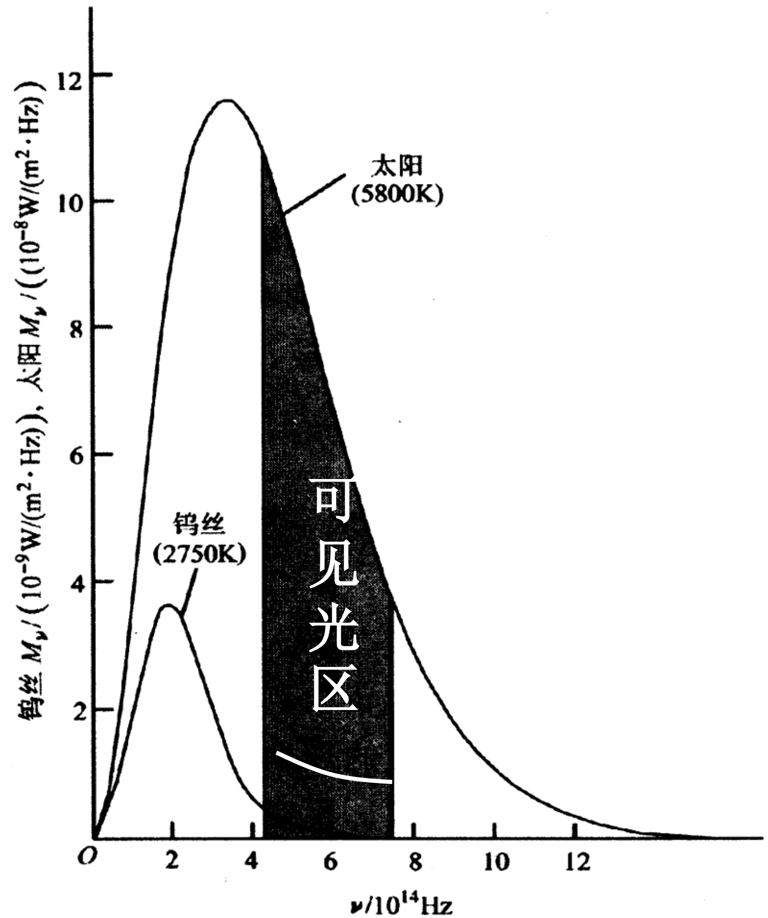
Quantum Revolution



黑体辐射

Radiation heat is also an electromagnetic wave!





不同温度下的黑体辐射曲线　　钨丝和太阳的热辐射曲线

Kirchhoff (1859)

It is highly important task to find this function. Great difficulties stand in the way of its experimental determination. Nevertheless, there appear grounds for the hope that it has a simple form, as do all functions which do not depend on the properties of individual bodies and which one has become acquainted with before now.

$$\rho(\nu, T)$$

从经典电动力学和统计物理理论推出，

著名公式：　瑞利–金斯公式

$$M_\nu(T) = \frac{2\pi \nu^2}{c^2} kT$$

“紫外灾难”

