2A Multivariable Calculus 2013

Ex Sheet 4

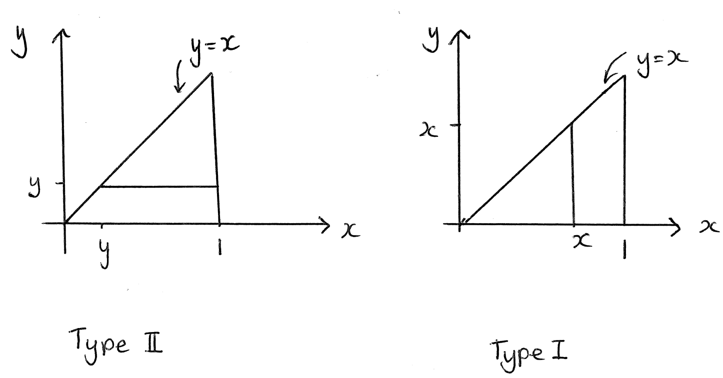
Tutorial Exercises

T1 By reversing the order of integration, evaluate

$$\text{(a)} \int_0^1 dy \int_y^1 \sinh(x^2)\,dx, \quad \text{(b)} \int_1^e dx \int_{\log x}^1 \frac{e^{-y^2}}{x}\,dy.$$

Solution

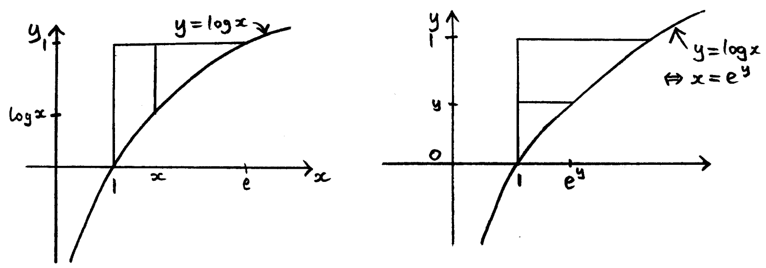
(a) Sketching the two formulations of the integral we get



So the integral is

$$\int_0^1 \left(\int_0^x \sinh(x^2)\,dy \right) dx = \int_0^1 x\sinh(x^2)\,dx = \frac{1}{2}\left[\cosh(x^2)\right]_0^1 = \frac{1}{2}(\cosh 1 - 1).$$

(b)

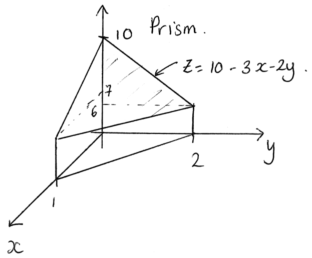


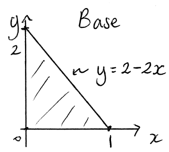
The integral is

$$\int_0^1 \left(\int_1^{e^y} \frac{e^{-y^2}}{x}\,dx \right) dy = \int_0^1 ye^{-y^2}\,dy = -\frac{1}{2}\left[e^{-y^2}\right]_0^1 = \frac{1}{2}(1-e^{-1}).$$

T2 Find the volume of the prism whose base is the triangle with vertices at $(0,0,0)$, $(1,0,0)$ and $(0,2,0)$, which has sides parallel to the z-axis and the top of which is the plane $3x+2y+z=10$.

Solution





We have,

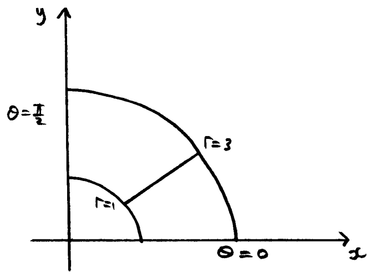
$$\begin{aligned}\text{Volume} = \int\int_T 10 - 3x - 2y\,dxdy &= \int_0^1 dx \int_0^{2-2x} 10 - 3x - 2y\,dy \\ &= \int_0^1 [10y - 3xy - y^2]_0^{2-2x}\,dx \\ &= \int_0^1 10(2-2x) - 3x(2-2x) - (2-2x)^2\,dx \\ &= 2\int_0^1 x^2 - 9x + 8\,dx = 2\Big[\frac{x^3}{3} - \frac{9x^2}{2} + 8x\Big]_0^1 = \frac{23}{3}.\end{aligned}$$

T3 Evaluate

$$\int\int xy^2\;dx\;dy$$

over the region in the first quadrant that lies outside the circle $x^2 + y^2 = 1$ but inside the circle $x^2 + y^2 = 9$.

