

2018

AP<sup>®</sup>

 CollegeBoard

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# AP Calculus BC

## Scoring Guidelines

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## Question 1

(a)  $\int_0^{300} r(t) dt = 270$

According to the model, 270 people enter the line for the escalator during the time interval  $0 \leq t \leq 300$ .

2 :  $\left\{ \begin{array}{l} 1 : \text{integral} \\ 1 : \text{answer} \end{array} \right.$

(b)  $20 + \int_0^{300} (r(t) - 0.7) dt = 20 + \int_0^{300} r(t) dt - 0.7 \cdot 300 = 80$

According to the model, 80 people are in line at time  $t = 300$ .

2 :  $\left\{ \begin{array}{l} 1 : \text{considers rate out} \\ 1 : \text{answer} \end{array} \right.$

(c) Based on part (b), the number of people in line at time  $t = 300$  is 80.

The first time  $t$  that there are no people in line is

$$300 + \frac{80}{0.7} = 414.286 \text{ (or 414.285) seconds.}$$

1 : answer

(d) The total number of people in line at time  $t$ ,  $0 \leq t \leq 300$ , is modeled by

$$20 + \int_0^t r(x) dx - 0.7t.$$

$$r(t) - 0.7 = 0 \Rightarrow t_1 = 33.013298, t_2 = 166.574719$$

4 :  $\left\{ \begin{array}{l} 1 : \text{considers } r(t) - 0.7 = 0 \\ 1 : \text{identifies } t = 33.013 \\ 1 : \text{answers} \\ 1 : \text{justification} \end{array} \right.$

$t$	People in line for escalator
0	20
$t_1$	3.803
$t_2$	158.070
300	80

The number of people in line is a minimum at time  $t = 33.013$  seconds, when there are 4 people in line.

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**Question 2**

(a)  $p'(25) = -1.179$

At a depth of 25 meters, the density of plankton cells is changing at a rate of  $-1.179$  million cells per cubic meter per meter.

$$2 : \begin{cases} 1 : \text{answer} \\ 1 : \text{meaning with units} \end{cases}$$

(b)  $\int_0^{30} 3p(h) \, dh = 1675.414936$

There are 1675 million plankton cells in the column of water between  $h = 0$  and  $h = 30$  meters.

$$2 : \begin{cases} 1 : \text{integrand} \\ 1 : \text{answer} \end{cases}$$

(c)  $\int_{30}^K 3f(h) \, dh$  represents the number of plankton cells, in millions, in the column of water from a depth of 30 meters to a depth of  $K$  meters.

The number of plankton cells, in millions, in the entire column of water is given by  $\int_0^{30} 3p(h) \, dh + \int_{30}^K 3f(h) \, dh$ .

Because  $0 \leq f(h) \leq u(h)$  for all  $h \geq 30$ ,

$$3 \int_{30}^K f(h) \, dh \leq 3 \int_{30}^K u(h) \, dh \leq 3 \int_{30}^{\infty} u(h) \, dh = 3 \cdot 105 = 315.$$

The total number of plankton cells in the column of water is bounded by  $1675.415 + 315 = 1990.415 \leq 2000$  million.

$$3 : \begin{cases} 1 : \text{integral expression} \\ 1 : \text{compares improper integral} \\ 1 : \text{explanation} \end{cases}$$

(d)  $\int_0^1 \sqrt{(x'(t))^2 + (y'(t))^2} \, dt = 757.455862$

The total distance traveled by the boat over the time interval  $0 \leq t \leq 1$  is 757.456 (or 757.455) meters.

$$2 : \begin{cases} 1 : \text{integrand} \\ 1 : \text{total distance} \end{cases}$$

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**Question 3**

(a)  $f(-5) = f(1) + \int_1^{-5} g(x) dx = f(1) - \int_{-5}^1 g(x) dx$   
 $= 3 - \left(-9 - \frac{3}{2} + 1\right) = 3 - \left(-\frac{19}{2}\right) = \frac{25}{2}$

