1B24: WAVES, OPTICS AND ACOUSTICS
Revision notes

R.1 Simple Oscillations and their Description

R.1.1 Motion in a circle, projection on a line, phasors

Remember the link between harmonic motion and motion in a cricle: the rotating vector is called a **phasor**. Simple harmonic motion is the projection of circular motion onto one axis.

relation to complex numbers

$$x(t) = A\cos(\omega_0 t + \phi) = Re\left[Ae^{i(\omega_0 t+\phi)}\right]$$

Any physical quantity, however, is real, and is obtained from the complex form by taking the Real part

R.2 Combinations of Oscillations

R.2.1 Superposition of two motions

same frequency – same amplitude

The superposition of two oscillations may be treated in the phasor representation. We are adding together two vectors, both rotating with the same angular velocity. Thus the resultant will also be rotating with that angular velocity. We could equally well (or, perhaps, more easily) use the complex exponential notation.

different frequencies - beats

The sum of two oscillations with different frequencies is the product of two functions, with half-sum and half-difference frequencies. The higher-frequency term is called the *carrier* wave, the lower-frequency wave which modulates the amplitude of the carrier is the *envelope*. This is the phenomenon of *beats*. Note that what the ear, for example, detects as the beat frequency is the variation of *intensity*, which is double the envelope frequency: that is, the beat frequency is the difference between the two original frequencies.

R.3 The Wave Equation – Basic Properties

R.3.1 The one-dimensional wave equation

The general form of a wave equation is:

$$\frac{\partial^2 \psi}{\partial t^2} = c^2 \frac{\partial^2 \psi}{\partial x^2},$$

with c being the wave speed.

$h(ct - x) + g(ct + x)$

The most general form of solution has the form

$$\psi(x, t) = h(ct - x) + g(ct + x),$$

representing waves travelling to the right $(ct - x)$ and to the left $(ct + x)$ — note that what determines the direction of travel is the *relative* sign of the t term and the x term.

define phase, wavelength, wavenumber, k-number or wavevector

If we are going to work with sinusoidal, or complex exponential, functions, then for a frequency ω we want to convert the combination $ct - x$, which has the dimensions of length, to a quantity measured in radians. We can do this if we multiply it by $2\pi/\lambda$, and take

$$\psi(x, t) = \psi_0 e^{i\frac{2\pi}{\lambda}(ct - x)}.$$

The spacing between successive peaks in space is λ, the wavelength. The spacing between successive peaks in time is λ/c, the period, so the frequency is c/λ, often called ν or f, the angular frequency $\omega = 2\pi\nu$ is $2\pi c/\lambda$. The combination $2\pi/\lambda$ is called the wave vector, or wave number, often denoted by k. We can write the general form of the wave in a number of equivalent ways:

$$\begin{aligned}
\psi(x,t) &= \psi_0 e^{i\frac{2\pi}{\lambda}(ct-x)} \\
&= \psi_0 e^{i2\pi(\nu t-\frac{x}{\lambda})} \\
&= \psi_0 e^{i\omega(t-\frac{x}{c})} \\
&= \psi_0 e^{i(\omega t-kx)}
\end{aligned}$$

$$c = \lambda\nu = \frac{\omega}{k}.$$

The quantity we have defined by $c = \omega/k$ gives, in a sinusoidal wave, the speed at which peaks and troughs (points of constant phase) move through the medium - it is called the *phase velocity.*

linearity/superposition

We know that as the wave equation is linear, we may superpose solutions and still get a solution which is a solution of the wave equation.

R.4 Single-Frequency Waves and Waves on Strings

R.4.1 Transverse waves on a stretched string

wave equation

Derivation:

- Look at forces on small section of string
- Transverse force is tension times slope of string (small displacements)
- Nett force on section is tension times difference in slopes at ends of section
- Hence nett force is proportional to second derivative of displacement
- Set this equal to mass of section times acceleration

Hence

$$\frac{\partial^2 y}{\partial t^2} = \frac{T}{\rho}\frac{\partial^2 y}{\partial x^2}, \tag{R.1}$$

that is, a wave equation with wave speed $c = \sqrt{T/\rho}$. For a wave on a string, the transverse velocity depends on the frequency and the amplitude, and varies with time. The wave velocity is a constant: in a linear wave (the only sort we deal with) it is independent of amplitude, although (dispersion) it may depend on frequency.

