

**Part B (BC): Graphing calculator not allowed****Question 6****9 points****General Scoring Notes**

- The model solution is presented using standard mathematical notation.
- Answers (numeric or algebraic) need not be simplified. Answers given as a decimal approximation should be accurate to three places after the decimal point. Within each individual free-response question, at most one point is not earned for inappropriate rounding.

The Taylor series for a function  $f$  about  $x = 4$  is given by

$$\sum_{n=1}^{\infty} \frac{(x-4)^{n+1}}{(n+1)3^n} = \frac{(x-4)^2}{2 \cdot 3} + \frac{(x-4)^3}{3 \cdot 3^2} + \frac{(x-4)^4}{4 \cdot 3^3} + \cdots + \frac{(x-4)^{n+1}}{(n+1)3^n} + \cdots$$
 and converges to  $f(x)$  on its interval of convergence.

|          | Model Solution                                                                                                                                                                   | Scoring                                                  |
|----------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------|
| <b>A</b> | Using the ratio test, find the interval of convergence of the Taylor series for $f$ about $x = 4$ . Justify your answer.                                                         |                                                          |
|          | $\left  \frac{(x-4)^{n+2}}{(n+2)3^{n+1}} \cdot \frac{(n+1)3^n}{(x-4)^{n+1}} \right  = \left  \frac{(x-4)(n+1)}{3(n+2)} \right $                                                  | Sets up ratio <b>Point 1 (P1)</b>                        |
|          | $\lim_{n \rightarrow \infty} \left  \frac{(x-4)(n+1)}{3(n+2)} \right  = \left  \frac{x-4}{3} \right  \lim_{n \rightarrow \infty} \frac{n+1}{n+2} = \left  \frac{x-4}{3} \right $ | Limit of ratio <b>Point 2 (P2)</b>                       |
|          | $\left  \frac{x-4}{3} \right  < 1 \text{ when } -3 < x-4 < 3.$<br><br>Thus, the series converges when $1 < x < 7$ .                                                              | Interior of interval of convergence <b>Point 3 (P3)</b>  |
|          | When $x = 1$ , the series is $\sum_{n=1}^{\infty} \frac{(-1)^{n+1} \cdot 3}{n+1}$ , which converges by the alternating series test.                                              | Considers both endpoints <b>Point 4 (P4)</b>             |
|          | When $x = 7$ , the series is $\sum_{n=1}^{\infty} \frac{3}{n+1}$ , which diverges by limit comparison to the harmonic series.                                                    | Analysis and interval of convergence <b>Point 5 (P5)</b> |
|          | Therefore, the series converges for $1 \leq x < 7$ .                                                                                                                             |                                                          |

## Scoring Notes for Part A

- **P1** is earned by presenting a correct ratio with or without absolute values. Once earned, **P1** is banked (i.e., subsequent errors in simplification or evaluation do not impact scoring for **P1**). **P2** is not earned if there are any errors in simplification or evaluation of the limit.
- **P1** is earned for ratios mathematically equivalent to any of the following:

$$\frac{(x-4)^{n+2}}{(n+2)3^{n+1}} \cdot \frac{(n+1)3^n}{(x-4)^{n+1}}, \frac{(x-4)^{n+2}}{(n+2)3^{n+1}}, \frac{(x-4)^{n+1}}{(n+1)3^n} \cdot \frac{n3^{n-1}}{(x-4)^n}, \text{ or } \frac{(x-4)^{n+1}}{(n+1)3^n} \cdot \frac{n3^{n-1}}{(x-4)^n}.$$

- **P1** is also earned for ratios mathematically equivalent to the following reciprocal ratios:

$$\frac{(x-4)^{n+1}}{(n+1)3^n} \cdot \frac{(n+2)3^{n+1}}{(x-4)^{n+2}}, \frac{(x-4)^{n+1}}{(n+1)3^n}, \frac{(x-4)^n}{n3^{n-1}} \cdot \frac{(n+1)3^n}{(x-4)^{n+1}}, \text{ or } \frac{(x-4)^n}{n3^{n-1}} \cdot \frac{(n+1)3^n}{(x-4)^{n+1}}.$$

A response that presents any of these reciprocal ratios earns **P1** and is eligible for **P2**, **P3**, and **P4**, but not **P5**.

- A response that does not present a ratio is not eligible for **P2**.
- A response that does not use the absolute value of a ratio can earn both **P1** and **P2**.
- A response that does not use absolute value in computing the limit is eligible for **P3** if the expression  $-1 < \frac{x-4}{3} < 1$  or an equivalent inequality is presented.
- A response that presents an incorrect limit of form  $\frac{|x-4|}{b}$ , where  $b > 0$ , is eligible for **P3**.

**P3** is then earned for correctly finding an interval with interior  $(1, 7)$  or  $(4-b, 4+b)$ .

Note:  $|x-4| < b$  is not sufficient to earn **P3**.  $x-4 < b$  can earn **P3** if this is resolved to  $-b+4 < x < b+4$ .

- **P4** is earned for considering both endpoints of the correct interval or both endpoints of an incorrect interval that has earned **P3**.
- To earn **P5**, a response must correctly analyze the series at  $x = 1$  and  $x = 7$ , and present the correct interval of convergence. Naming of an appropriate test is sufficient for the analysis at each endpoint. In addition to the tests listed in the model solution, the direct comparison test to an appropriate series or the integral test may also be used.