2 :  $\begin{cases} 1 : \text{integral} \\ 1 : \text{answer} \end{cases}$

(b)  $\int_1^6 g(x) dx = \int_1^3 g(x) dx + \int_3^6 g(x) dx$   
 $= \int_1^3 2 dx + \int_3^6 2(x-4)^2 dx$   
 $= 4 + \left[\frac{2}{3}(x-4)^3\right]_{x=3}^{x=6} = 4 + \frac{16}{3} - \left(-\frac{2}{3}\right) = 10$

3 :  $\begin{cases} 1 : \text{split at } x = 3 \\ 1 : \text{antiderivative of } 2(x-4)^2 \\ 1 : \text{answer} \end{cases}$

(c) The graph of  $f$  is increasing and concave up on  $0 < x < 1$  and  $4 < x < 6$  because  $f'(x) = g(x) > 0$  and  $f'(x) = g(x)$  is increasing on those intervals.

2 :  $\begin{cases} 1 : \text{intervals} \\ 1 : \text{reason} \end{cases}$

(d) The graph of  $f$  has a point of inflection at  $x = 4$  because  $f'(x) = g(x)$  changes from decreasing to increasing at  $x = 4$ .

2 :  $\begin{cases} 1 : \text{answer} \\ 1 : \text{reason} \end{cases}$

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## Question 4

(a)  $H'(6) \approx \frac{H(7) - H(5)}{7 - 5} = \frac{11 - 6}{2} = \frac{5}{2}$

$H'(6)$  is the rate at which the height of the tree is changing, in meters per year, at time  $t = 6$  years.

(b)  $\frac{H(5) - H(3)}{5 - 3} = \frac{6 - 2}{2} = 2$

Because  $H$  is differentiable on  $3 \leq t \leq 5$ ,  $H$  is continuous on  $3 \leq t \leq 5$ .

By the Mean Value Theorem, there exists a value  $c$ ,  $3 < c < 5$ , such that  $H'(c) = 2$ .

(c) The average height of the tree over the time interval  $2 \leq t \leq 10$  is given by  $\frac{1}{10 - 2} \int_2^{10} H(t) dt$ .

$$\begin{aligned} \frac{1}{8} \int_2^{10} H(t) dt &\approx \frac{1}{8} \left( \frac{1.5 + 2}{2} \cdot 1 + \frac{2 + 6}{2} \cdot 2 + \frac{6 + 11}{2} \cdot 2 + \frac{11 + 15}{2} \cdot 3 \right) \\ &= \frac{1}{8} (65.75) = \frac{263}{32} \end{aligned}$$

The average height of the tree over the time interval  $2 \leq t \leq 10$  is  $\frac{263}{32}$  meters.

(d)  $G(x) = 50 \Rightarrow x = 1$

$$\frac{d}{dt}(G(x)) = \frac{d}{dx}(G(x)) \cdot \frac{dx}{dt} = \frac{(1+x)100 - 100x \cdot 1}{(1+x)^2} \cdot \frac{dx}{dt} = \frac{100}{(1+x)^2} \cdot \frac{dx}{dt}$$

$$\left. \frac{d}{dt}(G(x)) \right|_{x=1} = \frac{100}{(1+1)^2} \cdot 0.03 = \frac{3}{4}$$

According to the model, the rate of change of the height of the tree with respect to time when the tree is 50 meters tall is  $\frac{3}{4}$  meter per year.