Solution



In polar coordinates, the integral is

$$\begin{aligned}\int_0^{\pi/2} d\theta \int_1^3 r^4\cos\theta\sin^2\theta\,dr &= \int_0^{\pi/2}\cos\theta\sin^2\theta d\theta \int_1^3 r^4\,dr \\ &= \int_0^1 u^2\,du\Big[\frac{r^5}{5}\Big]_1^3 = \frac{242}{15}.\end{aligned}$$

T4 Evaluate

$$\int\int_R y(x^2+y^2)\;dx\;dy$$

where R is

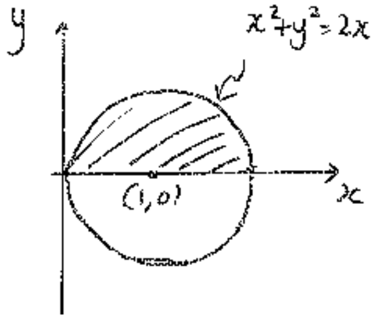
a) the part of the interior of the circle $x^2 + y^2 = 2x$ that lies in the first quadrant,

b) the part of the interior of the circle $x^2 + y^2 = 2x$ that lies above the line $y = x$.

c) the region in the first quadrant inside $x^2 + y^2 = 4ax$ but outside $x^2 + y^2 = 2ax$, where $a > O$.

Solution

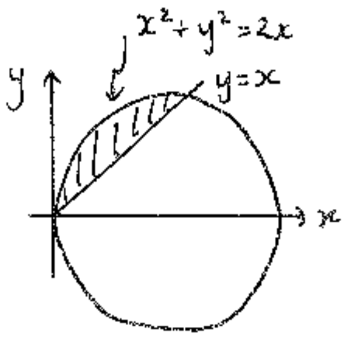
(a)



Since, $x^2 + y^2 = 2x$, in polar coordinates this is $r^2 = 2r\cos\theta$, i.e. $r = 2\cos\theta$.

$$\begin{aligned}\int_0^{\pi/2} d\theta \int_0^{2\cos\theta} r^4 \sin\theta\, dr &= \int_0^{\pi/2} \sin\theta\, d\theta \int_0^{2\cos\theta} r^4\, dr \\ &= \int_0^{\pi/2} \sin\theta \left[\frac{r^5}{5}\right]_0^{2\cos\theta} d\theta \\ &= \int_0^{\pi/2} \frac{32\sin\theta\cos^5\theta}{5}\, d\theta = \frac{32}{5}\int_1^0 -u^5\, du = \frac{16}{15}.\end{aligned}$$

(b)



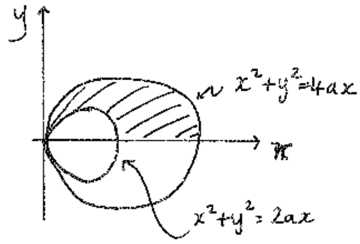
Since, $x^2 + y^2 = 2x$, in polar coordinates this is $r^2 = 2r\cos\theta$, i.e. $r = 2\cos\theta$. Also the line $y = x$ makes the angle $\pi/4$ with the y-axis, so the theta varies between $\pi/2$ and $\pi/4$.

$$\begin{aligned}I = \int_{\pi/4}^{\pi/2} d\theta \int_0^{2\cos\theta} r^4 \sin\theta\, dr &= \int_{\pi/4}^{\pi/2} \sin\theta \left[\frac{r^5}{5}\right]_0^{2\cos\theta} d\theta \\ &= \int_{\pi/4}^{\pi/2} \frac{32}{5} \sin\theta\cos^5\theta\, d\theta\end{aligned}$$

Making a change of variables, $u = \cos\theta$, so $du = -\sin\theta\, d\theta$.

$$I = \frac{32}{5}\left[\frac{-\cos^6\theta}{6}\right]_{\pi/4}^{\pi/2} = \frac{32}{30}\cdot\frac{1}{8} = \frac{2}{15}.$$