- B** Find the first three nonzero terms and the general term of the Taylor series for  $f'$ , the derivative of  $f$ , about  $x = 4$ .

$$f'(x) = \frac{(x-4)}{3} + \frac{(x-4)^2}{9} + \frac{(x-4)^3}{27} + \cdots + \frac{(x-4)^n}{3^n} + \cdots$$

First three terms

**Point 6 (P6)**

General term

**Point 7 (P7)****Scoring Notes for Part B**

- **P6** is earned by presenting the first three nonzero terms in a list or as part of a polynomial or series.
- **P7** is earned by identifying the correct general term (either individually or as part of a polynomial or series).

- C** The Taylor series for  $f'$  described in part B is a geometric series. For all  $x$  in the interval of convergence of the Taylor series for  $f'$ , show that  $f'(x) = \frac{x-4}{7-x}$ .

The Taylor series for  $f'$  is a geometric series with first term

$$\frac{x-4}{3} \text{ and common ratio } \frac{x-4}{3}.$$

$$f'(x) = \frac{\frac{x-4}{3}}{1 - \frac{x-4}{3}} = \frac{x-4}{3 - (x-4)} = \frac{x-4}{7-x}$$

Verification

**Point 8 (P8)****Scoring Notes for Part C**

- A response of  $f'(x) = \frac{\frac{x-4}{3}}{1 - \frac{x-4}{3}}$  is sufficient to earn **P8**.

- D** It is known that the radius of convergence of the Taylor series for  $f$  about  $x = 4$  is the same as the radius of convergence of the Taylor series for  $f'$  about  $x = 4$ . Does the Taylor series for  $f'$  described in part B converge to  $f'(x) = \frac{x-4}{7-x}$  at  $x = 8$ ? Give a reason for your answer.

It follows from the work in part A that the interior of the interval of convergence of the Taylor series for  $f'$  is  $1 < x < 7$ .

Therefore,  $x = 8$  would be outside the interval of convergence of  $f'$ , and the Taylor series for  $f'$  would not converge to

$$f'(x) = \frac{x-4}{7-x} \text{ at } x = 8.$$

Answer with reason **Point 9 (P9)**

### Scoring Notes for Part D

- A response of “no,  $x = 8$  is outside the interval of convergence” is sufficient to earn **P9**.
- **P9** can be earned with a response consistent with an incorrect interval of convergence imported from part A.
- Alternate solutions:
  - Because the series for  $f'(x)$  is geometric, this converges to  $f(x)$  for all values of  $x$  such that the common ratio  $\frac{x-4}{3}$  is between  $-1$  and  $1$ .  

$$-1 < \frac{x-4}{3} < 1 \Rightarrow -3 < x-4 < 3 \Rightarrow 1 < x < 7$$
  - Because  $x = 8$  is outside the interval  $1 < x < 7$ , the series for  $f'$  does not converge to  $f'(x) = \frac{x-4}{7-x}$  at  $x = 8$ .
  - For  $x = 8$ , the series is given by  $\sum_{n=1}^{\infty} \left(\frac{4}{3}\right)^n$ , which is a geometric series with  $r = \frac{4}{3} > 1$ .  
 Therefore, the series diverges for  $x = 8$ .

**Part B (BC): Graphing calculator not allowed****Question 6****9 points****General Scoring Notes**

The model solution is presented using standard mathematical notation.

Answers (numeric or algebraic) need not be simplified. Answers given as a decimal approximation should be correct to three places after the decimal point. Within each individual free-response question, at most one point is not earned for inappropriate rounding.

The Maclaurin series for a function  $f$  is given by  $\sum_{n=1}^{\infty} \frac{(n+1)x^n}{n^2 6^n}$  and converges to  $f(x)$  for all  $x$  in the interval of convergence. It can be shown that the Maclaurin series for  $f$  has a radius of convergence of 6.

| Model Solution                                                                                                                                                                                                   | Scoring                                             |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------|
| (a) Determine whether the Maclaurin series for $f$ converges or diverges at $x = 6$ . Give a reason for your answer.                                                                                             |                                                     |
| At $x = 6$ , the series is $\sum_{n=1}^{\infty} \frac{(n+1)6^n}{n^2 6^n} = \sum_{n=1}^{\infty} \frac{n+1}{n^2}$ .                                                                                                | Considers $\frac{(n+1)6^n}{n^2 6^n}$ <b>1 point</b> |
| Because $\frac{n+1}{n^2} > \frac{1}{n}$ for all $n \geq 1$ and the harmonic series $\sum_{n=1}^{\infty} \frac{1}{n}$ diverges, the series $\sum_{n=1}^{\infty} \frac{n+1}{n^2}$ diverges by the comparison test. | Answer with reason <b>1 point</b>                   |

**Scoring notes:**

- To earn the first point using either the comparison or limit comparison test, a response must consider the term  $\frac{(n+1)6^n}{n^2 6^n}$ . This could be shown by considering the term  $\frac{n+1}{n^2}$ , either individually or as part of a sum.
- To earn the second point using the comparison test a response must demonstrate that the terms  $\frac{n+1}{n^2}$  are larger than the terms in a divergent series.
  - “ $\frac{n+1}{n^2} > \frac{1}{n}$ , diverges” earns both points.
  - The response does not need to use the term “comparison test,” but the response cannot declare use of an incorrect test.
- Alternate solution (limit comparison test):

At  $x = 6$ , the series is  $\sum_{n=1}^{\infty} \frac{(n+1)6^n}{n^2 6^n} = \sum_{n=1}^{\infty} \frac{n+1}{n^2}$ .

