radiative transfer measurements. We shall stand away from electromagnetic complexity, and half-shut our eyes as we reconstruct radiometry. In the next chapter we shall shut our eyes completely and think about what we have seen in Vol. I.

The outline of this chapter is as follows. We begin in Sec. 2.1 with the operational definition of radiant flux. It is always good practice to give as many means of visualization of a newly defined concept as mutual consistency will allow. For this reason, and also to pave the way for a more versatile presentation of the concepts of hydrologic optics than that of Chapter 1, we develop in Sec. 2.2 the three main ways to conceptually view the notion of radiant flux. The principal properties of radiant flux, as they are used in geometrical radiometry, are developed in Sec. 2.3. Then, in close succession, the principal derived concepts of radiometry are developed: radiance and various forms of irradiance, along with theorems governing and examples illustrating their salient properties. Throughout our development we shall emphasize the *geometrical* aspects of radiometry rather than their physical aspects. The latter aspects, to the degree that we shall need to study them in this work, are reserved for discussion in Sec. 2.1. However, some notice must also be taken of the physical aspects of radiometry in preparing to construct the bridge between radiometric and photometric concepts. Therefore, in Sec. 2.12, we pause to develop those concepts of photometry which facilitate the operational definition of the notion of luminous flux--the photometric counterpart to radiant flux. With the radiometric discussions as a model, the various derived photometric concepts are then readily attained. The chapter closes with some remarks on generalized photometric concepts.

Our present viewpoint of geometrical radiometry and photometry may then be summarized in the following definitions of these disciplines, which we adopt: *Radiometry is the science of the measurement of radiant energy. Geometrical Radiometry is the union of euclidean geometry and Radiometry: it measures and describes the flow of radiant energy of given frequency through volumes, across surfaces, along lines, and at points in space.* With this in mind we can go on to say that: *Geometrical Photometry measures the visual, erythemal, photoelectric, or photographic response, by given receptors, to the quantities of geometrical radiometry, with respect to different frequencies of radiant energy.*

2.1 Radiant Flux

We now take up the details of an operational definition of radiant flux. The heart of the definition we shall adopt consists of the postulation of some physical device which can sense and record in quantitative detail the presence of light--or radiant energy in general--in a neighborhood of a point in space. There are several devices available for such a purpose. Of those currently available, the photoelectric devices are most satisfactory from the point of view of sensitivity and quantitative precision. We pause briefly to survey this class of devices.

Basic Photoelectric Effects

The class of light-measuring devices known collectively as *photoelectric cells* consists of three broad sets, each set being characterized by a distinctive mode of interaction of light with matter and the particular form of electrical response arising from that interaction. These responses are denoted by the terms *photoemissive* , *photoconductive*, and *photovoltaic*. A comparison of the characteristic features of these phenomena is readily made by means of Fig. 2.1.

Part (a) of the figure depicts the electrical essence of a *photoemissive cell* (or *phototube*). Light, indicated by the arrow, is incident on a negatively charged electrode. The impact of the incident light dislodges electrons from the surface of the electrode and these are drawn across the gap to the relatively positively charged electrode within the element. The seat of electromotive force is supplied by a battery or other means and so continuously replenishes the supply of electrons on the negative electrode. The net result of the incident light is a small but measurable current of electrons flowing through a current meter, as shown in the figure. The swarm of electrons, liberated at the electrode by the incident light, streams across the gap between the electrodes and thereby completes the circuit. If there is no incident light on the electrode, then under normal conditions, there are no electrons liberated from the electrode to complete the circuit, and there is consequently no current registered by the meter. Generally, the greater the amount of light incident on the receiving electrode, the correspondingly greater is the resultant current in the circuit. By a careful calibration, the meter can be made to read directly the rate of incidence of radiant energy on the receiving electrode. The photoemissive effect just described is the most recently discovered of the three effects. It was discovered in crude form in 1887 by Heinrich Hertz as a by-product of his classical researches on electromagnetism. Under subsequent refinements, over the years, it has become the principal effect used in photoelectric devices. The theory of the photoemissive effect was not evolved until about eighteen years after its discovery. The theory of the photoemissive effect itself forms a major epoch in the history of physics, for its completion eventually required the concept of the photon as introduced by Einstein in 1905.

