الجامعة التكنولوجية

قسم الهندسة الكيمياوية

المرحلة الاولى

فيزياء البيئة

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Similarly, the apparent emissivity at a zenith angle ψ or $\varepsilon a(\psi)$ can be taken as the flux density of downward radiation at ψ divided by $\zeta\, T^4_a$. Many measurements show that the dependence of $\varepsilon a(\psi)$ on ψ over short periods can be expressed as

$\varepsilon a(\psi) = a + b \ln (u \sec \psi)$, (5.23)

where u is precipitable water (corrected for the pressure dependence of radiative emission) and a and b are empirical constants that change with the vertical gradient of temperature and with the distribution of aerosol (Unsworth and Monteith, 1975). Integration of this equation over a hemisphere using Eq. (4.9) gives the effective (hemispherical emissivity as

$\varepsilon a = a + b\, (\ln u + 0.5)$. (5.24)

Comparing Eqs. (5.23) and (5.24) shows that the hemispherical emissivity is identical to the emissivity at a representative angle $\psi\_$ such that

$\ln (u \sec\psi\_) = \ln u + \ln \sec\psi\_ = \ln u + 0.5$.

It follows that $\ln \sec\psi\_ = 0.5$, giving $\psi\_ = 52.5°$ irrespective of the values of a and b. Hence a directional radiometer recording the radiance at $52.5°$ could be used tomonitor the value of εa for cloudless skies, and Ld would be given by Eq. (5.22).

Formulae for estimating εa for cloudless skies were reviewed by Prata (1996) and Niemela et al. (2001). The most successful equation was

$\varepsilon a = 1 - (1 + aw) \exp -[(b + cw)0.5]$,

where$w$is the precipitablewater content of the atmosphere in kgm−2, and the empirical constants are $a = 0.10$ kg−1 m−2, $b = 1.2$, $c = 0.30$ kg−1 m2. Values of w were given approximately by

$w = 4.65 ea/Ta$,

where e_a is water vapor pressure near the ground (Pa) and T_a is air temperature (K). An even simpler formula for estimating **Ld** was developed by Unsworth and Monteith (1975), viz.

Ld $= c + d\zeta\, T^4_a$. (5.25)

For measurements in the English Midlands, which covered a temperature range from −6 to 26 ∘C, the empirical constants were $c = -119\pm16$Wm−2 and $d = 1.06\pm0.04$. The uncertainty of a single estimate of **Ld** was ±30Wm−2. Measurements in Australia (Swinbank, 1963) gave similar values of c and d but with much less scatter. The lack of an explicit dependence of **Ld** on humidity in expressions such as Eq. (5.25) is probably because there is often a strong correlation between air temperature and humidity in the lower atmospheric layers responsible for most of the radiant emission.

Using a linear approximation to the dependence of full radiation on temperature above a base of 283 K allows Eq. (5.25) to be written in the form

$L_d = 213 + 5.5T_a$, (5.26)

where T_a is air temperature in °C. Outward long-wave radiation, assumed to be ζT_a^4 (i.e. $\varepsilon = 1$), is given by a similar approximation as

$L_u = 320 + 5.2T_a$ (5.27)

The net loss of long-wave radiation is therefore

$L_u - L_d = 107 - 0.3T_a$ (5.28)

implying that 100Wm−2 is a good average figure for the net loss to a clear sky (see Figure 14).

If the cloudless atmosphere emitted like a full radiator (an incorrect but commonly applied simplification in climatology texts), an expression for the *effective radiative temperature* T_b of the atmosphere could be obtained by writing

$L_d = 320 + 5.2T_b = 213 + 5.5T_a$,

so that
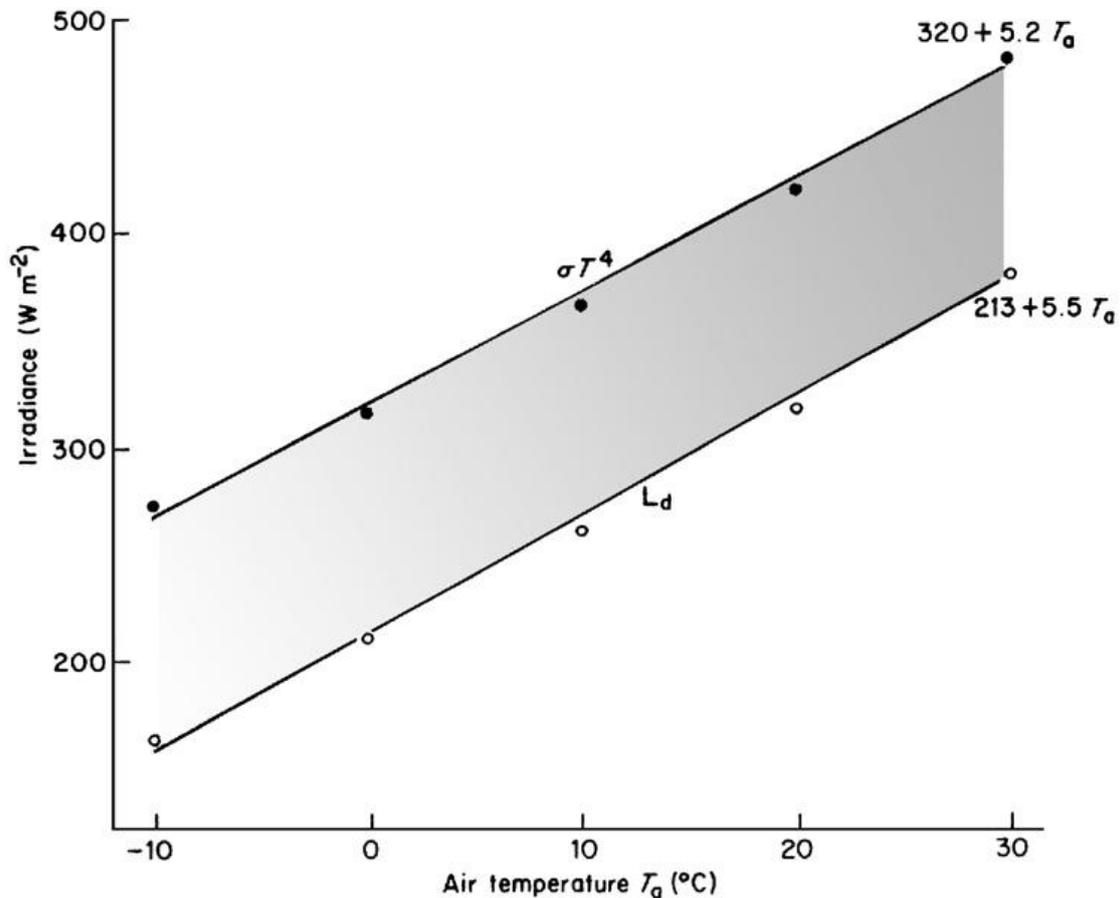
$T_b = 5.5T_a - 107 / 5.2 = T_a - 21 + 0.06T_a$

Figure 14 Black-body radiation at Ta (full circles) and long-wave radiation from clear sky (open circles) from Eq. (5.25). Straight lines are approximations from Eqs. (5.26) and (5.27), respectively.

This relation shows that when T _ a is between 0 and 20∘C, the mean effective radiative temperature of a cloudless sky is usually about 21–19 ∘Cbelowthemean air temperature near the ground.

In general, for climatological work, the more complex formulae for estimating **L**d that require humidity or precipitable water data have little additional merit over the simpler expressions above since the main uncertainty lies in the influence of cloud—the next topic.

2 Terrestrial Radiation from Cloudy Skies

Clouds dense enough to cast a shadow on the ground emit long-wave radiation like full radiators at the cloud base temperature of the water droplets or ice crystals from which they are formed. The presence of cloud increases the flux of atmospheric radiation received at the surface because the radiation from water vapor and carbon dioxide in the lower atmosphere is supplemented by emission from clouds in the waveband which the gaseous emission lacks, particularly from 8 to 13 μm (see Figure 12). Because most of the gaseous component of atmospheric radiation reaching the surface originates below the base of clouds, the gaseous component of the downward flux can be treated as if the sky was cloudless with an apparent emissivity εa. From Kirchhoff's principle, the transmissivity of radiation from the cloud through the air layer beneath cloud base is 1−εa, and if the cloud base temperature is Tc the downward radiation received at the surface from a fully overcast sky will be

Ld = εaζ T 4 a + (1 − εa)ζ T 4 c . (5.29)

Using the linear approximation Eq. (4.5)with δT = Ta−Tc, and ignoring second-order terms in δT, Tc can be eliminated by writing

ζ T 4 c = ζ(Ta − δT)4 ≈ ζ T 4 a − 4ζ T 3 a δT = ζ T 4 a (1 − 4δT /Ta).

Hence Eq. (5.29) may be written

Ld = ζ T 4

a {1 − 4(1 − εa)δT /Ta} (5.30)

and the emissivity is

εa = **L**d/ζ T 4 a = 1 − 4(1 − εa)δT /Ta.

The analysis of a series of measurements near Oxford, England () gave an annual mean of $\delta T = 11$ K with a seasonal variation of ± 2 K, figures consistent with a mean cloud base at about 1 km, higher in summer than in winter. Taking 283 K as a mean value of T_a for this location gives $4\delta T / T_a = 0.16$, so that the emissivity of a completely overcast sky (cloud fraction $c = 1$) at this site would be

$$\varepsilon_a(1) = \mathbf{L}_d / \zeta \, T^4_a = 1 - 0.16 \{1 - \varepsilon_a\} = 0.84 + 0.16\varepsilon_a. \quad (5.31)$$

For a sky covered with a fraction c of cloud, interpolation gives

$$\varepsilon_a(c) = c\varepsilon_a(1) + (1 - c)\varepsilon_a = (1 - 0.84c)\varepsilon_a + 0.84c. \quad (5.32)$$

The main limitation to this formula lies in the choice of appropriate values for cloud temperature and for δT which depend on base height and therefore on cloud type. It is important to remember that the formulae presented in this section are statistical correlations of radiative fluxes with weather variables at particular sites and do not describe direct functional relationships. For prediction, they are most accurate when the air temperature does not increase or decrease rapidly with height near the surface and when the air is not exceptionally dry or humid. They are therefore appropriate for climatological studies of radiation balance but are often not accurate enough for micrometeorological analyses over periods of a few hours. In particular, the simple equations cannot be used to investigate the diurnal variation of $\mathbf{L}_d$. At most sites, the amplitude of $\mathbf{L}_d$ in cloudless weather is much smaller than the amplitude of $\mathbf{L}_u$, behavior to be expected because changes of atmospheric temperatures are governed by, and follow, changes of surface temperature.

Net Radiation

All surfaces receive short-wave radiation during daylight and exchange long-wave radiation continuously with the atmosphere. The net rate at which a surface receives radiation of long and short wavelengths is called the *net radiation balance*, or *net radiation*. (The term *balance* is used in the same sense as in a bank balance, which may be positive, negative, or zero depending on gains and losses.) Thus the net radiation received by unit area of a horizontal surface with reflection coefficient ρ is defined by the equation

$$\mathbf{R}n = (1 - \rho)\mathbf{S}t + \mathbf{L}d - \mathbf{L}u. \quad (5.33)$$

The concept of the net radiation balance can also be applied at the global scale: maps and animations of the seasonal variation of the earth's net radiation balance may be found at

http://earthobservatory.nasa.gov/GlobalMaps/view.php?d1=CERES_NETFLUX_M.

*Micro*climatological applications of Eq. (5.33) are considered. Here, a discussion of the net receipt of radiation by a standard horizontal surface is needed to round off the chapter, although net radiation is not strictly a *macro*climatological quantity: it depends on the temperature, emissivity, and reflectivity of a surface. Net radiation is measured routinely at only a few climatological stations partly because of the problem of providing a standard surface but also because instruments in the past were difficult to maintain. More robust instruments consisting of four independent sensors for the components of $\mathbf{R}n$ are now available from several manufacturers (e.g. from Kipp and Zonen B.V., Delft, The Netherlands) which make the task of observing and interpreting Rn at climatological sites more feasible. Examples of annual and daily measurements follow.

Figure 15 shows the annual change of components in the net radiation balance of a short grass surface at Hamburg, Germany (54◦N, 10◦E) from February 1954 to January 1955. Each entry in the graph represents the gain or loss of radiation for a period of 24 h. The largest term in the balance is $\mathbf{L}u$, the long-wave emission from the grass surface, ranging between winter and summer from about 23 to about 37 MJ m−2 day−1. The equivalent mean radiative flux density, found by dividing by the number of seconds in a day (86,400), is 270–430Wm−2. The minimum values of downward atmospheric radiation $\mathbf{L}d$ (corresponding to about 230Wm−2) were recorded in spring, presumably in cloudless anticyclonic conditions bringing very cold dry airmasses; and maximum values (≈ 380 W m−2) were recorded duringwarm humid weather in the autumn. The net loss of long-wave radiation was about 60Wm−2 on average (cf. 100Wm−2 for cloudless skies on p. 72) andwas almost zero on a few, very foggy days in autumn and winter.

In the lower half of the diagram, the income of short-wave radiation forms a Manhattan skyline with much larger day-to-day changes and a much larger seasonal amplitude than the income of long-wave radiation. The maximum value of $\mathbf{S}t$ is about 28 MJ m−2 day−1 (320Wm−2) and $\mathbf{S}t$ is smaller than Ld on every day of the year .The reflected radiation is about 0.25$\mathbf{S}t$ except on a few days in January and February

when snow increased the reflection coefficient to between 0.6 and 0.8. The net radiation $\mathbf{Rn}$ given by $(1 − \rho)\mathbf{St} + \mathbf{Ld} − \mathbf{Lu}$ is shown in the top half of the graph. During summer at this northerly site (54◦N), the ratio of daily $\mathbf{Rn}/\mathbf{St}$ was almost constant from day to day at about 0.57, but the ratio decreased during the autumn and
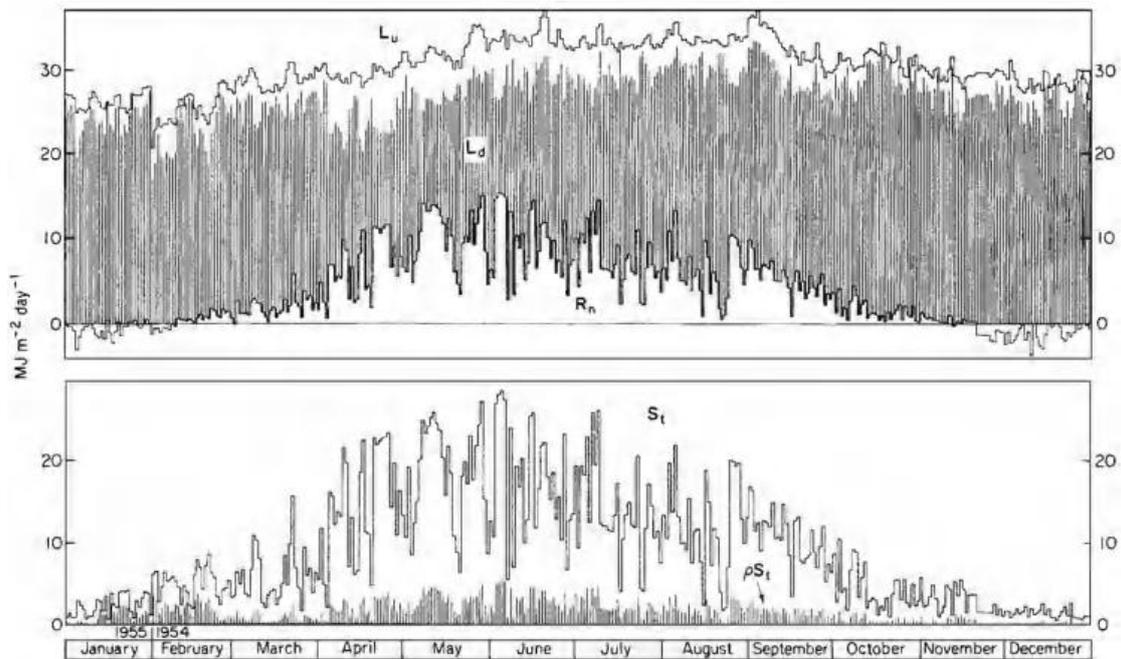

Figure 15 Annual radiation balance at Hamburg, Germany, 1954/55: $\mathbf{St}$, total solar radiation; $\rho\mathbf{St}$, reflected solar radiation; $\mathbf{Lu}$, upward long-wave radiation; $\mathbf{Ld}$, downward long-wave radiation; $\mathbf{Rn}$, net radiation (after Fleischer, 1955).

reached zero in November. From November until the beginning of February daily $\mathbf{Rn}$ was negative on most days. In summer, net radiation and mean air temperature were positively correlated with sunshine. In winter, with the sun low in the sky and the days short, the correlation was negative: sunny cloudless days were days of minimum net radiation with the mean air temperature below average.

Staff at the University of Bergen maintained records of incoming short- and long wave radiation for many years and overcame the problem of maintaining a standard surface by using black-body radiation at air temperature for $\mathbf{Lu}$ and by adopting a reflection coefficient of 0.2 (grass) or 0.7 (snow) as appropriate (The device of referring net radiation to a surface at air temperature is convenient in *micro*climatology too (see p. 229) and deserves to be more widely adopted.) The

shaded part of Figure 16 represents the difference between the fluxes **L**d and **L**u i.e. the net loss of long-wave radiation; the bold line is **R**n. In cloudless weather, the diurnal change in the two long-wave components is much smaller than the change of short-wave radiation which follows an almost sinusoidal curve. The curve for net radiation is therefore almost parallel to the **S**t curve during the day, decreases to a minimum value in the early evening, and then increases very slowly for the rest of the night (because the lower atmosphere is cooled by radiative exchange with the earth's surface). In summer, the period during which **R**n is positive is usually about 2 or 3 h shorter than the period during which **S**t is positive. Comparison of the curves for clear spring and winter days (Figure 15a and b) shows that the seasonal change of **R**n/**S**t noted in Figure 14 is a consequence of

(i) the shorter period of daylight in winter and (ii) much smaller maximum values of **S**t, in winter, unmatched by an equivalent decrease in the net long-wave loss. Figures 17 and 18 show the net radiation balances during several cloudless days of short grass (Corvallis, Oregon), and of an old-growth Douglas fir/Western Hemlock forest(Wind River, Washington State) in the Pacific Northwest of the USA. By day, solar radiation is the dominant influence on the radiation balance. The reflection coefficient for solar radiation is about 0.23 for the grass and 0.07 for the forest, a consequence of the optical properties of the foliage and the canopy structure.