2 :  $\left\{ \begin{array}{l} 1 : \text{estimate} \\ 1 : \text{interpretation with units} \end{array} \right.$

2 :  $\left\{ \begin{array}{l} 1 : \frac{H(5) - H(3)}{5 - 3} \\ 1 : \text{conclusion using Mean Value Theorem} \end{array} \right.$

2 :  $\left\{ \begin{array}{l} 1 : \text{trapezoidal sum} \\ 1 : \text{approximation} \end{array} \right.$

3 :  $\left\{ \begin{array}{l} 2 : \frac{d}{dt}(G(x)) \\ 1 : \text{answer} \end{array} \right.$

Note: max 1/3 [1-0] if no chain rule

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## Question 5

(a)  $\text{Area} = \frac{1}{2} \int_{\pi/3}^{5\pi/3} (4^2 - (3 + 2 \cos \theta)^2) d\theta$

(b)  $\frac{dr}{d\theta} = -2 \sin \theta \Rightarrow \left. \frac{dr}{d\theta} \right|_{\theta=\pi/2} = -2$

$$r\left(\frac{\pi}{2}\right) = 3 + 2 \cos\left(\frac{\pi}{2}\right) = 3$$

$$y = r \sin \theta \Rightarrow \frac{dy}{d\theta} = \frac{dr}{d\theta} \sin \theta + r \cos \theta$$

$$x = r \cos \theta \Rightarrow \frac{dx}{d\theta} = \frac{dr}{d\theta} \cos \theta - r \sin \theta$$

$$\left. \frac{dy}{dx} \right|_{\theta=\pi/2} = \left. \frac{dy/d\theta}{dx/d\theta} \right|_{\theta=\pi/2} = \frac{-2 \sin\left(\frac{\pi}{2}\right) + 3 \cos\left(\frac{\pi}{2}\right)}{-2 \cos\left(\frac{\pi}{2}\right) - 3 \sin\left(\frac{\pi}{2}\right)} = \frac{2}{3}$$

The slope of the line tangent to the graph of  $r = 3 + 2 \cos \theta$

at  $\theta = \frac{\pi}{2}$  is  $\frac{2}{3}$ .

— OR —

$$y = r \sin \theta = (3 + 2 \cos \theta) \sin \theta \Rightarrow \frac{dy}{d\theta} = 3 \cos \theta + 2 \cos^2 \theta - 2 \sin^2 \theta$$

$$x = r \cos \theta = (3 + 2 \cos \theta) \cos \theta \Rightarrow \frac{dx}{d\theta} = -3 \sin \theta - 4 \sin \theta \cos \theta$$

$$\left. \frac{dy}{dx} \right|_{\theta=\pi/2} = \left. \frac{dy/d\theta}{dx/d\theta} \right|_{\theta=\pi/2} = \frac{3 \cos\left(\frac{\pi}{2}\right) + 2 \cos^2\left(\frac{\pi}{2}\right) - 2 \sin^2\left(\frac{\pi}{2}\right)}{-3 \sin\left(\frac{\pi}{2}\right) - 4 \sin\left(\frac{\pi}{2}\right) \cos\left(\frac{\pi}{2}\right)} = \frac{2}{3}$$

The slope of the line tangent to the graph of  $r = 3 + 2 \cos \theta$

at  $\theta = \frac{\pi}{2}$  is  $\frac{2}{3}$ .

(c)  $\frac{dr}{dt} = \frac{dr}{d\theta} \cdot \frac{d\theta}{dt} = -2 \sin \theta \cdot \frac{d\theta}{dt} \Rightarrow \frac{d\theta}{dt} = \frac{dr}{dt} \cdot \frac{1}{-2 \sin \theta}$

$$\left. \frac{d\theta}{dt} \right|_{\theta=\pi/3} = 3 \cdot \frac{1}{-2 \sin\left(\frac{\pi}{3}\right)} = \frac{3}{-\sqrt{3}} = -\sqrt{3} \text{ radians per second}$$

$$3 : \begin{cases} 1 : \text{constant and limits} \\ 2 : \text{integrand} \end{cases}$$