$$k = 1.380658 \times 10^{-23} J \cdot K^{-1}$$

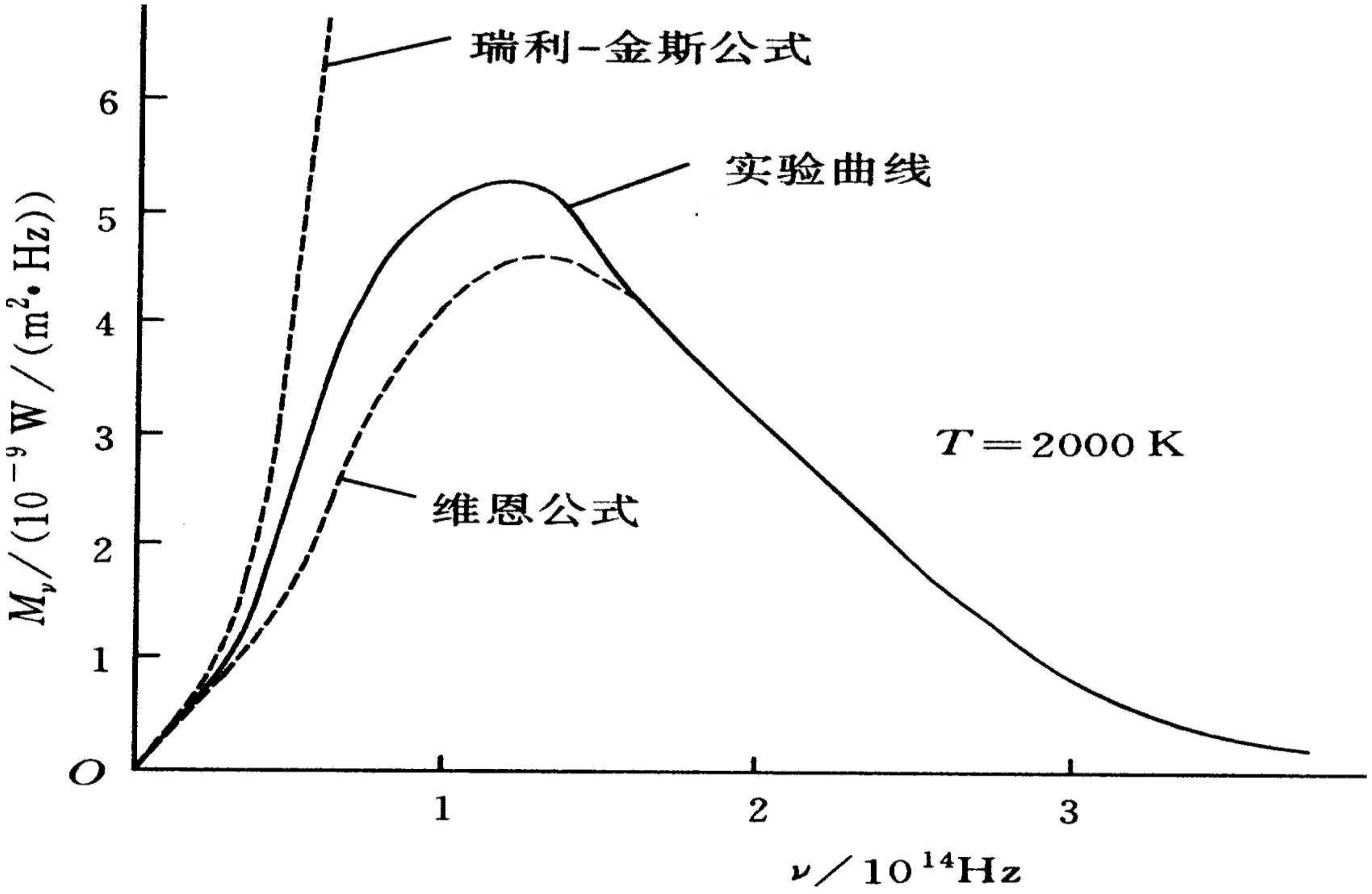
从热力学理论及实验数据的分析得出，

著名公式：　维恩公式

$$M_\nu(T) = \alpha \nu^3 e^{-\beta \nu / T}$$

α, β 为常数

物理学晴朗天空中的一朵乌云!

