SECOND-ORDER LINEAR DIFFERENTIAL EQUATIONS

A **second-order linear differential equation** has the form

$$\boxed{1} \qquad P(x)\frac{d^2y}{dx^2} + Q(x)\frac{dy}{dx} + R(x)y = G(x)$$

where P, Q, R, and G are continuous functions. Equations of this type arise in the study of the motion of a spring. In *Additional Topics: Applications of Second-Order Differential Equations* we will further pursue this application as well as the application to electric circuits.

In this section we study the case where $G(x) = 0$, for all x, in Equation 1. Such equations are called **homogeneous** linear equations. Thus, the form of a second-order linear homogeneous differential equation is

$$\boxed{2} \qquad P(x)\frac{d^2y}{dx^2} + Q(x)\frac{dy}{dx} + R(x)y = 0$$

If $G(x) \neq 0$ for some x, Equation 1 is **nonhomogeneous** and is discussed in *Additional Topics: Nonhomogeneous Linear Equations*.

Two basic facts enable us to solve homogeneous linear equations. The first of these says that if we know two solutions y_1 and y_2 of such an equation, then the **linear combination** $y = c_1y_1 + c_2y_2$ is also a solution.

$\boxed{3}$ **Theorem** If $y_1(x)$ and $y_2(x)$ are both solutions of the linear homogeneous equation (2) and c_1 and c_2 are any constants, then the function

$$y(x) = c_1y_1(x) + c_2y_2(x)$$

is also a solution of Equation 2.

Proof Since y_1 and y_2 are solutions of Equation 2, we have

$$P(x)y_1'' + Q(x)y_1' + R(x)y_1 = 0$$

and

$$P(x)y_2'' + Q(x)y_2' + R(x)y_2 = 0$$

Therefore, using the basic rules for differentiation, we have

$$\begin{aligned} P(x)y'' &+ Q(x)y' + R(x)y \\ &= P(x)(c_1y_1 + c_2y_2)'' + Q(x)(c_1y_1 + c_2y_2)' + R(x)(c_1y_1 + c_2y_2) \\ &= P(x)(c_1y_1'' + c_2y_2'') + Q(x)(c_1y_1' + c_2y_2') + R(x)(c_1y_1 + c_2y_2) \\ &= c_1[P(x)y_1'' + Q(x)y_1' + R(x)y_1] + c_2[P(x)y_2'' + Q(x)y_2' + R(x)y_2] \\ &= c_1(0) + c_2(0) = 0 \end{aligned}$$

Thus, $y = c_1y_1 + c_2y_2$ is a solution of Equation 2. ■

The other fact we need is given by the following theorem, which is proved in more advanced courses. It says that the general solution is a linear combination of two **linearly independent** solutions y_1 and y_2. This means that neither y_1 nor y_2 is a constant multiple of the other. For instance, the functions $f(x) = x^2$ and $g(x) = 5x^2$ are linearly dependent, but $f(x) = e^x$ and $g(x) = xe^x$ are linearly independent.

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$\boxed{4}$ **Theorem** If y_1 and y_2 are linearly independent solutions of Equation 2, and $P(x)$ is never 0, then the general solution is given by

$$y(x) = c_1y_1(x) + c_2y_2(x)$$

where c_1 and c_2 are arbitrary constants.

Theorem 4 is very useful because it says that if we know *two* particular linearly independent solutions, then we know *every* solution.

In general, it is not easy to discover particular solutions to a second-order linear equation. But it is always possible to do so if the coefficient functions P, Q, and R are constant functions, that is, if the differential equation has the form

$$\boxed{5} \qquad \boxed{ay'' + by' + cy = 0}$$

where a, b, and c are constants and $a \neq 0$.