running waves

The solutions we have written down, functions of the form $e^{i(\omega t \pm kx)}$, are running waves - they travel along the x axis either left to right $(-)$ or right to left $(+)$.

normal modes, harmonics

We need to introduce *boundary conditions*, which may involve specifying displacements or 'forces' at the ends.

$$y(x,t) = ae^{i(\omega t + kx)} + be^{i(\omega t - kx)}. \tag{R.2}$$

with $y(x,t) = 0$ at $x = 0$, $x = L$ for all t: $x = 0$ gives $a + b = 0$. Two equal and opposite running waves give a standing wave with nodes at the ends of the string Then we have

$$y(x,t) = ce^{i\omega t}\sin(kx)$$

whence

$$\lambda_n = \frac{2L}{n} \tag{R.3}$$

nodes/antinodes of standing wave

Define them - node=zero displacement, antinode = maximum displacement; fixed positions on string vibrating in normal mode.

R.4.2 Longitudinal and Transverse Waves: Polarisation

R.5 Acoustic waves

R.5.1 Elastic waves in a rod

Note that in these notes we have selected just one wave system for which to derive the wave equation in detail. You should be able to do the same for a string or a gas: the basic ideas are very similar. The one slightly tricky point to remember is that the tension in the string and the stress (force per area) in the rod *pull* on the ends, but pressure *pushes*.

Suppose that at a point x along the rod an element of the rod (a thin disk) has been displaced by ξ as a result of wave passing down the rod. If at a point a little further along, at $x + \mathrm{d}x$, the displacement is $\xi + \mathrm{d}\xi$, then the element which was of length $\mathrm{d}x$ has been stretched. The amount of the stretch is

$$\mathrm{d}\xi = \frac{\partial \xi}{\partial x}\mathrm{d}x.$$

Remember that ξ is the *change* in position of a marker on the rod. The force at each point, then, is given by the local strain (change in length divided by length), i.e.

$$F(x) = AY\frac{\partial \xi}{\partial x}$$

If we had a rod under constant tension, of course, the *fractional* extension would be constant along the rod, and $\xi = \frac{F}{AY}x$.

If the amount of stretching is not constant along the rod, the force will not be constant either. In fact the force at $x + \mathrm{d}x$ will be

$$F' = F + \mathrm{d}F = F + \frac{\partial F}{\partial x}\mathrm{d}x$$

and the nett force on the element $\mathrm{d}x$ is therefore

$$F' - F = \frac{\partial F}{\partial x}\mathrm{d}x,$$

so that

$$F' - F = AY\frac{\partial^2 \xi}{\partial x^2}\mathrm{d}x.$$

The mass of the element of thickness dx and area A is $\rho A\mathrm{d}x$, and its change in position is given by ξ, so

$$\rho A\mathrm{d}x\frac{\partial^2\xi}{\partial t^2} = AY\frac{\partial^2\xi}{\partial x^2}\mathrm{d}x$$

or

$$\frac{\partial^2\xi}{\partial t^2} = \frac{Y}{\rho}\frac{\partial^2\xi}{\partial x^2}. \tag{R.4}$$

R.5.2 Elastic waves in a bulk solid

compression waves and shear waves

Remember that different types of wave exist, but that's about all you need to know.

R.5.3 Sound waves in a gas

$$B = -\frac{\text{change in pressure}}{\text{fractionalchangeinvolume}} = -\frac{\mathrm{d}P}{\mathrm{d}V/V} = -V\frac{\mathrm{d}P}{\mathrm{d}V}. \tag{R.5}$$

$$\frac{\partial^2\xi}{\partial t^2} = \frac{B_\mathrm{a}}{\rho_0}\frac{\partial^2\xi}{\partial x^2} \tag{R.6}$$

that is, a wave with velocity $v = \sqrt{B_\mathrm{a}/\rho_0}$. We use the adiabatic bulk modulus because the changes which the wave induces are fast compared with the time-scales for heat transfer through the gas.

$$PV^\gamma = \text{constant} \tag{R.7}$$

where γ is a constant characteristic of the type of gas. Thus the wave velocity $v = \sqrt{B_\mathrm{a}/\rho_0} = \sqrt{\gamma P_0/\rho_0}$.

