

## Sample Assessment Exercises

This document contains one exercise and solution for each standard. The goal is to give you an idea of what the exercises might look like, and what the expectations for a complete solution are.

**C1.** Find the general solution to

$$y' + y = -t^2.$$

**Solution:** First, we find a general solution to the homogeneous equation (removing all non- $y$  terms)

$$y'_h + y_h = 0.$$

Since this is a first-order constant coefficient ODE, we know the answer is a modification of  $ke^x$ . We find that  $y_h = ke^{-x}$  is valid, since

$$y'_h + y_h = \frac{d}{dx}[ke^{-x}] + ke^{-x} = -ke^{-x} + ke^{-x} = 0.$$

The simplest particular solution for this homogeneous ODE is  $y_0 = e^{-x}$ , so we use variation of parameters by assuming there is a non-homogeneous particular solution  $y_p = vy_0 = ve^{-x}$  for some function  $v$  (which we now need to find).

Using the product rule we find  $y'_p = v'e^{-t} - ve^{-t}$ , so we may substitute into the original ODE to find

$$y'_p + y_p = (v'e^{-t} - ve^{-t}) + ve^{-t} = v'e^{-t} = -t^2.$$

Thus  $v' = -t^2e^t$ , so (after integrating by parts twice) we conclude  $v = \int -t^2e^t dt = -t^2e^t + 2te^t - 2e^t$ . Thus  $y_p = ve^{-t} = (-t^2 + 2t - 2)e^te^{-t} = -t^2 + 2t - 2$ , so the general solution is

$$y = y_h + y_p = ke^{-t} - t^2 + 2t - 2.$$

□

**C2.** Consider the following scenario: A water droplet with a radius of  $10 \mu\text{m}$  has a mass of about  $4 \times 10^{-15} \text{kg}$  and a terminal velocity of  $3 \frac{\text{cm}}{\text{s}}$ . The droplet is dropped from rest.

- (a) Write down an IVP modelling the velocity of the water droplet.
- (b) What is its velocity after 0.01 s?

**Solution:** The forces acting on the water droplet are gravity ( $mg$  downwards) and air resistance; in a water droplet this size, this is proportional to its velocity. Let  $b$  denote this drag coefficient; then by Newton's second law (if we let up be the positive direction and down be negative), we have

$$m \frac{dv}{dt} = -mg - bv.$$

Note that we have  $-mg$  since gravity always acts downwards, and  $-bv$  because the drag acts in the opposite direction of  $v$ . It is actually convenient to let  $a = \frac{b}{m}$ , and divide this equation by the mass, yielding

$$\frac{dv}{dt} = -g - av.$$

The initial condition is that it is dropped from rest, i.e.  $v(0) = 0$ , so an IVP modelling velocity is

$$\frac{dv}{dt} = -g - av \quad v(0) = 0.$$

This is a separable differential equation; we thus have

$$\int \frac{1}{g + av} dv = \int (-1) dt.$$

Thus,  $\frac{1}{a} \ln |g + av| = -t + c_1$ , or  $|g + av| = e^{-at+ac_1} = c_2 e^{-at}$  (where  $c_2 = e^{ac_1}$ ). To avoid the pesky absolute value sign, we can absorb a potential negative into the constant to write  $g + av = c_3 e^{-at}$ , or (letting  $c_0 = \frac{c_3}{a}$ )

$$v = -\frac{g}{a} + c_0 e^{-at}.$$

Note that  $\lim_{t \rightarrow \infty} v = -\frac{g}{a}$ , so since we are given the terminal velocity, so after converting to meters per second we can solve  $-0.03 = -\frac{9.8}{a}$  to obtain  $a = \frac{9.8}{0.03}$ . We also know that it is dropped from rest, so we compute  $0 = v(0) = -0.03 + c_0$ , so  $c_0 = 0.03$ . Thus our model for velocity is

$$v = -0.03 + 0.03 e^{-\frac{9.8}{0.03} t}.$$

Then we simply compute  $v(0.01) = -0.03 + 0.03 e^{-\frac{9.8}{0.03}(0.01)} \approx -0.029$ . So after 0.01 s, the drop is falling approximately 2.9  $\frac{\text{cm}}{\text{s}}$ .