It's not hard to think of some likely candidates for particular solutions of Equation 5 if we state the equation verbally. We are looking for a function y such that a constant times its second derivative y'' plus another constant times y' plus a third constant times y is equal to 0. We know that the exponential function $y = e^{rx}$ (where r is a constant) has the property that its derivative is a constant multiple of itself: $y' = re^{rx}$. Furthermore, $y'' = r^2e^{rx}$. If we substitute these expressions into Equation 5, we see that $y = e^{rx}$ is a solution if

$$ar^2e^{rx} + bre^{rx} + ce^{rx} = 0$$

or

$$(ar^2 + br + c)e^{rx} = 0$$

But e^{rx} is never 0. Thus, $y = e^{rx}$ is a solution of Equation 5 if r is a root of the equation

$$\boxed{6} \qquad \boxed{ar^2 + br + c = 0}$$

Equation 6 is called the **auxiliary equation** (or **characteristic equation**) of the differential equation $ay'' + by' + cy = 0$. Notice that it is an algebraic equation that is obtained from the differential equation by replacing y'' by r^2, y' by r, and y by 1.

Sometimes the roots r_1 and r_2 of the auxiliary equation can be found by factoring. In other cases they are found by using the quadratic formula:

$$\boxed{7} \qquad r_1 = \frac{-b + \sqrt{b^2 - 4ac}}{2a} \qquad r_2 = \frac{-b - \sqrt{b^2 - 4ac}}{2a}$$

We distinguish three cases according to the sign of the discriminant $b^2 - 4ac$.

CASE I ▫ $b^2 - 4ac > 0$

In this case the roots r_1 and r_2 of the auxiliary equation are real and distinct, so $y_1 = e^{r_1x}$ and $y_2 = e^{r_2x}$ are two linearly independent solutions of Equation 5. (Note that e^{r_2x} is not a constant multiple of e^{r_1x}.) Therefore, by Theorem 4, we have the following fact.

$\boxed{8}$ If the roots r_1 and r_2 of the auxiliary equation $ar^2 + br + c = 0$ are real and unequal, then the general solution of $ay'' + by' + cy = 0$ is

$$y = c_1e^{r_1x} + c_2e^{r_2x}$$

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In Figure 1 the graphs of the basic solutions $f(x) = e^{2x}$ and $g(x) = e^{-3x}$ of the differential equation in Example 1 are shown in black and red, respectively. Some of the other solutions, linear combinations of f and g, are shown in blue.

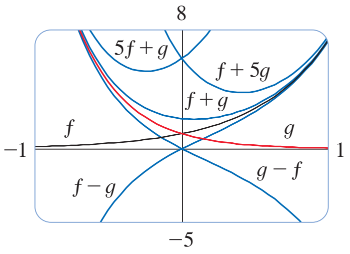

FIGURE 1

EXAMPLE 1 Solve the equation $y'' + y' - 6y = 0$.

SOLUTION The auxiliary equation is

$$r^2 + r - 6 = (r - 2)(r + 3) = 0$$

whose roots are $r = 2, -3$. Therefore, by (8) the general solution of the given differential equation is

$$y = c_1 e^{2x} + c_2 e^{-3x}$$

We could verify that this is indeed a solution by differentiating and substituting into the differential equation. ■

EXAMPLE 2 Solve $3\dfrac{d^2y}{dx^2} + \dfrac{dy}{dx} - y = 0$.

SOLUTION To solve the auxiliary equation $3r^2 + r - 1 = 0$ we use the quadratic formula:

$$r = \frac{-1 \pm \sqrt{13}}{6}$$

Since the roots are real and distinct, the general solution is

$$y = c_1 e^{(-1+\sqrt{13})x/6} + c_2 e^{(-1-\sqrt{13})x/6}$$ ■

CASE II ▫ $b^2 - 4ac = 0$

In this case $r_1 = r_2$; that is, the roots of the auxiliary equation are real and equal. Let's denote by r the common value of r_1 and r_2. Then, from Equations 7, we have

9 $$r = -\frac{b}{2a} \qquad \text{so} \quad 2ar + b = 0$$

We know that $y_1 = e^{rx}$ is one solution of Equation 5. We now verify that $y_2 = xe^{rx}$ is also a solution:

$$\begin{aligned} ay_2'' + by_2' + cy_2 &= a(2re^{rx} + r^2xe^{rx}) + b(e^{rx} + rxe^{rx}) + cxe^{rx} \\ &= (2ar + b)e^{rx} + (ar^2 + br + c)xe^{rx} \\ &= 0(e^{rx}) + 0(xe^{rx}) = 0 \end{aligned}$$

The first term is 0 by Equations 9; the second term is 0 because r is a root of the auxiliary equation. Since $y_1 = e^{rx}$ and $y_2 = xe^{rx}$ are linearly independent solutions, Theorem 4 provides us with the general solution.

