

Examples Sheet 3

The starred questions are intended as extras: do them if you have time, but not at the expense of unstarred questions on later sheets.

1. Find the general solutions of:

(i) $y'' + 5y' + 6y = e^{3x}$;

(ii) $y'' + 9y = \cos 3x$;

(iii) $y'' - 2y' + y = (x - 1)e^x$.

2. The function $y(x)$ satisfies the linear equation

$$y'' + p(x)y' + q(x)y = 0 .$$

The Wronskian $W(x)$ of two independent solutions, denoted $y_1(x)$ and $y_2(x)$, is defined to be

$$W(x) = \begin{vmatrix} y_1 & y_2 \\ y_1' & y_2' \end{vmatrix} .$$

Let $y_1(x)$ be given. Use the Wronskian to determine a first-order inhomogeneous differential equation for $y_2(x)$. Hence, show that

$$y_2(x) = y_1(x) \int_{x_0}^x \frac{W(t)}{[y_1(t)]^2} dt . \tag{*}$$

Show that $W(x)$ satisfies

$$\frac{dW}{dx} + p(x)W = 0 .$$

Verify that $y_1(x) = 1 - x$ is a solution of

$$xy'' - (1 - x^2)y' - (1 + x)y = 0 . \tag{†}$$

Hence, using (*) with $x_0 = 0$ and expanding the integrand in powers of t to order t^3 , find the first three non-zero terms in the power-series expansion for a solution, y_2 , of (†) that is independent of y_1 and satisfies $y_2(0) = 0$, $y_2'(0) = 1$.

3. Find the general solutions of the following discrete equations:

(i) $y_{n+2} + y_{n+1} - 6y_n = n^2$;

(ii) $y_{n+2} - 3y_{n+1} + 2y_n = n$;

(iii) $y_{n+2} - 4y_{n+1} + 4y_n = a^n$, where $a \neq 2$.

For (iii), by expressing a^n as a Taylor series about $a = 2$, find the general solution in the case $a = 2$.

4. (i) Find the solution of $y'' - y' - 2y = 0$ that satisfies $y(0) = 1$ and is bounded as $x \rightarrow \infty$.

(ii) Solve the related difference equation

$$(y_{n+1} - 2y_n + y_{n-1}) - \frac{1}{2}h(y_{n+1} - y_{n-1}) - 2h^2y_n = 0,$$

and show that if $0 < h \ll 1$ the solution that satisfies $y_0 = 1$ and for which y_n is bounded as $n \rightarrow \infty$ is approximately $y_n = (1 - h + h^2/2)^n$. Explain the relation with the solution of Part (i).

5. Show that

$$\frac{1}{r^2} \frac{d}{dr} \left(r^2 \frac{dT}{dr} \right) \equiv \frac{1}{r} \frac{d^2}{dr^2} (rT)$$

and hence solve the equation

$$\frac{1}{r^2} \frac{d}{dr} \left(r^2 \frac{dT}{dr} \right) = k^2 T, \text{ for } r \neq 0$$

subject to the conditions that $\lim_{r \rightarrow 0} T(r)$ is finite and $T(1) = 1$.

6. Given the solution $y_1(x)$, find a second solution of the following equations:

(i) $x(x + 1)y'' + (x - 1)y' - y = 0$, with $y_1(x) = (x + 1)^{-1}$;

(ii) $xy'' - y' - 4x^3y = 0$, with $y_1(x) = e^{x^2}$.

*7. The n functions $y_j(x)$ ($1 \leq j \leq n$) are independent solutions of the equation

$$y^{(n)}(x) + p_1(x)y^{(n-1)}(x) + \dots + p_{n-1}(x)y'(x) + p_n(x)y(x) = 0.$$

Let \mathbf{W} be the $n \times n$ matrix whose i, j element W_{ij} is $y_j^{(i-1)}(x)$ (so that the determinant $|\mathbf{W}| = W$, the Wronskian). Find a matrix \mathbf{A} , which does not explicitly involve the y_j , such that

$$\mathbf{W}' = \mathbf{A}\mathbf{W},$$

where \mathbf{W}' is the matrix whose elements are given by $(\mathbf{W}')_{ij} = W'_{ij}$. Using the identity

$$(\ln |\mathbf{W}|)' = \text{Tr} (\mathbf{W}'\mathbf{W}^{-1}) ,$$

express W in terms of $p_1(x)$.

8. Let $y(x)$ satisfy the inhomogeneous equation

$$y'' - 2x^{-1}y' + 2x^{-2}y = f(x) . \quad (*)$$

Set

$$\begin{pmatrix} y \\ y' \end{pmatrix} = u(x) \begin{pmatrix} y_1 \\ y_1' \end{pmatrix} + v(x) \begin{pmatrix} y_2 \\ y_2' \end{pmatrix} ,$$

where $y_1(x)$ and $y_2(x)$ are two independent solutions of (*) when $f(x) = 0$, and $u(x)$ and $v(x)$ are unknown functions. Obtain first-order differential equations for $u(x)$ and $v(x)$, and hence find the most general solution of (*) in the case $f(x) = x \sin x$. Are the functions $u(x)$ and $v(x)$ completely determined by this procedure?

