

Vector Calculus: Example Sheet 1

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1. Sketch the curve in the plane given parametrically by

$$\mathbf{x}(t) = (a \cos^3 t, a \sin^3 t), \quad 0 \leq t \leq 2\pi.$$

Calculate $\dot{\mathbf{x}}(t)$ at each point and hence find its total length.

2. A circular helix is given by

$$\mathbf{x}(t) = (a \cos t, a \sin t, ct), \quad t \in \mathbb{R}.$$

Calculate the tangent \mathbf{t} , curvature κ , principal normal \mathbf{n} , binormal \mathbf{b} and torsion τ . Give a sketch of the curve indicating the directions of the vectors $\{\mathbf{t}, \mathbf{n}, \mathbf{b}\}$.

3. Show that a planar curve $\mathbf{x}(t) = (x(t), y(t), 0)$ has curvature

$$\kappa(t) = \frac{|\dot{x}\ddot{y} - \dot{y}\ddot{x}|}{(\dot{x}^2 + \dot{y}^2)^{3/2}}.$$

Find the minimum and maximum values of the curvature on the ellipse

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$$

4. Evaluate explicitly each of the line integrals

$$\int (x \, dx + y \, dy + z \, dz), \quad \int (y \, dx + x \, dy + dz), \quad \int (y \, dx - x \, dy + e^{x+y} \, dz)$$

along (i) the straight line path from the origin to $(1, 1, 1)$, and (ii) the parabolic path given parametrically by $(x, y, z) = (t, t, t^2)$ from $t = 0$ to $t = 1$. For which of these integrals do the two paths give the same results, and why?

5. Consider the vector fields $\mathbf{F}(\mathbf{x}) = (3x^2yz^2, 2x^3yz, x^3z^2)$ and $\mathbf{G}(\mathbf{x}) = (3x^2y^2z, 2x^3yz, x^3y^2)$. Compute the line integrals $\int \mathbf{F} \cdot d\mathbf{x}$ and $\int \mathbf{G} \cdot d\mathbf{x}$ along the following paths, each of which consist of straight line segments joining the specified points:

- (i) $(0, 0, 0) \rightarrow (1, 1, 1)$,
- (ii) $(0, 0, 0) \rightarrow (0, 0, 1) \rightarrow (0, 1, 1) \rightarrow (1, 1, 1)$,
- (iii) $(0, 0, 0) \rightarrow (1, 0, 0) \rightarrow (1, 1, 0) \rightarrow (1, 1, 1)$.

Are either of the differentials $\mathbf{F} \cdot d\mathbf{x}$ or $\mathbf{G} \cdot d\mathbf{x}$ exact?

6. A curve C is given parametrically by

$$\mathbf{x}(t) = (\cos(\sin nt) \cos t, \cos(\sin nt) \sin t, \sin(\sin nt)) \quad 0 \leq t \leq 2\pi,$$

where n is some fixed integer. Sketch the curve. Show that

$$\oint_C \mathbf{F} \cdot d\mathbf{x} = 2\pi, \quad \text{where} \quad \mathbf{F}(\mathbf{x}) = \left(-\frac{y}{x^2 + y^2}, \frac{x}{x^2 + y^2}, 0 \right)$$

and C is traversed in the direction of increasing t . Can $\mathbf{F}(\mathbf{x})$ be written as the gradient of a scalar function? Comment on your results.

[Hint: when sketching the curve, you may find it helpful to use spherical polar coordinates, defined by $x = r \sin \theta \cos \phi$, $y = r \sin \theta \sin \phi$ and $z = r \cos \theta$ with $\theta \in [0, \pi]$ and $\phi \in [0, 2\pi)$.]

7. Obtain the equation of the plane which is tangent to the surface $z = 3x^2y \sin(\pi x/2)$ at the point $x = y = 1$.

Take East to be in the direction $(1, 0, 0)$ and North to be $(0, 1, 0)$. In which direction will a marble roll if placed on the surface at $x = 1$, $y = \frac{1}{2}$?

8. Use the substitution $x = r \cos \phi$, $y = \frac{1}{2}r \sin \phi$, to evaluate

$$\int_D \frac{x^2}{x^2 + 4y^2} dA$$

where D is the region between the two ellipses $x^2 + 4y^2 = 1$, $x^2 + 4y^2 = 4$.

9. A closed curve C in the $z = 0$ plane consists of the arc of the parabola $y^2 = 4ax$ ($a > 0$) between the points $(a, \pm 2a)$ and the straight line joining $(a, \mp 2a)$. The area inclosed by C is D . Show, by calculating the integrals explicitly, that

$$\oint_C (x^2y dx + xy^2 dy) = \int_D (y^2 - x^2) dA = \frac{104}{105}a^4$$

10. The region D is bounded by the segments $x = 0, 0 \leq y \leq 1; y = 0, 0 \leq x \leq 1; y = 1, 0 \leq x \leq \frac{3}{4}$, and by an arc of the parabola $y^2 = 4(1 - x)$. Consider a mapping into the (x, y) -plane from the (u, v) -plane defined by the transformation $x = u^2 - v^2, y = 2uv$. Sketch D and also the two regions in the (u, v) -plane which are mapped into it. Hence evaluate

$$\int_D \frac{dA}{(x^2 + y^2)^{1/2}}$$

11. Compute the volume of a cone of height h and radius a using (a) cylindrical polars, (b) spherical polars.

12. By using a suitable change of variables, calculate the volume within an ellipsoid

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} \leq 1.$$

13*. Compute the volume of the region V defined by the intersection of the three cylinders

$$V = \{(x, y, z) \in \mathbb{R}^3 : x^2 + y^2 \leq 1, y^2 + z^2 \leq 1, z^2 + x^2 \leq 1\}.$$

[Warning: The sole purpose of this question is to show you that volume integrals can be arbitrarily hard. Only attempt if that's your thing.]