10 If the auxiliary equation $ar^2 + br + c = 0$ has only one real root r, then the general solution of $ay'' + by' + cy = 0$ is

$$y = c_1 e^{rx} + c_2 xe^{rx}$$

EXAMPLE 3 Solve the equation $4y'' + 12y' + 9y = 0$.

SOLUTION The auxiliary equation $4r^2 + 12r + 9 = 0$ can be factored as

$$(2r + 3)^2 = 0$$

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■■ Figure 2 shows the basic solutions $f(x) = e^{-3x/2}$ and $g(x) = xe^{-3x/2}$ in Example 3 and some other members of the family of solutions. Notice that all of them approach 0 as $x \to \infty$.

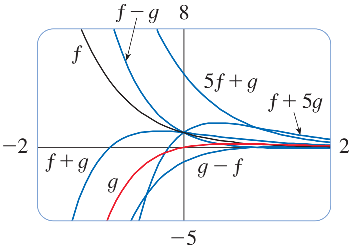

FIGURE 2

so the only root is $r = -\frac{3}{2}$. By (10) the general solution is

$$y = c_1 e^{-3x/2} + c_2 x e^{-3x/2}$$ ■

CASE III ▫ $b^2 - 4ac < 0$

In this case the roots r_1 and r_2 of the auxiliary equation are complex numbers. (See *Additional Topics: Complex Numbers* for information about complex numbers.) We can write

$$r_1 = \alpha + i\beta \qquad r_2 = \alpha - i\beta$$

where α and β are real numbers. [In fact, $\alpha = -b/(2a)$, $\beta = \sqrt{4ac - b^2}/(2a)$.] Then, using Euler's equation

$$e^{i\theta} = \cos\theta + i\sin\theta$$

from *Additional Topics: Complex Numbers*, we write the solution of the differential equation as

$$\begin{aligned} y &= C_1 e^{r_1 x} + C_2 e^{r_2 x} = C_1 e^{(\alpha + i\beta)x} + C_2 e^{(\alpha - i\beta)x} \\ &= C_1 e^{\alpha x}(\cos\beta x + i\sin\beta x) + C_2 e^{\alpha x}(\cos\beta x - i\sin\beta x) \\ &= e^{\alpha x}[(C_1 + C_2)\cos\beta x + i(C_1 - C_2)\sin\beta x] \\ &= e^{\alpha x}(c_1\cos\beta x + c_2\sin\beta x) \end{aligned}$$

where $c_1 = C_1 + C_2$, $c_2 = i(C_1 - C_2)$. This gives all solutions (real or complex) of the differential equation. The solutions are real when the constants c_1 and c_2 are real. We summarize the discussion as follows.

11 If the roots of the auxiliary equation $ar^2 + br + c = 0$ are the complex numbers $r_1 = \alpha + i\beta$, $r_2 = \alpha - i\beta$, then the general solution of $ay'' + by' + cy = 0$ is

$$y = e^{\alpha x}(c_1\cos\beta x + c_2\sin\beta x)$$

■■ Figure 3 shows the graphs of the solutions in Example 4, $f(x) = e^{3x}\cos 2x$ and $g(x) = e^{3x}\sin 2x$, together with some linear combinations. All solutions approach 0 as $x \to -\infty$.

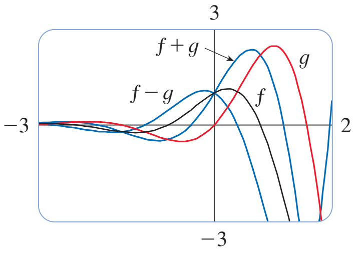

FIGURE 3

EXAMPLE 4 Solve the equation $y'' - 6y' + 13y = 0$.