□

**C3.** Find the general solution to

$$y'' + 6y' + 13y = 0.$$

**Solution:** We begin by writing the auxiliary equation  $r^2 + 6r + 13 = 0$  and finding the roots. There are many ways to do this; here, we complete the square:

$$0 = r^2 + 6r + 13 = r^2 + 6r + 9 + 4 = (r + 3)^2 + 4.$$

Thus, we can easily solve to obtain  $r = -3 \pm 2i$ . Thus the general solution is

$$y = c_1 e^{-3t} \cos(2t) + c_2 e^{-3t} \sin(2t).$$

□

**C4.** Find the solution to

$$y'' + 10y' + 24y = 0$$

when  $y(0) = -3$  and  $y'(0) = 2$ .

**Solution:** The auxiliary equation is  $r^2 + 10r + 24 = 0$ , which has roots  $r = -6$  and  $r = -4$ . Thus, the general solution is of the form  $y = c_1 e^{-4t} + c_2 e^{-6t}$ .

$$\begin{aligned} -3 &= y(0) = c_1 + c_2 \\ 2 &= y'(0) = -4c_1 - 6c_2 \end{aligned}$$

Solving this system yields  $c_1 = -8$  and  $c_2 = 5$ , so the solution to the IVP is

$$y = -8e^{-4t} + 5e^{-6t}$$

□

**C5.** Find the general solution to

$$y'' + 10y' + 24y = e^{-4t}$$

**Solution:** First, we find a general solution to the homogenous equation  $y'' + 10y' + 24y = 0$ . We begin by writing the auxilliary equation  $r^2 + 10r + 24 = 0$ , which has roots  $r = -6$  and  $r = -4$ . Thus, the general solution is of the form  $y = c_1e^{-4t} + c_2e^{-6t}$ .

We use variation of parameters to find a particular solution,  $y_p = v_1e^{-4t} + v_2e^{-6t}$  for some functions  $v_1, v_2$ . We assume for convenience  $v_1'e^{-4t} + v_2'e^{-6t} = 0$ , so that  $y_p' = -4v_1e^{-4t} - 6v_2e^{-6t}$ , and  $y_p'' = -4v_1'e^{-4t} + 16v_1e^{-4t} - 6v_2'e^{-6t} + 36v_2e^{-6t}$ . Substituting into the original ODE and simplifying yields

$$e^{-4t} = y_p'' + 10y_p' + 14y_p = -4v_1'e^{-4t} - 6v_2'e^{-6t}.$$

Combining with our earlier assumption we have the system

$$\begin{aligned} v_1'e^{-4t} + v_2'e^{-6t} &= 0 \\ -4v_1'e^{-4t} - 6v_2'e^{-6t} &= e^{-4t} \end{aligned}$$

Multiply both equations by  $e^{4t}$  for convenience:

$$\begin{aligned} v_1' + v_2'e^{-2t} &= 0 \\ -4v_1' - 6v_2'e^{-2t} &= 1 \end{aligned}$$

Then six times the first equation plus the second yields  $2v_1' = 1$ , so  $v_1 = \int \frac{1}{2} dt = \frac{1}{2}t$ . Substituting back into the first yields  $v_2' = -\frac{1}{2}e^{2t}$ , so  $v_2 = \int -\frac{1}{2}e^{2t} dt = -\frac{1}{4}e^{2t}$ , and thus

$$y_p = \frac{1}{2}te^{-4t} - \frac{1}{4}e^{-4t},$$

and thus the general solution is

$$y = \frac{1}{2}te^{-4t} + c_1e^{-4t} + c_2e^{-6t}.$$

□

**C6.** Consider the following scenario: A 2kg mass is suspended by a spring (with spring constant 8kg/s<sup>2</sup>). The mass is pulled down 1m from its equilibrium position and released from rest.

- Write down an IVP modelling the position of the mass.
- How long does it take for the mass to return to its equilibrium point?

**Solution:** Let  $y$  denote the vertical distance from equilibrium; then the forces acting are gravity and the spring force, giving the ODE

$$my'' = -ky.$$

Substituting in the values of the constants  $m = 2$  and  $k = 8$ , we have

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

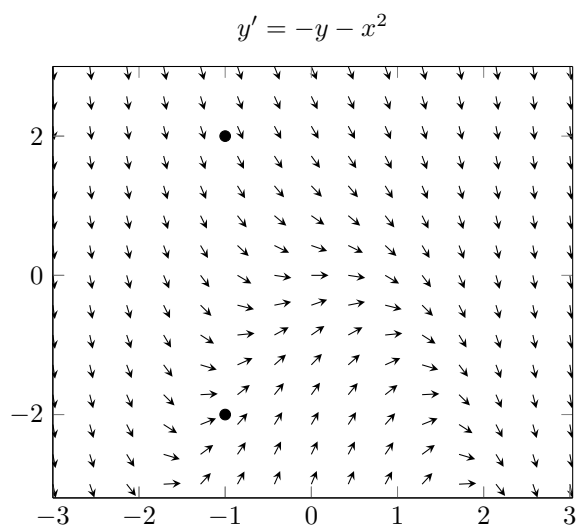
Note that the initial conditions are  $y(0) = -1$  and  $y'(0) = 0$ , so an IVP model is

