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.

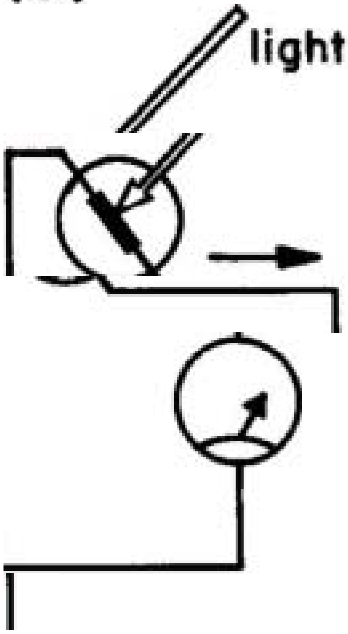
Part (a) of the figure depicts the electrical essence *of a photoemissive cell (or phototube) . Light,* indicated by the arrow, is incident on a negatively charged electrode.

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 190S.

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*-based theory of semiconductors

photo emissive **element**
f
photo conductive element
f
electromotive force

(a)



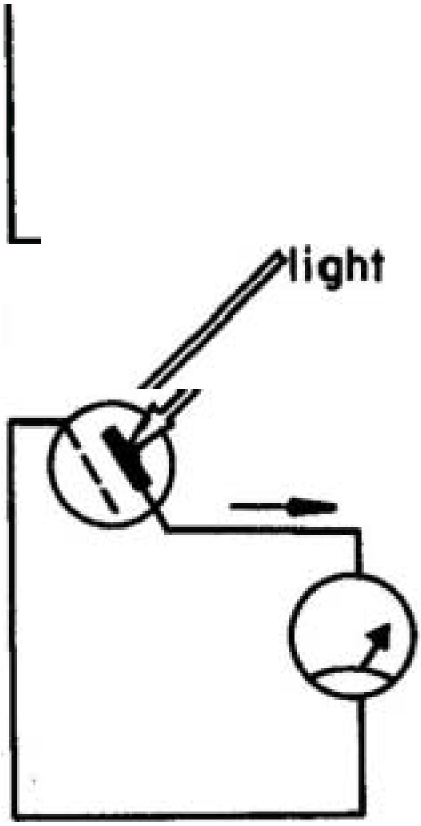


FIG. 2.1 The Basic types of photoelectric cells

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 sepa*rated, 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 re*gion 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,**

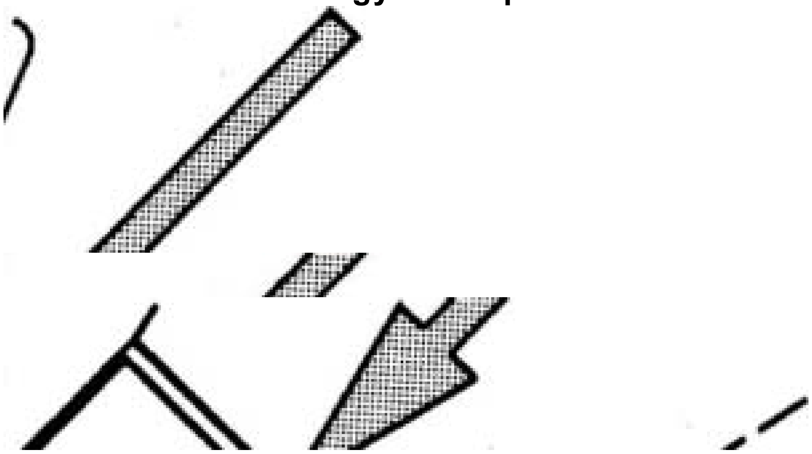
Operational Definition of **Radiant Flux**

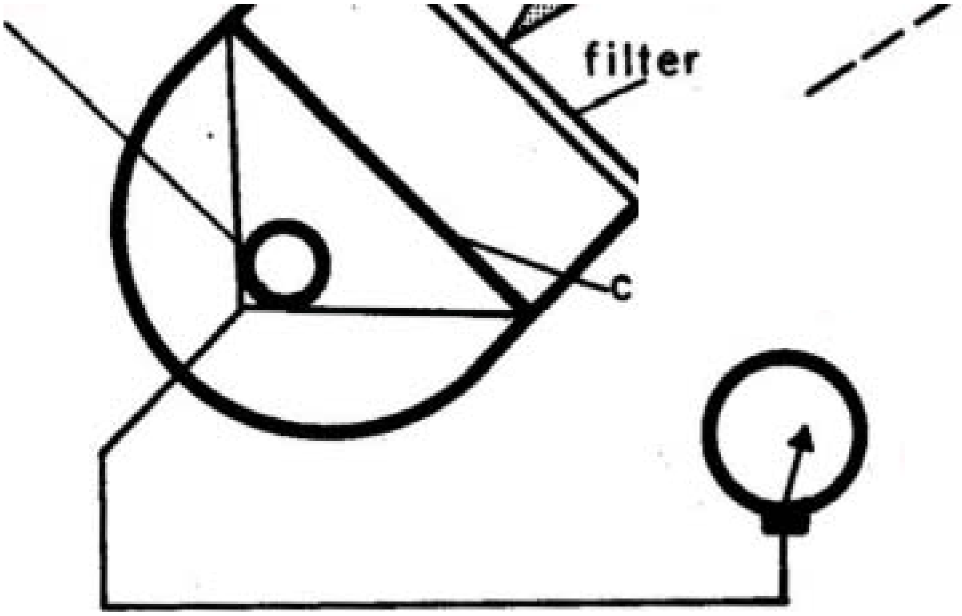
We now present the operational definition of radiant flux. The brief preliminary excursion into the basic photoelectric effects just completed will endow the definition procedures below with a measure of realism that perhaps may not have been possible had we not paused to make some contact with physical 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

photoelectric element
L
collecting directions D (variable, but not exceeding a
1
hemisphere)
incident radiant energy of frequencies F





ollecting surface S
dial R

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 require*ment 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 pre-assigned 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 radio metric standard with a known *rate of radiant energy [radiant flux]* output (see Chapter b, 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 v 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 "§(S,D,t,F)". The reading R is thereby associated with this particular S,D,t, and F in the radiometric environment. Thus "f (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 aoutes/sec, or synonymously, watts, This pairing process therefore generates a function, the radiant flux function denoted by 'IV., which assigns to each collection (S,D,t,F) of surface, direction, frequency and time parameters the nonnegative number t(S,D,t,F) in the manner just described.

The definition of radiant flux given above is an oper*ational 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 f (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].