Problem 44

Euler Equations. In each of Problems 40 through 45, use the substitution introduced in Problem 34 in Section 3.3 to solve the given differential equation.

$$4t^2y'' - 8ty' + 9y = 0, \qquad t > 0$$

Solution

The Hard Way

Make the substitution $x = \ln t$ in the ODE. Then

$$e^x = t \quad \rightarrow \quad e^{2x} = t^2,$$

and the ODE becomes

$$4e^{2x}\frac{d^2y}{dt^2} - 8e^x\frac{dy}{dt} + 9y = 0.$$

The aim now is to find what the derivatives are in terms of this new variable by using the chain rule.

$$\frac{dy}{dt} = \frac{dy}{dx}\frac{dx}{dt} = \frac{dy}{dx}\left(\frac{1}{t}\right) = \frac{dy}{dx}\left(\frac{1}{e^x}\right) = e^{-x}\frac{dy}{dx}$$

$$\frac{d^2y}{dt^2} = \frac{d}{dt}\left(\frac{dy}{dt}\right) = \frac{dx}{dt}\frac{d}{dx}\left(e^{-x}\frac{dy}{dx}\right) = \frac{1}{t}\left(-e^{-x}\frac{dy}{dx} + e^{-x}\frac{d^2y}{dx^2}\right) = \frac{1}{e^x}\left(-e^{-x}\frac{dy}{dx} + e^{-x}\frac{d^2y}{dx^2}\right)$$

Substitute these expressions into the ODE.

$$4e^{2x}\frac{1}{e^x}\left(-e^{-x}\frac{dy}{dx} + e^{-x}\frac{d^2y}{dx^2}\right) - 8e^x\left(e^{-x}\frac{dy}{dx}\right) + 9y = 0$$

$$4e^x\left(-e^{-x}\frac{dy}{dx} + e^{-x}\frac{d^2y}{dx^2}\right) - 8\frac{dy}{dx} + 9y = 0$$

$$-4\frac{dy}{dx} + 4\frac{d^2y}{dx^2} - 8\frac{dy}{dx} + 9y = 0$$

$$4\frac{d^2y}{dx^2} - 12\frac{dy}{dx} + 9y = 0 \tag{1}$$

As a result of making the substitution $x = \ln t$, the coefficients of the derivatives are now constant. The solution is then of the form $y = e^{rx}$.

$$y = e^{rx} \quad \rightarrow \quad \frac{dy}{dx} = re^{rx} \quad \rightarrow \quad \frac{d^2y}{dx^2} = r^2e^{rx}$$

Substitute these expressions into the ODE.

$$4(r^2e^{rx}) - 12(re^{rx}) + 9(e^{rx}) = 0$$

Divide both sides by e^{rx}.

$$4r^2 - 12r + 9 = 0$$

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

$$r = \left\{\frac{3}{2}\right\}$$

Consequently, one solution to the ODE is $y = e^{3x/2}$. Use the method of reduction of order here to find the general solution: Plug $y(x) = c(x)e^{3x/2}$ into equation (1).

$$4\frac{d^2}{dx^2}[c(x)e^{3x/2}] - 12\frac{d}{dx}[c(x)e^{3x/2}] + 9[c(x)e^{3x/2}] = 0$$

Evaluate the derivatives using the product rule.

$$4\frac{d}{dx}\left[c'(x)e^{3x/2} + \frac{3}{2}c(x)e^{3x/2}\right] - 12\left[c'(x)e^{3x/2} + \frac{3}{2}c(x)e^{3x/2}\right] + 9[c(x)e^{3x/2}] = 0$$

$$4\left[c''(x)e^{3x/2} + \frac{3}{2}c'(x)e^{3x/2} + \frac{3}{2}c'(x)e^{3x/2} + \frac{9}{4}c(x)e^{3x/2}\right] - 12\left[c'(x)e^{3x/2} + \frac{3}{2}c(x)e^{3x/2}\right] + 9[c(x)e^{3x/2}] = 0$$

$$4c''(x)e^{3x/2} + \cancel{6c'(x)e^{3x/2}} + \cancel{6c'(x)e^{3x/2}} + \cancel{9c(x)e^{3x/2}} - \cancel{12c'(x)e^{3x/2}} - \cancel{18c(x)e^{3x/2}} + \cancel{9c(x)e^{3x/2}} = 0$$

$$4c''(x)e^{3x/2} = 0$$

Divide both sides by $4e^{3x/2}$.