The upward long-wave radiation varies less over the forest than over the grass because the tree foliage remains close to air temperature during the day whereas the short grass gets much warmer than the air. At night, the net radiation over both surfaces is most strongly negative shortly after sunset when the canopies are warmer than they are later in the night, and consequently lose more radiation to the cloudless sky. Unusually, net radiation at night is similar in magnitude over both canopies. More typically, if wind speeds had been similar over the grass and the forest, heat stored in the soil would have flowed upwards to keep the grass canopy warmer than the more isolated forest canopy. It is likely that the dry soil in summer did not conduct heat effectively in this example. Figures 17 and 18 demonstrate a good correlation between **R**n and **S**t which could be used to estimate **R**n from total solar radiation records (a method that has commonly been used (e.g. Kaminsky and Dubayah, 1997)). However, the principles
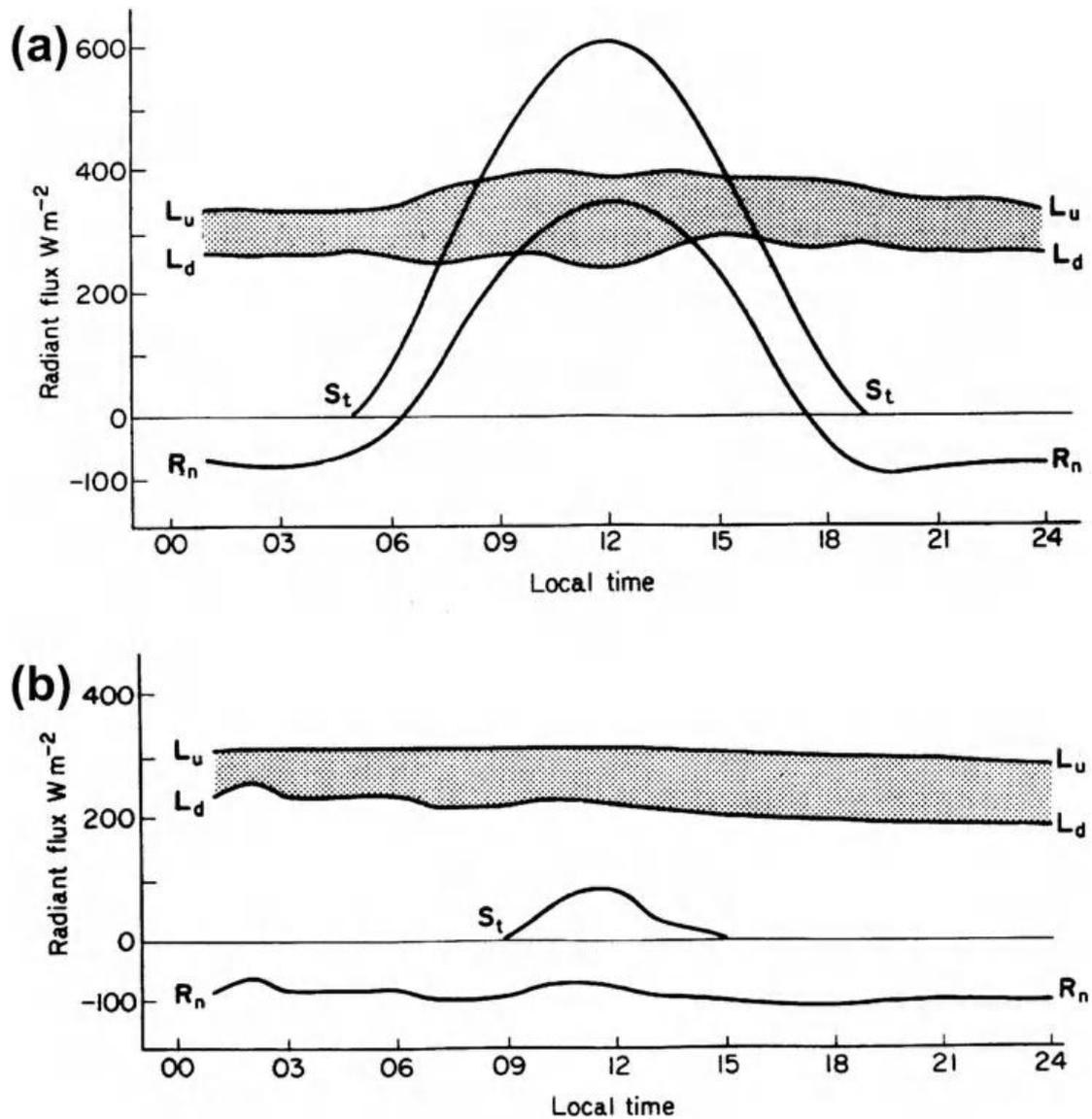
Figure 16 Radiation balance at Bergen, Norway (60◦N, 5◦E): (a) on 13 April 1968, (b) on 11 January 1968. The gray area shows the net long-wave loss and the line **R**n is net radiation.

Note that net radiation was calculated from measured fluxes of incoming short- and long-wave radiation, assuming that the reflectivity of the surface was 0.20 in April (e.g. vegetation) and 0.70 in January (e.g. snow). The radiative temperature of the surface was assumed equal to the measured air temperature.
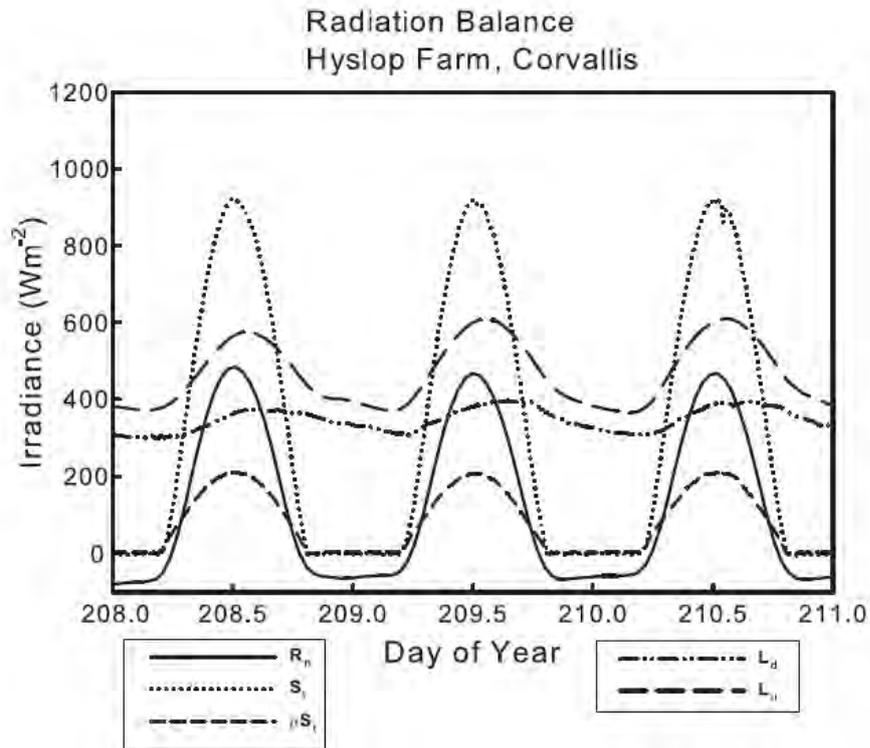
Radiation Balance
Hyslop Farm, Corvallis

Figure 17 Components of the net radiation balance during three cloudless days over short grass near Corvallis Oregon (45◦N, 123◦W). (data courtesy of Reina Nakamura, Oregon State University.)
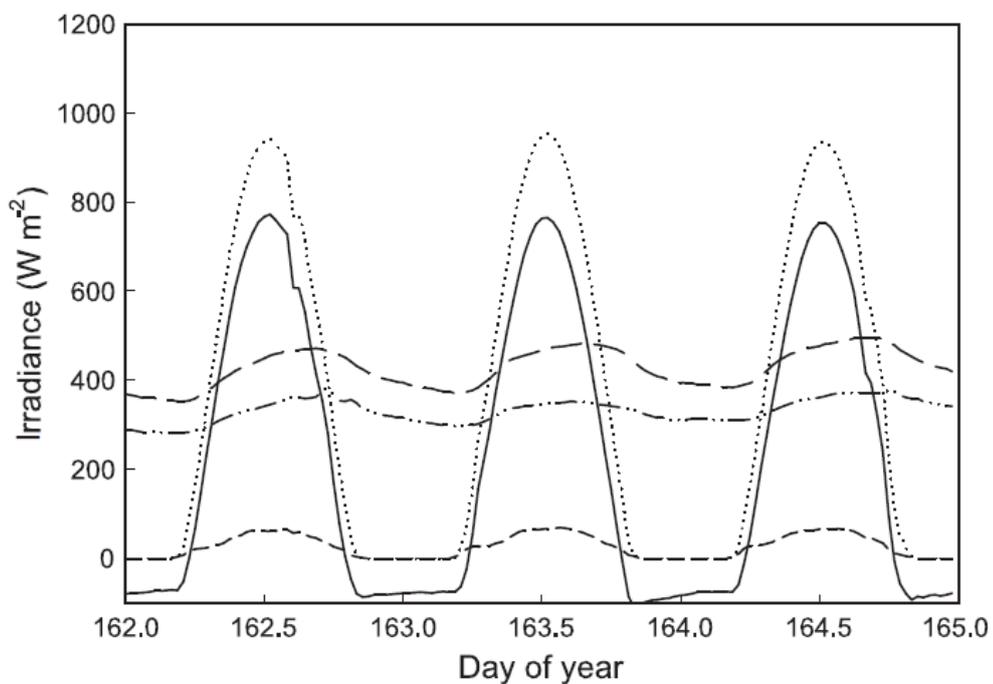

Figure 18 Components of the net radiation balance during three cloudless days over an old growth Douglas fir/Western Hemlock forest at Wind River Experimental

Forest, Washington, (46°N, 120°W). Legends and line type are as in Fig. 5.17. (data courtesy of Ken Bible, University of Washington.)

summarized in this chapter show that such an approach is not only site dependent, but also surface dependent, so that methods for estimating **R**n from its components are preferable (Offerle et al., 2003).

In the material just presented we have concentrated primarily on radiation fluxes when skies are cloudless because these conditions provide maximum daily energy to the surface and are most amenable to analysis. In overcast weather, with low cloud, **L**d becomes almost equal to $\zeta T 4 a$, so the net long-wave exchange is close to zero and **R**n is almost zero at night. During the day under overcast skies **R**n ≈ $(1 - \rho)$**S**t.

Problems

1. Estimate the time difference between sunset and the beginning of civil twilight in Greenwich, England (51.5°N, 0.0°W) on 21 June (solar declination 23.5°).

2. Use the simple model for solar radiation under cloudless skies (p. 64) to estimate the direct, diffuse, and total solar irradiance on a horizontal surface at 45°N at local solar noon on 21 June for three values of aerosol optical thickness, 0.05, 0.20, 0.40. Assume that the optical thickness for molecular attenuation is 0.30.

3. Using the results of Question 2, estimate the daily insolation at 45°N at solar noon on 21 June for the three aerosol loadings assuming cloudless sky.

4. Assuming a cloudless sky, estimate the downward long-wave irradiance and the atmospheric emissivity at the ground when the air temperature is 25 °C. If the sky was covered by 50% cloud, estimate the long-wave irradiance in this case. Why are these values only climatological approximations?

5. Four solar radiometers are exposed side by side. A and B have clear glass domes transmitting all wave lengths in the solar spectrum; C and D have domes that transmit 95% of the radiant energy from 700 to 3000 nm and no radiation below 700 nm. A and C receive global (total) radiation whereas B and D have a shade ring that intercepts 10% of radiation from the sky as well as all the direct solar beam. On a cloudless summer day the instruments give the following outputs: A 11.00 mV; B 1.30 mV; C 5.30 mV; and D 0.25 mV. Assuming that all instruments have the same sensitivity, 12.0 μVW−1 m−2, calculate

(i) the ratio of diffuse to global radiation,

(ii) the fraction of photosynthetically active radiation (0.4–0.7 μm) in the diffuse component,

(iii) the fraction of visible radiation in the direct solar beam, and

(iv) the global irradiance in the photosynthetically active waveband.

6. A farmer plans to plant seeds in a field of soil with a solar radiation reflection coefficient $\rho s = 0.20$. She decides that the soil will be warmer (and germination more rapid) if she spreads a thin layer of black soot over it, decreasing the solar radiation reflection coefficient to $\rho\_s = 0.05$. To assess the effect of the change, she prepares adjacent plots and records the following data around noon on a cloudless day: Incident total solar irradiance $\mathbf{S}t = 900 Wm{-2}$ (same for both plots). Difference in net radiation $\mathbf{R}n(soot\text{-}covered) - \mathbf{R}n(bare\ soil) = 69 Wm{-2}$. Radiative temperature of bare soil $Ts = 303\ K$.

Estimate the radiative temperature of the soot-covered surface, stating any assumptions that you need to make.

Steady-State Heat Balance

(i) Water Surfaces, Soil, and Vegetation The heat budgets of plants and animals will now be examined in the light of the principles and processes considered in previous chapters. The First Law of Thermodynamics states that when a balance sheet is drawn up for the flow of heat in any physical or biological system, income and expenditure must be exactly equal. In environmental physics, radiation and metabolism are the main sources of heat income; radiation, convection, and evaporation are methods of expenditure.

For any component of a system, physical or biological, a balance between the income and expenditure of heat is achieved by adjustments of temperature. If, for example, the income of radiant heat received by a leaf began to decrease because the sun was obscured by cloud, leaf temperature would fall, reducing expenditure on convection and evaporation. If the leaf had no mass and therefore no heat capacity, the decrease in expenditure would exactly balance the decrease in income, second by second. For a real leaf with a finite heat capacity, the decrease in temperature would lag behind the decrease in radiation and so would the decrease in expenditure on convection and evaporation, but the First Law of Thermodynamics would still be satisfied because the

reduced income from radiant heat would be supplemented by the heat given up by the leaf as it cooled. This chapter is concerned with the heat balance of relatively simple systems in which

(a) temperature is constant so that changes in heat storage are zero and

(b) metabolic heat is a negligible term in the heat budget. The heat budget of warm blooded animals, controlled by metabolism.

1 Heat Balance Equation

The heat balance of any organism can be expressed by an equation with the form

$$R_n + M = C + \lambda E + G. \quad (13.1)$$

The individual terms are

R_n = net gain of heat from radiation,

M = net gain of heat from metabolism,

C = loss of sensible heat by convection,

λE = loss of latent heat by evaporation,

G = loss of heat by conduction to environment.

The over bars in Eq. (13.1) indicate that each term is an average heat flux per unit surface area. (In the rest of this chapter, they are implied but not printed.) In this context, it is convenient to define surface area as the area from which heat is lost by convection although this is not necessarily identical to the area from which heat is gained or lost by radiation. The conduction term G is included for completeness but is negligible for plants and has rarely been measured for animals. An equation similar to (13.1) applies to bare soil surfaces or water bodies but without the term M.

The grouping of terms in the heat balance equation is dictated by the arbitrary sign convention that fluxes directed away from a surface are positive. (When temperature decreases with distance z from a surface so that $\partial T / \partial z < 0$, the outward flux of heat $C \propto -\partial T / \partial z$ is a positive quantity, see p. 29.) The sensible and latent heat fluxes C and λE are therefore taken as *positive* when they represent losses of heat from the surface to the atmosphere, and as *negative* when they represent gains. On the left-hand side of the equation, R and M are positive when they represent gains and negative when they represent losses of heat. When both sides of a heat balance equation are positive, the equation is a statement of how the total supply of heat available from sources is

divided between individual sinks. When both sides are negative, the equation shows how the total demand for heat from sinks is divided between available sources.

The sections which follow deal with the size and manipulation of individual terms in the heat balance equation (13.1), with some fundamental physical implications of the equation, and with several examples of biological applications.

1.1 Convection and Long-Wave Radiation

When the surface of an organism loses heat by convection, the rate of loss per unit area is determined by the scale of the system as well as by its geometry, by wind speed, and by temperature gradients. Convection is usually accompanied by an exchange of long-wave radiation between the organism and its environment at a rate which depends on geometry and on differences of radiative temperature but is independent of scale. The significance of scale can be demonstrated by comparing convective and radiative losses from an object such as a cylinder with diameter d and uniform surface temperature T_0 exposed in a wind tunnel whose internal walls are kept at the temperature T of the air flowing through the tunnel with velocity u. When Re exceeds 10^3, the resistance to heat transfer by convection increases with d according to the relation $r_H = d/(\kappa Nu) \propto d^{0.4} V^{-0.6}$

In contrast, the corresponding resistance to heat transfer by radiation r_R (p. 41) is independent of d. Figure 13.1 compares r_H and r_R for cylinders of different diameters at wind speeds of 1 and 10 m s^{-1} chosen to represent outdoor conditions. Corresponding rates of heat loss are shown in the right-hand axis for a surface temperature excess $(T_0 - T)$ of 1 K.
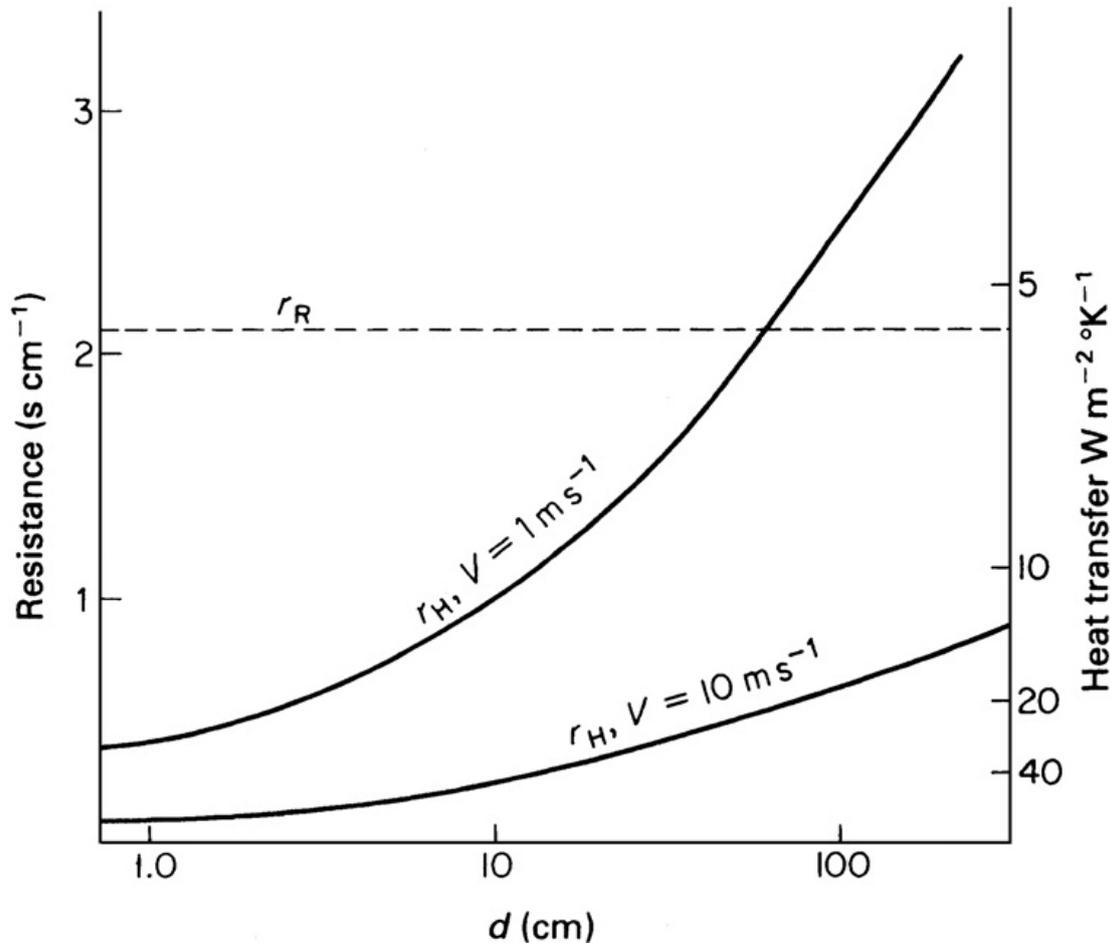
Figure 1 Dependence of resistance to convective heat transfer rH and resistance to radiative heat exchange rR as a function of body size represented by the characteristic dimension of a cylinder d.

The cylinder is assumed exposed in a wind tunnel where air and wall radiative temperatures are identical. The curves are calculated for wind speeds, V, of 1 m s−1 and 10 m s−1. The right-hand axis shows the rate of heat transfer assuming a difference of 1 K between cylinder surface temperature and air/wall radiative temperature. Because the dependence of rH on scale and windspeed is similar for planes, cylinders, and spheres provided that the appropriate dimension is used to calculate Nusselt numbers, a number of generalizations may be based on Figure 13.1. For organisms on the scale of a small insect or leaf (0.1 < d < 1 cm), rH is much smaller than rR, implying that convection is a much more effective mechanism of heat transfer than long-wave radiation. The organism is tightly coupled to air temperature but not to the radiative temperature of the environment. For organisms on

the scale of a farm animal or a man *(10 < d < 100 cm)* rH and rR are of comparable importance at low wind speeds.

For very large mammals *(d > 100 cm)*, rH can exceed rR at low wind speeds, and in this case the surface temperature will be coupled more closely to the radiative temperature of the environment than to the air temperature. These predictions are consistent with measurements on locusts and on piglets, for example, and they emphasize the importance of wall temperature as distinct from air temperature in determining the thermal balance of large farm animals in buildings with little ventilation. They also explain why warming the air in a cold room does not induce a feeling of comfort for people occupying the room if the radiative temperature of the walls remains low. When an organism with an emissivity of unity and a surface temperature of $T0$ exchanges heat (a) by convection to air at temperature T and (b) by radiation to an environment with a mean radiative temperature equal to air temperature, the net rate at which heat is gained or lost is

$$\rho c_p \left\{ (T - T_0)/r_H + \left((T - T_0)/r_R \right) \right\} = \rho c_p \left\{ (T - T_0)/r_{HR} \right\}, \qquad (13.2)$$

where rHR $= \_ r^{-1}$ H $+ r^{-1}$ R $\_^{-1}$ is a combined resistance for convection (p. 31) and long-wave radiation formed by grouping the component resistances in parallel because the fluxes are in parallel.

Heat Balance of Thermometers

1 Dry-Bulb

As an introduction to the more relevant physics of the wet-bulb thermometer, it is worth considering the implications of the general heat balance equation for a dry-bulb thermometer (i.e. a thermometer with a dry sensing element). For measurements in the open, it is essential to avoid heating a thermometer by direct exposure to sunlight, so screening is employed. In several common designs used for precise measurements of air temperature, a thermometer with a cylindrical bulb is housed in a tube through which air is drawn rapidly, and for the sake of the following discussion we assume that the tube completely surrounds the bulb. If the tube itself is exposed to sunshine, its temperature, Ts, may be somewhat above the temperature of the air (T) and of the thermometer (Tt).