(c)



Since, $x^2 + y^2 = 4ax$ on the outer circle, in polar coordinates this is $r = 4a\cos\theta$. The inner circle gives $x^2 + y^2 = 2ax$, in polar coordinates $r = 2a\cos\theta$.

$$\begin{aligned} I = \int_0^{\pi/2} d\theta \int_{2a\cos\theta}^{4a\cos\theta} r^4 \sin\theta\, dr &= \int_0^{\pi/2} \sin\theta \left[\frac{r^5}{5}\right]_{2a\cos\theta}^{4a\cos\theta} d\theta \\ &= \frac{1}{5}\int_0^{\pi/2} (1024a^5\cos^5\theta - 32a^5\cos^5\theta)\sin\theta\, d\theta \\ &= \frac{a^5}{5}(1024-32)\int_0^{\pi/2} \sin\theta\cos^5\theta\, d\theta \\ &= \frac{a^5 992}{5}\int_1^0 -u^5\, du = \frac{496a^5}{15}. \end{aligned}$$

The last line was found by using the change of variables $u = \cos\theta$.

T5 Evaluate the following integrals by converting to polar coordinates

(a) $\displaystyle\int_0^1 dy \int_y^{\sqrt{2-y^2}} 3(x+y)\, dx$, (b) $\displaystyle\int_0^2 dx \int_0^{\sqrt{2x-x^2}} \sqrt{x^2+y^2}\, dy$.

Solution

(a)

$$\begin{aligned} \int_0^1 dy \int_y^{\sqrt{2-y^2}} 3(x+y)\, dx &= \int_0^{\pi/4} d\theta \int_0^{\sqrt{2}} 3r^2(\cos\theta + \sin\theta)\, dr \\ &= \int_0^{\pi/4} 2\sqrt{2}(\cos\theta+\sin\theta)\, d\theta = 2\sqrt{2}. \end{aligned}$$

(b)

$$\begin{aligned} \int_0^2 dx \int_0^{\sqrt{2x-x^2}} \sqrt{x^2+y^2}\, dy &= \int_0^{\pi/2} d\theta \int_0^{2\cos\theta} r^2\, dr \\ &= \frac{8}{3}\int_0^{\pi/2} \cos^3\theta\, d\theta = 16/9 \end{aligned}$$

Further Exercises

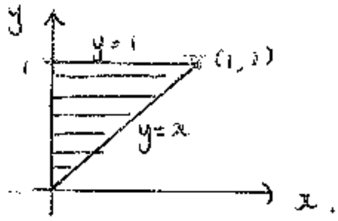
F1 By changing the order of integration, evaluate the following integrals

$$\text{(a)} \int_0^1 dx \int_x^1 \frac{x}{1+y^3}\, dy, \quad \text{(b)} \int_0^1 dx \int_{x^2}^1 x^3\sqrt{y^3+15}\, dy,$$

$$\text{(c)} \int_0^2 dx \int_{x^3}^8 \frac{x^2}{(1+y^2)^2}\, dy.$$

Solution

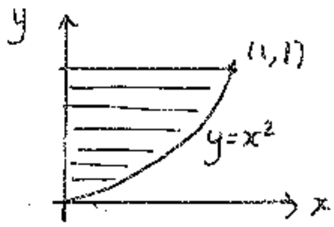
(a)



We cannot easily integrate $1/(1+y^3)$ with respect to y, so we change the order of the integration.

$$\begin{aligned}
\int_0^1 dy \int_0^y \frac{1}{1+y^3}\, dx &= \int_0^1 \frac{1}{1+y^3}\Big[\frac{x^2}{2}\Big]_0^y dy = \frac{1}{2}\int_0^1 \frac{y^2}{1+y^3}\, dy \\
&= \frac{1}{2}\int_1^2 \frac{1}{3u}\, du \text{ (where } u = 1+y^3\text{)} \\
&= \frac{1}{6}[\log u]_1^2 = \frac{1}{6}[\log(1+y^3)]_0^1 = \frac{1}{6}\log 2.
\end{aligned}$$