R.5.4 Characteristic impedance

general form

The impedance is the ratio of the generalised force to the response.

wave in gas

$$Z = \text{Specific acoustic impedance} = \frac{\text{excess pressure}}{\text{particle velocity}} = \frac{p}{\dot{\xi}} = \sqrt{B_{\mathrm{a}}\rho}. \tag{R.8}$$

of a string

$$Z = \frac{\text{Transverse force}}{\text{particle velocity}} = \sqrt{T\rho}. \tag{R.9}$$

R.6 Energy in Waves - Reflection of Waves

R.6.1 Energy transport in waves

Sum of KE and PE: both oscillate, so average over a period (or over a wavelength) Overall, then, the energy density in a sound wave is

$$\langle E_{\mathrm{tot}} \rangle = \frac{1}{2}\rho_0\omega^2\xi_0^2 = \frac{1}{2}Z\omega^2\xi_0^2/c. \tag{R.10}$$

The rate at which energy is transferred, the energy flux, is the product of energy density and wave velocity,

$$I = c\langle E \rangle = \frac{1}{2}\omega^2 Z\xi_0^2. \tag{R.11}$$

$$I = \langle W \rangle = \frac{1}{2}B_{\mathrm{a}}k\omega\xi_0^2 = \frac{1}{2}\rho_0\omega^2\xi_0^2 c = \frac{1}{2}\omega^2 Z\xi_0^2,$$

the intensity, which is exactly $c\langle E \rangle$.

Examples: sound in air and water

Measurement of Sound

If $I/I_0 = 10^b$, then I is said to be b bels louder than I_0. Correspondingly, one decibel (db) is a factor of $10^{0.1} \approx 1.3$, three decibels (3 db) is $10^{0.3} \approx 2$.

R.6.2 Joined strings

Boundary conditions: continuity of displacement *and* force — *not* just continuity of slope (though for the string it amounts to the same thing).

$$\mathtt{r} = \frac{Z_1 - Z_2}{Z_1 + Z_2} \tag{R.12}$$

$$\mathtt{t} = \frac{2Z_1}{Z_1 + Z_2}. \tag{R.13}$$

relative signs of incident, reflected and transmitted waves.

Reflect from a denser medium, change sign (remember case of fixed end, effectively infinitely dense medium).

R.6.3 Acoustic waves in dissimilar media - reflection and transmission

a) directly

b) in terms of impedance

Note that the values of R and T give

$$R + T = 1, \tag{R.14}$$

which expresses the conservation of energy.

R.6.4 Impedance matching - quarter-wave plates

Perfect transmission between two media, with no reflection, may be achieved by inserting a matching layer with an impedance which is the geometric mean of the impedances of the two original media, and with a thickness which is one quarter of a wavelength in the matching medium.

Matching air and glass

R.7 Dispersion: phase and group velocity

R.7.1 Phase and group velocity

Refractive index of materials

$$\text{refractive index} = \frac{\text{speed of light in free space}}{\text{speed of light in material}}$$

simple two-frequency treatment

Two waves - mathematics similar to that for beats.

envelope function and carrier

Group velocity

$$v_{\mathrm{g}} = \frac{\mathrm{d}\omega}{\mathrm{d}k}$$

Phase velocity

$$v_{\mathrm{p}} = \frac{\omega}{k}$$

$$v_{\mathrm{g}} = \frac{\partial\omega}{\partial k} = \frac{\partial(v_{\mathrm{p}}k)}{\partial k} = v_{\mathrm{p}} + k\frac{\partial v_{\mathrm{p}}}{\partial k},$$

e.g. Waves on fluid surfaces

R.7.2 Waves in more than one dimension

plane waves in three dimensions

We can therefore generalize our expression for a wave to three dimensions, as

$$\xi(x,t) = Ae^{i(\omega t - \mathbf{k}.\mathbf{x})}$$

for a wave travelling in the *direction* $\mathbf{k}/|\mathbf{k}|$ and with a wavelength $2\pi/|\mathbf{k}|$.

cylindrical and spherical waves

Here we have a phase which varies with distance from the source, not direction (i.e. a kr in place of $\mathbf{k}.\mathbf{x}$).

energy fluxes

Leads to the $1/(kr)$ for spherical waves, $1/\sqrt{kr}$ for cylindrical waves.

Curvature of Wavefront

Negligible at large distances (Fraunhofer limit).