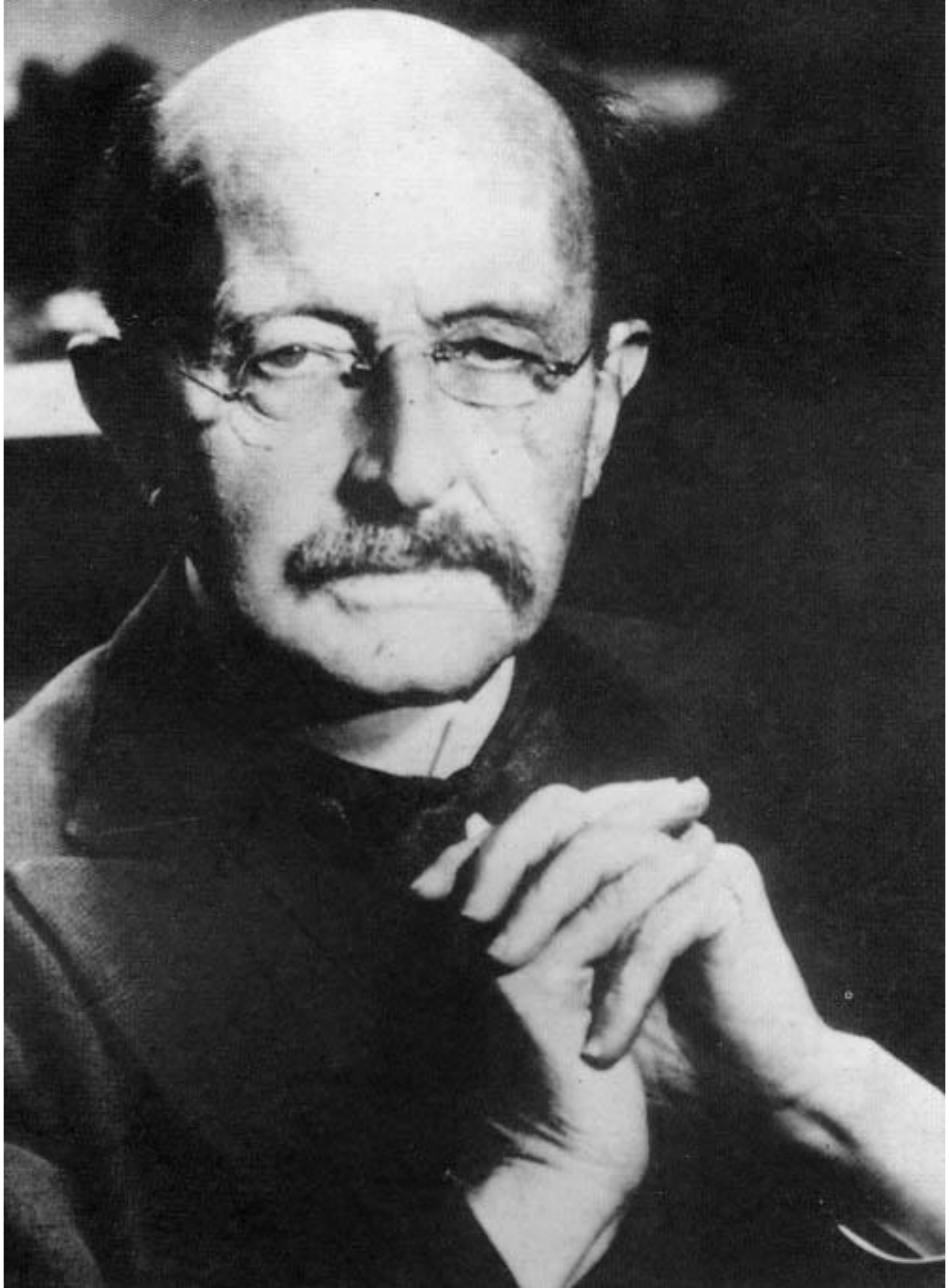


$$\rho(\nu,T)=\frac{8\pi\nu^2}{c^3}\frac{h\nu}{e^{h\nu/kT}-1}$$

1900年10月19日——Planck辐射定律诞生之日

Max Planck (1925)

After a few weeks of the most strenuous work of my life, the darkness lifted and an unexpected vista began to appear.



普朗克

1858-1947

普朗克：

“一定要不惜任何代价，找到一个理论根据”。

1900.12.14普朗克在德国物理学会上报告了论文“关于正常谱中能量分布的理论”

从理论上推出了普朗克公式

推导的基本物理思想：

辐射黑体中的分子、原子可看作线性谐振子，振动时向外辐射能量（也可吸收能量）

- 经典理论：振子的能量取“连续值”
- 普朗克假定：振子的能量不连续：

$E=n\varepsilon \quad n=1,2,3\ldots \qquad \varepsilon = h\nu$ — 能量子

$E=n\varepsilon \quad n=1,2,3\ldots \qquad \varepsilon = h\nu$

$$\Delta E = (\Delta n)h\nu$$

物体发射或吸收电磁辐射时, 交换能量的最小单位是"能量子" $\varepsilon = h\nu$

由此得到了普朗克的热辐射公式:

