using the dye fluorescein\(^7\) in place of crystal violet. In
this dye the absorption is much weaker, and the fringes
behaved as if the cover glass had been coated in patches
on its back with a glass of a higher index of refraction, so
that dark fringes ran directly into bright fringes over the
dye streaks.

Additional comments are in order on how the photo-
graph of Fig. 3 was made. Individual cover glasses were
selected for use on the basis of the relative uniformity of
their fringe pattern. The crystal violet dye was applied in
alcohol solution as thickly as possible with a cotton swab.
The light from a mercury street lamp some fifty meters
away was used together with a Wratten K2 filter (yellow).
The use of this filter improved the visibility of the fringes
by absorbing light from lines toward the blue end of the
mercury spectrum. Exposures were for several sec-
onds with Kodak Tri-X film. No lens was needed; the
cover glass reflected light from the street lamp directly
onto the film from a distance of about 10 cm. Extraneous
light was excluded by a simple cardboard baffle. It was
necessary to check that no interference pattern appeared
beneath the dye streaks when the cover glass was viewed
from behind. Otherwise it would not have been possible
to distinguish the effect discussed here from shifts pro-
duced by reflection from the air side of the dye layer.
Pictures using fluorescein were made in the same way.
This dye was also applied in alcohol solution. Its hygro-
scopic properties made it more difficult to work with than
crystal violet.

The interferometer described here is derived from a
class of more refined instruments that have been used to
study the optical properties of metals.\(^6\)--\(^9\) Although un-
suited for quantitative measurements it demonstrates
convincingly the scattering phase shift associated with the
process of absorption.

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\(^\circ\)Work supported jointly by the U.S. Energy Research and Develop-
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\(^7\)Here as fluorescein disodium salt (Eastman).
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**Concerning a widespread error in the description of the photoelectric
effect**

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The purpose of this note is to draw attention to a wide-
spread error appearing in elementary physics textbooks.
The error is connected with descriptions of Millikan's ex-
periments on the photoelectric effect. The experiment is a
classical one illustrated schematically in Fig. 1.

Light with a frequency \(\nu\) is incident on the emitter (the
emitter and collector are both metals, but are not neces-
sarily the same kind of metal). Photoemitted electrons are
picked up by the collector and detected as current by the
ammeter. It is found that for every frequency that can
stimulate a photocurrent with no applied back-voltage
from the battery in the circuit, there exists a back-voltage
just sufficient to cause the photocurrent to cease. This is
called the stopping potential, \(V\). Plotting \(eV\) vs \(\nu\) (Fig. 2),
one obtains a straight line described by the relation

\[ eV = h\nu - \phi. \]  

(1)

The general form of (1) is in accord with Einstein's
theory of photoemission.\(^1\)

We have checked several elementary physics textbooks
of recent vintage\(^3\)--\(^5\) in which the experiment is discussed;
in all of them it is incorrectly claimed that \(\phi\) in Eq. (1)
equals the work function, \(\phi_e\), of the emitter, and there-
fore that \(\phi_e\) can be directly measured by the setup of Fig.
1. The common argument is basically that, since an elec-

![Fig. 1. Schematic illustration of Millikan's classical photoelectric effect experiment.](image)

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Fig. 2. Electronic charge times the stopping potential, $eV$, as determined in the experiment illustrated in Fig. 1, plotted versus the frequency $\nu$ of the incident light.

Fig. 3. Energy of an electron at various points in the phototube of Fig. 1: Maximum energy inside the emitter (A) and the collector (D) and minimum energy in the space between emitter and collector (line BC). $\phi_e$ and $\phi_c$ are the respective work functions. (a) No back-voltage applied, $\phi_e < \phi_c$; (b) finite back-voltage $V$ applied, $\phi_e < \phi_c$; (c) same as (b) but with $\phi_e > \phi_c$.

tron that has just left the emitter because of absorption of a photon of energy $h\nu$ can have a maximum kinetic energy $T_{\text{max}} = h\nu - \phi_e$, therefore a back-voltage $V$ given by

$$eV = T_{\text{max}} = h\nu - \phi_e$$

will be required to prevent all electrons from reaching the collector.