The net long-wave radiation received by the thermometer from the housing (assuming emissivity $\varepsilon = 1$) is

$$\mathbf{R_n} = \sigma \left(T_s^4 - T_t^4 \right) = \rho c_p \left(T_s - T_t \right) / r_R$$

using the definition of rR on p. 41 with the assumption that Ts − Tt is small. The loss of heat by convection from the bulb to the air is

$$\mathbf{C} = \rho c_p \left(T_t - T \right) / r_H.$$

In equilibrium, heat balance equation (13.1) reduces to $\mathbf{R_n} = \mathbf{C}$ and rearrangement of terms in Eq. (13.4) gives

$$T_t = \frac{r_H T_s + r_R T}{r_R + r_H}$$

indicating that the temperature recorded by the thermometer (the apparent temperature) is a weighted mean between the true temperature of the air and the temperature of the thermometer housing. There are two main ways in which the difference between apparent and true air temperature can be minimized:

i. by making rH much smaller than rR (i.e. decoupling the sensor from the radiative environment), either by adequate ventilation or by choosing a thermometer with very small diameter (see Figure 13.1). The numerator in Eq. (13.5) then tends to rRT and the denominator to rR.

ii. by making Ts very close to T , e.g. by using a reflective metal or white painted screen, by introducing insulation between outer and inner surfaces, or by increasing ventilation on both sides of the screen.

In the standard instrument known as an *Assmann psychrometer*, the screen is a double-walled cylinder, nickel-plated on the outer surface, and aspirated at about 3 m s−1. Since the diameter of the mercury-in-glass thermometer it contains is about 3 mm, Figure 1 illustrates that it is effectively decoupled from its radiative environment

(rH _ rR).

2 Wet-Bulb

The concept of a ―wet-bulb temperature" is central to the environmental physics of systems in which latent heat is a major heat balance component, and it has two distinct connotations: the *thermodynamic wet-bulb temperature*, which is a theoretical abstraction and the temperature of a thermometer with its sensing element covered with a wet sleeve, which, at best, is a close approximation to the thermodynamic wet-bulb temperature.

A value for the thermodynamic wet-bulb temperature can be derived by considering the behavior of a sample of air enclosed with a quantity of pure water in a container with perfectly insulating walls. This is an *adiabatic system* within which the sum of sensible and latent heat must remain constant. The initial state of the air can be specified by its temperature T, vapor pressure e, and total pressure p. Provided e is smaller than es(T), the saturated vapor pressure at T, water will evaporate and both e and p will increase. Because the system is adiabatic, the increase of latent heat represented by the increase in water vapor concentration must be balanced by a decrease in the amount of sensible heat which is realized by cooling the air. The process of humidifying and cooling continues until the cooling air becomes saturated at a temperature T _ which, by definition, is the thermodynamic wet-bulb temperature i.e. the thermodynamic wet bulb temperature is the minimum temperature which may be achieved by bringing an air parcel to saturation by evaporation in adiabatic conditions. The corresponding saturated vapor pressure is es$(T$ _ $)$.

To relate T _ and es$(T$ _ $)$ to the initial state of the air, the initial water vapor concentration is approximately $\rho\varepsilon e/p$ when p is much larger than e (see p. 15). When the vapor pressure rises from e to es$(T$ _ $)$, the total change in latent heat content per unit volume is $\lambda\rho\varepsilon$ _ es$(T$ _ $) - e$ $/p$. The corresponding amount of heat supplied by cooling unit volume of air from T to T _ is ρcp$(T - T$ _ $)$. (A small change in the heat content of water vapor is included in more rigorous treatments but is usually unimportant in micrometeorological problems.) Equating latent and sensible heat

$$\lambda \rho \varepsilon \left[e_s(T') - e \right] / p = \rho c_p \left(T - T' \right)$$

and rearranging terms gives

$$e = e_s(T') - (c_p p / \lambda \varepsilon)(T - T').$$

The group of terms *(cp p/λε)* is often called the "psychrometer constant" for reasons explained shortly, but it is neither constant (because p is atmospheric pressure and λ changes somewhat with temperature) nor exact (because of the approximations made).

The psychrometer constant is often assigned the symbol γ and, at a standard pressure of 101.3 kPa, has a value of about 66 Pa K−1 at 0 °C increasing to 67 Pa K−1 at 20 °C. Thus

$$e = e_s(T') - \gamma (T - T').$$

Another useful quantity which has the same dimensions as γ is the change of saturation vapor pressure with temperature or $\partial e_s(T)/\partial T$, usually given the symbol (or s) . This quantity can be used to obtain a simple (but approximate) relation between the saturation vapor pressure deficit $D = e_s(T) - e$ and the wet-bulb depression $B = T - T\_$. When the saturation vapor pressure at wet-bulb temperature $T\_$ is written as

$$e_s(T') \approx e_s(T) - \Delta \left(T - T' \right),$$

where is evaluated at a mean temperature of $(T + T\_)/2$, the psychrometer equation (13.7) becomes

$$e \approx e_{\mathrm{s}}(T) - (\Delta + \gamma)(T - T')$$

or

$$D \approx (\Delta + \gamma) B.$$

Equation (13.7) can be represented graphically by plotting *es(T)* against *T* (Figure 13.2). The curve QYP represents the relation between saturation vapor pressure and temperature and the point X represents the state of any sample of air in terms of *e* and *T* . Suppose the wet-bulb temperature of the air is *T* _ and that the point Y represents the state of air saturated at this temperature. The equation of the straight line XY joining the points *(T, e), (T* _ *, es(T* _ *))* is

$$e - e_{\mathrm{s}}\left(T'\right) = \mathrm{slope} \times \left(T - T'\right).$$

Comparison of Eqs. (13.7) and (13.11) shows that the slope of XY is −γ. The wet-bulb temperature of any sample of air can therefore be obtained graphically by drawing a line with slope −γ through the appropriate coordinates *T* and *e* to intercept the saturation curve at a point whose abscissa is *T* _.

If a sample of air in the state given by X was cooled toward the state represented by the point Y, the path XY shows how temperature and vapor pressure would change in adiabatic evaporation, i.e. with the total heat content of the system constant. Similarly, starting from Y and moving to X, the path YX shows how *T* and *e* would change
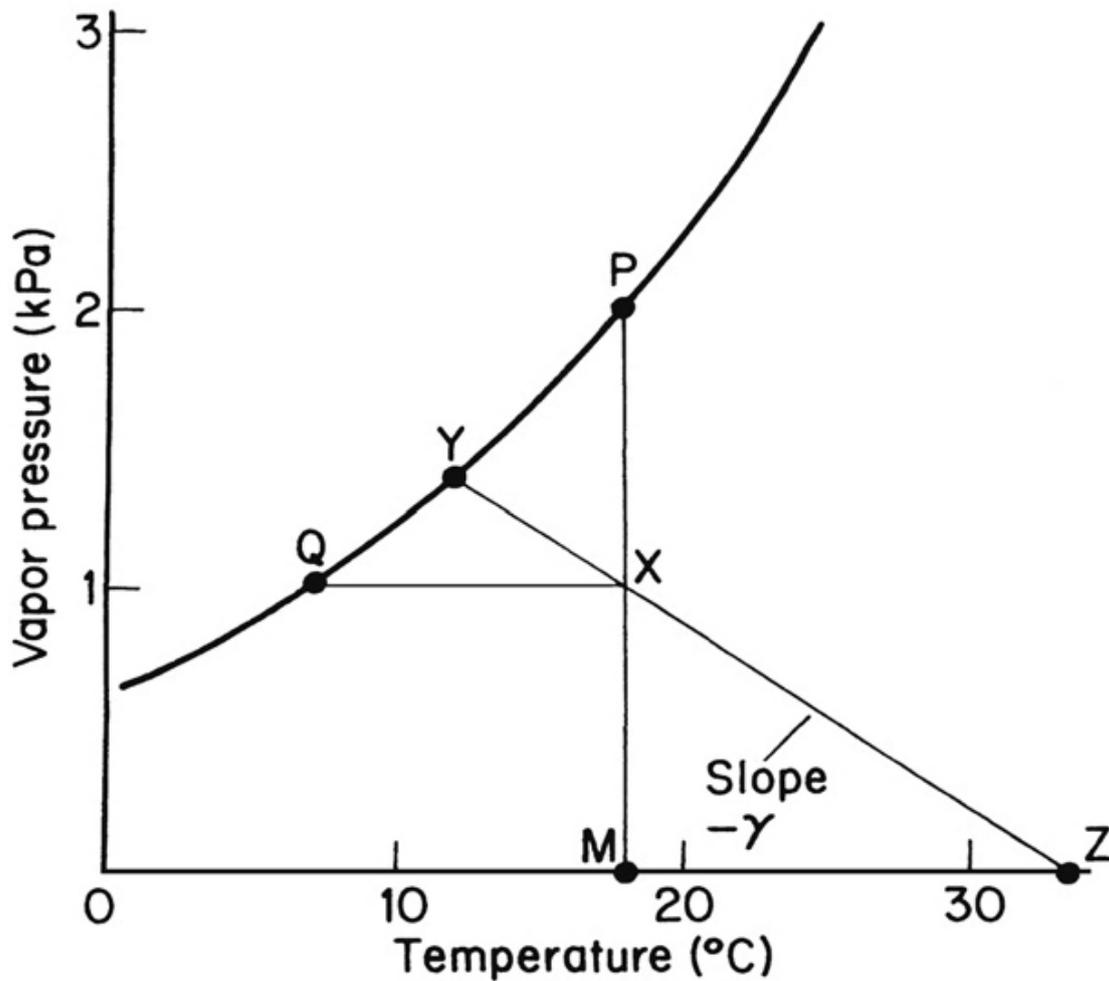
Figure 2 The relation between dry-bulb temperature, wet-bulb temperature, equivalent temperature, vapor pressure, and dew point. The point X represents air at 18 °C and 1 kPa vapor pressure. The line YXZ with a slope of $-\gamma$ gives the wet-bulb temperature from Y (12 °C) and the equivalent temperature from Z (33.3 °C). The line QX gives the dew-point temperature from Q (7.1 °C). The line XP gives the saturation vapor pressure from P (2.1 kPa).

if water vapor were condensed adiabatically from air that was initially saturated. As condensation proceeded, the temperature of the air would rise until all the vapor had condensed. This state is represented by the point Z at which $e = 0$. The corresponding temperature $T\mathrm{e}$ is called the ―*equivalent temperature*" of the air. As Z has coordinates $(T\mathrm{e}, 0)$, the equation of the line ZX can be written in the form

$T\mathrm{e} = T + e/\gamma.$ (13.12)

Alternatively, the equation of YZ can be written

$Te = T\_ + es\_T\_\_/\gamma$, (13.13)

showing that the equivalent and wet-bulb temperatures are uniquely related. Both $T\_$ and Te remain unchanged when water is evaporated or condensed adiabatically within a sample of air.

Moving from theoretical principles to a real wet-bulb thermometer, it is necessary to account for the finite rate at which heat is lost by evaporation and gained by convection and radiation.

Suppose that a thermometer bulb covered with a wet sleeve has a temperature Tw when it is exposed to air at temperature T and surrounded by a screen that is also at air temperature. The rate at which heat is gained by convection and radiation is

$\mathbf{C} + \mathbf{Rn} = \rho cp\_T - Tw\_/r\mathrm{HR}$. ((cf. Eq. (13.2)). The rate at which latent heat is lost may be found by applying the principles of equation (11.3) to give

$\lambda\mathbf{E} = \lambda \{\chi s(Tw) - \chi\} /rv$. (13.15)

where χ is absolute humidity. Using the relations in Eq. (2.28), Eq. (13.15) may be written

$\lambda\mathbf{E} = \_\lambda\rho\varepsilon/p\_\_es\_Tw\_ - e\_/rv = \rho cp\_es\_Tw\_ - e\_/\gamma rv$. (13.16)

In equilibrium, $\lambda\mathbf{E} = \mathbf{Rn} + \mathbf{C}$ from which

$e = es\_Tw\_ - \gamma\_rv/r\mathrm{HR}\_\_T - Tw\_$. (13.17)

It is often convenient to regard ($\gamma\ rv/r\mathrm{HR}$) (or simply ($\gamma\ rv/r\mathrm{H}$) in some circumstances explained below) as a *modified psychrometer constant*, written $\gamma *$. That is

$e = es\_Tw\_ - \gamma *\_T - Tw\_$. (13.17a)

Comparing Eqs. (13.7a) and (13.17), it is clear that the measured wet-bulb temperature will not be identical to the thermodynamic wet-bulb temperature unless $rv = r\mathrm{HR}$. Because $rv = (\kappa/D)0.67r\mathrm{H}$, which may be written $rv = 0.93r\mathrm{H}$ (p. 181), this condition implies that

$0.93r\mathrm{H} = \_r^{-1}\mathrm{H} + r^{-1}\mathrm{R}\_^{-1}$ (13.18)

from which $r\mathrm{H} = 0.075r\mathrm{R}$. At 20 ∘C, $r\mathrm{R} = 2.1$ s cm−1, so the thermodynamic and measured wet-bulb temperatures would be identical when $r\mathrm{H} = 0.17$ s cm−1. A wet-bulb thermometer would therefore record a temperature above or below the thermodynamic wet-bulb temperature depending on whether $r\mathrm{H}$ was greater or less than this value.

Because both r_v and r_H are functions of windspeed and r_R is not, $\gamma *$ decreases with increasing wind speed and, when r_v is much less than r_R, tends to a constant value independent of wind speed, viz.

$\gamma * = \gamma \_ r_v/r_H \_ = 0.93\gamma.$ (13.19)

In the Assmann psychrometer, regarded as a standard for measuring vapor pressure in the field, the resistances corresponding to the instrument specification already given are $r_v = 0.149$ s cm−1, $r_H = 0.156$ s cm−1 giving $\gamma * = 63$ Pa K−1. A much more detailed discussion of psychrometry leading to a standard value of 62 Pa K−1 for the Assman psychrometer was given by Wylie (1979).With this and similar instruments, the error involved in using γ instead of $\gamma *$ is often negligible in micrometeorological work.

A further source of psychrometer error not considered here (but treated by Wylie, 1979) is the conduction of heat along the stem of the thermometer which can be minimized by using a long sleeve and/or a thermometer with very small diameter.

Problems

1. A cylindrical thermometer element, diameter 3 mm is enclosed in a radiation shield that excludes all solar radiation but is 5.0 °C warmer than the true air temperature which is 20 °C. If the thermometer is to record a temperature within 0.1 °C of true air temperature, at what wind speed must the element be ventilated? (Assume long-wave emissivities of 1.0.)

2. Awet-bulb thermometer in a radiation shield has a cylindrical element 4 mm diameter. Estimate the radiative resistance assuming that the temperatures of the wet-bulb and the shield are about 10 °C. Hence, plot a graph to show how the difference between measured and thermodynamic wet-bulb temperatures would vary with ventilation speed over the range 0.5–5 m s−1 .

3. A leaf has a boundary layer resistance for heat transfer (both surfaces in parallel) of 40 s m−1, and a combined stomatal and boundary layer resistance of 110 s m−1. Taking air temperature as 22 °C and vapor pressure as 1.0 kPa, set up a spread sheet to calculate the rates of sensible heat transfer **C**, latent heat transfer λ**E**, and the sum **C**+λ**E** as a function of leaf temperature over the range 20–26 °C. Hence find

graphically or otherwise the leaf temperature when the net radiation absorption by the leaf is 300 W m−2.

4. For the data in question 3, use the Penman-Monteith Equation to determine the latent heat flux from the leaf and hence determine the sensible heat flux and leaf temperature.

5. Show, using the Penman-Monteith Equation, that the necessary condition for dewfall is − $\mathbf{R}$n > ρcp {es (T) − e} r−1 H , and that the maximum rate of dew-fall is $\mathbf{E}$max = $\mathbf{R}$n/λ(+ γ *). On a cloudless night, the net radiation flux density of an isolated leaf at air temperature T (K) is given by the empirical expression $\mathbf{R}$n = (0.206e0.5−0.47)ζ T 4, where e (kPa) is the vapor pressure. Neglecting other sources of heat, plot a graph to show how the maximum rate of dew-fall on the leaf varies with air temperature on the range 0–25 ∘C, and explain your results.

6. A marathon runner, treated as a cylinder with diameter 33 cm moving at 19 km h−1 relative to the surrounding air, has a net radiation load of 300 W m−2. The air temperature and vapor pressure are 30 ∘C and 2.40 kPa, respectively. Assuming that the runner's skin is covered with sweat that is a saturated salt solution for which the relative humidity of air in contact with the solution is 75%. Estimate the rate of latent heat loss. If all the salt could be washed off when the runner was sprayed with water, what would be the new rate of latent heat loss?

7. On the Oregon coast, Sitka spruce is frequently exposed to wind-driven sea spray. In the extreme case where water on needle surfaces is saturated with sea salt (equilibrium relative humidity 75%), by how much would the needle decoupling coefficient be changed relative to needles with pure water on their surfaces?
Assume a wind speed of 5 m s−1 and needle dimension of 1 mm.

Heat Balance Components

Metabolism (M)

Standard measurements of the *basal metabolic rate* (BMR) are made when an animal has been deprived of food and is resting in an environment wheremetabolic rate is independent of external temperature. It has been widely accepted by animal physiologists that the basal metabolic rate of an animal $\mathbf{M}$b (expressed here in watts and not watts per unit surface area as elsewhere) can be related to simply body mass *W* by the empirical *allometric equation*

$$\mathbf{M}b = BW^n, \quad (14.2)$$

where B is a constant, implying that $\ln\mathbf{M}b$ is a linear function of $\ln W$. Based on statistical analysis of many sets of measurements on animals of a wide range of sizes, animal physiologists concluded in the mid-20th century that $n = 0.75$ in Eq. (14.2), which became known as the 3⁄4 power law and has been widely used by animal ecologists to model metabolism in relation to body size in ecology. Kleiber (1965) suggested that, for *intra*-specific work, $B = 3.4$ (with units of W per kg$^{0.75}$); Hemmingsen (1960) found that $B = 1.8$ was a better value for inter-specific comparisons over a range of mass from 0.01 to 10 kg. For application to humans, where knowledge of BMR is important in exercise physiology and dietetics, more complicated expressions are often used, taking into account gender, height, weight, and age (Frankenfield et al., 2005); they generally agree with Eq. (14.2) within 10–20%. Hemmingsen's (1960) review also showed that the BMR of a poikilotherm kept at a body temperature of 20 ∘C is about 5% of the value for a homeotherm of the same mass with a deep body temperature of 39 ∘C. Hibernating mammals metabolize energy at about the same rate as poikilotherms of the same mass. Figure 14.1 plots the relations between BMR and body weight proposed by Hemmingsen for homeotherms and poikilotherms, and includes observed data from animals working at metabolic rates up to their maximum.