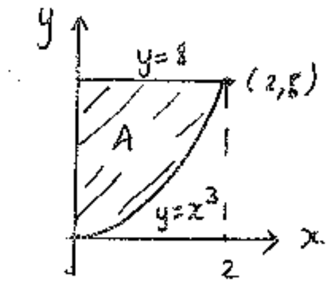
(b)



We have,

$$\begin{aligned}
\int_0^1 dy \int_0^{\sqrt{y}} x^3\sqrt{y^3+15}\, dx &= \int_0^1 \sqrt{y^3+15}\Big[\frac{x^4}{4}\Big]_0^{\sqrt{y}} dy \\
&= \frac{1}{4}\int_0^1 y^2\sqrt{y^3+15}\, dy \\
&= \frac{1}{4}\int_{15}^{16} \frac{\sqrt{u}}{3}\, du \text{ (where } u = 1+y^3,\ \tfrac{1}{3}du = y^2 dy.) \\
&= \frac{1}{12}\Big[\frac{u^{3/2}}{3/2}\Big]_{15}^{16} = \frac{2}{36}[16^{3/2} - 15^{3/2}] \\
&= \frac{1}{18}[64 - 15\sqrt{15}].
\end{aligned}$$

(c)



We have,

$$\int_0^8 dy \int_0^{y^{1/3}} \frac{x^2}{(1+y^2)^2}\,dx = \int_0^8 \frac{1}{(1+y^2)^2}\left[\frac{x^3}{3}\right]_0^{y^{1/3}} dy$$
$$= \frac{1}{3}\int_0^8 \frac{y}{(1+y^2)^2}\,dy$$
$$= \frac{1}{3}\int_1^{65} \frac{\frac{1}{2}}{u^2}\,du \text{ (where } u = 1+y^2,\ \frac{1}{2}du = y dy.)$$
$$= \frac{1}{6}\left[-\frac{1}{u}\right]_1^{65} = \frac{1}{6}\cdot\frac{64}{65} = \frac{32}{195}.$$

F2 Find the volume of the section of the cylinder $x^2+y^2=1$, between the planes $z=0$ and $x+y+z=2$.

Solution

The required volume is

$$V = \iint_D 2 - x - y\,dxdy,$$

where D is the circle $x^2+y^2=1$. In polar coordinates, this is

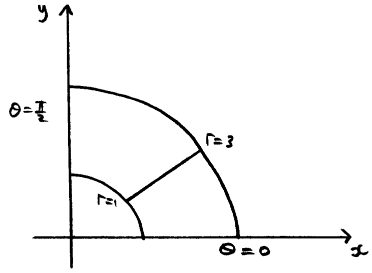
$$V = \int_0^{2\pi}\left(\int_0^1 (2 - r\cos\theta - r\sin\theta) r\,dr\right)\,d\theta = \int_0^{2\pi}\left[r^2 - \tfrac{1}{3}r^3\cos\theta - \tfrac{1}{3}r^3\sin\theta\right]_0^1 d\theta$$
$$= \int_0^{2\pi} 1 - \tfrac{1}{3}\cos\theta - \tfrac{1}{3}\sin\theta\,d\theta = 2\pi.$$

F3 Use polar coordinates to evaluate

$$\iint_D \cos\left(x^2+y^2\right)\,dA$$

where D is the region in the first quadrant between the circles with centre $(0,0)$ and radii 1 and 3 respectively.

Solution



In polar coordinates, the integral is

$$\int_0^{\pi/2}\left(\int_1^3 r\cos(r^2)\,dr\right)d\theta = \int_0^{\pi/2} d\theta \int_1^9 \frac{1}{2}\cos u\,du$$
$$= \frac{\pi}{4}(\sin 9 - \sin 1)\,.$$

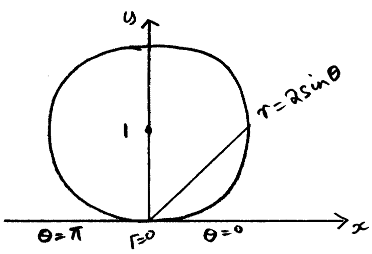
F4 Evaluate

$$\iint_D \sqrt{x^2+y^2}\,dA$$

where D is the disk with centre $(0,1)$ and radius 1.