R.8 Moving sources and Receivers

The treatment we adopt assumes that the wave is propagated in some medium, with respect to which the source, or the observer, or both, are moving. This will introduce an asymmetry between the source and the observer. Although we shall use this same formalism when we discuss light: this is an approximation, as we know from the principle of relativity that there is no preferred frame of reference, and that all that matters is the *relative* motion of the source and the observer. Nevertheless, as long as the velocities involved are not too close to light speeds, our result will be quite accurate for light.

R.8.1 Doppler effect

Source moving with velocity v_s towards an observer in a medium in which the wave speed is c. If the frequency of the source is f, in a time t it will have emitted ft waves, but in the region in front of the source these will have been emitted into a distance $(c - v_s)t$. Thus the wavelength is

$$\lambda' = \frac{(c - v_s)t}{ft}$$

or

$$\frac{(c - v_s)}{f.}$$

In a time t a stationary observer will receive the waves in a distance ct, which will be ct/λ' wavelengths, so the observed frequency will be

$$f' = fc/(c - v_s).$$

If observer is moving with speed v_o away from the source, in time t the waves received will be those in a distance $(c - v_o)t$, and if the wavelength is λ the frequency will therefore be

$$f' = \frac{(c - v_o)t}{\lambda} \frac{1}{t}$$

or

$$f' = \frac{f(c - v_o)t}{c}$$

If both source and observer are moving

$$f' = f(c - v_o)/(c - v_s),$$

taking a positive velocity as being along the source-observer distance.

R.9 Interference - Basic phenomena

R.9.1 Young's slits

Constructive interference when path length difference is an integer number of wavelengths, so bright lines at

$$\frac{yh}{x} = m\lambda.$$

R.9.2 sum of signals from several dipoles — simple diffraction grating

If we have a large number of sources, we can add them together using the phasor or the complex number picture. This is one of several places (Fabry-Perot, matched filter are others) where adding signals gives a geometric progression.

Far from array, looking at an angle θ off axis, with sources h apart, phase difference δ between successive sources will be

$$\delta = \frac{2\pi}{\lambda} h \sin\theta$$

and the total signal from N of them will be

$$Re^{i(\omega t+\phi)} = Ae^{i\omega t} + Ae^{i(\omega t+\delta)} + ...$$

which is a geometric series with common ratio $e^{i\delta}$, so

$$Re^{i(\omega t+\phi)} = Ae^{i\omega t}\frac{1-e^{Ni\delta}}{1-e^{i\delta}}$$

which results in

$$Re^{i(\omega t+\phi)} = Ae^{i(\omega t+(N-1)\delta/2}\frac{\sin(N\delta/2)}{\sin(\delta/2)}.$$

Finally,

$$I(\theta) = I(0)\left[\frac{\sin\left(\frac{N\pi h}{\lambda}\sin(\theta)\right)}{N\sin\left(\frac{\pi h}{\lambda}\sin(\theta)\right)}\right]^2.$$

Whenever

$$\sin\theta = m\frac{\lambda}{h}$$

where m is any integer, there is a peak of amplitude N.

Diffraction grating

Resolving power is

$$\frac{\lambda}{(\Delta\lambda)_{\text{min}}} = mN,$$

where m is the order of diffraction and N is the number of lines in the grating.

R.10 Diffraction

R.10.1 Huygens's principle

Every point on a primary wavefront serves as the source of spherical secondary wavelets, such that the primary wavelet at a later time is the envelope of these secondary wavelets. The wavelets advance with a speed and frequency which are equal to those of the primary wave at every point in space.

R.10.2 Huygens-Fresnel principle

Every point on a primary wavefront serves as the source of spherical secondary wavelets. The amplitude of the field at any point is the superposition of all these wavelets, taking account of their amplitudes and phases.

R.10.3 Fraunhofer diffraction

The range at which wavefront curvature becomes important, the Rayleigh distance, for an aperture d is d^2/λ.

Ignoring the variation of amplitude with distance, and absorbing the phase change on the path length D into the constant term, we have the comparatively simple result

$$E = \text{constant} \int_S e^{-i(k_x x' + k_y y')} \mathrm{d}S',$$

where the integral is over the area of the aperture which is in the $x'y'$ plane, or

$$E = \text{constant} \int_S e^{-i(k\alpha x' + k\beta y')} \mathrm{d}S'$$

where α and β are the direction cosines of the ray travelling from the aperture to the point of observation.