Referring basal metabolic rates to the 3/4 power of body mass is inconsistent with the physics of heat transfer since most of the energy produced in metabolism is lost from
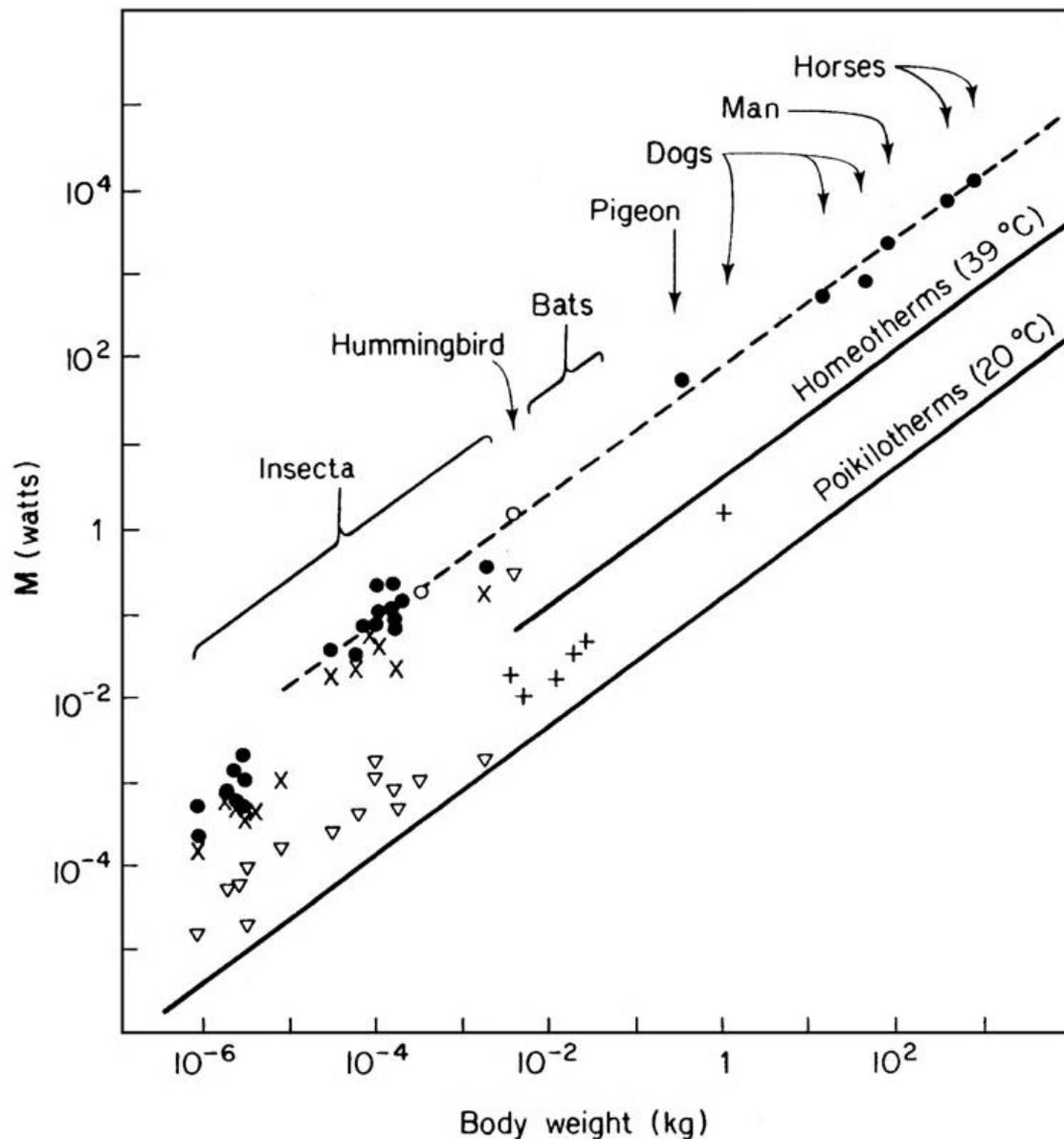

Figure 1 Relation between body weight and basal metabolic rate (BMR) of homeotherms (upper continuous line), maximum metabolic rate for sustained work by homeotherms (upper pecked line), and basal rate for poikilotherms at 20 ∘C (lower continuous line) (from Hemmingsen, 1960).

the surface of the animal. For any set of objects with identical geometry but different in size, surface area is proportional to the 2/3 power of mass, assuming constant mass per unit volume. It follows that if basal metabolic rates were proportional to surface

area, they would be proportional to the 2/3 power of mass, at least when animals of like geometry are compared. In a careful re-examination of experimental data to retain only metabolic measurements taken in conditions conducive to the basal rate, Prothero (1984) found that n was closer to 2/3 than to 3/4. More recently, Roberts et al. (2010) further criticized the empirical basis of the 3/4 power law and developed a physically realistic analysis relating BMR to body size that included heat flow from the core to the surface of an animal and heat loss from the surface. Assuming that mammals of sizes ranging from a mouse to a man could be described by an ellipsoidal shape, they used experimental data in their analysis to show that Eq. (14.2) fitted their data with constants $n = 2/3$ and $B = 4.9$ with $\mathbf{M}$b in Watts and Win kg. Figure 2 shows their equation and the observed BMR data that they used. The figure also shows the relation proposed by Kleiber (1965) with $n = 3/4$ and $B = 3.4$
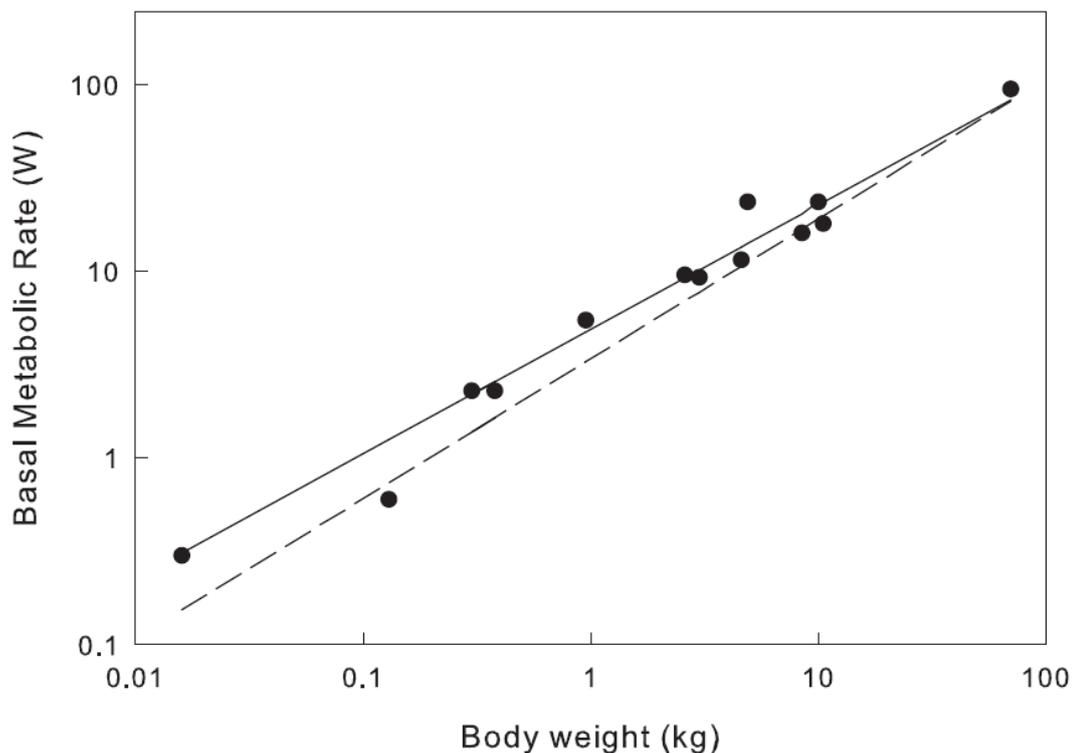

Figure 2 Relation between basal metabolic rate (BMR) of mammals and body weight. Data points represent BMR for animals ranging in size from a mouse to a human. The continuous line is the relation with $\mathbf{M} \propto W2/3$ proposed by Roberts et al. (2010); the dashed line is the relation with $\mathbf{M} \propto W3/4$ as proposed by Kleiber (1965).

Figure 14.2 shows that the proportionality between BMR and metabolic rate holds for mammals ranging in size from a mouse (0.02 kg) to a human (70 kg). The average basal metabolic rate for a mammal per unit of body surface area is about 50 W m−2. This is much smaller than the flux of short-wave radiation absorbed by a dark-coated animal in bright sunshine (say 300 W m−2) but is comparable with the energy that might be absorbed under shade. On a cloudless night, the basal metabolic rate is comparable to the net loss of heat by long-wave radiation from a surface close to air temperature. For walking or climbing, the efficiency with which man and domestic animals use additional metabolic energy is about 30%. To work against gravity at a rate of 20 W m−2, for example, metabolism must increase by about 60 W m−2. The power expended in walking increases with velocity and, in man, reaches 700 W at 2 m s−1 (about 7 km h−1 or 4.3 mph).

For rapid forms of locomotion such as running or flying, the work done against wind resistance is proportional to the wind force times the distance traveled. When the drag coefficient of a moving body is independent of velocity, the drag force should be proportional to V^2 (p. 139), and as the distance traveled is proportional to V, the rate of energy dissipation should increase with V^3. However, studies on birds by Tucker (1969) revealed a range of velocities (e.g. 7–12 m s−1 for gulls) in which the rate of energy production was almost independent of V, implying a remarkable decrease of drag coefficient with increasing velocity. To reduce the energy required to overcome drag forces, athletes such as sprinters and swimmers wear skin-tight suits of special fabrics, but the benefits may be more psychological than physiological. However, a tail-wind definitely helps sprinters; the maximum permitted tail-wind of 2 m s−1 could reduce the 100 mrunning time for a champion sprinter by more than 0.1 s by decreasing the energy expended on overcoming form drag (Barrow, 2012).

Latent Heat (λE)

In the absence of sweating or panting, the loss of latent heat from an animal is usually a small fraction of metabolic heat production and takes place both from the lungs during breathing (*respiratory evaporation*) and from the skin as a result of the diffusion of water vapor, sometimes politely referred to as ―insensible perspiration." For a man inhaling completely dry air, the vapor pressure difference between inhaled and exhaled air is about 5.2 kPa and the heat used for respiratory evaporation λE_r is the latent heat equivalent of about 0.8 mg of water vapor per ml of absorbed oxygen

(Burton and Edholm, 1955). With round figures of 2.4 J mg−1 for the latent heat of vaporization of water and 21 J ml−1 oxygen for the heat of oxidation (respiration), $\lambda E_r/M$ is about 10%.When airwith a vapor pressure of 1.2 kPa is breathed (e.g. air at about50%relative humidity and 20 ◦C), the difference of vapor pressure decreases to 4 kPa and $\lambda E_r/M$is about 7%.

In the absence of sweating, the latent heat loss from human skin (λE_s) is roughly twice the loss from respiratory evaporation, implying a total evaporative loss of the order of 25–30% of **M** depending on vapor pressure. When sweating, however, a human can produce about 1.5 kg of fluid per hour, equivalent to 600 W m−2 if the environment allows sweat to evaporate as fast as it is produced. More commonly, the rate of evaporation is restricted to a value determined by resistances and vapor pressure differences. Excess sweat then drips off the body or soaks into hair and clothing.

Sheep and pigs lack glands of the type that allow man to sweat profusely but species such as cattle and horses can lose substantial amounts of water by sweating. Dogs and cats have sweat glands only on their foot pads so lose very little heat by this mode. Sheep, dogs, and cats compensate for their inability to sweat by panting in hot environments. For cattle exposed to heat stress, the respiratory system can account for 30% of total evaporative heat loss, the remaining 70% coming from the evaporation of sweat from the skin surface and from wetted hair. The maximum evaporative heat loss from ruminants is only a little larger than metabolic heat production, whereas a sweating man can lose far more heat by evaporation than he produces metabolically if he is exposed to strong sunlight.

Inter-specific differences in $\lambda E/M$ and in mechanisms of evaporation may play an important part in adaptation to dry environments. Relatively small values of $\lambda E/M$ have been reported for a number of desert rodents which appear to conserve water evaporated from the lungs by condensation in the nasal passages where the temperature is about 25 ◦C (Schmidt-Nielsen, 1965). The respiratory system operates as a form of counter-current heat exchanger. In contrast, measurements of total evaporation from a number of reptiles yield figures ranging from 4 to 9 mg of water per ml of oxygen.

These figures imply that 50−100% of the heat generated by metabolism was dissipated by the evaporation of water, lost mainly through the cuticle. For differing animal species, the amount of body water available for evaporation depends on body

volume ,whereas the maximum rate of cutaneous evaporation depends on surface area. At one extreme, insects have such a large surface: volume ratio that evaporative cooling is an impossible luxury. Humans and larger animals can use water for limited periods to dissipate heat during stress and, in general, the larger the animal the longer it can survive without an external water supply. The camel, for example, can lose up to 30% of its body mass without harm when deprived of drinking water for long periods because it has several physiological adaptations to survive dehydration. But humans become critically dehydrated after a water loss of only about 12% of their body weight—typically about 8 l of water.

Convection (C)

Convective heat loss from animals can be an important component in the energy balance. Using principles discussed in previous chapters we can investigate the relation between skin temperature, wind speed, net radiation absorbed, and animal size. Figure 3 illustrates this analysis graphically. The left-hand side of Figure.3 demonstrates how resistance to convective heat transfer between an organism and its environment decreases as body size decreases, a significant relation in animal ecology (see also Figure 13.1). The right-hand side of the diagram, for which the theoretical basis will be discussed later (p. 262), shows the linear relationship between R_{ni} and $r^{-1} HR$ for specified values of $(T_f - T)$, the temperature difference between the organism and its environment when convection and isothermal net radiation are equated (see Eq. (13.2)). In the example given, an organism with characteristic dimension 2 cm has $r^{-1} H = 6.7$ cm s^{-1}. Transferring this to the right-hand side of the figure, we see that,
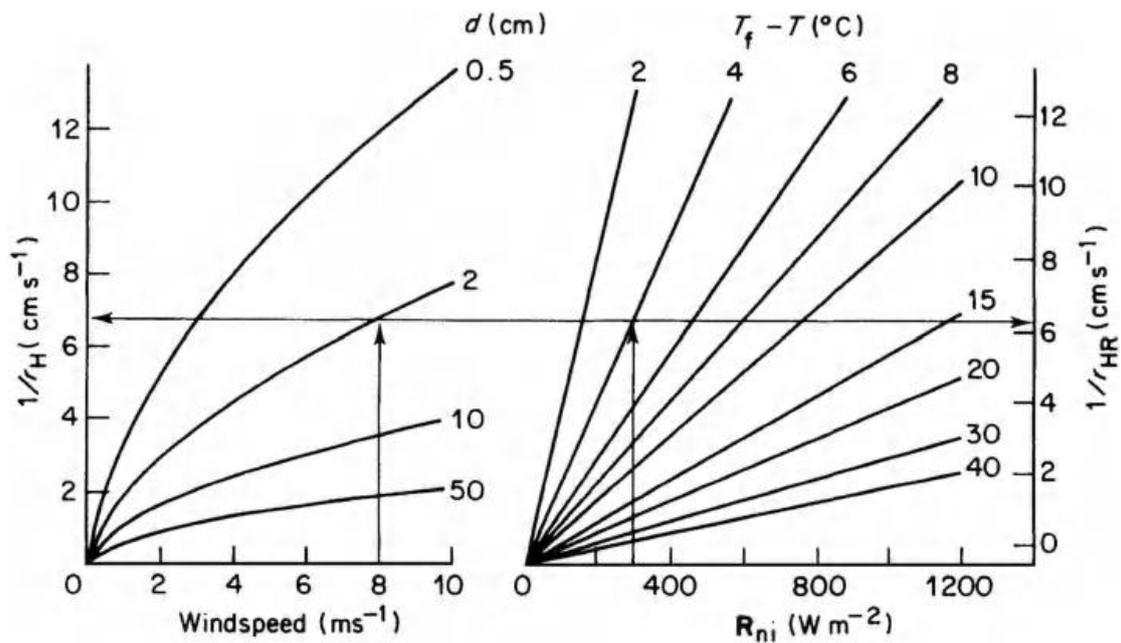
Figure 3 Diagram for estimating the thermal radiation increment (see text and p. 262) when wind speed, body size, and net radiation are known. For example, at 8 m s−1 an animal with d = 2 cmhas r−1 H = 6.7 cm s−1 and r−1 HR = 6.2 cm s−1. When **R**ni = 300 W m−2, Tf − T is 4 ◦C.

when **R**ni = 300 W m−2, $(Tf − T)$, the amount by which the effective air temperature exceeds the actual air temperature because of radiative loading (see p. 262), is 4 ◦C. Schmidt-Nielsen (1965) regarded both convective and radiative exchanges as proportional to surface area and concluded that, in the desert, ―the small animal with its relatively larger relative surface area is in a much less favourable position for maintaining a tolerably low body temperature." It is true that small animals are unable to keep cool by evaporating body water, but when convection is the dominant mechanism of heat loss they can lose heat more rapidly (per unit surface area) than large animals exposed to the same wind speed. In this context, the main disadvantage of smallness is microclimatic: because wind speed increases with height above the ground, small animals moving close to the surface are exposed to slower wind speeds than larger mammals. As rH is approximately proportional to $(d/V)0.5$, an animal with d = 5 cm exposed to a wind of 0.1 m s−1 will be coupled to air temperature in the same way as a much larger animal with d = 50 cm exposed to wind at 1 m s−1. Insects and birds in flight and tree-climbing animals escape this limitation.

Conduction (G)

Few attempts have been made to measure the conduction of heat from an animal to the surface on which it is lying. Mount (1968) measured the heat lost by young pigs to different types of floor materials and found that the rate of conduction was strongly affected by posture as well as by the temperature difference between the body core and the substrate. When the temperature of the floor (and air) was low, the animals assumed a tense posture and supported their trunks off the floor, but as the temperature was raised, they relaxed and stretched to increase contact with the floor. Figure 4 shows the heat loss per unit area, recalculated from Mount's data, for newborn pigs in a relaxed posture. As the heat flow was approximately proportional to the temperature difference, the thermal resistance for each type of floor can be calculated from the slope of the lines. The resistances are about 8, 17, and 58 s cm−1 for concrete, wood, and polystyrene, respectively. As the corresponding resistances for convective and radiative transfer are usually around 1–2 s cm−1 (Figure 13.1), it follows that heat losses by conduction to the floor of an animal house are likely to be significant only when it is made of a relatively good heat conductor such as concrete. Conduction will be negligible when the floor is wood or concrete covered with a thick layer of straw.

Gatenby (1977) measured the conduction of heat beneath a sheep with a fleece length of about 2 cm lying on grass in the open. When the deep soil temperature was 10 ◦C, downward fluxes of about 160 W/m2 of contact surface were measured when the sheep lay down, equivalent to about 40 W/m2 of body surface and therefore comparable with the loss by convection. Energy requirements for free-ranging animals therefore depend to some extent on the time spent lying, on soil temperature, and on the thermal properties of the ground.

Storage (S)

As discussed in more detail below, most homeotherms have mechanisms that maintain their core body temperature almost constant over a wide range of
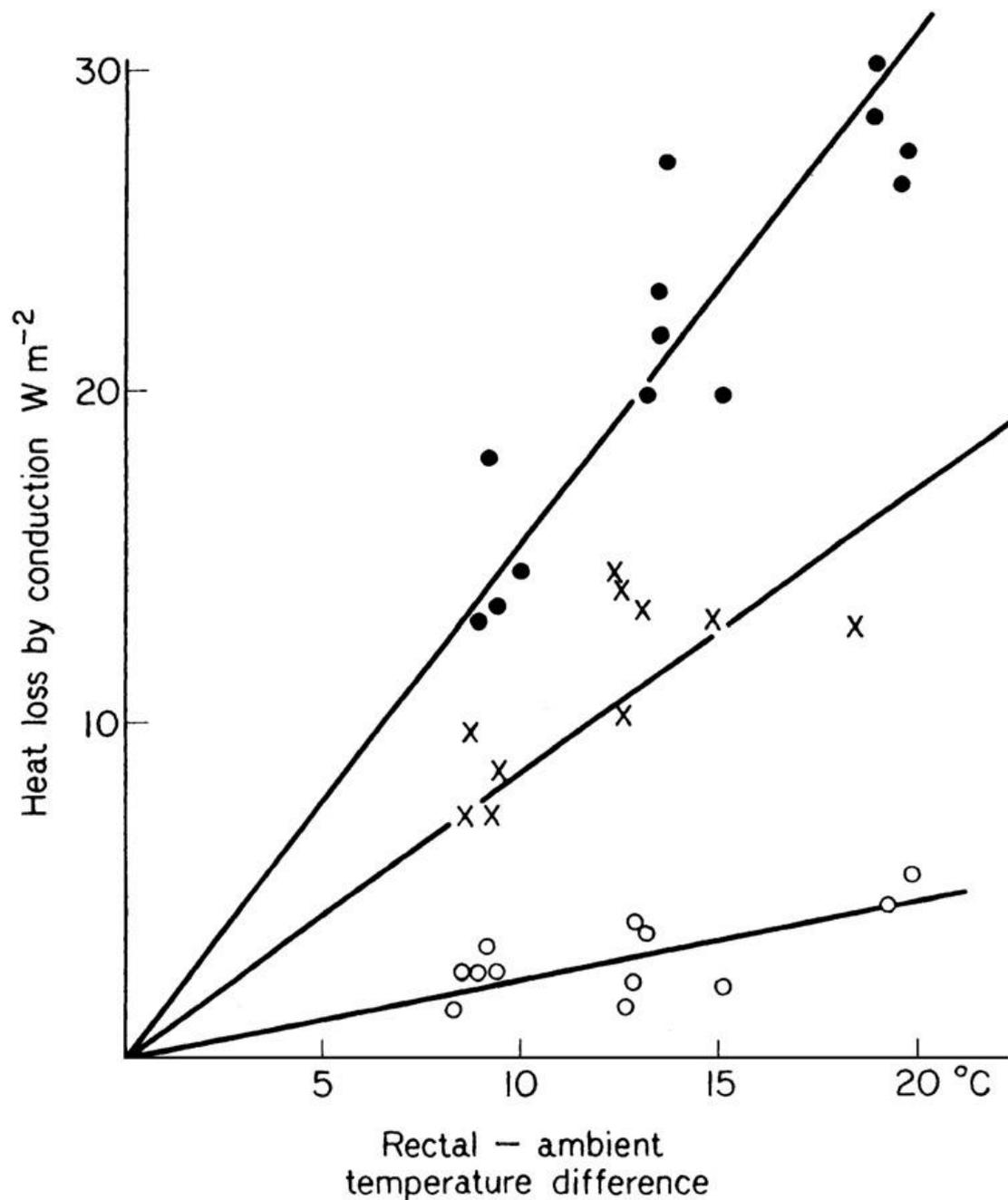
environmental

Figure 4 Measurements of heat lost by conduction from a pig to different types of floor covering expressed aswatts per square meter of total body area (after Mount, 1967).