$$3 : \begin{cases} 1 : \frac{dy}{d\theta} = \frac{dr}{d\theta} \sin \theta + r \cos \theta \\ \text{or } \frac{dx}{d\theta} = \frac{dr}{d\theta} \cos \theta - r \sin \theta \\ 1 : \frac{dy}{dx} = \frac{\frac{dr}{d\theta} \sin \theta + r \cos \theta}{\frac{dr}{d\theta} \cos \theta - r \sin \theta} \\ 1 : \text{answer} \end{cases}$$

$$3 : \begin{cases} 1 : \frac{dr}{dt} = \frac{dr}{d\theta} \cdot \frac{d\theta}{dt} \\ 1 : \frac{d\theta}{dt} = \frac{dr}{dt} \cdot \frac{1}{-2 \sin \theta} \\ 1 : \text{answer with units} \end{cases}$$

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## Question 6

(a) The first four nonzero terms are  $\frac{x^2}{3} - \frac{x^3}{2 \cdot 3^2} + \frac{x^4}{3 \cdot 3^3} - \frac{x^5}{4 \cdot 3^4}$ .

The general term is  $(-1)^{n+1} \frac{x^{n+1}}{n \cdot 3^n}$ .

$$(b) \lim_{n \rightarrow \infty} \left| \frac{\frac{(-1)^{n+2} x^{n+2}}{(n+1)(3^{n+1})}}{\frac{(-1)^{n+1} x^{n+1}}{n \cdot 3^n}} \right| = \lim_{n \rightarrow \infty} \left| \frac{-x}{3} \cdot \frac{n}{n+1} \right| = \left| \frac{x}{3} \right|$$

$$\left| \frac{x}{3} \right| < 1 \text{ for } |x| < 3$$

Therefore, the radius of convergence of the Maclaurin series for  $f$  is 3.

— OR —

The radius of convergence of the Maclaurin series for  $\ln(1+x)$  is 1, so the series for  $f(x) = x \ln\left(1 + \frac{x}{3}\right)$  converges absolutely for  $\left|\frac{x}{3}\right| < 1$ .

$$\left| \frac{x}{3} \right| < 1 \Rightarrow |x| < 3$$

Therefore, the radius of convergence of the Maclaurin series for  $f$  is 3.

When  $x = -3$ , the series is  $\sum_{n=1}^{\infty} (-1)^{n+1} \frac{(-3)^{n+1}}{n \cdot 3^n} = \sum_{n=1}^{\infty} \frac{3}{n}$ , which diverges by comparison to the harmonic series.

When  $x = 3$ , the series is  $\sum_{n=1}^{\infty} (-1)^{n+1} \frac{3^{n+1}}{n \cdot 3^n} = \sum_{n=1}^{\infty} (-1)^{n+1} \frac{3}{n}$ , which converges by the alternating series test.

The interval of convergence of the Maclaurin series for  $f$  is  $-3 < x \leq 3$ .

(c) By the alternating series error bound, an upper bound for  $|P_4(2) - f(2)|$  is the magnitude of the next term of the alternating series.

$$|P_4(2) - f(2)| < \left| -\frac{2^5}{4 \cdot 3^4} \right| = \frac{8}{81}$$

2 :  $\begin{cases} 1 : \text{first four terms} \\ 1 : \text{general term} \end{cases}$

5 :  $\begin{cases} 1 : \text{sets up ratio} \\ 1 : \text{computes limit of ratio} \\ 1 : \text{radius of convergence} \\ 1 : \text{considers both endpoints} \\ 1 : \text{analysis and interval of convergence} \end{cases}$

— OR —

5 :  $\begin{cases} 1 : \text{radius for } \ln(1+x) \text{ series} \\ 1 : \text{substitutes } \frac{x}{3} \\ 1 : \text{radius of convergence} \\ 1 : \text{considers both endpoints} \\ 1 : \text{analysis and interval of convergence} \end{cases}$

2 :  $\begin{cases} 1 : \text{uses fifth-degree term} \\ \quad \text{as error bound} \\ 1 : \text{answer} \end{cases}$