A *photoconductive cell* is schematically depicted in part (b) of Fig. 2.1. It was found experimentally in 1873 by Willoughby Smith that the conductivity of the metal selenium increases when light is incident on it. This effect can therefore be put to use in sensing and recording the presence of light, in the manner shown in the figure. The greater amount of light incident on the selenium cell results in a correspondingly greater amount of current flowing through the current meter. When no light is incident on the photoconductive element, there is under normal conditions a small known amount of current (the *dark current*) flowing in the circuit. The full understanding of the photoconductive effect on a microscopic level was achieved only recently using the quantum-

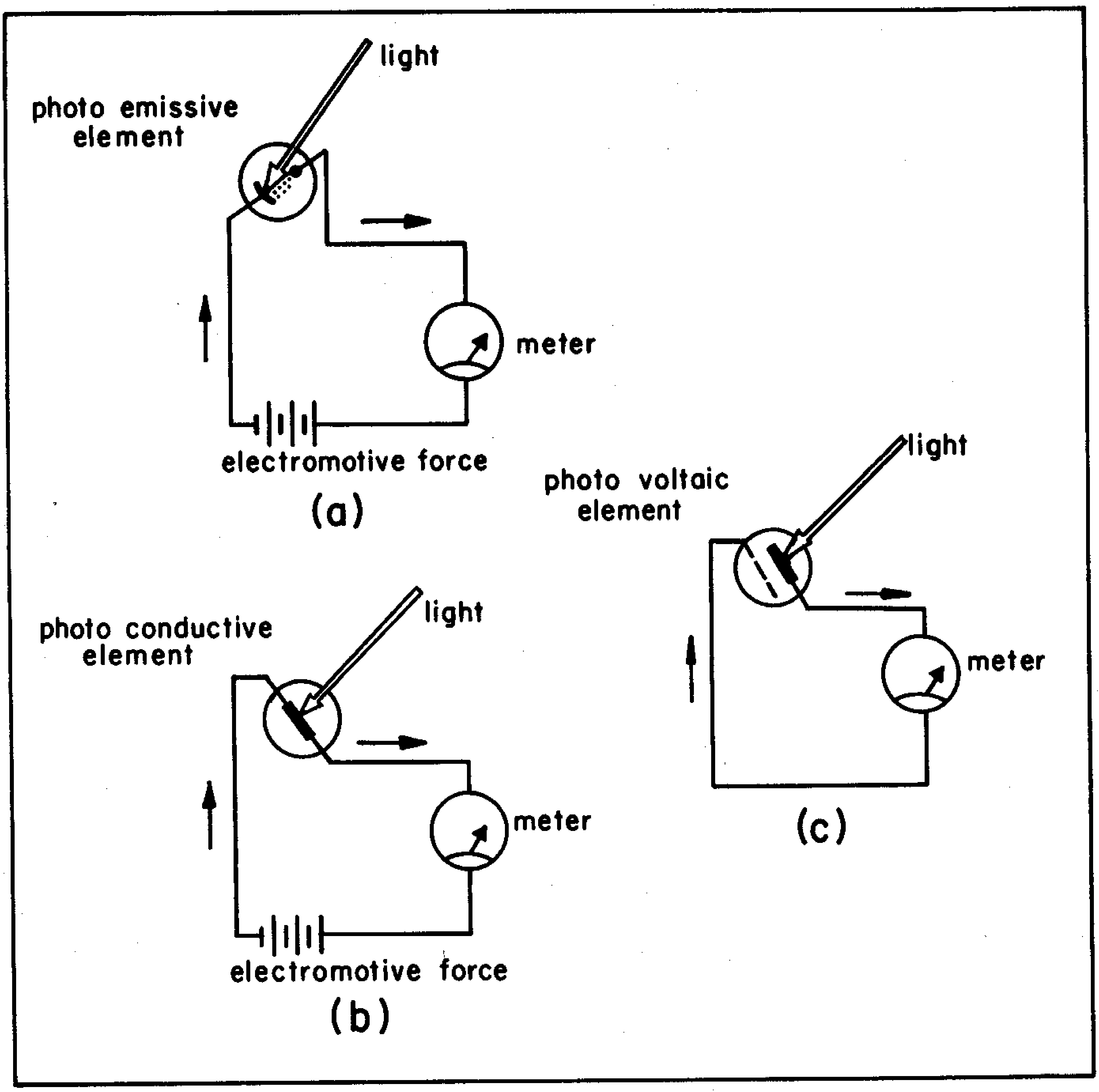

FIG. 2.1 The Basic types of photoelectric cells

based theory of semiconductors. On the basis of this understanding, one can test and use all manners of semiconductors as possible photoconductive materials.