•—concrete; X—wood; _—polystyrene. conditions. On the other hand, the body temperatures of poikilotherms vary in response to external heat inputs. All animals alter their behavior to avoid extreme conditions, e.g. seeking shade, sheltering from wind, or adopting a nocturnal lifestyle. In desert environments where day-time air temperatures may be much larger than body temperature and minimizing evaporative

loss is important, some homeotherms allow their body temperature to increase during the day, thus reducing the need for evaporative cooling not only by storing heat but also by reducing sensible heat gain (i.e. reducing the air-skin temperature gradient) and increasing long-wave radiation loss. The stored heat is dissipated at night by sensible and radiative heat loss. Schmidt-Nielsen et al. (1956) studied the body temperature of dromedary camels kept in full desert sun. When the camels were allowed to drink water at the beginning of each day, the body temperature varied by about 2.1 ∘C between day and night, but when the camels were eprived of water their body temperatures during the day were up to 6.5 ∘C greater
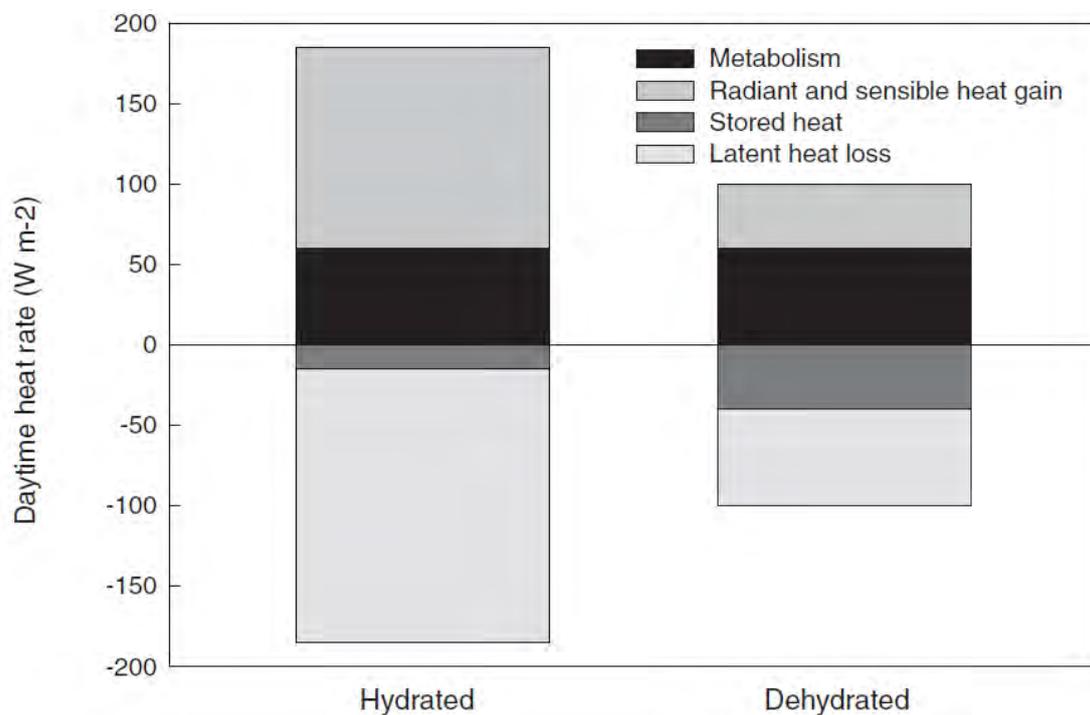
Figure 5 Heat balance components of a camel in a desert environment when hydrated and dehydrated, expressed as mean heat rates *(W m−2)* over the 10 h during which external heat loads were largest (based on data from Schmidt-Neilsen et al. 1956).

than at night. Such a range would be life-threatening for many mammals. For a camel weighing 260 kg, assuming a body specific heat of 3.6 kJ kg−1 K, the daytime heat storage rate **S** averaged 15 W m−2 for the hydrated and 42 W m−2 for the dehydrated animals. Schmidt-Neilsen also measured evaporation rate **E** from the skin (ignoring the small respiratory evaporation rate), and estimated metabolic heat production **M**. Using the heat balance Eq. (14.1), he interpreted the residual **E** + **S** − **M** as the heat

gained from net radiation and sensible heat. Figure 14.5 illustrates the heat balances over the hottest 10 h of the day for the hydrated and dehydrated camels. When water was available, the animals balanced their energy gains principally by evaporation of sweat; when dehydrated, the sweating rate was much decreased, and heat storage was similar in magnitude to the loss of heat by evaporation. Some of the large reduction in the radiant and sensible heat gain is probably due to postural changes that the camels adopted to reduce radiation interception when short of water.

Although heat storage is not viable as a long-term component of the heat balance of most homeotherms, it is important during short bursts of activity. For example, Taylor and Lyman (1972) found that running antelopes generated heat at about 40 times their resting metabolic rate, and the increase of their body temperature of up to 6 ∘C over 5– 15 min (depending on running speed) accounted for 80–90% of this heat. For humans, body temperature T_b also increases during exercise in direct proportion to the metabolic rate $\mathbf{M}$ until the limits for thermoregulation are reached. A convenient approximation for humans (Kerslake, 1972) is

$T_b = 36.5 + 4.3 \times 10^{-3}\ \mathbf{M}$,

where T_b is in Celsius when $\mathbf{M}$ is in W m^{-2}.

Specification of the Environment—The Effective Temperature

The thermo-neutral diagram has been used mainly to summarize observations of metabolic rate in livestock or humans exposed to the relatively simple environment of a calorimeter. In the real world, metabolic rate depends on several microclimatic factors in addition to air temperature, notably radiation, wind speed, and vapor pressure.

Attempts have therefore been made to replace the simple measure of actual air temperature used in the previous discussion with an *effective temperature* which incorporates the major elements of microclimate. Two examples are now given, the first dealing with the radiative component of the heat balance equation.

1 Radiation Increment

When the radiant flux is expressed in terms of net isothermal radiation, the heat balance equation may be written

$\mathbf{R}_{ni} + (\mathbf{M} - \lambda E) = \rho c_p (T_0 - T)/r_{HR}$, (14.13)

where λE is here assumed to be a relatively small term, independent of T. Suppose

that the thermal effect of radiation on an organism can be handled by substituting for air temperature an *effective* temperature T_f such that

$$(M - \lambda E) = \rho c_p \_ T_0 - T_f\_ / r_{HR}. \quad (14.14)$$

Then eliminating $M - \lambda E$ from Eqs. (14.13) and (14.14) gives

$$T_f = T + \{R_{ni} r_{HR} / \rho c_p\}, \quad (14.15)$$

where the term in curly brackets is similar to the radiation increment used by Burton and Edholm (1955), Mahoney and King (1977), and many others. Figure 3 provides a graphical method of estimating the temperature increment $T_f - T$ when windspeed and net radiation are known. Given the characteristic dimension of an organism d and the velocity of the surrounding air V, the corresponding value of r_H can be read from the left-hand vertical axis and r_{HR} derived from Equation (13.2) can be read from the right-hand axis. From the right-hand section of the figure, the coordinates of r_{HR} and R_{ni} define a unique value of $T_f - T$. An example is shown for $V = 8$ m s^{-1}, $d = 2$ cm, which gives $1/r_H = 6.8$ cm s^{-1} from the left-hand axis and $1/r_{HR} = 6.3$ cm s^{-1} from the right-hand axis. At $R_{ni} = 300$ W m^{-2}, $T_f - T = 4$ K. In a system where the resistances are fixed, the relation between temperature gradients and heat fluxes can be displayed by plotting temperature against flux as in Figure 7. By definition, a resistance is proportional to a temperature difference divided by a flux and is therefore represented by the slope of a line in the figure. From a start at the bottom left-hand corner, T_f is determined by drawing a line (1) with slope $r_{HR}/\rho c_p$ to intercept the line $x = R_{ni}$ at $y = T_f$. Rearranging Equation (14.15), the equation of this line is
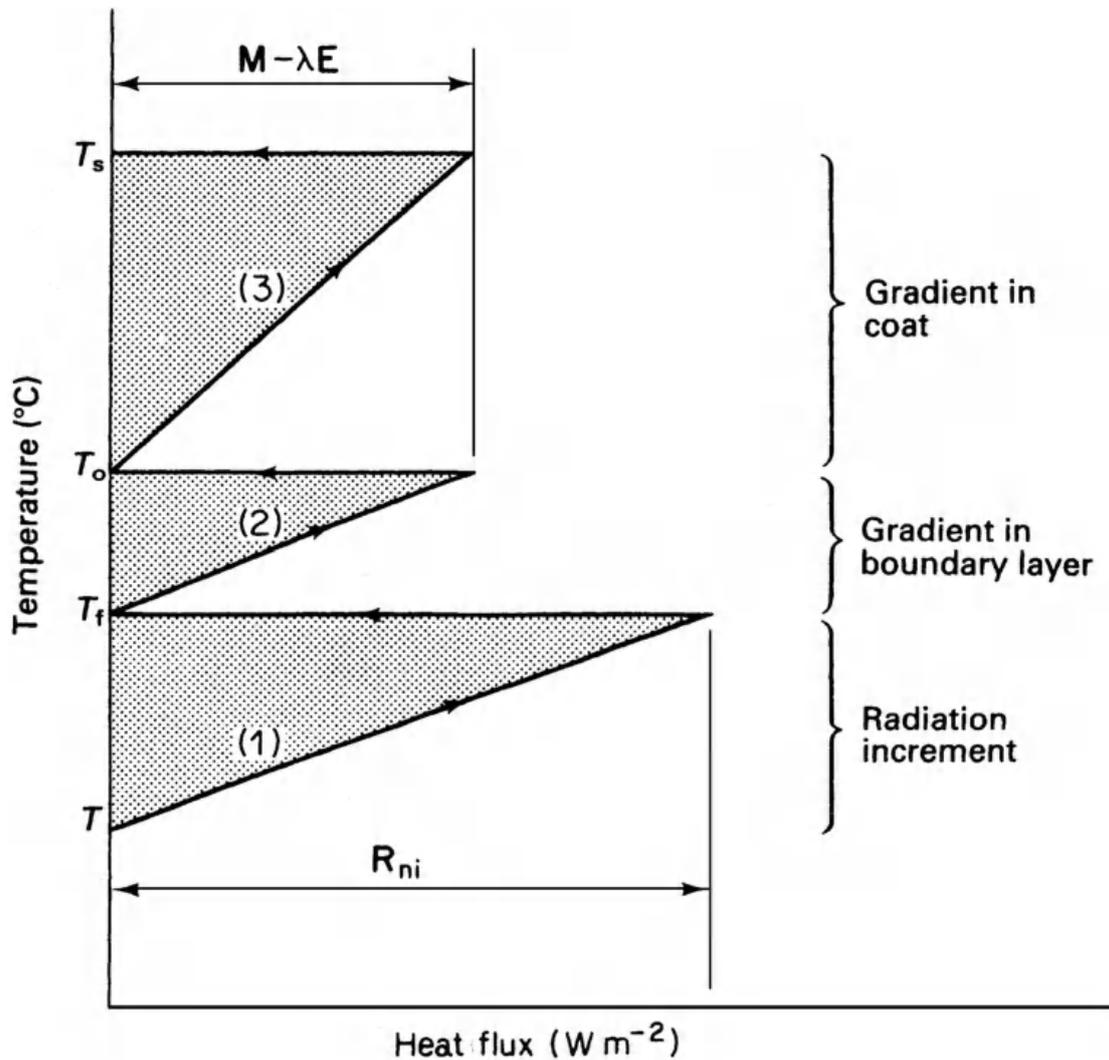
$$T_f - T = r_{HR} R_{ni} / \rho c_p.$$

Figure 7 Main features of temperature/heat-flux diagram for dry systems. T_s is skin temperature, T_0 is coat surface temperature, T_f is effective environment temperature, and T is air temperature.

The temperature of the surface T_0 is now found by drawing a second line (2) with the same slope as (1) to intersect $x = \mathbf{M} - \lambda \mathbf{E}$ at $y = T_0$. The equation of this line (see Equation (14.14)) is

$$T_0 - T_f = r\text{HR}(\mathbf{M} - \lambda \mathbf{E})/\rho c_p. \quad (14.17)$$

Finally, for an animal covered with a layer of hair, a mean skin temperature T_s can be determined if the mean coat resistance r_c is known. Provided that evaporation is confined to the surface of the skin and the respiratory system, the increase of temperature through the coat is represented by the line (3) whose equation is

$$T_s - T_0 = r_c(\mathbf{M} - \lambda \mathbf{E})/\rho c_p. \quad (14.18)$$

This form of analysis can be used to solve two types of problems. When the environment of an animal is prescribed in terms of wind speed, temperature, and net radiation, it is possible to use a thermo-neutral diagram to explore the physiological states in which the animal can survive. Conversely, when physiological conditions are specified, a corresponding range of environmental conditions can be established, forming an ecological ―niche" or ―climate space" (Gates, 1980).

4 Apparent Equivalent Temperature

A second type of environmental index is needed when the loss of latent heat from an organism is predominantly by the evaporation of sweat from the skin. When the losses of sensible and latent heat occur from the same surface, temperature and vapor pressure can be combined in a single variable which may be called the *apparent equivalent temperature*. To derive this quantity, the heat balance equation is written,

$$\mathbf{R}_{ni} + \mathbf{M} = \rho c_p (T_0 - T) r_{HR} + \rho c_p (e_0 - e) \gamma r_v , \quad (14.20)$$

where T_0 and e_0 are mean values for the skin surface and T and e refer to the air.

If γ is replaced by $\gamma* = \gamma (r_v / r_{HR})$, Eq. (14.20) can be written

$$\mathbf{R}_{ni} + \mathbf{M} = \rho c_p \_ T*_{eo} - T*_e \_ / r_{HR}, \quad (14.21)$$

where $T*_e$ is the apparent equivalent temperature of ambient air given by $T + e/\gamma*$ and therefore equal to the equivalent temperature derived on p. 223 when $r_v = r_{HR}$. By analogy with the radiation increment, $e/\gamma*$ may be regarded as a humidity increment. The mean value of the apparent equivalent temperature at the surface is $T*_{eo}$. In principle, the apparent equivalent temperature should be used in a thermo-neutral diagram in place of conventional temperature when the metabolic rate of an animal is measured in an environment where vapor pressure changes as well as temperature. Extending this process a stage further, the apparent equivalent temperature of the environment can be modified to take account of the radiation increment by writing

$$T*_{eR} = T*_e + \mathbf{R}_{ni} r_{HR}/\rho c_p. \quad (14.22)$$

The quantity $T*_{eR}$ is an index of the thermal environment which allows the heat balance equation to be reduced to the form

$$(1 - x)\mathbf{M} = \rho c_p \_ T*_{eo} - T*_{eR} \_ r_{HR}, \quad (14.23)$$

where x is the fraction of metabolic heat dissipated by respiration. A thermo-neutral

diagram using $T * eR$ as a thermal index rather than T or $T * e$ would be valid for changes in radiant heat load as well as in vapor pressure and temperature.

This type of formulation provides a relatively straightforward way of investigating the heat balance of a naked animal whose skin is either dry or entirely wetted by sweat. The intermediate case of partial wetting is more difficult to handle because the value of $T * e$ depends on fractional wetness which is not known *a priori*. A complete solution of the relevant equations for an animal leads to a complex expression within which the structure of the original Penman equation can be identified (McArthur, 1987).

Problems

1. The metabolic heat production **M** of a cow standing in strong sunshine at air temperature 22.0 °C is 140 W m−2. The average solar irradiance of the animal is 300 W m−2 and the effective radiative temperature of the surroundings is equal to air temperature. The mean temperatures of the skin and coat surface are 34.0 and 31.6 °C, respectively, and the rates of evaporative loss from the respiratory system and the skin surface are $4.5 \times 10-3$ g m−2 s−1 and $40 \times 10-3$ g m−2 s−1, respectively. Calculate the thermal resistances of (i) the boundary layer around the cow (rHR) and (ii) the coat (rc). If shading reduces the average solar irradiance of the animal by two-thirds, and other environmental variables remain unchanged, calculate the corresponding reduction in the rate of evaporation from the skin necessary to maintain a steady heat balance if **M** remains constant. (Assume that changes in respiratory evaporation can be neglected and that the absorption of solar radiation occurs close to the outer surface of the coat, which has a reflection coefficient of 0.40.)

2. A pig, trunk diameter 0.50 m, with its skin covered in wet mud at 30°C is exposed in still air when air temperature is 25 °C and relative humidity is 30%. Calculate the resistance rv for water vapor transfer from the skin to the atmosphere, (i) ignoring humidity gradients and (ii) taking humidity into account. Calculate the evaporative flux of water per unit skin area. What percentage error would you have made if you had ignored effects of humidity gradients on rv? What other factors would determine the evaporation rate in practice?

3. Pigs wallow in wet mud to increase body cooling by evaporation. Calculate the maximum air temperature at which a pig could maintain a state of thermal equilibrium

(i) if the skin was completely dry and (ii) if the skin was completely covered in wet mud. Assume the following:

Minimum metabolic heat production rate 60 W m−2

Rate of latent heat loss by respiration 10 W m−2

Radiative heat load from the environment 240 W m−2

Skin temperature 33 ∘C

Vapor pressure of air 1.0 kPa

Combined resistance to radiative and convective heat transfer 80 s m−1

Mean resistance to conduction through mud layer 8 s m−1

x-rays, microwaves

Introduction

Radio and television signals, x-rays, microwaves each is a form of electromagnetic radiation. If steam and internal combustion engines symbolize the Industrial Revolution, and microprocessors and memory chips now power the Information Revolution, it almost seems that we have neglected to recognize the ―Electromagnetic Revolution." Think about it: Can you imagine life without television sets or cell phones? You may long for such a life, or wonder how people ever survived without these devices! These examples are from the world of engineered electromagnetic radiation. Even if you think we might all prosper without such technologies to entertain us, do our cooking, carry our messages, and diagnose our illnesses, you would be hard-pressed to survive without light. This form of electromagnetic radiation brings the Sun's energy to the Earth, warming the planet and supplying energy to plants, and in turn to creatures like us that depend on them. There are primitive forms of life that do not depend on the Sun's energy, but without light there would be no seeing, no room with a view, no sunsets, and no Rembrandts.

Some of the electromagnetic radiation that reaches your eyes was created mere nanoseconds earlier, like the light from a lamp. Other electromagnetic radiation is still propagating at its original speed through the cosmos, ten billion years or more after its birth. An example of this is the microwave background radiation, a pervasive remnant of the creation of the universe that is widely studied by astrophysicists.

Back here on Earth, this chapter covers the fundamental physical theory of electromagnetic radiation. Much of it builds on other topics, particularly the studies of

waves, electric fields and magnetic fields. **Electromagnetic radiation: Rainbows and radios. Sundazzled reflections. Shadowlamps and lampshadows. Red, white, and blue.**


1 - The electromagnetic spectrum
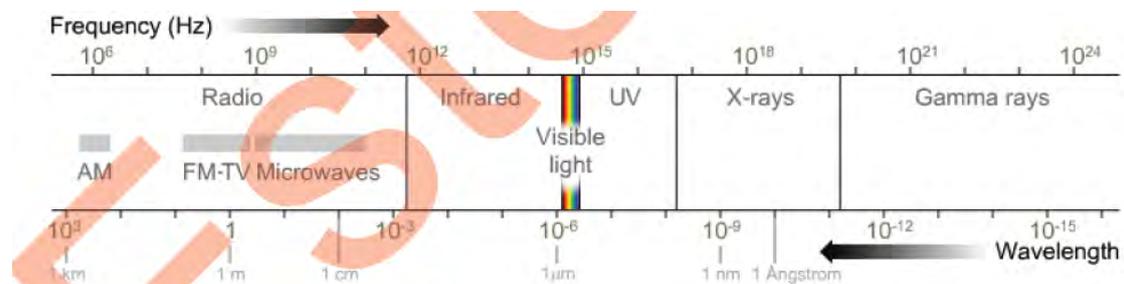
Electromagnetic spectrum: Electromagnetic radiation ordered by frequency or wavelength.