Because  $\lim_{n \rightarrow \infty} \frac{\frac{n+1}{n^2}}{\frac{1}{n}} = \lim_{n \rightarrow \infty} \frac{n^2 + n}{n^2} = 1$  and the harmonic series  $\sum_{n=1}^{\infty} \frac{1}{n}$  diverges, the series

$\sum_{n=1}^{\infty} \frac{n+1}{n^2}$  diverges by the limit comparison test.

- To earn the second point using the limit comparison test, a response must correctly write the limit of the ratio of the terms in the given series to the terms of a divergent series and demonstrate that the limit of this ratio is 1.
- The response does not need to use the term “limit comparison test,” but the response cannot declare use of an incorrect test.

**Total for part (a)    2 points**

- (b) It can be shown that  $f(-3) = \sum_{n=1}^{\infty} \frac{(n+1)(-3)^n}{n^2 6^n} = \sum_{n=1}^{\infty} \frac{n+1}{n^2} \left(-\frac{1}{2}\right)^n$  and that the first three terms of this series sum to  $S_3 = -\frac{125}{144}$ . Show that  $|f(-3) - S_3| < \frac{1}{50}$ .

$f(-3) = \sum_{n=1}^{\infty} \frac{(n+1)(-3)^n}{n^2 6^n} = \sum_{n=1}^{\infty} \frac{(n+1)}{n^2} \left(-\frac{1}{2}\right)^n$  is an alternating series with terms that decrease in magnitude to 0.

By the alternating series error bound,  $\sum_{n=1}^3 \frac{n+1}{n^2} \left(-\frac{1}{2}\right)^n = -\frac{125}{144}$

approximates  $f(-3)$  with error of at most

$$\left| \frac{4+1}{4^2} \left(-\frac{1}{2}\right)^4 \right| = \frac{5}{256} < \frac{5}{250} = \frac{1}{50}.$$

Thus,  $|f(-3) - S_3| < \frac{1}{50}$ .

Uses fourth term **1 point**

Verification **1 point**

**Scoring notes:**

- The first point is earned for correctly using  $x = -3$  in the fourth term. (Listing the fourth term as part of a polynomial is not sufficient.) Using  $x = -3$  in any term of degree five or higher does not earn this point.
- The expression  $\frac{4+1}{4^2} \left(-\frac{1}{2}\right)^4$  earns the first point, but just  $\frac{5}{256}$  does not earn the first point.
- A response including the expression  $\frac{4+1}{4^2} \left(-\frac{1}{2}\right)^4$  that is subsequently simplified incorrectly earns the first point but not the second.
- To earn the second point the response must state that the series for  $f(-3)$  is alternating or that the alternating series error bound is being used.
  - A response of just “Error  $\leq \frac{4+1}{4^2} \left(-\frac{1}{2}\right)^4 < \frac{1}{50}$ ” (or any equivalent mathematical expression) earns both points, provided it is accompanied by an indication that the series is alternating.
- A response that declares the error is equal to  $\frac{5}{256}$  (or any equivalent form of this value) does not earn the second point.

**Total for part (b) 2 points**

- (c) Find the general term of the Maclaurin series for  $f'$ , the derivative of  $f$ . Find the radius of convergence of the Maclaurin series for  $f'$ .

|                                                                                                                                               |                                |
|-----------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------|
| The general term of the Maclaurin series for $f'$ is<br>$\frac{(n+1)nx^{n-1}}{n^2 6^n} = \frac{(n+1)x^{n-1}}{n \cdot 6^n}.$                   | General term<br><b>1 point</b> |
| Because the radius of convergence of the Maclaurin series for $f$ is 6, the radius of convergence of the Maclaurin series for $f'$ is also 6. | Radius<br><b>1 point</b>       |

**Scoring notes:**

- A response of  $\frac{(n+1)nx^{n-1}}{n^2 6^n}$  earns the first point. Any expression mathematically equivalent to this also earns the first point.
- The response need not simplify  $\frac{(n+1)nx^{n-1}}{n^2 6^n}$ , but any presented simplification must be correct in order to earn the first point.
- The second point is earned only for a supported answer of 6. The second point can be earned without the first.
- Alternate solution for second point (ratio test):

$$\lim_{n \rightarrow \infty} \left| \frac{\frac{(n+2)x^n}{(n+1)6^{n+1}}}{\frac{(n+1)x^{n-1}}{n \cdot 6^n}} \right| = \lim_{n \rightarrow \infty} \left| \frac{n(n+2)}{(n+1)^2} \cdot \frac{x}{6} \right| = \frac{|x|}{6} < 1 \Rightarrow |x| < 6$$

Therefore, the radius of convergence of the Maclaurin series for  $f'$  is 6.

- Alternate solution for second point (root test):

$$\lim_{n \rightarrow \infty} \sqrt[n]{\frac{(n+1)|x|^{n-1}}{n \cdot 6^n}} = \lim_{n \rightarrow \infty} \left( \frac{n+1}{n} \right)^{1/n} \cdot |x|^{-1/n} \cdot \frac{|x|}{6} = 1 \cdot 1 \cdot \frac{|x|}{6} < 1 \Rightarrow |x| < 6$$

Therefore, the radius of convergence of the Maclaurin series for  $f'$  is 6.