$$M_\nu(T) = \frac{2\pi h}{c^2}\frac{\nu^3}{e^{h\nu/kT}-1} \qquad (\clubsuit)$$

$$h = 6.55\times 10^{-34}\ \mathrm{J\cdot s}$$

$h\nu \gg kT$, 时: $(\clubsuit) \longrightarrow$ 维恩公式

$h\nu \ll kT$ 时: $(\clubsuit) \longrightarrow$ 瑞利–金斯公式

$$\frac{d^2S}{dU^2} = -\frac{1}{\beta\nu U + U^2/k} \qquad (h = k\beta)$$

Inspired by Mr. Boltzmann,…

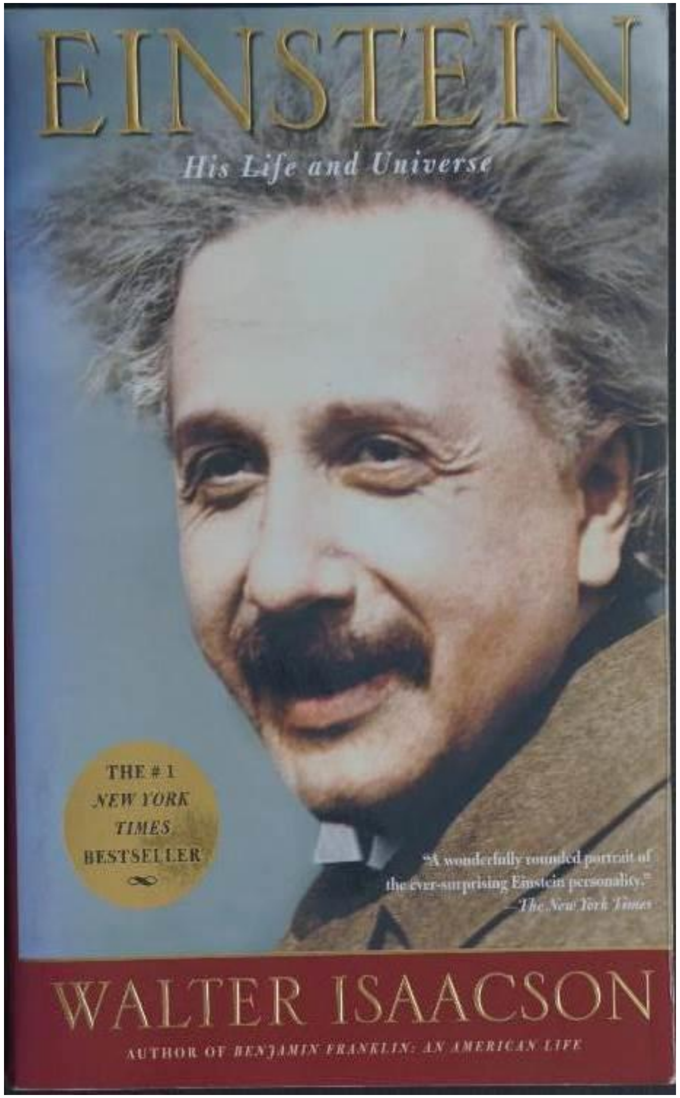
$$S = k\left[\left(\frac{p}{n}+1\right)\ln\left(\frac{p}{n}+1\right) - \frac{p}{n}\ln\frac{p}{n}\right] \qquad U = \frac{p\varepsilon}{n}$$

$$S = k\left[\left(\frac{U}{h\nu}+1\right)\ln\left(\frac{U}{h\nu}+1\right) - \frac{U}{h\nu}\ln\frac{U}{h\nu}\right]$$