SOLUTION The auxiliary equation is $r^2 - 6r + 13 = 0$. By the quadratic formula, the roots are

$$r = \frac{6 \pm \sqrt{36 - 52}}{2} = \frac{6 \pm \sqrt{-16}}{2} = 3 \pm 2i$$

By (11) the general solution of the differential equation is

$$y = e^{3x}(c_1\cos 2x + c_2\sin 2x)$$ ■

INITIAL-VALUE AND BOUNDARY-VALUE PROBLEMS

An **initial-value problem** for the second-order Equation 1 or 2 consists of finding a solution y of the differential equation that also satisfies initial conditions of the form

$$y(x_0) = y_0 \qquad y'(x_0) = y_1$$

where y_0 and y_1 are given constants. If P, Q, R, and G are continuous on an interval and $P(x) \neq 0$ there, then a theorem found in more advanced books guarantees the existence and uniqueness of a solution to this initial-value problem. Examples 5 and 6 illustrate the technique for solving such a problem.

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EXAMPLE 5 Solve the initial-value problem

$$y'' + y' - 6y = 0 \qquad y(0) = 1 \qquad y'(0) = 0$$

■■ Figure 4 shows the graph of the solution of the initial-value problem in Example 5. Compare with Figure 1.

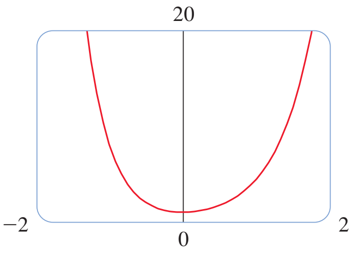

FIGURE 4

SOLUTION From Example 1 we know that the general solution of the differential equation is

$$y(x) = c_1 e^{2x} + c_2 e^{-3x}$$

Differentiating this solution, we get

$$y'(x) = 2c_1 e^{2x} - 3c_2 e^{-3x}$$

To satisfy the initial conditions we require that

$$y(0) = c_1 + c_2 = 1 \tag{12}$$

$$y'(0) = 2c_1 - 3c_2 = 0 \tag{13}$$

From (13) we have $c_2 = \frac{2}{3}c_1$ and so (12) gives

$$c_1 + \tfrac{2}{3}c_1 = 1 \qquad c_1 = \tfrac{3}{5} \qquad c_2 = \tfrac{2}{5}$$

Thus, the required solution of the initial-value problem is

$$y = \tfrac{3}{5}e^{2x} + \tfrac{2}{5}e^{-3x}$$ ■

EXAMPLE 6 Solve the initial-value problem

$$y'' + y = 0 \qquad y(0) = 2 \qquad y'(0) = 3$$

■■ The solution to Example 6 is graphed in Figure 5. It appears to be a shifted sine curve and, indeed, you can verify that another way of writing the solution is

$$y = \sqrt{13}\,\sin(x + \phi) \quad \text{where } \tan\phi = \tfrac{2}{3}$$

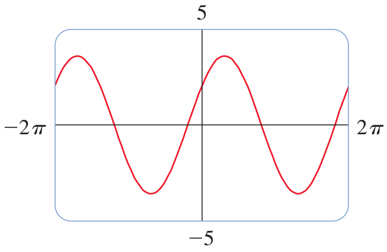

FIGURE 5

SOLUTION The auxiliary equation is $r^2 + 1 = 0$, or $r^2 = -1$, whose roots are $\pm i$. Thus $\alpha = 0$, $\beta = 1$, and since $e^{0x} = 1$, the general solution is

$$y(x) = c_1 \cos x + c_2 \sin x$$

Since $$y'(x) = -c_1 \sin x + c_2 \cos x$$

the initial conditions become

$$y(0) = c_1 = 2 \qquad y'(0) = c_2 = 3$$

Therefore, the solution of the initial-value problem is

$$y(x) = 2\cos x + 3\sin x$$ ■

A **boundary-value problem** for Equation 1 consists of finding a solution y of the differential equation that also satisfies boundary conditions of the form

$$y(x_0) = y_0 \qquad y(x_1) = y_1$$

In contrast with the situation for initial-value problems, a boundary-value problem does not always have a solution.