A *photovoltaic cell* is schematically depicted in part (c) of Fig. 2.1. The photovoltaic element consists of two dissimilar substances in close contact (shown slightly separated, for clarity). Light incident on the photovoltaic element generates a difference of electric potential between the two basic parts of the element and as a consequence a current flows in the circuit. This current is measured by a current meter included in the circuit. When no light is incident on the element, no electromotive force is normally produced in the parts of the element, and consequently no current flows in the circuit. Generally, the greater the amount of incident light on the element of the cell, the greater the resultant potential, and the greater the ensuing current in the circuit. The photovoltaic effect antedates both other effects discussed above. It appears that Edmond Becquerel first observed it in 1839 when a liquid electrolyte containing two immersed electrodes connected through a galvanometer was irradiated by sunlight. Becquerel eliminated the possibility of a thermal voltaic effect generated by differential heating of the electrodes and thereby was led to believe that the light itself gave rise to an electric potential between the electrodes which in turn gave rise to a current in the galvanometer.

The theory of the photovoltaic effect requires the quantum picture of the structure of matter for its complete formulation. However both the photoconductive and photovoltaic effects can be intuitively pictured as being something like weaker versions of the photoemissive effect: on the one hand, in the case of the photoconductive cell, instead of knocking electrons completely free of an area of selenium surface, the incident light on the surface merely gives them enough energy to skim through the lattice of the positive nuclei of the selenium atoms. If there is an existing voltage in the metal, the footloose electrons in the irradiated region are then more readily moved along in a more or less organized manner by the potential difference. On the other hand, the mechanism of the photovoltaic effect is relatively complex. For our descriptive purposes here it may be explained in terms of the effects generated by inherently different electromotive forces of the chemical elements. When two substances of different electromotive force are placed in close proximity (e.g., the dotted and solid elements schematically shown in part (c) of Fig. 2.1) the pull exerted by the positive nuclei of the atoms of one of the substances on electrons is greater than that of the corresponding pull by the other substance. As a result some electrons are swapped from the 'weaker' to the 'stronger' substance when the substances are placed into close contact. However, the electrons captured by the stronger substance can be relatively easily dislodged by irradiation of the boundary between the substances, and thus be caused to move in the resultant electric field naturally existing between the two substances. The magnitude of the potential of this field under irradiation is very nearly the difference in the electromotive forces of the substances.

Operational Definition of Radiant Flux

We now present the operational definition of radiant flux. The brief preliminary excursion into the basic photoelectric effects just completed will endow the definition procedures below with a measure of realism that perhaps may not have been possible had we not paused to make some contact with physical reality. However, the logical basis of the definition of radiant flux and its manifold properties discussed subsequently are quite independent of what radiation measuring devices are used in practice. Indeed, the concepts of radiometry as used in practice are all constructable in terms of the basic notion of radiant flux and appropriate geometrical notions such as surface areas and solid angles. The concept of radiant flux in turn and its few basic geometric properties are now so well established that they can actually be axiomatized for the purpose of developing a self-contained discipline of geometrical radiometry. In the present development we shall steer a middle road between these extreme alternatives. We shall not go so far as to develop in complete detail an axiomatic theory of radiometry, but we shall indicate the fundamental properties of radiant flux that would occur in such a formulation. The notion of radiant flux will for the most part be handled as an empirically-based concept. However, we shall not, beyond the general suggestions given in the discussion of photoelectric devices above, fix in any detail the form of the device which is used to sense and record the incident flow of radiant energy. In sum, we shall henceforth agree that we have some light-sensitive device which can accurately, quickly, and repeatedly reproduce a quantitive measure of the instantaneous flow of radiant energy onto some well defined surface which acts as a collecting surface for the incident energy. Except for some suggestive remarks in Sec. 2.2, the notion of 'radiant energy' will remain undefined in this work. We take it as given.