Electromagnetic radiation is a traveling wave that consists of electric and magnetic fields. Before delving into the details of such waves, we will discuss the electromagnetic spectrum, a system by which the types of electromagnetic radiation are classified. The illustration of the electromagnetic spectrum above orders electromagnetic waves by frequency and by wavelength. In the diagram, frequency **increases** and wavelength **decreases** as you move from the left to the right. The chart's scale is based on powers of 10. Wavelengths range from more than 100 meters for AM radio signals to as small as 10$\square$16 meters for gamma rays.

All electromagnetic waves travel at the same speed in a vacuum. This speed is designated by the letter *c* and is called the speed of light. (The letter *c* comes from *celeritas,* the Latin word for speed. It might be more accurate to refer to it as the speed of electromagnetic radiation.) The speed of light in a vacuum is exactly 299,792,458 m/s, and it is only slightly less in air.

The unvarying nature of this speed has an important implication: The wavelength of electromagnetic radiation is inversely proportional to its frequency. As you may recall, the speed of a wave equals the product of its frequency and wavelength. This means that if you know the wavelength of the wave, you can determine its frequency (and vice versa). For instance, an electromagnetic wave with a wavelength of 300 meters, in the middle of the AM radio band, has a frequency of 1×10^6 Hz. This equals 3×10^8 m/s, the speed of light, divided by 300 m. The frequencies of electromagnetic waves range from less than one megahertz, or 10^6 Hz, for long radio waves to over 10^{24} Hz for gamma rays. We will now review some of the bands of electromagnetic radiation and their manifestations. The lowest frequencies are often utilized for radio
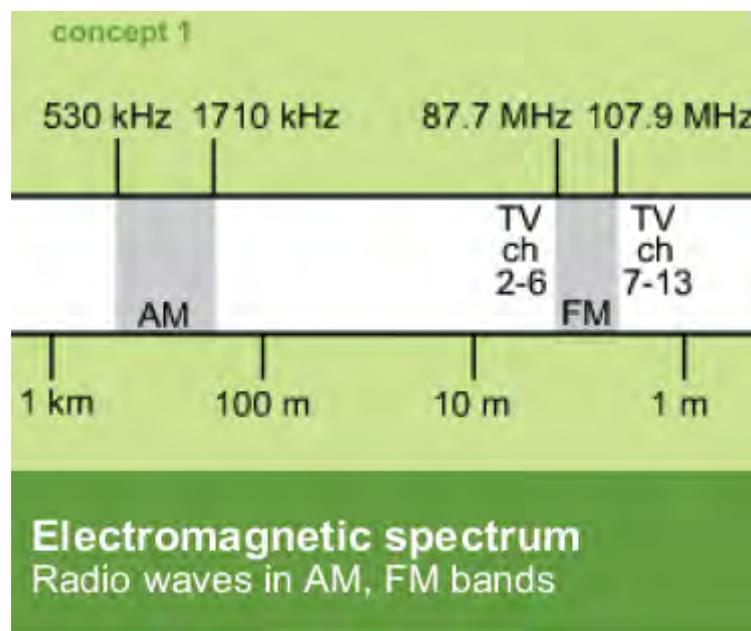
Electromagnetic wave: A wave consisting of electric and magnetic fields oscillating transversely to the direction of propagation.

Physicist James Clerk Maxwell's brilliant studies pioneered research into the nature of electromagnetic waves. He correctly concluded that oscillating electric and magnetic fields can constitute a self-propagating wave that he called electromagnetic radiation. His law of induction (a changing electric field causes a magnetic field) combined with Faraday's law (a changing magnetic field causes an electric field) supplies the basis for understanding this kind of wave.

As the diagrams to the right show, the electric and magnetic fields in an electromagnetic wave are perpendicular to each other and to the direction of propagation of the wave. These illustrations also show the amplitudes of the fields varying sinusoidally as functions of position and time. Electromagnetic waves are an example of *transverse waves*. The fields can propagate outward from a source in all directions at the speed of light; for the sake of visual clarity, we have chosen to show them moving only along the *x* axis.

The animated diagram in Concept 2 and the illustrations below are used to emphasize three points. First, the depicted wave moves away from the source. For example, if you push the ―transmit" button on a walkie-talkie, a wave is initiated that travels away from the walkie-talkie. Second, at any fixed location in the path of the wave, both fields change over time. The wave below is drawn at intervals that are fractions *T*/4 of the period *T*. Look at the point P below, on the light blue vertical plane. The vectors from point P represent the direction and strength of the electric and magnetic fields at this point. As you can see, the vectors, and the fields they represent, change over time at P. Concept 2 shows them varying continuously with time at the point P.

Third, the diagrams reflect an important fact: The electric and magnetic fields have the same frequency and phase. That is, they reach their peaks and troughs simultaneously. A wave on a string provides a good starting point for understanding electromagnetic waves. Both electromagnetic radiation and a wave on a string are transverse waves. The strengths of the two fields constituting the radiation can be described using sinusoidal functions, just as we can use a sinusoidal function to calculate the transverse displacement of a particle in a string through which a wave is moving. There is a crucial difference, though: Electromagnetic radiation consists of electric and magnetic fields, and does not require a medium like a string for its propagation. Electromagnetic waves can travel in a vacuum. If this is troubling to you, you are in good company. It took some brilliant physicists a great deal of hard work to convince the world that light and other electromagnetic waves do not require a medium of transmission.

Furthermore, when electromagnetic waves radiate in all directions from a compact source like an antenna or a lamp, the radiation emitted at a particular instant travels outward on the surface of an expanding sphere, and its strength diminishes with distance from the source. The waves cannot be truly sinusoidal, since the amplitude of a sinusoidal function never diminishes. In the sections that follow we will analyze

plane waves, which propagate through space, say in the positive *x* direction, in parallel planar wave fronts rather than expanding spherical ones. They are good approximations to physical waves over small regions that are distant from the source of the waves. Plane waves never diminish in strength; they can be accurately modeled using sinusoidal functions, and we will do so.
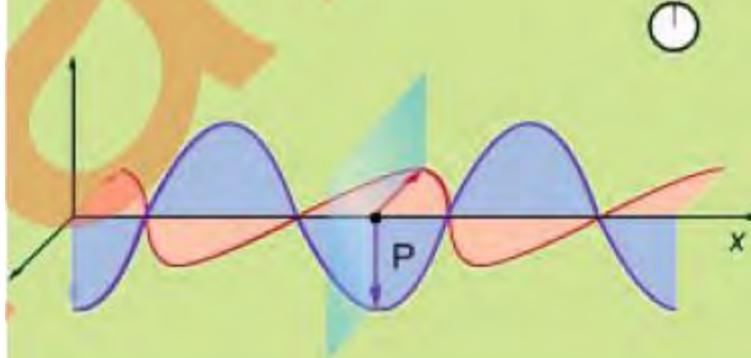

concept 1
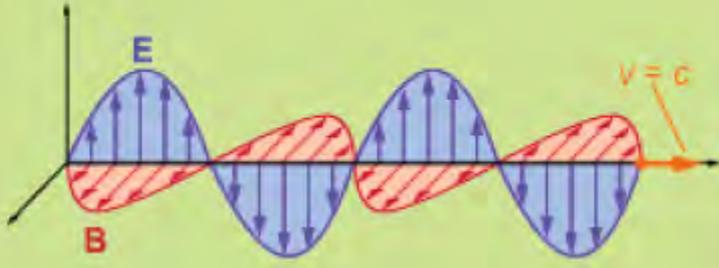
Electromagnetic waves
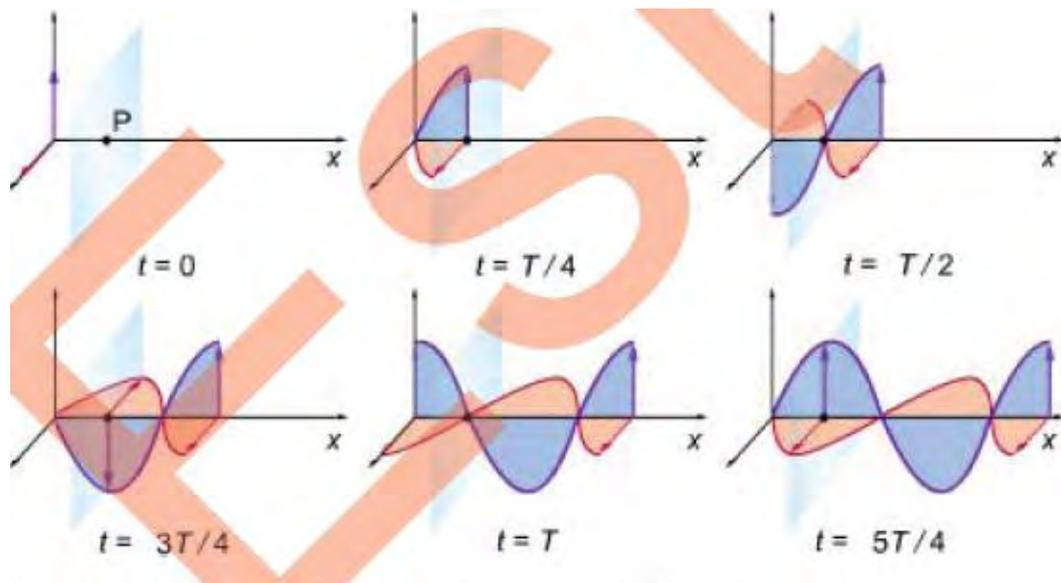Consist of electric and magnetic fields
· Perpendicular to each other
Propagate as transverse waves
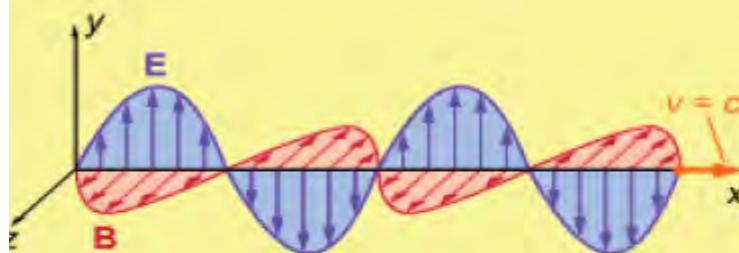· Perpendicular to direction of travel

concept 2

Electric, magnetic fields
Vary in strength over time at each point
Have same frequency and are in phase
Drive each other by changing strength

$t = 0$ $t = T/4$ $t = T/2$

$t = 3T/4$ $t = T$ $t = 5T/4$

equation 1

$v = c$

Speed of an electromagnetic wave

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

c = speed of electromagnetic wave
ω = angular frequency of wave
k = angular wave number of wave
μ_0 = permeability of free space
Constant $\mu_0 = 4\pi \times 10^{-7}$ T·m/A
ε_0 = permittivity of free space
Constant $\varepsilon_0 = 8.854 \times 10^{-12}$ C²/N·m²

example 1

What is the speed of an electromagnetic wave in a vacuum?

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

$$\mu_0 \varepsilon_0 = (4\pi \times 10^{-7})(8.854 \times 10^{-12})$$

$$\mu_0 \varepsilon_0 = 1.113 \times 10^{-17} \text{ s}^2/\text{m}^2$$

$$\sqrt{\mu_0 \varepsilon_0} = 3.336 \times 10^{-9} \text{ s/m}$$

$$c = 2.998 \times 10^8 \text{ m/s}$$

Creating electromagnetic waves: antennas Radio antennas create electromagnetic waves. A radio antenna is part of an overall system called a radio transmitter that converts the information contained in sound waves into electromagnetic waves. A radio receiver then reverses the process, converting the signals from electromagnetic waves back to sound waves. The system depicted to the right shows the fundamentals of a radio transmitter. In the illustrations, the terminals of an AC generator are connected to two rods of conducting material: an antenna. The AC generator produces an emf □ that varies sinusoidally over time. The emf drives positive

through the surface by the wave, per unit area, is called the *area power density* of the wave. The area power density is equal to the magnitude S of the Poynting vector. The surface area through which the instantaneous power density is measured is perpendicular to the direction of the wave's propagation. When radiation reaches a physical surface obliquely, the cosine of its angle with the area vector can be used to calculate the power conveyed to the surface. This is analogous to the calculation of electric or magnetic flux.

As Equation 1 shows, the Poynting vector equals the cross product of the vectors representing the electric and magnetic fields of the electromagnetic radiation, divided by the permeability constant. Since these fields are always perpendicular to one another, the sine of the angle between them, used to evaluate the magnitude of the cross product, always equals one, and can be effectively ignored when calculating the instantaneous area power density S. The units of the Poynting vector are watts per square meter. The direction of **S** is determined by the right-hand rule. If you apply the rule, wrapping your fingers from **E** to **B** and noting the direction of your thumb, you can correctly determine that it is parallel to the direction of propagation of the wave. When **E** reverses its direction, so does **B**, and the direction of **S** remains the same, ̶pointing" (heh, heh) in the direction of the wave's motion.

As an electromagnetic wave passes through a surface, the strengths of its electric and magnetic fields there change sinusoidally with time. Since the Poynting vector is the product of these fields, it changes sinusoidally over time, as well. In fact, it varies with values between zero and Emax Bmax$/\mu0$, with a frequency twice that of the fields. If you are curious why it has this frequency, recall from the field equations that E and B are both cosine functions of time at a fixed point. Then use the trigonometric identity $\cos2 t = [1 + \cos 2t]/2$.
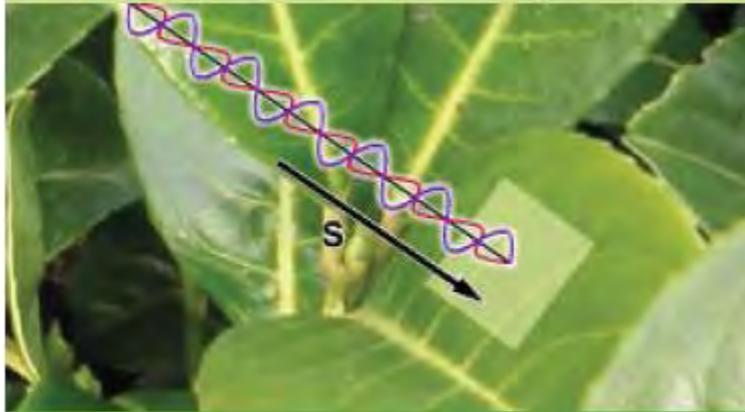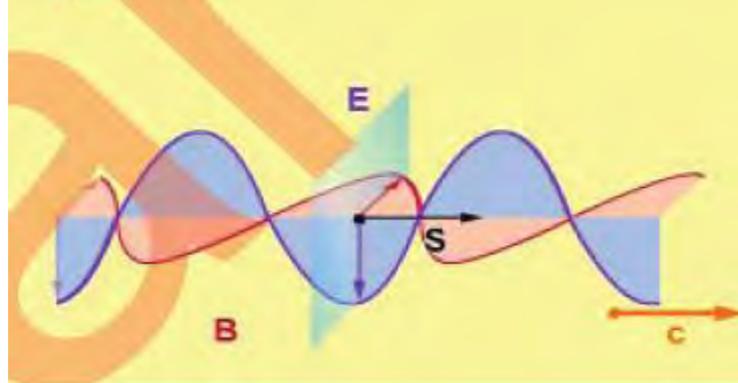
Poynting vector
Power per unit surface area
Surface perpendicular to wave direction

equation 1

Poynting vector

$$S = \frac{1}{\mu_0} \mathbf{E} \times \mathbf{B}$$

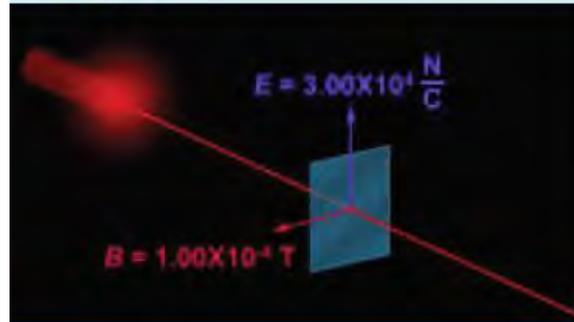$\mathbf{S}$ = Poynting vector
S = instantaneous area power density
μ_0 = permeability of free space
$\mathbf{E}$ = electric field
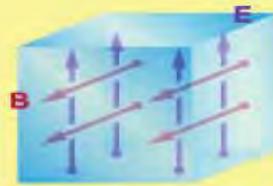$\mathbf{B}$ = magnetic field

Units: watts per square meter (W/m^2)

example 1

$E = 3.00 \times 10^4 \frac{N}{C}$

$B = 1.00 \times 10^{-4}$ T

At this instant, what is the area power density of the ruby laser light?

$S = EB / \mu_0$

$$S = \frac{(3.00 \times 10^4 \frac{N}{C})(1.00 \times 10^{-4}\,T)}{4\pi \times 10^{-7}\frac{T \cdot m}{A}}$$

$S = 2.39 \times 10^6$ W/m^2

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equation 2

E

B

Electric, magnetic energy densities

$$u_E = \frac{\varepsilon_0 E^2}{2} \qquad u_B = \frac{B^2}{2\mu_0}$$

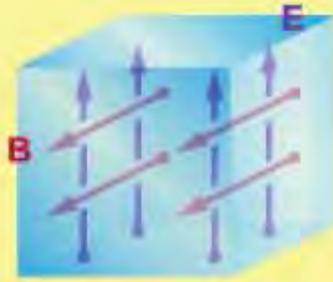Since $E^2/B^2 = c^2 = 1/\mu_0\varepsilon_0$, then

$$u_E = u_B$$

The total energy density is

$$u = u_E + u_B = 2u_E = 2u_B$$

u_E = electric field energy density
u_B = magnetic field energy density
u = total energy density

equation 3

Average energy per unit volume
Average value of u over time

$$u_{avg} = \frac{\varepsilon_0 E_{max}^2}{2}$$

u_{avg} = average total energy density
Units: joules per cubic meter (J/m³)

How electromagnetic waves travel through matter Light and other forms of electromagnetic radiation can travel through a vacuum, and it is often simplest to study them in that setting. However, radiation can also pass through matter: If you look through a glass window, you are viewing light that has passed through the Earth's atmosphere and the glass. Other forms of radiation such as radio waves pass through matter, as well.

This section focuses on how such transmission occurs. It relies on a classical model of electrons and atoms that predates quantum theory. In this model, electrons orbit an atom. They have a resonant frequency that depends on the kind of atom. On a larger scale, atoms themselves and the molecules composed of them also have resonant thermal frequencies at which they can vibrate or rotate.
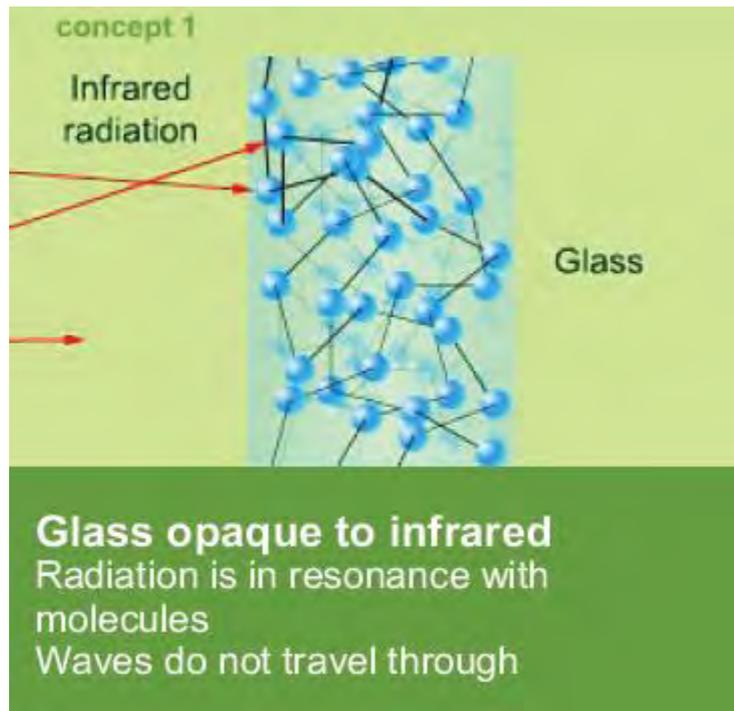
We will use the example of light striking the glass in a window to discuss how substances transmit (or do not transmit) electromagnetic radiation. When an electromagnetic wave encounters a window, it collides with the molecules that make up the glass. If the frequency of the wave is near the resonant thermal frequency of

the glass molecules, which is true for infrared radiation, the amplitude of the molecules' vibrations increases. They absorb the energy transported by the wave, and dissipate it throughout the glass by colliding with other molecules and heating up the window. Because it absorbs so much infrared energy, the glass is opaque to radiation of this frequency, preventing its transmission.