EXAMPLE 7 Solve the boundary-value problem

$$y'' + 2y' + y = 0 \qquad y(0) = 1 \qquad y(1) = 3$$

SOLUTION The auxiliary equation is

$$r^2 + 2r + 1 = 0 \qquad \text{or} \qquad (r + 1)^2 = 0$$

whose only root is $r = -1$. Therefore, the general solution is

$$y(x) = c_1 e^{-x} + c_2 x e^{-x}$$

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■■ Figure 6 shows the graph of the solution of the boundary-value problem in Example 7.

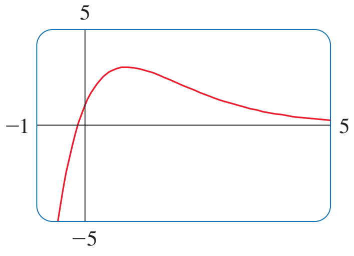

FIGURE 6

The boundary conditions are satisfied if

$$y(0) = c_1 = 1$$

$$y(1) = c_1 e^{-1} + c_2 e^{-1} = 3$$

The first condition gives $c_1 = 1$, so the second condition becomes

$$e^{-1} + c_2 e^{-1} = 3$$

Solving this equation for c_2 by first multiplying through by e, we get

$$1 + c_2 = 3e \qquad \text{so} \qquad c_2 = 3e - 1$$

Thus, the solution of the boundary-value problem is

$$y = e^{-x} + (3e - 1)xe^{-x}$$ ■

Summary: Solutions of $ay'' + by' + c = 0$

Roots of $ar^2 + br + c = 0$	General solution
r_1, r_2 real and distinct	$y = c_1 e^{r_1 x} + c_2 e^{r_2 x}$
$r_1 = r_2 = r$	$y = c_1 e^{rx} + c_2 x e^{rx}$
r_1, r_2 complex: $\alpha \pm i\beta$	$y = e^{\alpha x}(c_1 \cos \beta x + c_2 \sin \beta x)$

EXERCISES

A Click here for answers.

S Click here for solutions.

1–13 ■ Solve the differential equation.

1. $y'' - 6y' + 8y = 0$

2. $y'' - 4y' + 8y = 0$

3. $y'' + 8y' + 41y = 0$

4. $2y'' - y' - y = 0$

5. $y'' - 2y' + y = 0$

6. $3y'' = 5y'$

7. $4y'' + y = 0$

8. $16y'' + 24y' + 9y = 0$

9. $4y'' + y' = 0$

10. $9y'' + 4y = 0$

11. $\dfrac{d^2y}{dt^2} - 2\dfrac{dy}{dt} - y = 0$

12. $\dfrac{d^2y}{dt^2} - 6\dfrac{dy}{dt} + 4y = 0$

13. $\dfrac{d^2y}{dt^2} + \dfrac{dy}{dt} + y = 0$

14–16 ■ Graph the two basic solutions of the differential equation and several other solutions. What features do the solutions have in common?

14. $6\dfrac{d^2y}{dx^2} - \dfrac{dy}{dx} - 2y = 0$

15. $\dfrac{d^2y}{dx^2} - 8\dfrac{dy}{dx} + 16y = 0$

16. $\dfrac{d^2y}{dx^2} - 2\dfrac{dy}{dx} + 5y = 0$

17–24 ■ Solve the initial-value problem.

17. $2y'' + 5y' + 3y = 0, \quad y(0) = 3, \quad y'(0) = -4$

18. $y'' + 3y = 0, \quad y(0) = 1, \quad y'(0) = 3$

19. $4y'' - 4y' + y = 0, \quad y(0) = 1, \quad y'(0) = -1.5$

20. $2y'' + 5y' - 3y = 0, \quad y(0) = 1, \quad y'(0) = 4$

21. $y'' + 16y = 0, \quad y(\pi/4) = -3, \quad y'(\pi/4) = 4$

22. $y'' - 2y' + 5y = 0, \quad y(\pi) = 0, \quad y'(\pi) = 2$

23. $y'' + 2y' + 2y = 0, \quad y(0) = 2, \quad y'(0) = 1$

24. $y'' + 12y' + 36y = 0, \quad y(1) = 0, \quad y'(1) = 1$

25–32 ■ Solve the boundary-value problem, if possible.