$$2y'' + 8y = 0 \qquad y(0) = -1, \quad y'(0) = 0.$$

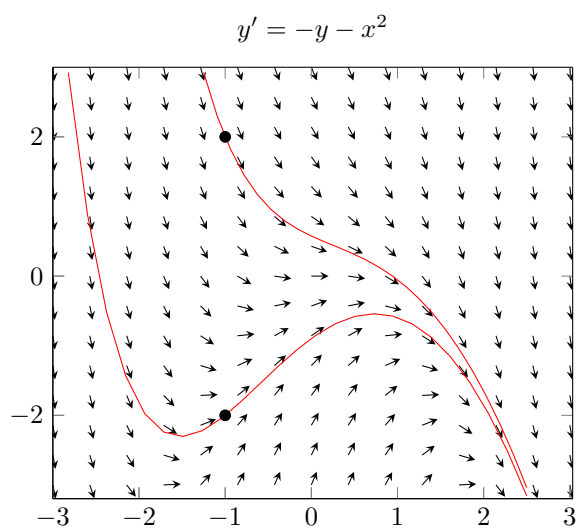
Simplifying, we have  $y'' + 4y = 0$ , so the general solution is  $y = c_1 \cos(2t) + c_2 \sin(2t)$ . The initial conditions are  $y(0) = -1$  and  $y'(0) = 0$ , which imply  $c_1 = -1$  and  $c_2 = 0$ , so the system is modelled by  $y = -\cos(2t)$ . This is first zero when  $2t = \frac{\pi}{2}$ , i.e. when  $t = \frac{\pi}{4}$ . Thus the mass takes  $\frac{\pi}{4}$  s to return to its equilibrium point.

□

**F1.** Sketch a solution curve through each point marked in the slope field.



**Solution:**



□

**F2.** Solve  $y' + xy = x$ .

**Solution:** Rearranging, we have  $y' = x - xy = x(1 - y)$ , so we see the equation is separable, and write

$$\frac{y'}{1 - y} = x.$$

Thus we compute  $\int \frac{y'}{1-y} dx = \int \frac{1}{1-y} dy = -\ln|1-y| + c_1$ , and  $\int x dx = \frac{1}{2}x^2 + c_2$ . Thus, we have (letting  $c_3 = c_2 - c_1$ )

$$-\ln|1-y| = \frac{1}{2}x^2 + c_3.$$

Then exponentiating, we have (letting  $c_4 = \pm e^{-c_3}$ )  $1-y = c_4 e^{-\frac{1}{2}x^2}$ , so (with  $c = -c_4$ ) the general solution is

$$y = 1 + ce^{-\frac{1}{2}x^2}.$$

□

**F3.** A ball has a mass of 0.1kg and a drag coefficient of 0.001kg/m. It is thrown with a velocity of 20m/s.

- (a) Write down an IVP modelling the horizontal velocity of the ball (ignore any vertical movement in the ball).
- (b) How long does it take the ball to travel 20m?

**Solution:** The only force acting on the ball is air resistance (drag), so we have

$$mv' = -bv^2.$$

Substituting in our constants (and dividing through by  $m$ ), we have

$$v' = -0.1v^2.$$

The initial condition is that it is travelling 20m/s, i.e.  $v(0) = 20$ , giving the IVP

$$v' = -0.1v^2, v(0) = 20.$$

Solving this separable ODE, we obtain  $v = \frac{20}{1+2t}$ . To model the position of the ball, we integrate again, obtaining  $x = \int \frac{20}{1+2t} dt = 10 \ln|1+2t| + C$ ; using  $x(0) = 0$ , we see  $C = 0$ . Then we simply need to solve  $x(t) = 20$ , i.e.  $20 = 10 \ln|1+2t|$ , so  $t = \frac{1}{2}(e^2 - 1) \approx 3.19$ s.

□

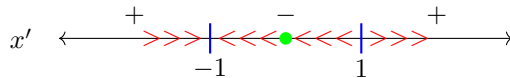
**F4.** Consider the autonomous equation

$$\frac{dx}{dt} = x^2 - 1.$$

- (a) Find and classify the critical points.
- (b) Describe the long term behavior of the solution passing through the point  $x(4) = 0$ .