We would like to show in a simple way that, while the expression for $T_{\text{max}}$ is correct, Eq. (2) for the stopping potential is incorrect, and that $\phi$ in Eq. (1) is not $\phi_e$ but $\phi_c$, the work function of the collector. Equation (1) should thus be written

$$eV = h\nu - \phi_c.$$  

Since room temperature is a very low temperature as far as the electrons in a metal are concerned, we shall derive Eq. (3) for the case of zero temperature. This is a simpler case because then the difference between free energy and internal energy disappears. The derivation assumes no sophisticated knowledge of the behavior of electrons in metals and should therefore be suitable for an elementary undergraduate course.

Let us first consider the situation when $V = 0$ [Fig. 3(a)]. The maximum energy of electrons in the emitter and the collector must be the same since the electrodes are connected metallically. The hydrostatic case of communicating vessels can be used as a useful, though not completely accurate, analog. We shall take this common energy as the zero of energy. The work function of a metal is defined as the minimum energy necessary to transfer an electron from just inside the metal to just outside the metal. If the work functions of the emitter and the collector are different, then clearly an electron at rest just outside the emitter will have a different energy from an electron at rest just outside the collector. The difference in the energies of the electrons at rest just outside the two electrodes is called the contact potential difference (CPD). It is just equal to the difference in the two work functions.

When we insert a voltage (a battery) into the circuit, the maximum energy of the electrons in the two electrodes will not be the same any more. The difference between the energies at the two points A and D is by defini-
Gauge and Lorentz transformations: An example

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The teaching of gauge transformations in undergraduate electricity and magnetism courses seems always to pose problems for most undergraduate students because of its inherent abstractness and the lack of examples of its use. Few books whether graduate or undergraduate dwell much on the subject and most of the time they treat the subject very briefly. This is mainly because after using the nonuniqueness of the potentials to select either the Lorentz or Coulomb gauge there is a lack of further examples. The author has found the following example to be illuminating to undergraduates at the junior and senior level in both the need and usefulness of the gauge transformation and a convenient way to introduce the concept of infinitesimal Lorentz transformations continuous with the identity.

Let us suppose that we have chosen the Coulomb gauge

$$\nabla \cdot A' = 0$$

in an inertial frame $S'$. Then we ask the following question. How are the potentials $\phi'$ and $A'$ of the Coulomb gauge in $S'$ related to the potentials $\phi$ and $A$ of the Coulomb gauge in an inertial frame $S$ moving with constant velocity with respect to $S'$?

If the Lorentz transformations between the electromagnetic fields have already been developed the students will know that the Coulomb gauge is a noncovariant gauge, and if not the following will certainly illustrate this fact. Using infinitesimal Lorentz transformations because of their inherent simplicity, it is known that $A'$ and $\phi'$ will transform into a set of potentials in $S$ but not necessarily $A$ and $\phi$. Let the potentials in $S$ related to $A'$ and $\phi'$ by infinitesimal Lorentz transformations be $A''$ and $\phi''$. Then

$$A' = A'' - \beta \phi'''$$

$$\phi' = \phi'' - \beta \cdot A''$$

where $\beta = \nu/c$ and $\nu$ is the velocity of $S'$ with respect to $S$. Using the transformation

$$\nabla' = \nabla + \beta \frac{\partial}{\partial t}$$

and Eqs. (2) and (3), Eq. (1) to the first order in $\beta$ becomes

$$\nabla A'' + \beta \left( \frac{1}{c} \frac{\partial A''}{\partial t} - \nabla \phi''' \right) = 0.$$

Obviously the transformed potentials do not belong to the Coulomb gauge in $S$, which is a good illustration of the noncovariant nature of the Coulomb gauge.

Now it is known that for two observers, one in $S$ and one in $S'$, each would have the right to choose the Coulomb gauge in his inertial frame to solve an electromagnetic problem common to both observers and each would obtain the correct solutions which are related to each other by the Lorentz transformations between electromagnetic fields so that there must exist potentials in $S$ which belong to the Coulomb gauge. Therefore, $A$ and $\phi$ must be related to $A''$ and $\phi''$ by a gauge transformation.