9. A large oil tanker of mass M floats on the sea of density ρ . Suppose the tanker is given a small downward displacement z . The upward force is equal to the weight of water displaced (Archimedes' Principle). If the cross-sectional area A of the tanker at the water surface is constant, show that this upward force is $g\rho Az$, and hence that

$$\ddot{z} + \frac{g\rho A}{M}z = 0 .$$

Suppose now that a mouse exercises on the deck of the tanker producing a vertical force $f \sin \omega t$, where $\omega = (g\rho A/M)^{1/2}$. Show that the tanker will eventually sink. In practice, as the vertical motion of the tanker increases, waves will be generated. Suppose they produce an additional damping force $2k\dot{z}$. Discuss the motion for a range of values of k .

10. Find and sketch the solution of

$$\ddot{y} + y = H(t - \pi) - H(t - 2\pi) ,$$

where H is the Heaviside step function, subject to the initial conditions

$$y(0) = \dot{y}(0) = 0$$

and with $y(t)$ and $\dot{y}(t)$ continuous at $t = \pi$ and $t = 2\pi$.

11. Solve

$$y'' - 4y = \delta(x - a) ,$$

where δ is the Dirac delta function, subject to the condition that $y(x)$ is continuous at $x = a$ and boundary conditions that y is bounded as $|x| \rightarrow \infty$. Sketch the solution.

12. Solve

$$\ddot{y} + 2\dot{y} + 5y = 2\delta(t),$$

where δ is the Dirac delta function, given that $y = 0$ for $t < 0$. Give an example of a physical system that this equation and boundary condition describes.

*13. Show that, for suitably chosen $P(x)$, the transformation $y(x) = P(x)v(x)$ reduces the equation

$$y'' + p(x)y' + q(x)y = 0$$

to the form

$$v'' + J(x)v = 0. \quad (*)$$

The sequence of functions $v_n(x)$ is defined, for a given function $J(t)$ and in a given range $0 \leq x \leq R$, by $v_0(x) = a + bx$ and

$$v_n(x) = \int_0^x (t-x)J(t)v_{n-1}(t) dt \quad (n \geq 1).$$

Show that $v_n''(x) + J(x)v_{n-1} = 0$ ($n \geq 1$) and deduce that $v(x) = \sum_{n=0}^{\infty} v_n(x)$ satisfies (*) with the initial conditions $v(0) = a$, $v'(0) = b$. [You may assume that the sum that defines $v(x)$ converges sufficiently nicely to allow term-by-term differentiation. In fact, you can show by induction that if $|J(x)| < m$ and $|v_0(x)| < A$ for the range of x under consideration, then $|v_n(x)| \leq Am^n x^{2n}/(2n)!$ – try it! Convergence is therefore exponentially fast.]

What do these results tell us about the existence problem for general second-order linear equations with given initial conditions?

*14. This question concerns the expanding universe. Einstein's equations for a flat, isotropic and homogeneous universe can be written as

$$\frac{\ddot{a}}{a} = -\frac{4\pi}{3}(\rho + 3p) + \frac{\Lambda}{3}, \quad H \equiv \left(\frac{\dot{a}}{a}\right) = \left(\frac{8\pi}{3}\rho + \frac{\Lambda}{3}\right)^{1/2},$$

where a is the scale factor measuring the expansion of the universe ($\dot{a} > 0$), ρ and p are, respectively, the time-dependent energy density and pressure of matter, Λ is the (non-negative) cosmological constant and $H > 0$ is the Hubble parameter. Use these equations to establish the following: if $\Lambda = 0$ (or otherwise negligible) and $\rho + 3p > 0$, the acceleration $\ddot{a} < 0$ and the graph of $a(t)$ must be concave downward implying that $a = 0$ at a finite time in the past (the big bang). Using the tangent of the graph at the present time, $t = t_0$, show that the age of the universe is bounded above by $H^{-1}(t_0)$.

Consider the physical situations of a matter-dominated universe ($\Lambda = 0$ and $p = 0$) and a radiation-dominated universe ($\Lambda = 0$ and $p = \rho/3$). In each case, reduce the two equations above to one single second-order differential equation for a that is homogeneous in t (invariant under $t \rightarrow \lambda t$) and then show that there is a solution of the type $a = t^\alpha$. Determine the value of α for each case and verify that $\ddot{a} < 0$.

Now consider a Λ -dominated expanding universe ($\rho = 0$ and $p = 0$). Show that $a \propto e^{\beta t}$ and determine the value of β . Verify that it corresponds to an accelerated universe ($\ddot{a} > 0$). This could describe the universe today and/or a very early period of exponential expansion known as inflation.

Comments and corrections may be sent by email to a.d.challinor@ast.cam.ac.uk