**Total for part (c) 2 points**



- (d) Let  $g(x) = \sum_{n=1}^{\infty} \frac{(n+1)x^{2n}}{n^2 3^n}$ . Use the ratio test to determine the radius of convergence of the Maclaurin series for  $g$ .

|                                                                                                                                                                                     |                       |         |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------|---------|
| $\left  \frac{\frac{(n+2)x^{2n+2}}{(n+1)^2 3^{n+1}}}{\frac{(n+1)x^{2n}}{n^2 3^n}} \right  = \left  \frac{(n+2)x^{2n+2}}{(n+1)^2 3^{n+1}} \cdot \frac{n^2 3^n}{(n+1)x^{2n}} \right $ | Sets up ratio         | 1 point |
| $\lim_{n \rightarrow \infty} \left  \frac{(n+2)n^2}{(n+1)^3} \cdot \left  \frac{x^2}{3} \right  \right  = \left  \frac{x^2}{3} \right $                                             | Limit                 | 1 point |
| $\left  \frac{x^2}{3} \right  < 1 \Rightarrow x^2 < 3 \Rightarrow  x  < \sqrt{3}$<br>The radius of convergence of $g$ is $\sqrt{3}$ .                                               | Radius of convergence | 1 point |

**Scoring notes:**

- The first point is earned by presenting a correct ratio with or without absolute values. Once earned, this point cannot be lost. Any errors in simplification or evaluation of the limit will not earn the second point.
- The first point is earned for ratios mathematically equivalent to any of the following:

$$\frac{\frac{(n+2)x^{2n+2}}{(n+1)^2 3^{n+1}}}{\frac{(n+1)x^{2n}}{n^2 3^n}}, \quad \frac{(n+2)x^{2n+2}}{(n+1)^2 3^{n+1}} \cdot \frac{n^2 3^n}{(n+1)x^{2n}}, \quad \frac{\frac{(n+1)x^{2n}}{n^2 3^n}}{\frac{(n-1)^2 3^{n-1}}{nx^{2n-2}}}, \quad \text{or} \quad \frac{(n+1)x^{2n}}{n^2 3^n} \cdot \frac{(n-1)^2 3^{n-1}}{nx^{2n-2}}.$$

- The first point is also earned for ratios mathematically equivalent to the following reciprocal ratios:

$$\frac{\frac{(n+1)x^{2n}}{n^2 3^n}}{\frac{(n+2)x^{2n+2}}{(n+1)^2 3^{n+1}}}, \quad \frac{(n+1)x^{2n}}{n^2 3^n} \cdot \frac{(n+1)^2 3^{n+1}}{(n+2)x^{2n+2}}, \quad \frac{\frac{nx^{2n-2}}{(n-1)^2 3^{n-1}}}{\frac{(n+1)x^{2n}}{n^2 3^n}}, \quad \text{or} \quad \frac{nx^{2n-2}}{(n-1)^2 3^{n-1}} \cdot \frac{n^2 3^n}{(n+1)x^{2n}}.$$

Responses including any of these reciprocal ratios can earn the second point for using limit notation to correctly find a limit of the absolute value of their ratio to be  $\left| \frac{3}{x^2} \right|$ . Such responses earn the third point only for a final answer of  $\sqrt{3}$  with a valid explanation for reporting the reciprocal of  $\frac{1}{\sqrt{3}}$ .

- To earn the second point a response must use the ratio and correctly evaluate the limit of the ratio, using correct limit notation.
- The third point is earned only for an answer of  $\sqrt{3}$  with supporting work.

**Total for part (d) 3 points**

**Total for question 6 9 points**

**Part B (BC): Graphing calculator not allowed****Question 6****9 points****General Scoring Notes**

The model solution is presented using standard mathematical notation.

Answers (numeric or algebraic) need not be simplified. Answers given as a decimal approximation should be correct to three places after the decimal point. Within each individual free-response question, at most one point is not earned for inappropriate rounding.

The function  $f$  is defined by the power series  $f(x) = x - \frac{x^3}{3} + \frac{x^5}{5} - \frac{x^7}{7} + \cdots + \frac{(-1)^n x^{2n+1}}{2n+1} + \cdots$  for all real numbers  $x$  for which the series converges.

| Model Solution                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | Scoring                                                       |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------|
| (a) Using the ratio test, find the interval of convergence of the power series for $f$ . Justify your answer.                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |                                                               |
| $\lim_{n \rightarrow \infty} \left  \frac{\frac{(-1)^{n+1} x^{2n+3}}{2n+3}}{\frac{(-1)^n x^{2n+1}}{2n+1}} \right  = \lim_{n \rightarrow \infty} \left  \frac{x^{2n+3}}{x^{2n+1}} \cdot \frac{2n+1}{2n+3} \right  = \lim_{n \rightarrow \infty} \left  x^2 \left( \frac{2n+1}{2n+3} \right) \right  =  x^2 $                                                                                                                                                                                                                                                                        | Sets up ratio <b>1 point</b>                                  |
| $ x^2  < 1$ for $ x  < 1$ .<br>The series converges when $-1 < x < 1$ .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | Identifies interior of interval of convergence <b>1 point</b> |
| When $x = -1$ , the series is $-1 + \frac{1}{3} - \frac{1}{5} + \cdots + \frac{(-1)^{n+1}}{2n+1} + \cdots$ .<br>The series is an alternating series whose terms decrease in absolute value to 0. The series converges by the Alternating Series Test.<br><br>When $x = 1$ , the series is $1 - \frac{1}{3} + \frac{1}{5} + \cdots + \frac{(-1)^n}{2n+1} + \cdots$ .<br>The series is an alternating series whose terms decrease in absolute value to 0. The series converges by the Alternating Series Test.<br><br>Therefore, the interval of convergence is $-1 \leq x \leq 1$ . | Considers both endpoints <b>1 point</b>                       |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | Analysis and interval of convergence <b>1 point</b>           |