Figure 2.2 depicts in more detail, and on a schematic level, the basic form of a widely used type of radiant flux meter. The sequence of events leading to a radiant flux measurement with the radiant flux meter is generally as follows. Radiant energy is incident on the filter of the meter. This energy is funneled in from the environment through a set D of directions. The filter ideally transmits a set F of frequencies of the incident energy and does not transmit any other frequencies. The transmitted frequencies then pass on to a plane collecting surface S. This surface acts to collect a representative amount of the transmitted flux from each

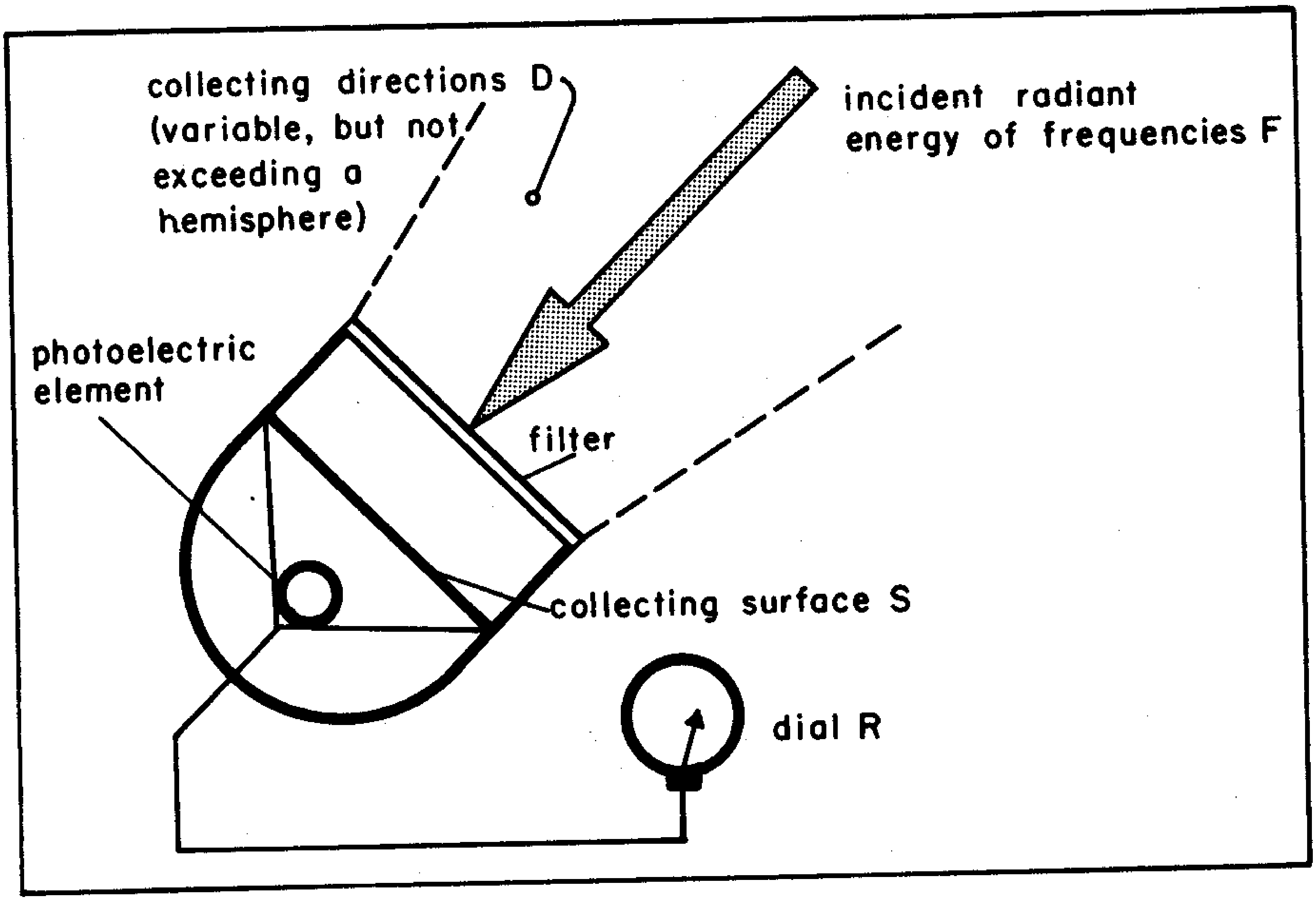

FIG. 2.2 Schematic detail of a radiant-flux meter

direction in D and to pass it on to the photosensitive element of some type of radiant energy sensor. The sensor is part of a circuit of a photoelectric cell, and the presence of the radiant energy flow on the filter thus becomes manifest in a dial reading R of the current meter in the photoelectric cell's circuit (see Fig. 2.1).