Scientists in the 19th century noted a phenomenon in greenhouses caused by the opaqueness of glass to infrared radiation, which they called the *greenhouse effect*. The glass in a greenhouse admits visible light from the Sun, which is then absorbed by the soil and plants inside. They reradiate the solar energy as longer infrared waves, which cannot pass back out through the glass and so help warm up the greenhouse. The same phenomenon occurs on a vaster scale in the atmosphere as gases like methane and carbon dioxide trap solar energy near the Earth's surface.

In contrast to infrared radiation, higher frequency radiation such as visible light does not resonate thermally with atoms or molecules, but may resonate with the electrons of the atoms of a substance. In glass, visible light experiences much less reduction in the amplitude of its waves than infrared radiation does, and most of its energy passes through the glass quite easily. Atoms with resonant electrons that do absorb energy from a light wave quickly pass on that energy by re-emitting it as radiation of the same frequency to other atoms, which in turn pass it on to their neighbors.

This chain of absorptions and re-emissions, called *forward scattering*, follows a path close to the light's original direction of travel. A beam of light that strikes a pane of glass will reach the ―last atom" on the far side of the pane in an extremely short time. We see the light after it emerges, and think of glass as transparent.

concept 1

Infrared radiation

Glass

Glass opaque to infrared
Radiation is in resonance with molecules
Waves do not travel through

concept 2

Glass

Glass transparent to visible light
Waves absorbed by electrons of atoms
Re-emitted from neighbor to neighbor
Waves pass through but are slowed

Radiation also can be *partially polarized,* having a few waves oscillating in all planes, but with most of its waves concentrated in a single plane. This is true of sunlight scattered by the atmosphere. As the photo above shows, the sky in certain directions is partially polarized in a vertical plane so that most of its light can pass through a pair of sunglasses whose transmission axis is vertical. Less light (but still some) passes through the rotated sunglasses. (Polarizing sunglasses are specifically intended to

reduce horizontally polarized glare reflected from roadways and water, not skylight.) Many forms of artificial electromagnetic radiation are polarized. A radio transmitter emits polarized radiation. If the rods of its antenna are vertical, then so is the electric field of every radio wave it creates. In this case, the most efficient receiving antenna is also vertically oriented; a horizontal receiving antenna would absorb radio waves much less efficiently. You may be familiar with this fact if you have ever tried to maneuver a radio antenna wire or a set of television ―rabbit ears" to get the best reception. (If you do not know what ―rabbit ears" are for television, well, before there was cable television, there was….)

concept 3

Transmitted light

Incident light

E-field component passes through filter
If transmission axis is vertical, filter …
· Transmits vertical E-field component
· Absorbs horizontal E-field component

concept 4

Transmission axes

What you see

Two Polaroid filters
Light passes through back (upper) filter
Then passes through front (lower) filter
Intensity depends on orientation of filters

Scattering of light *Scattering: Absorption and re-emission of light by electrons, resulting in dispersion and some polarization.*
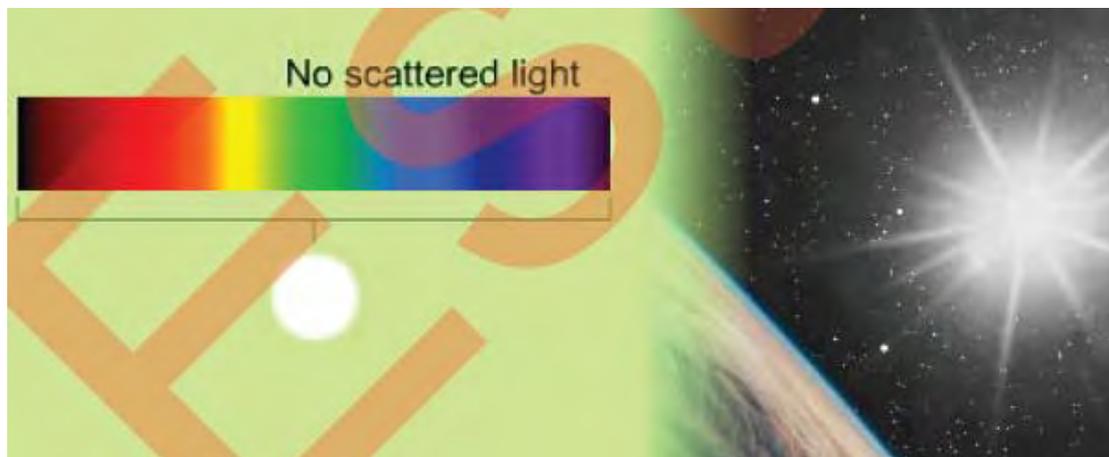
The answer to a classic question □ Why is the sky blue? □ rests in a phenomenon called scattering. In this section, we give a classical (as opposed to quantum mechanical) explanation of how scattering occurs. When light from the Sun strikes the electrons of various atoms in the Earth's atmosphere, the electrons can absorb the light's energy, oscillating and increasing their own energy. The electrons in turn re-emit this energy as light of the same wavelength. In effect, the oscillating electrons act like tiny antennas, emitting electromagnetic radiation in the frequency range of light.

An electron oscillates in a direction parallel to the electric field of the wave that energizes it, as shown in Concept 1. The electron then emits light polarized in a plane parallel to its vibration. We show a particular polarized wave that is re-emitted downward toward the ground, since we are concerned with what an observer on the surface of the Earth sees. Other light is scattered in other directions, including light scattered upward and light scattered forward in its original direction of travel. Scattering explains why we see the sky: Light passing through the atmosphere is redirected due to scattering toward the surface of the Earth. In contrast, for an astronaut observer in the vacuum of space, sunlight is not scattered at all so there is no sky glow:
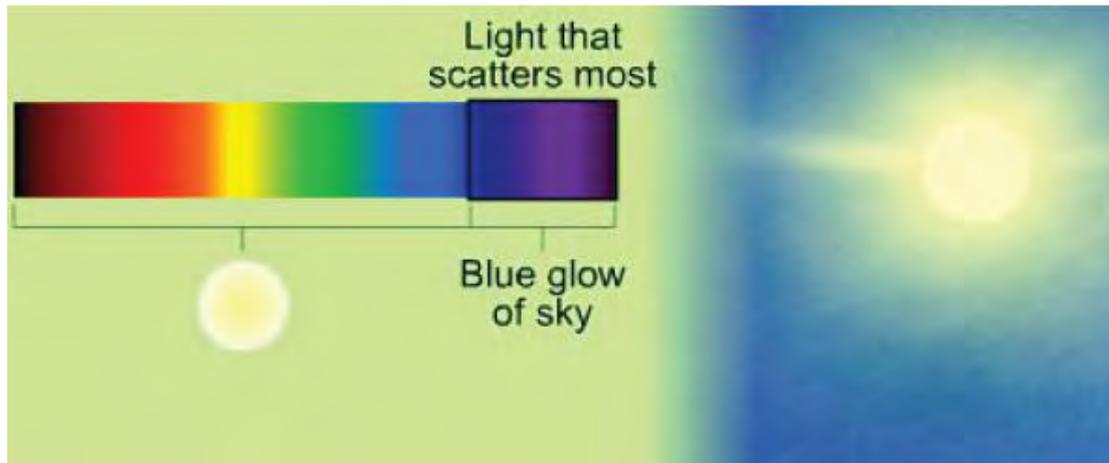
Except for the stars, the sky appears black. To the astronaut, the disk of the Sun, a combination of all colors, looks white. We illustrate this below: The full spectrum combines to form white light. The question remains, why is our sky blue rather than some other color? Light at the blue end of the visible spectrum, which has the shortest wavelength, is 10 times more resonant with the electrons of atmospheric atoms than red light. This means blue light is scattered more than red, so that more of it is redirected toward the ground.

Scattering also explains why we see the Sun as yellow rather than white. When you look up at the disk of the Sun from the Earth's surface, the bluest portion of its light has been scattered away to the sides. The remaining part of the Sun's direct light appears somewhat yellowish. You may also have noted how the Sun appears to change color when it sets. As the Sun's disk descends toward the horizon, its light must pass through a greater and greater thickness of atmosphere in order to reach you. Since a certain amount of sunlight is scattered aside for each kilometer of atmosphere

it passes through, its position at sunset causes it to lose large amounts of light at the blue end and even toward

concept 1

Electron vibrates horizontally

Light scattered down to ground observer

Scattering
Light from Sun hits electron
· Electron oscillates
· Re-emits polarized wave to ground
· Shortest wavelengths scattered most

No scattered light

View from space
No scattering: sky is black
Sun appears white

Light that scatters most

Blue glow of sky

Why the sky is blue (and the Sun is yellow)
Shortest waves are scattered: sky is blue
With blue scattered, Sun appears yellowish white

the concentration of the dissolved substance. The rotation is also proportional to a constant ▯0 called the *specific rotation* of the substance, which reflects the rotating power of its molecules. These relationships are summarized to the right in the *polarimeter equation*. Note that (and this is unusual for a physics equation) the rotation angle ▯ is measured in degrees rather than radians, and the clockwise direction is considered positive.

The *polarimeter* is a device that can be used to measure the net rotation of polarized light passing through an optically active solution. An experimenter directs polarized light through a container of the solution to be analyzed. The analyzer, which starts out parallel to the polarizer, does not transmit all the light from the polarizer because the light's plane of polarization has been rotated by the solution. The experimenter turns the analyzer to one side or the other until the transmitted light has maximum

brightness. Then she knows that the analyzer's transmission axis matches the rotated polarized light, and she can measure the angle $\square$ through which the analyzer has turned. The polarimeter equation gives an expression for the angle $\square$ of the analyzer at which the transmitted light will be the brightest. If the polarized light encounters more molecules of the optically active substance, either because the solution is more concentrated or because the immersed light path is longer, the rotation will be greater. Since the amount of rotation also depends on the wavelength of the light, the specific rotations $\square 0$ given in tables for particular dissolved substances are based on a polarimeter employing the 589 nm light that is emitted by a sodium vapor lamp. Dextrose and fructose molecules are chemically identical (they have the same atoms arranged in the same pattern) but they are mirror images of each other. Because of this they rotate polarized light by the same amount in opposite directions. Organic molecules such as *carvone* may exist in two mirror image forms; you smell carvone as caraway or spearmint, depending on which way the molecule twists. The scents are different because the smell receptors in the nose react differently to the mirror image forms. Using a polarimeter is one way to distinguish between the two forms of mirror image compounds. Also, if the specific rotation of a particular substance is known, the device can be used together with the polarimeter equation to determine the concentration of the substance in a solution. You are asked to perform such an analysis in the example problem to the right.

The diagrams below show the mirror image molecular forms of the citrus oil *limonene*, which is the essence of either orange or lemon, depending on the orientation of its molecules! (The gray spheres represent carbon atoms, and the blue spheres are hydrogen atoms.)
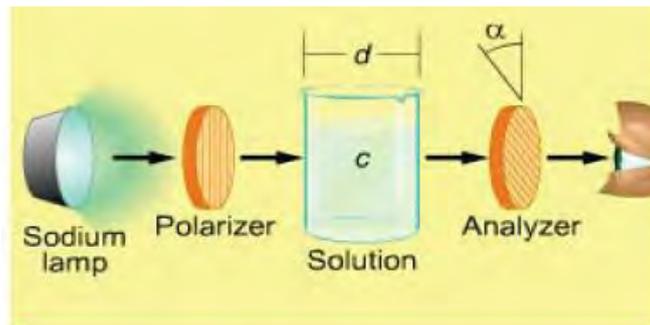
Polarimeter equation

$$\alpha = dc\alpha_0 / 100$$

α = rotation of light (° clockwise)
d = length of immersed light path (m)
c = concentration of substance (kg/m^3)
α_0 = specific rotation of substance
Units of α_0: °m^2/kg

example 1
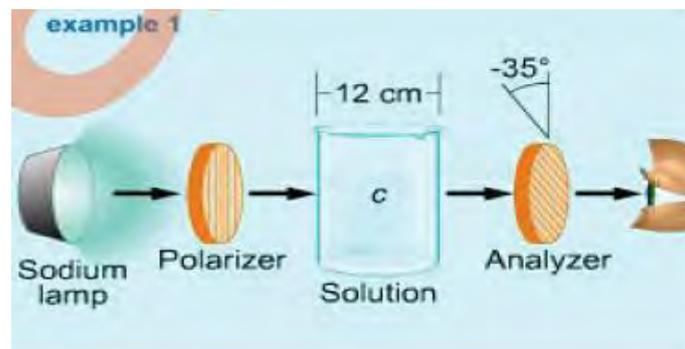
Carvone's specific rotation is +62.5 (caraway) or −62.5 (spearmint). What is the concentration of the carvone in this beaker?
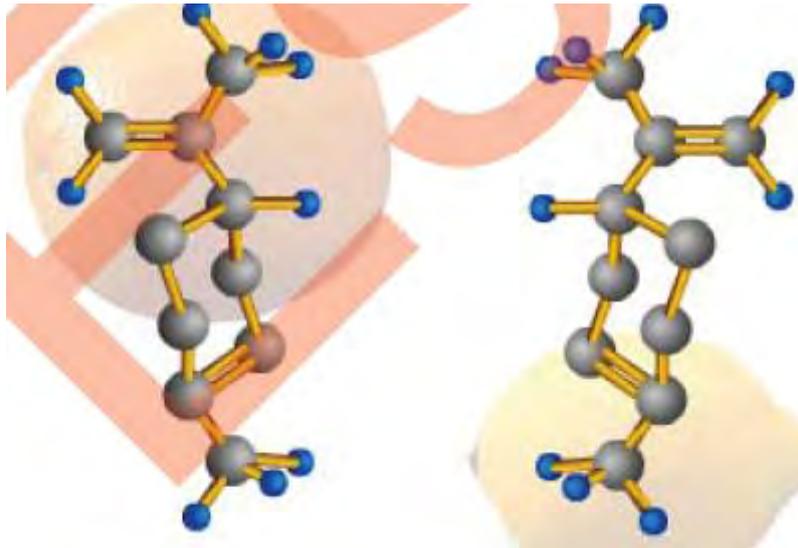
$$\alpha = dc\alpha_0 / 100$$

$$c = \frac{100\alpha}{d\alpha_0}$$

Counterclockwise rotation means spearmint, so we use $\alpha_0 = -62.5$:

$$c = \frac{(100)(-35°)}{(0.12\ \text{m})(-62.5\ °\text{m}^2/\text{kg})}$$

$$c = 470\ \text{kg/m}^3$$

34.23 - Physics at work: liquid crystal displays (LCDs) The liquid crystal display (LCD) in the watch face above demonstrates *variable optical activity* at work. LCDs are found in many common devices, including calculators, cellular telephones and clocks. There are two types of LCDs: backlit and reflective. The one shown above is a reflective LCD, but we will explore both types in this section. Backlit LCDs generate light behind their displays; reflective LCDs like the one above utilize ambient light. LCDs rely on polarization. The characters of a digital watch display consist of ―digit‖ segments: regions that can be made dark. These segments are filled with a substance called *liquid crystal* that is optically active

Reflective LCD
When power OFF, segment is not seen
When power ON, segment is black
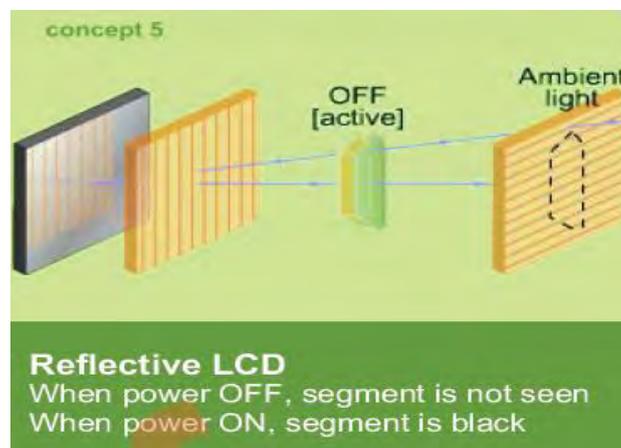
Gotchas

A light wave is a transverse wave. Yes. Both of its components, an electric and a magnetic field, oscillate perpendicularly to its direction of travel. *Radio signals and light waves are fundamentally different.* Both are forms of electromagnetic radiation, so we lean toward ―no‖ in response to this statement. The wavelength and frequency of radio transmissions and light are significantly different, and humans can see light, but not radio waves, so one could say ―yes‖. However, both are electromagnetic waves, and both move at the speed of light. *Intensity is the same thing as average energy density.* No, intensity represents the average rate of **power** transmission of an electromagnetic wave per unit **area**, perpendicular to the direction of propagation of the wave. Average energy density represents the average amount of **energy** contained in an electromagnetic wave per unit **volume**.

Proportionality of fields

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

Poynting vector

$$\mathbf{S} = \frac{1}{\mu_0} \mathbf{E} \times \mathbf{B}$$

Intensity of electromagnetic radiation

$$I = S_{avg} = \frac{E_{max}^2}{2\mu_0 c} = \frac{E_{rms}^2}{\mu_0 c}$$

$$I = \frac{P}{4\pi r^2}$$

Energy density

$$u_E = \frac{\varepsilon_0 E^2}{2}, \quad u_B = \frac{B^2}{2\mu_0}$$

$$u_E = u_B$$

$$u = u_E + u_B = 2u_E = 2u_B$$

$$u_{avg} = \frac{\varepsilon_0 E_{max}^2}{2}$$

Momentum transferred by radiation absorption

$$\Delta p = \frac{\Delta U}{c} \qquad \text{for a blackbody}$$

Light can refract □ change direction □ as it moves from one medium to another. For instance, if you stand at the edge of a pool and try to poke something underwater with a stick, you may misjudge the object's location. This is because the light from the object changes direction as it passes from the water to the air. You perceive the object to be closer to the surface than it actually is because you subconsciously assume that light travels in a straight line. Although refraction can cause errors like this, it can also serve many useful purposes. Optical microscopes, eyeglass lenses, and indeed the lenses in your eyes all use refraction to bend and focus light, forming images and causing objects to appear a different size or crisper than they otherwise would. Where a lens focuses light, and whether it magnifies an object, is determined by both the curvature of the lens and the material of which it is made. Scientists have developed quantitative tools to determine the nature of the images created by a lens. We will explore these tools thoroughly later, ―focusing" first, so to speak, on the principle of refraction underlying them. To begin your study of refraction, try the simulation to the right. Each of your helicopters can fire a laser □ a sharp beam of light □ at any of three submarines lurking under the sea. The submarines have lasers, too, and will shoot back at your craft. Your mission is to disable the submarines before they disarm your helicopters. When you make a hit, you can shoot again. Otherwise, the submarines get their turn to shoot until they miss. You play by dragging the aiming arrow underneath any one of your helicopters. Press FIRE and the laser beam will follow the direction of this arrow until it reaches the water, where refraction will cause the beam to change direction. In addition to hitting the submarines before they get you, you can conduct some basic experiments concerning the nature of refraction. As with reflection, the angle of incidence is measured from a line normal (perpendicular) to a surface. In this case, the surface is the horizontal boundary between the water and the air. Observe how the light bends at the boundary when you shoot straight down, at a zero angle of incidence, or grazing the water, at a large angle of incidence. You can create a large angle of incidence by having the far right helicopter, for example, aim at the submarine on the far left.

You can also observe how refraction differs when a laser beam passes from air to water (your lasers) and from water to air (the submarines' lasers). Observe the dashed normal line at each crossover point and answer the following question: Does the laser beam bend toward or away from that line as it changes media? You should notice that the laser beams of the submarines behave differently than those of the helicopters

when they change media. As a final aside: You may see that some of the laser beams of the submarines never leave the water, but reflect back from the surface between the water and the air. This is called total internal reflection.

Refraction: The change in the direction of light as it passes from one medium to another.

A material through which light travels is called a *medium* (plural: *media*). When light traveling in one medium encounters another medium, its direction can change. It can reflect back, as it would with a mirror. It can also pass into the second medium and change direction. This phenomenon, called refraction, is shown to the right. In the photo, a beam of light from a laser refracts (bends) as it passes from the air into the water. Light refracts when its speeds in the two media are different. Light travels faster through air than in water, and it changes direction as it moves from air into water, or from water into air. Although we are primarily interested in the refraction of light, all waves, including water waves, refract. Above, you see a photograph of surf wave fronts advancing parallel to a beach. Deep-ocean swells may approach a coastline from any angle, but they slow down as they encounter the shallows near the shore. The parts of a wave that encounter the shallow water earliest slow down first, and this causes the wave to refract. Sound waves can also refract. During a medical ultrasound scan, an acoustic lens can be used to focus the sound waves. The lens is made of a material in which sound travels faster than in water or body tissues.