25. $4y'' + y = 0, \quad y(0) = 3, \quad y(\pi) = -4$

26. $y'' + 2y' = 0, \quad y(0) = 1, \quad y(1) = 2$

27. $y'' - 3y' + 2y = 0, \quad y(0) = 1, \quad y(3) = 0$

28. $y'' + 100y = 0, \quad y(0) = 2, \quad y(\pi) = 5$

29. $y'' - 6y' + 25y = 0, \quad y(0) = 1, \quad y(\pi) = 2$

30. $y'' - 6y' + 9y = 0, \quad y(0) = 1, \quad y(1) = 0$

31. $y'' + 4y' + 13y = 0, \quad y(0) = 2, \quad y(\pi/2) = 1$

32. $9y'' - 18y' + 10y = 0, \quad y(0) = 0, \quad y(\pi) = 1$

33. Let L be a nonzero real number.
  (a) Show that the boundary-value problem $y'' + \lambda y = 0$, $y(0) = 0$, $y(L) = 0$ has only the trivial solution $y = 0$ for the cases $\lambda = 0$ and $\lambda < 0$.
  (b) For the case $\lambda > 0$, find the values of λ for which this problem has a nontrivial solution and give the corresponding solution.

34. If a, b, and c are all positive constants and $y(x)$ is a solution of the differential equation $ay'' + by' + cy = 0$, show that $\lim_{x\to\infty} y(x) = 0$.

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ANSWERS

S Click here for solutions.

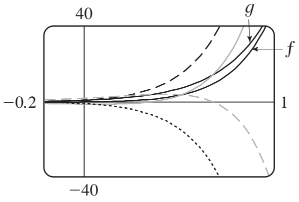
1. $y = c_1 e^{4x} + c_2 e^{2x}$ **3.** $y = e^{-4x}(c_1 \cos 5x + c_2 \sin 5x)$

5. $y = c_1 e^{x} + c_2 x e^{x}$ **7.** $y = c_1 \cos(x/2) + c_2 \sin(x/2)$

9. $y = c_1 + c_2 e^{-x/4}$ **11.** $y = c_1 e^{(1+\sqrt{2})t} + c_2 e^{(1-\sqrt{2})t}$

13. $y = e^{-t/2}\left[c_1 \cos\left(\sqrt{3}t/2\right) + c_2 \sin\left(\sqrt{3}t/2\right)\right]$

15.



All solutions approach 0 as $x \to -\infty$ and approach $\pm\infty$ as $x \to \infty$.

17. $y = 2e^{-3x/2} + e^{-x}$

19. $y = e^{x/2} - 2xe^{x/2}$

21. $y = 3 \cos 4x - \sin 4x$

23. $y = e^{-x}(2 \cos x + 3 \sin x)$

25. $y = 3 \cos\left(\frac{1}{2}x\right) - 4 \sin\left(\frac{1}{2}x\right)$

27. $y = \dfrac{e^{x+3}}{e^3 - 1} + \dfrac{e^{2x}}{1 - e^3}$

29. No solution

31. $y = e^{-2x}(2 \cos 3x - e^{\pi} \sin 3x)$

33. (b) $\lambda = n^2\pi^2/L^2$, n a positive integer; $y = C \sin(n\pi x/L)$

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SOLUTIONS

1. The auxiliary equation is $r^2 - 6r + 8 = 0 \;\Rightarrow\; (r-4)(r-2) = 0 \;\Rightarrow\; r = 4, r = 2$. Then by (8) the general solution is $y = c_1e^{4x} + c_2e^{2x}$.

3. The auxiliary equation is $r^2 + 8r + 41 = 0 \;\Rightarrow\; r = -4 \pm 5i$. Then by (11) the general solution is $y = e^{-4x}(c_1 \cos 5x + c_2 \sin 5x)$.

5. The auxiliary equation is $r^2 - 2r + 1 = (r-1)^2 = 0 \;\Rightarrow\; r = 1$. Then by (10), the general solution is $y = c_1e^x + c_2xe^x$.