**Scoring notes:**

- A response that includes the substitution error of the form  $x^{2(n+1)+1} = x^{2n+3}$  appearing as  $x^{2n+1+1} = x^{2n+2}$  in setting up a ratio is eligible for the first 3 points but does not earn the fourth point.
- The first point is earned by presenting a correct ratio with or without absolute values.
- To earn the second point a response must:
  - use the absolute value of the ratio, or resolve the lack of absolute values by concluding  $x^2 < 1$  (without any errors), and correctly evaluate the limit of the ratio, including correct limit notation, and
  - identify the interior of the interval of convergence. The response can use either interval notation or the compound inequality  $-1 < x < 1$  ( $|x| < 1$  is insufficient).
- The only incorrect interval eligible for the third point is  $0 < x < 1$ . In this case, to earn the third point, the response needs to evaluate the general term at  $x = 1$ .

**Total for part (a) 4 points**

- (b) Show that  $\left|f\left(\frac{1}{2}\right) - \frac{1}{2}\right| < \frac{1}{10}$ . Justify your answer.

The series for  $f\left(\frac{1}{2}\right)$  is an alternating series whose terms decrease in absolute value to 0. The first term of the series for  $f\left(\frac{1}{2}\right)$  is  $\frac{1}{2}$ . Using the alternating series error bound,  $f\left(\frac{1}{2}\right)$  differs from  $\frac{1}{2}$  by at most the absolute value of the second term of the series.

$$\left|f\left(\frac{1}{2}\right) - \frac{1}{2}\right| < \left|\frac{(-1)^1\left(\frac{1}{2}\right)^3}{3}\right| = \frac{1}{24} < \frac{1}{10}$$

Uses second term **1 point**Justification **1 point****Scoring notes:**

- The first point is earned by correctly using  $x = \frac{1}{2}$  in the second term (listing the second term as part of a polynomial is insufficient). Using  $x = \frac{1}{2}$  in any term of degree five or higher does not earn this point.
- To earn the second point a response must:
  - have earned the first point,
  - state that the series is alternating and that its terms decrease to zero, and
  - present the inequality  $\text{Error} < \frac{1}{24} < \frac{1}{10}$  (or the equivalent).
- A response that states  $\text{Error} = \frac{1}{24}$  does not earn the second point.

**Total for part (b) 2 points**

- (c) Write the first four nonzero terms and the general term for an infinite series that represents  $f'(x)$ .

|                                                                 |                  |                |
|-----------------------------------------------------------------|------------------|----------------|
| $f'(x) = 1 - x^2 + x^4 - x^6 + \cdots + (-1)^n x^{2n} + \cdots$ | First four terms | <b>1 point</b> |
|                                                                 | General term     | <b>1 point</b> |

**Scoring notes:**

- The first point is earned by presenting the first four nonzero terms in a list or as part of a polynomial or series.
- The second point is earned by identifying the general term (either individually or as part of a polynomial or series).
- Read “=” as “ $\approx$ ” as necessary.

**Total for part (c) 2 points**

- (d) Use the result from part (c) to find the value of  $f'\left(\frac{1}{6}\right)$ .

|                                                                                                                                                                                                                                                                                                                                                                         |        |                |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------|----------------|
| $f'\left(\frac{1}{6}\right) = 1 - \left(\frac{1}{6}\right)^2 + \left(\frac{1}{6}\right)^4 - \left(\frac{1}{6}\right)^6 + \cdots$ $f'\left(\frac{1}{6}\right) \text{ is a geometric series with } a = 1 \text{ and } r = -\frac{1}{36}.$ $f'\left(\frac{1}{6}\right) = \frac{a}{1-r} = \frac{1}{1-\left(-\frac{1}{36}\right)} = \frac{1}{\frac{37}{36}} = \frac{36}{37}$ | Answer | <b>1 point</b> |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------|----------------|

**Scoring notes:**

- The result from part (c) must be geometric in order to be eligible for this point.
- If a response imports an incorrect geometric series from part (c), this point is earned only for a consistent answer.

**Total for part (d) 1 point**

**Total for question 6 9 points**

---

# AP<sup>®</sup> Calculus BC

## 2015 Scoring Guidelines

---

© 2015 The College Board. College Board, Advanced Placement Program, AP, AP Central, and the acorn logo are registered trademarks of the College Board.

Visit the College Board on the Web: [www.collegeboard.org](http://www.collegeboard.org).

AP Central is the official online home for the AP Program: [apcentral.collegeboard.org](http://apcentral.collegeboard.org).