The surface between two media, such as air and water, is called an *interface*. As with mirrors, light rays are often used to depict how light refracts when it meets an interface. Lasers are often used to demonstrate refraction because they can create thin beams of light that do not

interactive 1

Aim lasers to disable submarines
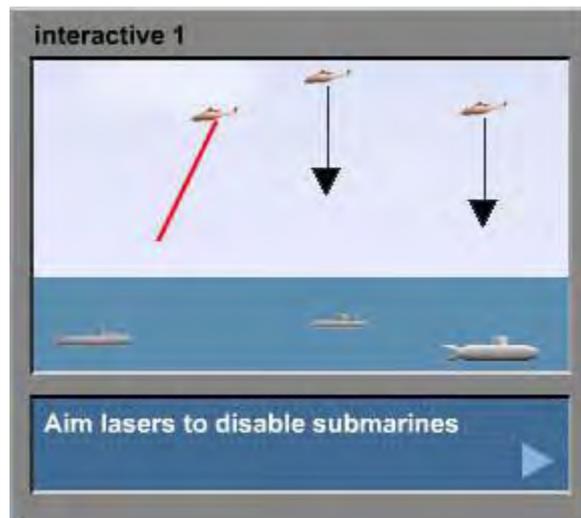
equation 2

	Index of refraction
Air	1.0003
Water	1.33
Vegetable oil	1.47
Crown glass	1.51
Salt	1.54
Flint glass	1.61
Corundum (ruby, sapphire)	1.77*
Diamond	2.42

At 20° C, λ = 589 nm   *Approximate value

Indices of refraction
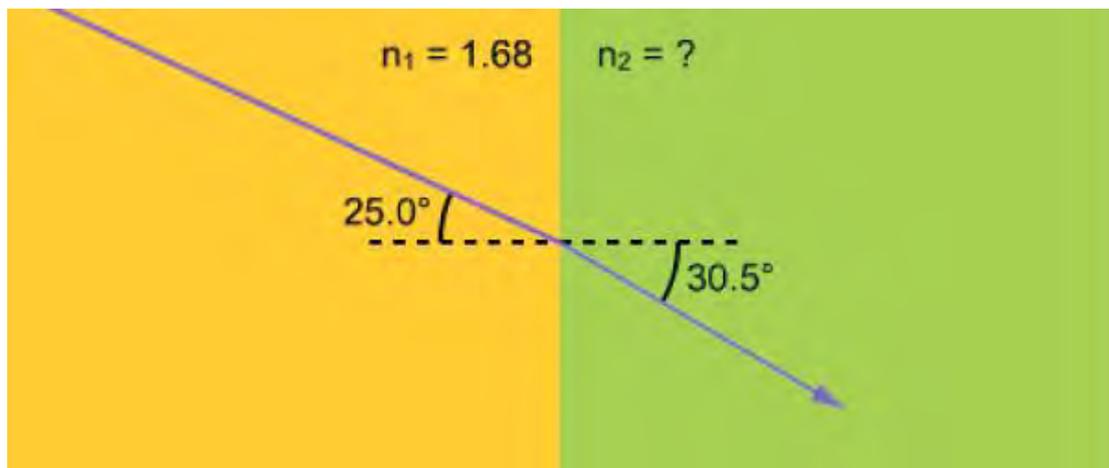
example 1

Vacuum, $c = 3.00 \times 10^8$ m/s

Crown glass, $v = 1.99 \times 10^8$ m/s

Green light travels at 1.99×10^8 m/s in crown glass. What is the index of refraction of the glass for this light?

$$n = \frac{c}{v}$$

$$n = \frac{3.00 \times 10^8 \text{ m/s}}{1.99 \times 10^8 \text{ m/s}}$$
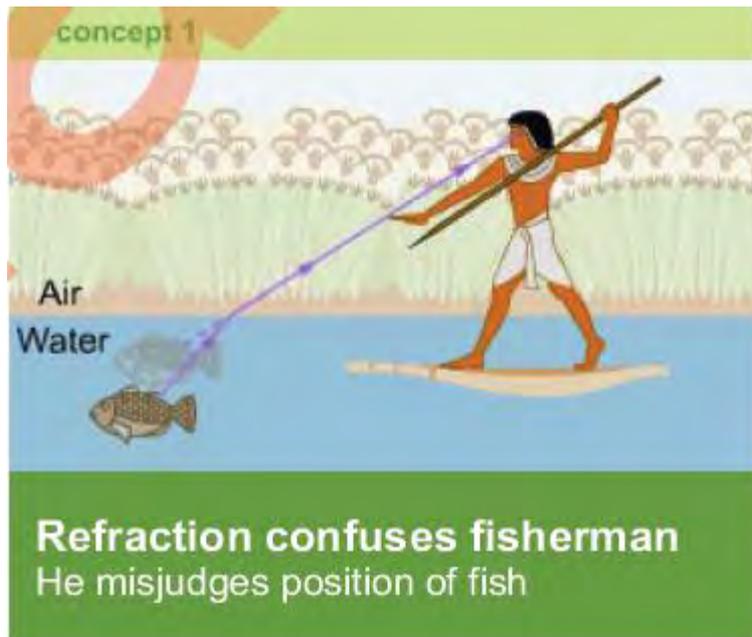
$$n = 1.51$$

$n_1 = 1.68 \qquad n_2 = ?$

$25.0°$

$30.5°$

What is the index of refraction of the second material?

Everyday effects of refraction The refraction of light can cause interesting and sometimes confusing results as the brain interprets the position of objects it sees via

refracted light. For instance, in the upper illustration to the right, you see an ancient Egyptian fisherman trying to spear a fish. The solid line indicates the refracted path of the light traveling from the fish to his eyes. Since his brain expects light to travel in a straight line, he projects the fish to be in the position indicated at the end of the dashed line, which causes him to think the fish is nearer to the surface than it is. Experienced spear fishermen know how to compensate for this effect. The fisherman is not the only one to experience the effects of refraction. The fish does, too. The light from the world above seen by the fish also refracts. Light coming straight down will pass through the water's surface unchanged, but light at any angle will refract, in the process giving the fish a wider field of view of the world above than it would have if there were no refraction. In essence, the fish sees a compressed wide-angle view of the scene above. Certain camera lenses, appropriately called fisheye lenses, can create the same effect, as illustrated in Concept 2. Another interesting consequence of Snell's law concerns light passing through a window. The light refracts as it travels from air to glass. After passing through the glass it refracts again at the second interface. The ratio of the indices of refraction is now reversed, so the initial change in angle is cancelled out. The light ray that emerges is parallel to the initial ray, but displaced a small amount. The amount of displacement is small enough that we ordinarily do not notice —window shift." However, if you place a newspaper page on a tabletop and cover half of it with a flat pane of glass, you will be able to observe the displacement effect.

concept 1

Air
Water

Refraction confuses fisherman
He misjudges position of fish

concept 2

A fisheye view
Wide-angle view compresses images

concept 3

Air   Glass

Light through a windowpane
Light refracts twice
Emerges parallel to initial ray

Wavelength of light in different media When light changes speed as it moves from one medium to another, its frequency stays the same but its wavelength changes. The

ratio of its wavelengths in the two media is the inverse of the ratio of the indices of refraction. We show this as an equation to the right and derive it below. Before deriving the equation, let's consider why the frequency stays the same, since this is an essential part of the derivation. The frequencies in the media must be the same, because if they were not, waves would either pile up at the interface or be destroyed. Neither occurs. You can witness this at the beach, where wave speed and wavelength may change as waves approach the beach, but the frequency of the waves does not change.

concept 1

n_1

$n_1 < n_2$

n_2

Frequency and wavelength
When light changes speed
· The frequency stays the same
· The wavelength changes

equation 1

n_1

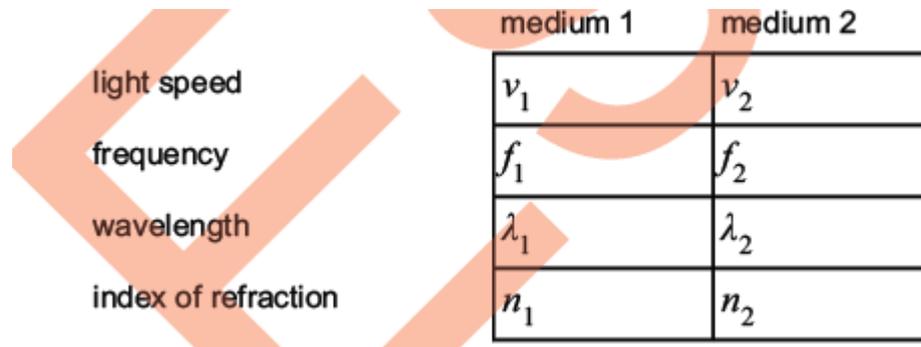λ_1

$n_1 < n_2$

n_2

λ_2

Wavelength, index ratios inversely proportional

$$\frac{\lambda_1}{\lambda_2} = \frac{n_2}{n_1}$$

λ = wavelength in medium
n = index of refraction

Variables

In this derivation, c represents the speed of light in a vacuum. For the other two media we define the variables in the following table:

	medium 1	medium 2
light speed	v_1	v_2
frequency	f_1	f_2
wavelength	λ_1	λ_2
index of refraction	n_1	n_2

Strategy

1. Use the equality of frequencies in the two media together with the wave speed equation to obtain a proportionality of the light speeds and wavelengths in the media.

2. Use the definition of the index of refraction to convert the previous proportion to one involving wavelengths and indices of refraction.

Physics principles and equations

The wave speed equation states that for any wave, the speed is the product of the wavelength and the frequency:

$$v = \lambda f$$

As a wave passes from one medium to another, its speed and wavelength may change, but its frequency must remain the same.

The definition of the index of refraction of a medium is

$$n = \frac{c}{v}$$

Step-by-step derivation

First, we explain the diagram you see above. The purple line is a light ray refracting at an interface. In the diagram, light travels more slowly in the lower medium than the upper. This could represent, for example, light passing from air into water. The gray lines perpendicular to the ray represent wave fronts. You see the wavelength labeled as λ (λ_i in the upper medium, λ_r in the lower medium). There are two right triangles in the diagram that share the hypotenuse labeled x. The bright yellow triangle shows

elements of a wave front that has not yet entered the lower medium. The dark orange triangle shows elements of a wave front that is now traveling in the lower medium. The angles of incidence and refraction θ_i and θ_r are also shown in the diagram. Because the wave fronts are perpendicular to the light rays, we can identify angles in each of the triangles that are equal to θ_i and θ_r. These base angles are shown in the diagram.

Variables

In this derivation, x represents the common hypotenuse of the two triangles in the diagram. For the incident and refractive media we define the variables in the following table.

	incident medium	refractive medium
angle	θ_i	θ_r
wavelength	λ_i	λ_r
index of refraction	n_i	n_r

Strategy

1. Consider the two triangles in the diagram. State the sines of their base angles θ_i and θ_r as trigonometric ratios of the triangles' sides.

2. Construct the ratio $\sin \theta_i / \sin \theta_r$. The common hypotenuse x will cancel out, leaving a ratio of wavelengths.

3. Restate the ratio of wavelengths as a ratio of indices of refraction to obtain Snell's law.

Physics principles and equations

The ratio of the wavelengths is inversely proportional to the ratio of the indices of refraction.

$$\frac{\lambda_i}{\lambda_r} = \frac{n_r}{n_i}$$

Step-by-step derivation

We construct the fraction sin □i / sin □r, and calculate the sines as the ratios of the sides of triangles. This leads to a ratio of wavelengths that can be replaced by a ratio of indices of refraction, yielding Snell's law.

Step		Reason
1.	$\sin \theta_i = \lambda_i / x, \sin \theta_r = \lambda_r / x$	definition of sine
2.	$\dfrac{\sin\theta_i}{\sin\theta_r} = \dfrac{\lambda_i/x}{\lambda_r/x}$	ratio using definition of sine
3.	$\dfrac{\sin\theta_i}{\sin\theta_r} = \dfrac{\lambda_i}{\lambda_r}$	simplify
4.	$\dfrac{\lambda_i}{\lambda_r} = \dfrac{n_r}{n_i}$	change of wavelength
5.	$\dfrac{\sin\theta_i}{\sin\theta_r} = \dfrac{n_r}{n_i}$	substitute equation 4 into equation 3

Interactive problem: helicopter and submarines

The simulation on the right is similar to the one in this chapter's introduction. As before, submarines lurk under the waves, but now you have only a single helicopter.

As before, you have a laser you can aim in an attempt to disable two submarines before they disable you. You keep shooting as long as you keep making hits. To shoot your laser, aim it by dragging the aiming arrow and fire it by clicking on FIRE. The angle of incidence is shown in an output gauge. As soon as you miss, it is the submarines' turn. Warning: The computer has been set to be far more accurate in this game than in the introductory one. Unless you are very precise with your shots, it is unlikely you will win. However, there is good news: Now you have more intellectual firepower because you have the aid of Snell's law. You are also given some assistance from an able comrade; she has computed the angles of refraction required for your laser to reach the submarines, as shown in the diagram. You should use 1.33 for the index of refraction of water, and 1.00 for the index of refraction of air. If you correctly set the angle of incidence when you aim each of your shots, you can make two straight hits and disable the submarines before they disable you.
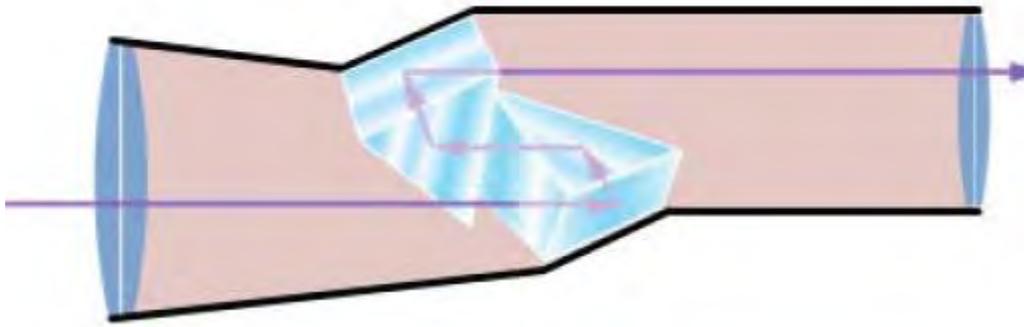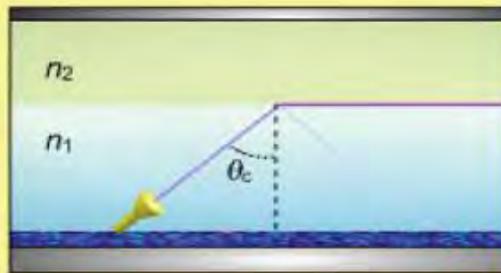
Critical angle

$$\sin\theta_c = \frac{n_2}{n_1}$$

θ_c = critical angle
n_1, n_2 = indices of refraction ($n_1 > n_2$)

example 1

You are cutting a sapphire to make it as brilliant as possible. Find the critical angle for the sapphire in air. The index of refraction of a sapphire is 1.77.

$$\sin\theta_c = \frac{n_{air}}{n_{sap}}$$

$$\theta_c = \arcsin\left(\frac{n_{air}}{n_{sap}}\right)$$

$$\theta_c = \arcsin\left(\frac{1.00}{1.77}\right)$$

$$\theta_c = 34.4°$$

Fiber optic cable is used to transfer information (in glass or plastic) using total internal reflection. Data (such as speech) is first encoded as modulations of a beam of laser light. The light remains inside the transparent cable as it travels due to its total internal reflection off the inner surfaces of the cable walls. In this way, light is transmitted through the cable with little loss. Using light instead of electricity to transfer information has several benefits. Light can be used to encode much more information than electric oscillations because of its extremely high frequency (more than 1014 Hz for red light), and fiber optic cable is immune to interference problems from nearby electrical applications

Step-by-step solution

We start by using trigonometry to establish a relationship between $\sin \square$ and $\sin \square c$. In the following steps we use Snell's law and the definition of the critical angle to find $\sin \square$ in terms of indices of refraction. Then we evaluate to find a value for the acceptance angle $\square$.

Step		Reason
1.	$\cos \beta = \sin \theta_c$	trigonometric identity
2.	$\sin\beta = \sqrt{1 - \cos^2\beta}$	trigonometric identity
3.	$\sin\beta = \sqrt{1 - \sin^2\theta_c}$	substitute equation 1 into equation 2

Step		Reason
4.	$n_0 \sin \alpha = n_1 \sin \beta$	Snell's law
5.	$\sin\alpha = \dfrac{n_1}{n_0}\sqrt{1 - \sin^2\theta_c}$	substitute equation 3 into equation 4
6.	$\sin\theta_c = \dfrac{n_2}{n_1}$	definition of critical angle
7.	$\sin \alpha = \dfrac{n_1}{n_0}\sqrt{1 - \dfrac{n_2^2}{n_1^2}}$	substitute equation 6 into equation 5
8.	$\sin \alpha = \dfrac{1.60}{1.00}\sqrt{1 - \dfrac{(1.50)^2}{(1.60)^2}}$ $\sin \alpha = 0.557$ $\alpha = 33.8°$	evaluate

**Interactive problem: laser target pistol**

In this simulation, you fire a laser pistol at two stationary targets. You want a bullseye, a shot that passes through the central black circle of the target. You happen

to be immersed in a fluid with an index of refraction of 1.60. When you shoot the laser from within the fluid, you have to account for the refraction of your laser beam as it passes from the fluid into the air. Some portion of the beam also reflects from the interface. If the incident angle is equal to or greater than the critical angle, all of the beam will reflect.

The laser pistol is designed so its beam always hits the interface between the fluid and the air at the same point. You drag the pistol from side to side to determine its angle of incidence. An output gauge tells you the horizontal distance between the pistol and where its beam passes through the interface. You are also told how far the pistol is below the surface, a value that stays constant.

There are two targets to hit: one above the surface of the fluid and the other below the surface. You will have to use a different strategy to hit each target. For each target you know its horizontal distance from where the laser passes through the interface, and its height above the fluid. You must strike each target in its center to succeed.

You have just read a fair number of facts. It may be useful now to look at the diagram and the simulation. You will probably find the lower target easier to hit, if you just reflect a bit. You can then bend your mind toward determining how to hit the upper target. A good way to start is to apply trigonometry to calculate the necessary angle of refraction. Then, using Snell's law and some more trigonometry, you can determine where to position the pistol. When you have calculated the correct horizontal distance, drag the pistol and press FIRE to test your answer.
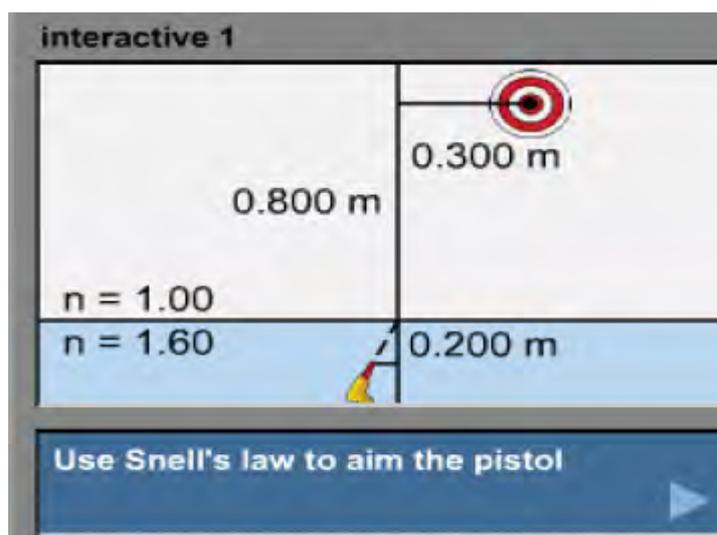
Light is a particle.

Many of the great scientists of the 17th and 18th centuries who made fundamental contributions to the study of optics, including Isaac Newton, thought that light consisted of a stream of ‒corpuscles," or particles. In the 20th century, Albert Einstein explained the photoelectric effect. His explanation, for which he was awarded the 1921 Nobel Prize, depended on the fact that light acts like a particle. This property of light led to the coining of the term ‒photon" for a single particle of light by the chemist Gilbert Lewis.

Light is a wave. Between the 18th and 20th centuries, physicists discovered many wave-like properties of light. They found that a number of phenomena they routinely observed with water waves they could also observe with light. For instance, the English scientist Thomas Young (1773-1829) showed that light could produce the same kinds of interference patterns that water waves produce. At the right, you see examples of interference patterns formed by light and by water waves. The similarities are striking. In this chapter, you will apply to light some of what you have studied about the interference of sound waves and traveling waves in strings. **Let there be light**. Is light a particle, a wave, or both? Perhaps an Early Authority had it right. Light is light. It is a combination of electric and magnetic fields. Trying to classify light as a particle or as a wave may be a fruitless effort □ better to revel in its unique properties. In this chapter, we will revel in its wave-like properties, and discuss the topic of interference. Your prior study of electromagnetic radiation modeled as a wave phenomenon will prove useful.