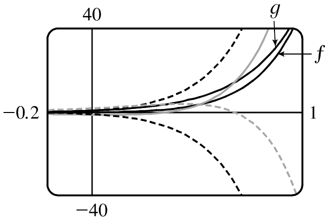
7. The auxiliary equation is $4r^2 + 1 = 0 \;\Rightarrow\; r = \pm\frac{1}{2}i$, so $y = c_1 \cos\left(\frac{1}{2}x\right) + c_2 \sin\left(\frac{1}{2}x\right)$.

9. The auxiliary equation is $4r^2 + r = r(4r+1) = 0 \;\Rightarrow\; r = 0, r = -\frac{1}{4}$, so $y = c_1 + c_2e^{-x/4}$.

11. The auxiliary equation is $r^2 - 2r - 1 = 0 \;\Rightarrow\; r = 1 \pm \sqrt{2}$, so $y = c_1e^{\left(1+\sqrt{2}\right)t} + c_2e^{\left(1-\sqrt{2}\right)t}$.

13. The auxiliary equation is $r^2 + r + 1 = 0 \;\Rightarrow\; r = -\frac{1}{2} \pm \frac{\sqrt{3}}{2}i$, so $y = e^{-t/2}\left[c_1 \cos\left(\frac{\sqrt{3}}{2}t\right) + c_2 \sin\left(\frac{\sqrt{3}}{2}t\right)\right]$.

15. $r^2 - 8r + 16 = (r-4)^2 = 0$ so $y = c_1e^{4x} + c_2xe^{4x}$.
The graphs are all asymptotic to the x-axis as $x \to -\infty$, and as $x \to \infty$ the solutions tend to $\pm\infty$.



17. $2r^2 + 5r + 3 = (2r+3)(r+1) = 0$, so $r = -\frac{3}{2}, r = -1$ and the general solution is $y = c_1e^{-3x/2} + c_2e^{-x}$. Then $y(0) = 3 \;\Rightarrow\; c_1 + c_2 = 3$ and $y'(0) = -4 \;\Rightarrow\; -\frac{3}{2}c_1 - c_2 = -4$, so $c_1 = 2$ and $c_2 = 1$. Thus the solution to the initial-value problem is $y = 2e^{-3x/2} + e^{-x}$.

19. $4r^2 - 4r + 1 = (2r-1)^2 = 0 \;\Rightarrow\; r = \frac{1}{2}$ and the general solution is $y = c_1e^{x/2} + c_2xe^{x/2}$. Then $y(0) = 1 \;\Rightarrow\; c_1 = 1$ and $y'(0) = -1.5 \;\Rightarrow\; \frac{1}{2}c_1 + c_2 = -1.5$, so $c_2 = -2$ and the solution to the initial-value problem is $y = e^{x/2} - 2xe^{x/2}$.

21. $r^2 + 16 = 0 \;\Rightarrow\; r = \pm 4i$ and the general solution is $y = e^{0x}(c_1 \cos 4x + c_2 \sin 4x) = c_1 \cos 4x + c_2 \sin 4x$. Then $y\left(\frac{\pi}{4}\right) = -3 \;\Rightarrow\; -c_1 = -3 \;\Rightarrow\; c_1 = 3$ and $y'\left(\frac{\pi}{4}\right) = 4 \;\Rightarrow\; -4c_2 = 4 \;\Rightarrow\; c_2 = -1$, so the solution to the initial-value problem is $y = 3\cos 4x - \sin 4x$.

23. $r^2 + 2r + 2 = 0 \;\Rightarrow\; r = -1 \pm i$ and the general solution is $y = e^{-x}(c_1 \cos x + c_2 \sin x)$. Then $2 = y(0) = c_1$ and $1 = y'(0) = c_2 - c_1 \;\Rightarrow\; c_2 = 3$ and the solution to the initial-value problem is $y = e^{-x}(2\cos x + 3\sin x)$.

25. $4r^2 + 1 = 0 \;\Rightarrow\; r = \pm\frac{1}{2}i$ and the general solution is $y = c_1 \cos\left(\frac{1}{2}x\right) + c_2 \sin\left(\frac{1}{2}x\right)$. Then $3 = y(0) = c_1$ and $-4 = y(\pi) = c_2$, so the solution of the boundary-value problem is $y = 3\cos\left(\frac{1}{2}x\right) - 4\sin\left(\frac{1}{2}x\right)$.