$$c''(x) = 0$$

Integrate both sides with respect to x.

$$c'(x) = C_1$$

Integrate both sides with respect to x once more.

$$c(x) = C_1x + C_2$$

Since $y(x) = c(x)e^{3x/2}$, the general solution is

$$y(x) = C_1xe^{3x/2} + C_2e^{3x/2}.$$

Finally, change back to the original variable with the initial substitution $x = \ln t$.

$$\begin{aligned} y(t) &= C_1(\ln t)e^{3(\ln t)/2} + C_2e^{3(\ln t)/2} \\ &= C_1(\ln t)e^{\ln t^{3/2}} + C_2e^{\ln t^{3/2}} \\ &= C_1t^{3/2}\ln t + C_2t^{3/2} \end{aligned}$$

The Easy Way

$$4t^2y'' - 8ty' + 9y = 0, \qquad t > 0$$

Since this is an Euler (or equidimensional) equation, the solution is of the form $y = t^r$.

$$y = t^r \quad \rightarrow \quad y' = rt^{r-1} \quad \rightarrow \quad y'' = r(r-1)t^{r-2}$$

Substitute these expressions into the ODE.

$$4t^2[r(r-1)t^{r-2}] - 8t[rt^{r-1}] + 9t^r = 0$$

$$4r(r-1)t^r - 8rt^r + 9t^r = 0$$

Divide both sides by t^r.

$$4r(r-1) - 8r + 9 = 0$$

$$4r^2 - 12r + 9 = 0$$

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

$$r = \left\{\frac{3}{2}\right\}$$

One solution to the ODE is then $t^{3/2}$. The ODE is homogeneous, so any constant multiple of this, $y = ct^{3/2}$, is also a solution. According to the method of reduction of order, the general solution is found by allowing c to vary as a function of t: $y(t) = c(t)t^{3/2}$. Substitute this into the original ODE to find what $c(t)$ is.

$$4t^2[c(t)t^{3/2}]'' - 8t[c(t)t^{3/2}]' + 9[c(t)t^{3/2}] = 0$$

Evaluate the derivatives by using the product rule.

$$4t^2\left[c'(t)t^{3/2} + \frac{3}{2}c(t)t^{1/2}\right]' - 8t\left[c'(t)t^{3/2} + \frac{3}{2}c(t)t^{1/2}\right] + 9[c(t)t^{3/2}] = 0$$

$$4t^2\left[c''(t)t^{3/2} + \frac{3}{2}c'(t)t^{1/2} + \frac{3}{2}c'(t)t^{1/2} + \frac{3}{4}c(t)t^{-1/2}\right] - 8t\left[c'(t)t^{3/2} + \frac{3}{2}c(t)t^{1/2}\right] + 9[c(t)t^{3/2}] = 0$$

$$4c''(t)t^{7/2} + 6c'(t)t^{5/2} + 6c'(t)t^{5/2} + \cancel{3c(t)t^{3/2}} - 8c'(t)t^{5/2} - \cancel{12c(t)t^{3/2}} + \cancel{9c(t)t^{3/2}} = 0$$

$$4c''(t)t^{7/2} + 4c'(t)t^{5/2} = 0$$

Solve for $c''(t)/c'(t)$.

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

The left side can be written as $d/dt[\ln c'(t)]$ by the chain rule.

$$\frac{d}{dt}[\ln c'(t)] = -\frac{1}{t}$$

Integrate both sides with respect to t.

$$\ln c'(t) = -\ln t + C_3$$

Exponentiate both sides.

$$\begin{aligned} c'(t) &= e^{-\ln t + C_3} \\ &= e^{\ln t^{-1} + C_3} \\ &= e^{\ln t^{-1}} e^{C_3} \\ &= t^{-1} e^{C_3} \end{aligned}$$

Integrate both sides with respect to t once more.

$$c(t) = e^{C_3} \ln t + C_4$$

Since the general solution is $y(t) = c(t)t^{3/2}$, we have

$$y(t) = e^{C_3} t^{3/2} \ln t + C_4 t^{3/2}.$$

Therefore, using a new constant C_5 for e^{C_3},

$$y(t) = C_5 t^{3/2} \ln t + C_4 t^{3/2}.$$