**Solution:**

Note that  $x^2 - 1 = (x-1)(x+1)$ , so there are equilibrium solutions at  $x = 1$  and  $x = -1$ . We can thus compute a phase line for  $x'$ :



We see that  $-1$  is a sink (stable), while  $1$  is a source (unstable). A trajectory passing through  $x(4) = 0$  will approach  $x = -1$  in the limit.

□

**F5.** Solve  $y' + xy = x^3$ .

**Solution:** First, we solve the homogeneous equation  $y' + xy = 0$ , which is separable:  $\frac{y'}{y} = -x$ , so  $\ln|y| = -\frac{1}{2}x^2 + c$ , or  $y = c_1 e^{-\frac{1}{2}x^2}$ . We then use variation of parameters to find a particular solution, writing  $y_p = v e^{-\frac{1}{2}x^2}$ ; substituting in and simplifying yields

$$x^3 = y'_p + x y_p = v' e^{-\frac{1}{2}x^2} - v x e^{-\frac{1}{2}x^2} + x v e^{-\frac{1}{2}x^2} = v' e^{-\frac{1}{2}x^2}.$$

Thus,  $v' = x^3 e^{\frac{1}{2}x^2}$ . This can be integrated by parts to obtain  $v = x^2 e^{\frac{1}{2}x^2} - 2e^{\frac{1}{2}x^2}$ , so  $y_p = v e^{-\frac{1}{2}x^2} = x^2 - 2$ . Thus the general solution is

$$y = c_1 e^{-\frac{1}{2}x^2} + x^2 - 2.$$

□

**F6.** One of the two ODEs below is exact. Identify which one, and solve it.

$$\begin{aligned}(x + 3y)y' + y &= 3x \\ (x + 3y)y' - y &= -3x\end{aligned}$$

**Solution:** Rewrite the first equation as  $y' = \frac{3x-y}{x+3y}$ ; if there is a function with  $\nabla F = \langle -(3x - y), x + 3y \rangle$ , then

$$\frac{d}{dt} F(x, y) = \frac{\partial F}{\partial x} \frac{\partial x}{\partial t} + \frac{\partial F}{\partial y} \frac{\partial y}{\partial t} = -(3x - y)(x + 3y) + (x + 3y)(3x - y) = 0,$$

so  $F(x, y) = c$  is a solution of the autonomous system.

Note that  $\langle -(3x - y), x + 3y \rangle$  is conservative, as  $\frac{\partial}{\partial x}(x + 3y) = 1 = \frac{\partial}{\partial y}(-3x + y)$ ; so a potential function  $F$  is found by integrating:  $F = \int x + 3y \, dy = xy + \frac{3}{2}y^2 + f(x)$ , and differentiating with respect to  $x$ , we have  $-3x + y = y + f'(x)$ , so  $f'(x) = -3x$ , in which case  $f(x) = \int -3x \, dx = -\frac{3}{2}x^2$ , so a potential function is  $F(x, y) = xy + \frac{3}{2}y^2 - \frac{3}{2}x^2$ . So the general solution to the ODE is

$$xy + \frac{3}{2}y^2 - \frac{3}{2}x^2 = c.$$

□

**S1.**

**Solution:**

□

**S2.** Consider the following scenario: Two competing fish species (red fish and blue fish) live in a lake. In the absence of one species, the lake will support 30,000 of the other fish (as the species competes among itself for resources). It is calculated that the competition coefficients are  $\alpha_{1,2} = \alpha_{2,1} = 0.5$ .

- (a) Write down a system of ODEs modelling the interaction of the two species.
- (b) If the lake is stocked with 12,000 blue fish and 40,000 red fish, what will happen to the populations in the long run?

**Solution:**

$$\begin{aligned}x' &= \frac{r_1}{30000} x (30000 - x - 0.5y) \\y' &= \frac{r_2}{30000} y (30000 - y - 0.5x)\end{aligned}$$

Then the nontrivial isoclines are  $x + 0.5y = 30000$  and  $0.5x + y = 30000$  which intersect at the (equilibrium) point 20000, 20000. Plotting the isoclines (TODO) shows that this a stable equilibrium (sink), so regardless of the initial populations, they will approach 20,000 of each species in the long run.

□

**S3.**

**Solution:**

□

**N1.**

**Solution:**

□

**N2.**

**Solution:**

□

**N3.**

**Solution:**

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**N4.**

**Solution:**

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**N5.**

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**D1.**

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