27. $r^2 - 3r + 2 = (r-2)(r-1) = 0 \;\Rightarrow\; r = 1, r = 2$ and the general solution is $y = c_1e^x + c_2e^{2x}$. Then $1 = y(0) = c_1 + c_2$ and $0 = y(3) = c_1e^3 + c_2e^6$ so $c_2 = 1/(1-e^3)$ and $c_1 = e^3/(e^3-1)$. The solution of the boundary-value problem is $y = \dfrac{e^{x+3}}{e^3-1} + \dfrac{e^{2x}}{1-e^3}$.

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29. $r^2 - 6r + 25 = 0 \quad\Rightarrow\quad r = 3 \pm 4i$ and the general solution is $y = e^{3x}(c_1 \cos 4x + c_2 \sin 4x)$. But $1 = y(0) = c_1$ and $2 = y(\pi) = c_1 e^{3\pi} \quad\Rightarrow\quad c_1 = 2/e^{3\pi}$, so there is no solution.

31. $r^2 + 4r + 13 = 0 \quad\Rightarrow\quad r = -2 \pm 3i$ and the general solution is $y = e^{-2x}(c_1 \cos 3x + c_2 \sin 3x)$. But $2 = y(0) = c_1$ and $1 = y\left(\frac{\pi}{2}\right) = e^{-\pi}(-c_2)$, so the solution to the boundary-value problem is $y = e^{-2x}(2 \cos 3x - e^{\pi} \sin 3x)$.

33. (a) *Case 1* ($\lambda = 0$)*:* $y'' + \lambda y = 0 \quad\Rightarrow\quad y'' = 0$ which has an auxiliary equation $r^2 = 0 \quad\Rightarrow\quad r = 0 \quad\Rightarrow$ $y = c_1 + c_2 x$ where $y(0) = 0$ and $y(L) = 0$. Thus, $0 = y(0) = c_1$ and $0 = y(L) = c_2 L \quad\Rightarrow\quad c_1 = c_2 = 0$. Thus, $y = 0$.

Case 2 ($\lambda < 0$)*:* $y'' + \lambda y = 0$ has auxiliary equation $r^2 = -\lambda \quad\Rightarrow\quad r = \pm\sqrt{-\lambda}$ (distinct and real since $\lambda < 0$) $\quad\Rightarrow\quad y = c_1 e^{\sqrt{-\lambda}x} + c_2 e^{-\sqrt{-\lambda}x}$ where $y(0) = 0$ and $y(L) = 0$. Thus, $0 = y(0) = c_1 + c_2$ $(*)$ and $0 = y(L) = c_1 e^{\sqrt{-\lambda}L} + c_2 e^{-\sqrt{-\lambda}L}$ $(\dagger)$.

Multiplying $(*)$ by $e^{\sqrt{-\lambda}L}$ and subtracting $(\dagger)$ gives $c_2\left(e^{\sqrt{-\lambda}L} - e^{-\sqrt{-\lambda}L}\right) = 0 \quad\Rightarrow\quad c_2 = 0$ and thus $c_1 = 0$ from $(*)$. Thus, $y = 0$ for the cases $\lambda = 0$ and $\lambda < 0$.

(b) $y'' + \lambda y = 0$ has an auxiliary equation $r^2 + \lambda = 0 \quad\Rightarrow\quad r = \pm i\sqrt{\lambda} \quad\Rightarrow\quad y = c_1 \cos\sqrt{\lambda}\,x + c_2 \sin\sqrt{\lambda}\,x$ where $y(0) = 0$ and $y(L) = 0$. Thus, $0 = y(0) = c_1$ and $0 = y(L) = c_2 \sin\sqrt{\lambda}L$ since $c_1 = 0$. Since we cannot have a trivial solution, $c_2 \neq 0$ and thus $\sin\sqrt{\lambda}\,L = 0 \quad\Rightarrow\quad \sqrt{\lambda}\,L = n\pi$ where n is an integer $\Rightarrow\quad \lambda = n^2\pi^2/L^2$ and $y = c_2 \sin(n\pi x/L)$ where n is an integer.

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