In order to obtain a usable measure of the flow of radiant energy, there is basically only one additional requirement on the radiant flux meter assembly, above and beyond the usual requirements on its components demanded by good mechanical and electrical engineering practice. The additional requirement is that its collecting surface S collect energy in a manner which is effectively independent of the direction of incidence of the energy on S. Thus, suppose a narrow beam of radiant energy is incident normally on S, and note the associated reading R of the dial of the meter. Then let the beam's incident angle vary slowly away from normal incidence, keeping the beam always to fall within the surface S. An ideal collecting surface will accept, diffuse, and pass on the energy of this varying beam to the sensor below so that the dial reading R remains fixed. When a collecting surface comes within some preassigned distance of this ideal, we shall call it a *cosine collector*. The reason for this terminology will become clear after the study of the concept of irradiance below. Briefly, it derives from the fact that if the collector is completely bathed in the flux of a homogeneous cylindrical beam, then the *recorded* flux will vary as the cosine of the angle the normal to the collector makes with the axis of the beam of flux. Henceforth, it will be assumed that the collecting surface of the radiant flux meter is a cosine collector.

We now can state the operational definition of radiant flux. We assume that the radiant flux meter, outfitted with a cosine collector S, has been calibrated against some radiometric standard with a known *rate of radiant energy* (*radiant flux*) output (see Chapter 6, Ref. [3]). Then we imagine that we have taken the meter into some radiometric environment such as the depths of some lake or ocean, or perhaps to some point in the atmosphere. The meter is then oriented so that at time t the surface S accepts through the set D of directions radiant flux comprised of a set F of frequencies, with a resultant associated reading R of the meter's dial. The calibration of the dial permits the assignation to this reading R of a *radiant flux* in the form of a nonnegative number denoted by "$\Phi(S,D,t,F)$". The reading R is thereby associated with this particular S,D,t, and F in the radiometric environment. Thus "$\Phi(S,D,t,F)$" denotes the *radiant flux* of frequencies in F which are incident on S, through D, at time t. The dimensions of radiant flux are *energy/time*, or synonymously, *power*, and convenient units are *joules/sec*, or synonymously, *watts*. This pairing process therefore generates a function, the *radiant flux function* denoted by "Φ", which assigns to each collection (S,D,t,F) of surface, direction, frequency and time parameters the nonnegative number $\Phi(S,D,t,F)$ in the manner just described.

The definition of radiant flux given above is an *operational definition* in the sense that it may be translated into a definite sequence of physical operations with a specific instrument in a given environment and which culminate in a unique nonnegative number $\Phi(S,D,t,F)$. This type of definition can be made to stand out in bold relief from still another type which may also be used as effectively as the operational definition in establishing the theory of radiometry. This alternative definition is known as the *constitutive definition* of radiant flux which uses only the concepts of the mathematical framework within which radiometry is modeled. In a constitutive definition there is no immediate appeal to physical operations with a specific instrument in a given environment. For an example of a constitutive definition of radiant flux and the other radiometric quantities, the reader may consult Secs. 109 and 131 of reference [251].

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2.2 The Meaning of 'Radiant Flux'

It will be helpful during the discussions of this and subsequent chapters to have in mind some visualizable construct of radiant flux. By having the reader picture in a relatively concrete manner the meaning of the term 'radiant flux', the various principles and laws of radiative transfer used throughout this work will become more readily understood and applied. We have already given the term 'radiant flux' a relatively concrete meaning by adopting an operational definition of the term. In this section we shall go one step further and suggest three ways in which one may visualize radiant flux directly. What we shall offer, then, are conceptual frameworks within which to view the notion of radiant energy and which, especially during theoretical discussions of radiative transfer, one may use in a heuristic manner.

One manner in which radiant flux may be visualized is by a means similar to that used in geometrical optics. In order to discuss the theory of lenses within geometrical optics one may use the method of ray tracing. The heart of this method resides in the concept of the "light ray" and a few simple rules of construction of a ray of light through a lens. Corresponding to this notion we have in geometrical radiometry the notion of a *line of flux*. One may thus visualize $\Phi(S,D,t,F)$ as proportional to the number of straight or curved lines having directions lying within the set D where they terminate on the surface S. The time t and set F of frequencies are usually fixed or understood during a discussion so that the lines of flux constitute a representation of the geometric construct of $\Phi(S,D,t,F)$. In this representation, the magnitude of $\Phi(S,D,t,F)$ is proportional to the number of such lines of flux, the proportionality factor being some fixed number of lines per unit of radiant flux. One may thus imagine the radiant energy as a fluid travelling along the lines of flux. The closer together the lines are within some region, the greater the radiant flux (i.e., radiant energy flow) through that region. The lines of flux are to be determined using the same formulas of geometrical optics as used in ray tracing. Whenever scattering takes place, however, some lines