*0*

## 2015 SCORING GUIDELINES

## Question 1

The rate at which rainwater flows into a drainpipe is modeled by the function  $R$ , where  $R(t) = 20\sin\left(\frac{t^2}{35}\right)$  cubic feet per hour,  $t$  is measured in hours, and  $0 \leq t \leq 8$ . The pipe is partially blocked, allowing water to drain out the other end of the pipe at a rate modeled by  $D(t) = -0.04t^3 + 0.4t^2 + 0.96t$  cubic feet per hour, for  $0 \leq t \leq 8$ . There are 30 cubic feet of water in the pipe at time  $t = 0$ .

- (a) How many cubic feet of rainwater flow into the pipe during the 8-hour time interval  $0 \leq t \leq 8$ ?
- (b) Is the amount of water in the pipe increasing or decreasing at time  $t = 3$  hours? Give a reason for your answer.
- (c) At what time  $t$ ,  $0 \leq t \leq 8$ , is the amount of water in the pipe at a minimum? Justify your answer.
- (d) The pipe can hold 50 cubic feet of water before overflowing. For  $t > 8$ , water continues to flow into and out of the pipe at the given rates until the pipe begins to overflow. Write, but do not solve, an equation involving one or more integrals that gives the time  $w$  when the pipe will begin to overflow.

(a)  $\int_0^8 R(t) dt = 76.570$

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

(b)  $R(3) - D(3) = -0.313632 < 0$   
 Since  $R(3) < D(3)$ , the amount of water in the pipe is decreasing at time  $t = 3$  hours.

2 :  $\begin{cases} 1 : \text{considers } R(3) \text{ and } D(3) \\ 1 : \text{answer and reason} \end{cases}$

(c) The amount of water in the pipe at time  $t$ ,  $0 \leq t \leq 8$ , is  $30 + \int_0^t [R(x) - D(x)] dx$ .

3 :  $\begin{cases} 1 : \text{considers } R(t) - D(t) = 0 \\ 1 : \text{answer} \\ 1 : \text{justification} \end{cases}$

$R(t) - D(t) = 0 \Rightarrow t = 0, 3.271658$

| $t$      | Amount of water in the pipe |
|----------|-----------------------------|
| 0        | 30                          |
| 3.271658 | 27.964561                   |
| 8        | 48.543686                   |

The amount of water in the pipe is a minimum at time  $t = 3.272$  (or 3.271) hours.

(d)  $30 + \int_0^w [R(t) - D(t)] dt = 50$

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

# 2015 SCORING GUIDELINES

## Question 2

At time  $t \geq 0$ , a particle moving along a curve in the  $xy$ -plane has position  $(x(t), y(t))$  with velocity vector  $v(t) = (\cos(t^2), e^{0.5t})$ . At  $t = 1$ , the particle is at the point  $(3, 5)$ .

- (a) Find the  $x$ -coordinate of the position of the particle at time  $t = 2$ .
- (b) For  $0 < t < 1$ , there is a point on the curve at which the line tangent to the curve has a slope of 2. At what time is the object at that point?
- (c) Find the time at which the speed of the particle is 3.
- (d) Find the total distance traveled by the particle from time  $t = 0$  to time  $t = 1$ .

(a)  $x(2) = 3 + \int_1^2 \cos(t^2) dt = 2.557$  (or 2.556)

$$3 : \begin{cases} 1 : \text{integral} \\ 1 : \text{uses initial condition} \\ 1 : \text{answer} \end{cases}$$

(b)  $\frac{dy}{dx} = \frac{dy/dt}{dx/dt} = \frac{e^{0.5t}}{\cos(t^2)}$

$$\frac{e^{0.5t}}{\cos(t^2)} = 2$$

$$t = 0.840$$

$$2 : \begin{cases} 1 : \text{slope in terms of } t \\ 1 : \text{answer} \end{cases}$$

(c) Speed =  $\sqrt{\cos^2(t^2) + e^t}$

$$\sqrt{\cos^2(t^2) + e^t} = 3$$

$$t = 2.196$$
 (or 2.195)

$$2 : \begin{cases} 1 : \text{speed in terms of } t \\ 1 : \text{answer} \end{cases}$$

(d) Distance =  $\int_0^1 \sqrt{\cos^2(t^2) + e^t} dt = 1.595$  (or 1.594)

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

## 2015 SCORING GUIDELINES

## Question 3

|                               |   |     |     |      |     |
|-------------------------------|---|-----|-----|------|-----|
| $t$<br>(minutes)              | 0 | 12  | 20  | 24   | 40  |
| $v(t)$<br>(meters per minute) | 0 | 200 | 240 | -220 | 150 |

Johanna jogs along a straight path. For  $0 \leq t \leq 40$ , Johanna's velocity is given by a differentiable function  $v$ . Selected values of  $v(t)$ , where  $t$  is measured in minutes and  $v(t)$  is measured in meters per minute, are given in the table above.

- (a) Use the data in the table to estimate the value of  $v'(16)$ .
- (b) Using correct units, explain the meaning of the definite integral  $\int_0^{40} |v(t)| dt$  in the context of the problem.

Approximate the value of  $\int_0^{40} |v(t)| dt$  using a right Riemann sum with the four subintervals indicated in the table.

- (c) Bob is riding his bicycle along the same path. For  $0 \leq t \leq 10$ , Bob's velocity is modeled by  $B(t) = t^3 - 6t^2 + 300$ , where  $t$  is measured in minutes and  $B(t)$  is measured in meters per minute.