$$\varepsilon = h\nu$$

1900年12月14日——量子论诞生之日

Einstein的光量子



1879-1955

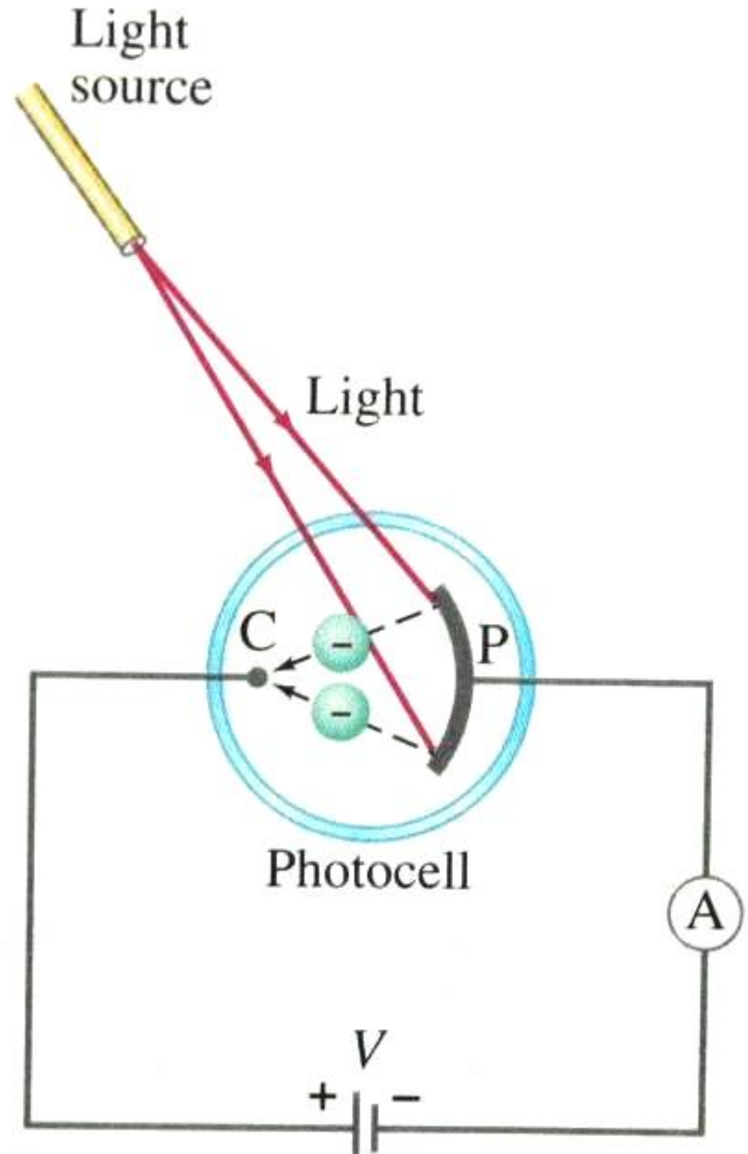


FIGURE 37–4 The photoelectric effect.

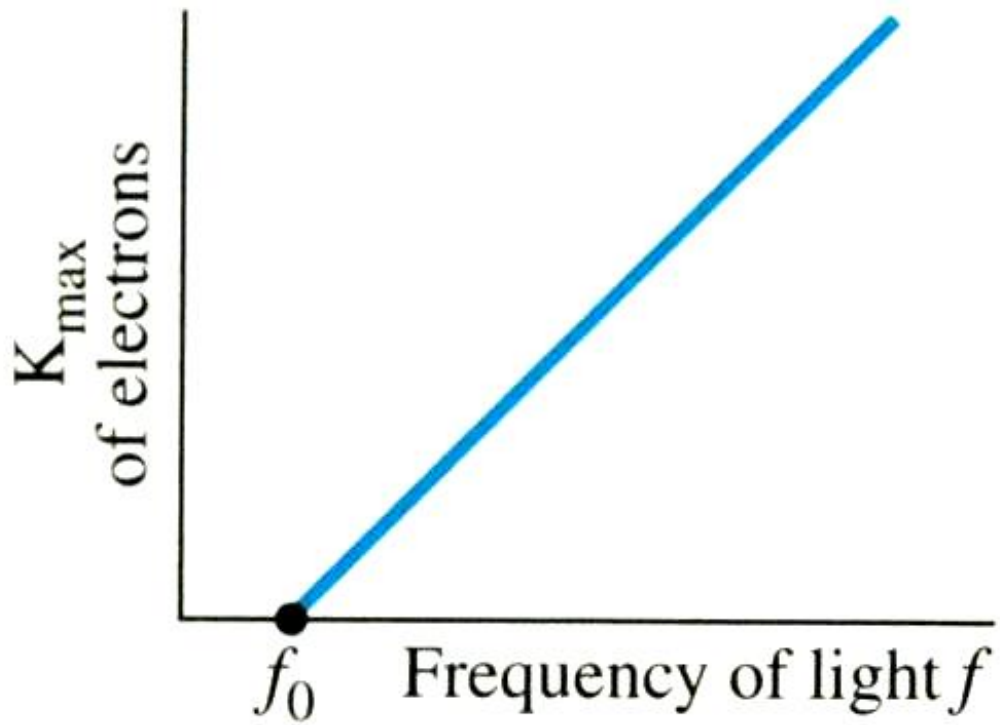


FIGURE 37–5 Photoelectric effect: the maximum kinetic energy of ejected electrons increases linearly with the frequency of incident light. No electrons are emitted if $f < f_0$.