R.10.4 slit

The intensity pattern (from above, assume constancy over y' and integrate over x' from $-d/2$ to $d/2$ where d is the slit width) is

$$I(\theta) = I(0) \left[\frac{\sin\left(\frac{\pi d}{\lambda}\sin(\theta)\right)}{\frac{\pi d}{\lambda}\sin(\theta)} \right]^2 .$$

R.10.5 grating

The grating is a pattern of N slits, each of width d, and spaced at a distance h between their centres along the x axis, and the diffracted amplitude from the grating is the product of the pattern from the arrangement of slits and the pattern from each slit.

$$I(\theta) = I(0) \left[\frac{\sin\left(\frac{N\pi h}{\lambda}\sin(\theta)\right)}{N\sin\left(\frac{\pi h}{\lambda}\sin(\theta)\right)} \right]^2 \left[\frac{\sin\left(\frac{\pi d}{\lambda}\sin(\theta)\right)}{\frac{\pi d}{\lambda}\sin(\theta)} \right]^2 .$$

R.11 Resolution of images

R.11.1 Rayleigh criterion for slit

Rayleigh's criterion states that two similar diffraction patterns can just be separated if the first zero of one pattern falls on the central peak of the other – this gives an adequate dip in intensity. This is Rayleigh's criterion for resolution, and requires an angular separation $> \lambda/d$.

R.11.2 Rayleigh for circular aperture

For a circular aperture, the diffraction is circular, and the first zero occurs at an angle of $1.22\lambda/d$, where d is now the *diameter* of the aperture.

R.12 Reflection and Refraction

R.12.1 Snel's law

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$$

R.12.2 phase change on reflection

For small angles of incidence, zero for reflection from a less optically dense material, π for reflection from a more optically dense material.

R.12.3 Slab

Slab of refractive index n_2 with a medium of refractive index n_1 on each side, then a ray incident at an angle θ_1 will be refracted to θ_2, where

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2).$$

The light is incident at an angle θ_1 then the optical path difference between paths is

$$\Delta = \frac{2dn_2}{\cos(\theta_2)}(1 - \sin^2(\theta_2)) = 2n_2 d \cos(\theta_2).$$

R.12.4 thin film

The commonest situation in which we see interference effects is in oil on the surface of puddles, or in thin soap films - assume normal incidence. For oil on water, we have constructive interference for a film of thickness h if

$$2h = (p + \frac{1}{2})\lambda_{\text{oil}} = (p + \frac{1}{2})\frac{\lambda_{\text{air}}}{n_{\text{oil}}},$$

where p is an integer.

R.12.5 Newton's rings

The geometry is fairly simple: take care over phase changes on reflection, especially if there is a liquid inserted between the lens and the plate. Circular fringes are formed.

R.12.6 wedge

Straight fringes.

R.13 Michelson Interferometer

The arrangement is very simple: a source (which may be extended) is divided by a partly-silvered mirror, travels to two mirrors, and is recombined again by the beam-splitter. Any path length difference gives rise to interference. Dark fringes given by

$$\cos(\theta) = p\frac{\lambda}{2d}.$$

R.13.1 compensating plate for white light

Gives equal path lengths through glass for the two optical paths.

R.13.2 measuring refractive index

Putting a different material (e.g. a different gas) into one arm also alters the path length – hence use of Michelson interferometer to measure refractive index.

R.13.3 precise measurements of wavelength

Visibility of fringes varies with path length difference for a doublet source.

R.14 Fabry-Perot Interferometer

The basic idea is to allow multiple reflections within a thin film. The arrangement of the Fabry-Perot interferometer uses two glass plates to form the reflecting surfaces. The pair of parallel plates is called an etalon.