Find Bob's acceleration at time  $t = 5$ .

- (d) Based on the model  $B$  from part (c), find Bob's average velocity during the interval  $0 \leq t \leq 10$ .

(a)  $v'(16) \approx \frac{240 - 200}{20 - 12} = 5 \text{ meters/min}^2$

1 : approximation

- (b)  $\int_0^{40} |v(t)| dt$  is the total distance Johanna jogs, in meters, over the time interval  $0 \leq t \leq 40$  minutes.

3 :  $\begin{cases} 1 : \text{explanation} \\ 1 : \text{right Riemann sum} \\ 1 : \text{approximation} \end{cases}$

$$\begin{aligned} \int_0^{40} |v(t)| dt &\approx 12 \cdot |v(12)| + 8 \cdot |v(20)| + 4 \cdot |v(24)| + 16 \cdot |v(40)| \\ &= 12 \cdot 200 + 8 \cdot 240 + 4 \cdot 220 + 16 \cdot 150 \\ &= 2400 + 1920 + 880 + 2400 \\ &= 7600 \text{ meters} \end{aligned}$$

- (c) Bob's acceleration is  $B'(t) = 3t^2 - 12t$ .  
 $B'(5) = 3(25) - 12(5) = 15 \text{ meters/min}^2$

2 :  $\begin{cases} 1 : \text{uses } B'(t) \\ 1 : \text{answer} \end{cases}$

(d) Avg vel  $= \frac{1}{10} \int_0^{10} (t^3 - 6t^2 + 300) dt$

$$\begin{aligned} &= \frac{1}{10} \left[ \frac{t^4}{4} - 2t^3 + 300t \right]_0^{10} \\ &= \frac{1}{10} \left[ \frac{10000}{4} - 2000 + 3000 \right] = 350 \text{ meters/min} \end{aligned}$$

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

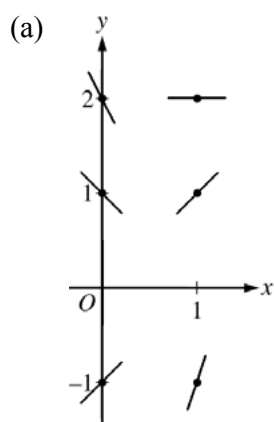


## 2015 SCORING GUIDELINES

## Question 4

Consider the differential equation  $\frac{dy}{dx} = 2x - y$ .

- (a) On the axes provided, sketch a slope field for the given differential equation at the six points indicated.
- (b) Find  $\frac{d^2y}{dx^2}$  in terms of  $x$  and  $y$ . Determine the concavity of all solution curves for the given differential equation in Quadrant II. Give a reason for your answer.
- (c) Let  $y = f(x)$  be the particular solution to the differential equation with the initial condition  $f(2) = 3$ . Does  $f$  have a relative minimum, a relative maximum, or neither at  $x = 2$ ? Justify your answer.
- (d) Find the values of the constants  $m$  and  $b$  for which  $y = mx + b$  is a solution to the differential equation.



$$2 : \begin{cases} 1 : \text{slopes where } x = 0 \\ 1 : \text{slopes where } x = 1 \end{cases}$$

(b)  $\frac{d^2y}{dx^2} = 2 - \frac{dy}{dx} = 2 - (2x - y) = 2 - 2x + y$

In Quadrant II,  $x < 0$  and  $y > 0$ , so  $2 - 2x + y > 0$ .  
Therefore, all solution curves are concave up in Quadrant II.

$$2 : \begin{cases} 1 : \frac{d^2y}{dx^2} \\ 1 : \text{concave up with reason} \end{cases}$$

(c)  $\left. \frac{dy}{dx} \right|_{(x,y)=(2,3)} = 2(2) - 3 = 1 \neq 0$

Therefore,  $f$  has neither a relative minimum nor a relative maximum at  $x = 2$ .

$$2 : \begin{cases} 1 : \text{considers } \left. \frac{dy}{dx} \right|_{(x,y)=(2,3)} \\ 1 : \text{conclusion with justification} \end{cases}$$

(d)  $y = mx + b \Rightarrow \frac{dy}{dx} = \frac{d}{dx}(mx + b) = m$

$$2x - y = m$$

$$2x - (mx + b) = m$$

$$(2 - m)x - (m + b) = 0$$

$$2 - m = 0 \Rightarrow m = 2$$

$$b = -m \Rightarrow b = -2$$

$$3 : \begin{cases} 1 : \frac{d}{dx}(mx + b) = m \\ 1 : 2x - y = m \\ 1 : \text{answer} \end{cases}$$

## 2015 SCORING GUIDELINES

## Question 5

Consider the function  $f(x) = \frac{1}{x^2 - kx}$ , where  $k$  is a nonzero constant. The derivative of  $f$  is given by

$$f'(x) = \frac{k - 2x}{(x^2 - kx)^2}.$$

- (a) Let  $k = 3$ , so that  $f(x) = \frac{1}{x^2 - 3x}$ . Write an equation for the line tangent to the graph of  $f$  at the point whose  $x$ -coordinate is 4.
- (b) Let  $k = 4$ , so that  $f(x) = \frac{1}{x^2 - 4x}$ . Determine whether  $f$  has a relative minimum, a relative maximum, or neither at  $x = 2$ . Justify your answer.
- (c) Find the value of  $k$  for which  $f$  has a critical point at  $x = -5$ .
- (d) Let  $k = 6$ , so that  $f(x) = \frac{1}{x^2 - 6x}$ . Find the partial fraction decomposition for the function  $f$ .