关于光的产生和转化的一个试探性观点①

(1905)

$$E_k = h\nu - W_0$$

在物理学家关于气体或其他有重物体所形成的理论观念同麦克斯韦关于所谓空虚空间中的电磁过程的理论之间，有着深刻的形式上的分歧。这就是，我们认为一个物体的状态是由数目很大但还是有限个数的原子和电子的坐标和速度来完全确定的；与此相反，为了确定一个空间的电磁状态，我们就需要用连续的空间函数，因此，为了完全确定一个空间的电磁状态，就不能认为有限个数的物理量就足够了。按照麦克斯韦的理论，对于一切纯电磁现象因而也对于光来说，应当把能量看作是连续的空间函数，而按照物理学家现在的看法，一个有重客体的能量，则应当用其中原子和电子所带能量的总和来表示。一个有重物体的能量不可能分成任意多个、任意小的部分，而按照光的麦克斯韦理论（或者更一般地说，按照任何波动理论），从一个点光源发射出来的光束的能量，则是在一个不断增大的体积中连续地分布的。

爱因斯坦的光量子论

爱因斯坦光量子假设(1905)

- 电磁辐射由以光速c运动的局限于空间某一小范围的光量子（光子）组成，$\varepsilon = h\nu$
- 光量子具有“整体性”，光的发射、传播、吸收都是量子化的。

对光电效应的解释:

一个光子将全部能量交给一个电子，电子克服金属对它的束缚，从金属中逸出。

$$\frac{1}{2} m u_m^2 = h\nu - A$$

A：逸出功

光量子假设解释了光电效应的全部实验规律！

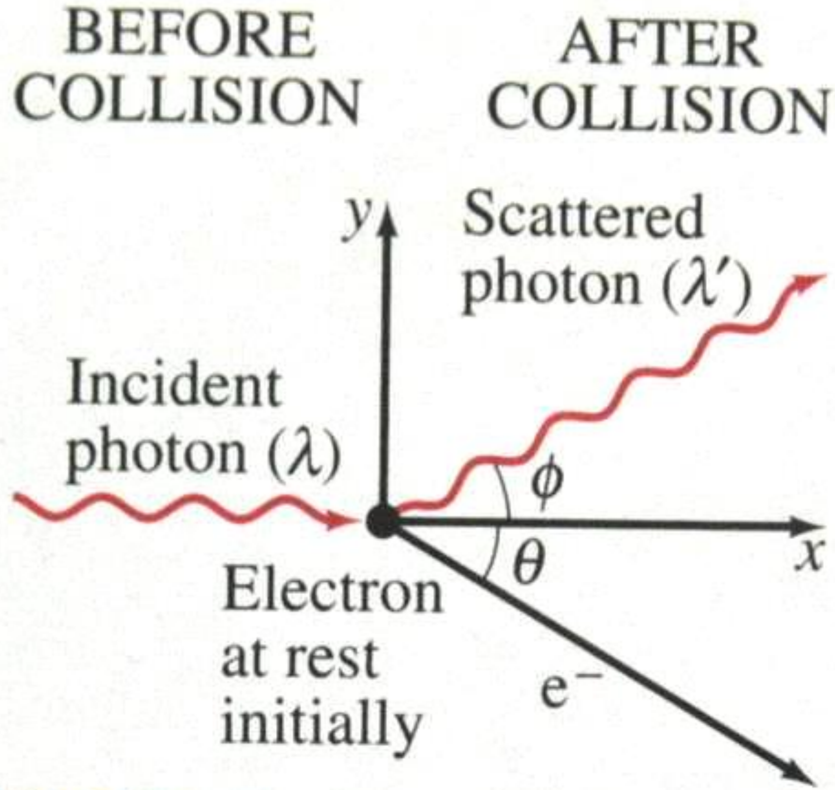


FIGURE 37–7 The Compton effect. A single photon of wavelength λ strikes an electron in some material, knocking it out of its atom. The scattered photon has less energy (some energy is given to the electron) and hence has a longer wavelength λ'.

R.A. Millikan (1948)

I spent ten years of my life testing that 1905 equation of Einstein's and contrary to all my expectations, I was compelled in 1915 to assert its unambiguous verification in spite of its unreasonableness, since it seemed to violate everything we knew about the interference of light.

Planck, Nernst, Rubens, and Warburg (1913)

That he may sometimes have missed the target in his speculations, as for example, in his hypothesis of light quanta , cannot really be held too much against him, for it is not possible to introduce fundamentally new ideas, even in the most exact sciences, without occasionally taking a risk.

任何在我出生就有的科学，本该如此；任何在我15~35岁之间诞生的科学，伟大革命；任何在我35岁之后诞生的科学，异端学说。

道格拉斯-亚当斯（英国音乐家、剧作家）

课后阅读：

路漫漫其修远兮——麦克斯韦方程进化史