R.14.1 Silvered or unsilvered surfaces

With reflection and transmission coefficients for the two sides of the etalon r, r', t and t', and a phase difference δ for light passing through the gap at an angle θ to the normal given by

$$\delta = \frac{2\pi}{\lambda} 2d\cos(\theta) + 2\phi$$

(where ϕ accounts for any phase change on reflection - if the mirrors are coated so as to increase the reflection coefficients ϕ may be between 0 and π) we find

$$I = I_0 \left(\frac{T}{1-R}\right)^2 \frac{1}{1 + F\sin^2(\delta/2)},$$

where

$$T = tt' \qquad R = rr' \qquad F = \frac{4R}{(1-R)^2}.$$

The resolving power may be increased by increasing the reflection coefficient. This can be done by silvering or by using appropriate dielectric layers - just as blooming a lens can reduce reflection, so appropriate coating can increase reflectivity.

$$\frac{\lambda}{\Delta\lambda_{\min}} = \frac{\pi d}{\lambda}\sqrt{F}.$$

R.15 Sign Conventions for Reflection and Refraction

Note that throughout our treatment of curved mirrors and lenses we assume small angles, i.e. we make the *paraxial approximation*.

We choose a so-called Cartesian convention, in which

- the origin of the Cartesian system is located at the vertex of the curved boundary or mirror, and at the centre of a thin lens, with the x axis directed along the optical axis from left to right.
- object, image, and centre of curvature distances are defined to be the x coordinates of the y, z planes which contain them. Thus distances to points or planes to the right of the vertex or lens centre are positive, those to the left are negative.
- light sources and objects are placed to the left of the first surface in the system, so that the light rays travel from left to right, but the object has a negative x coordinate and the object distance will thus be negative.
- angles are taken to be positive or negative dependent on whether their tangents are positive or negative.
- When *deriving* equations, just use geometry and put in the signs at the end to get general-purpose equations;
- When *using* the general-purpose equations, substitute distances *with the appropriate signs.*

R.16 Reflection at spherical surfaces

$$\frac{1}{l_1} + \frac{1}{l_2} = \frac{2}{r} = \frac{1}{f}$$

or, using u for object distance and v for image distance,

$$\frac{1}{u} + \frac{1}{v} = \frac{2}{r} = \frac{1}{f}.$$

We need to insert the signs appropriate to our *sign convention.*

R.17 Refraction at spherical surfaces

$$\frac{n_1}{l_1} - \frac{n_2}{l_2} = \frac{n_1 - n_2}{r}.$$

We now need to insert the signs appropriate to our *sign convention.*

R.17.1 Lenses

$$\frac{1}{v} - \frac{1}{u} = (n-1)\left(\frac{1}{r_1} - \frac{1}{r_2}\right) = \frac{1}{f}.$$

This is the basic equation for the behaviour of a thin lens.

R.17.2 principal foci and focal length

In drawing ray diagrams, there are three *principal rays*:

- one enters parallel to the optical axis and is refracted so as to pass directly or by projection through the second focal point;
- one passes directly or by projection through the first focal point, and emerges parallel to the optical axis;
- one passes undeviated through the centre of the lens (where the lens surfaces are locally parallel).

R.17.3 Magnifying glass

With the image at the near point

$$M = \frac{h'}{h} = \frac{250}{u} = 1 + \frac{250}{f},$$

and with the image at infinity

$$M = \frac{250}{f},$$

with distances in mm.

R.17.4 Cardinal or Principal points of thick lens system

For a thick lens system, we again have the same basic quantities as before – focal points and vertices of lenses – but where do we measure them from? We define the so-called *Cardinal Points* or *Principal Points* as follows:

- two *focal points*, defined in terms of entry or exit rays parallel to the axis;

- *principal planes*, defined by the locus of the points of intersection of the incident ray through the focus and the exit ray parallel to the axis (Q_1 and rmQ_2);
- the *principal points*, being the intersections of the principal planes with the axis;
- the *nodal points* where the ray through the optical centre of the lens (the ray which emerges parallel to its incident direction) intersects the axis.

R.17.5 Compound lenses

We can derive a general expression for the focal length of a two-lens system, made of two *thin* lenses, as follows.

$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2}.$$

In most cases, though, it is easier to work through the analysis of the system from first principles - as on problem sheet P20. Take the first lens, find the image it produces, take that image as the object for the second lens and calculate its position relative to the second lens taking into account the distance between the lenses. Plug this result, adjusted where necessary in accordance with the sign convention, into the lens formula for the second lens – and the job is done. Similarly, the overall magnification is the product of the magnifications produced by the individual lenses.

R.18 Optical Instruments

Have a look at the diagrams for these, just to get an idea of what to expect if you want to draw ray diagrams, locate images, for these systems.

R.18.1 compound microscope

R.18.2 astronomical telescope

R.18.3 terrestrial telescope

R.18.4 telephoto lens