Find  $\int f(x) dx$ .

$$(a) \quad f(4) = \frac{1}{4^2 - 3 \cdot 4} = \frac{1}{4} \quad f'(4) = \frac{3 - 2 \cdot 4}{(4^2 - 3 \cdot 4)^2} = -\frac{5}{16}$$

An equation for the line tangent to the graph of  $f$  at the point whose  $x$ -coordinate is 4 is  $y = -\frac{5}{16}(x - 4) + \frac{1}{4}$ .

$$(b) \quad f'(x) = \frac{4 - 2x}{(x^2 - 4x)^2} \quad f'(2) = \frac{4 - 2 \cdot 2}{(2^2 - 4 \cdot 2)^2} = 0$$

$f'(x)$  changes sign from positive to negative at  $x = 2$ .  
Therefore,  $f$  has a relative maximum at  $x = 2$ .

$$(c) \quad f'(-5) = \frac{k - 2 \cdot (-5)}{((-5)^2 - k \cdot (-5))^2} = 0 \Rightarrow k = -10$$

$$(d) \quad \frac{1}{x^2 - 6x} = \frac{1}{x(x - 6)} = \frac{A}{x} + \frac{B}{x - 6} \Rightarrow 1 = A(x - 6) + Bx$$

$$x = 0 \Rightarrow 1 = A \cdot (-6) \Rightarrow A = -\frac{1}{6}$$

$$x = 6 \Rightarrow 1 = B \cdot (6) \Rightarrow B = \frac{1}{6}$$

$$\frac{1}{x(x - 6)} = \frac{-1/6}{x} + \frac{1/6}{x - 6}$$

$$\int f(x) dx = \int \left( \frac{-1/6}{x} + \frac{1/6}{x - 6} \right) dx$$

$$= -\frac{1}{6} \ln|x| + \frac{1}{6} \ln|x - 6| + C = \frac{1}{6} \ln \left| \frac{x - 6}{x} \right| + C$$

2 :  $\begin{cases} 1 : \text{slope} \\ 1 : \text{tangent line equation} \end{cases}$

2 :  $\begin{cases} 1 : \text{considers } f'(2) \\ 1 : \text{answer with justification} \end{cases}$

1 : answer

4 :  $\begin{cases} 2 : \text{partial fraction decomposition} \\ 2 : \text{general antiderivative} \end{cases}$

## 2015 SCORING GUIDELINES

## Question 6

The Maclaurin series for a function  $f$  is given by  $\sum_{n=1}^{\infty} \frac{(-3)^{n-1}}{n} x^n = x - \frac{3}{2}x^2 + 3x^3 - \cdots + \frac{(-3)^{n-1}}{n} x^n + \cdots$  and converges to  $f(x)$  for  $|x| < R$ , where  $R$  is the radius of convergence of the Maclaurin series.

- (a) Use the ratio test to find  $R$ .
- (b) Write the first four nonzero terms of the Maclaurin series for  $f'$ , the derivative of  $f$ . Express  $f'$  as a rational function for  $|x| < R$ .
- (c) Write the first four nonzero terms of the Maclaurin series for  $e^x$ . Use the Maclaurin series for  $e^x$  to write the third-degree Taylor polynomial for  $g(x) = e^x f(x)$  about  $x = 0$ .

- (a) Let  $a_n$  be the  $n$ th term of the Maclaurin series.

$$\frac{a_{n+1}}{a_n} = \frac{(-3)^n x^{n+1}}{n+1} \cdot \frac{n}{(-3)^{n-1} x^n} = \frac{-3n}{n+1} \cdot x$$

$$\lim_{n \rightarrow \infty} \left| \frac{-3n}{n+1} \cdot x \right| = 3|x|$$

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

The radius of convergence is  $R = \frac{1}{3}$ .

- (b) The first four nonzero terms of the Maclaurin series for  $f'$  are  $1 - 3x + 9x^2 - 27x^3$ .

$$f'(x) = \frac{1}{1 - (-3x)} = \frac{1}{1 + 3x}$$

- (c) The first four nonzero terms of the Maclaurin series for  $e^x$  are

$$1 + x + \frac{x^2}{2!} + \frac{x^3}{3!}.$$

The product of the Maclaurin series for  $e^x$  and the Maclaurin series for  $f$  is

$$\begin{aligned} & \left( 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \cdots \right) \left( x - \frac{3}{2}x^2 + 3x^3 - \cdots \right) \\ &= x - \frac{1}{2}x^2 + 2x^3 + \cdots \end{aligned}$$

The third-degree Taylor polynomial for  $g(x) = e^x f(x)$

about  $x = 0$  is  $T_3(x) = x - \frac{1}{2}x^2 + 2x^3$ .

$$3 : \begin{cases} 1 : \text{sets up ratio} \\ 1 : \text{computes limit of ratio} \\ 1 : \text{determines radius of convergence} \end{cases}$$

$$3 : \begin{cases} 2 : \text{first four nonzero terms} \\ 1 : \text{rational function} \end{cases}$$

$$3 : \begin{cases} 1 : \text{first four nonzero terms} \\ \quad \text{of the Maclaurin series for } e^x \\ 2 : \text{Taylor polynomial} \end{cases}$$