Solution

The circle is $x^2+(y-1)^2=1$ i.e. $x^2+y^2=2y$, which is $r=2\sin\theta$ in polar coordinates.



Hence the integral is

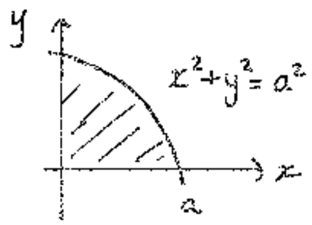
$$\int_0^{\pi}\left(\int_0^{2\sin\theta} r^2\,dr\right)d\theta = \frac{8}{3}\int_0^{\pi}\sin^3\theta\,d\theta = \frac{8}{3}\int_0^{\pi}(1-\cos^2\theta)\sin\theta\,d\theta$$
$$= -\frac{8}{3}\int_1^{-1}(1-u^2)\,du \text{ (where } u=\cos\theta)$$
$$= \frac{32}{9}.$$

F5 Evaluate

$$\int\int \frac{y^2}{x^2+y^2}\,dx\,dy$$

over the region in the first quadrant that lies inside the circle $x^2+y^2=a^2$, where $a>0$. What is the value of the same integral over the entire disc enclosed by this circle?

Solution

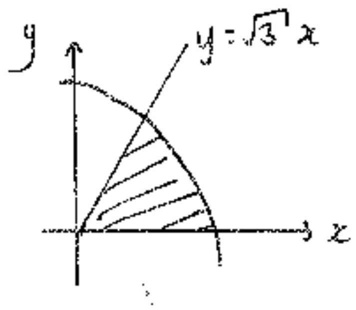


$$\int_0^{\pi/2} d\theta \int_0^a \frac{r^2 \sin^2\theta}{r}\, dr = \int_0^{\pi/2} \sin^2\theta \, d\theta \int_0^a r\, dr$$
$$= \frac{1}{2} \cdot \frac{\pi}{2} \Big[\frac{r^2}{2}\Big]_0^a = \frac{\pi a^2}{8}.$$

The integral over the entire disc is 4 times $\frac{\pi a^2}{8}$ by the symmetry of the sine function. The function $sin^2\theta$ is positive on the interval $[0, 2\pi]$ and the area under the curve between 0 and 2π is 4 times the area between 0 and $\pi/2$.

F6 Evaluate
$$\int\int x\sqrt{x^2+y^2}\, dx\, dy$$
over the finite region in the first quadrant enclosed by the x-axis, the line $y = \sqrt{3}x$ and the circle $x^2 + y^2 = a^2$, where $a > O$.

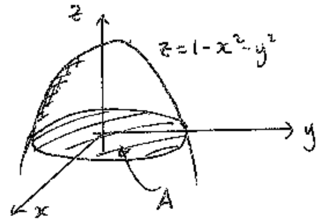
Solution



$$\int_0^{\pi/3} d\theta \int_0^a r^3 \cos\theta\, dr = \int_0^{\pi/3} \cos\theta\, d\theta \int_0^a r^3\, dr$$
$$= [\sin\theta]_0^{\pi/3} \Big[\frac{r^4}{4}\Big]_0^a = (\frac{\sqrt{3}}{2} - 0)\frac{a^4}{4} = \frac{\sqrt{3}a^4}{8}.$$

F7 An inflatable rubber tent takes the form of the paraboloid $z = 1 - x^2 - y^2$ for $z \geq 0$. Find the volume of air which it encloses.

Solution

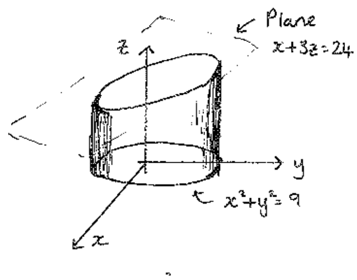


The paraboloid cuts the xy-plane where $z = 0$, i.e. when $x^2 + y^2 = 1$. Hence,

$$\begin{aligned}
\text{Volume of the tent} &= \int\int_A z\,dxdy \quad (\text{where } A \text{ is the interior of the circle } x^2+y^2=1) \\
&= \int_0^{2\pi} d\theta \int_0^1 (1-r^2)r\,dr = 2\pi \int_0^1 r - r^3\,dr \\
&= 2\pi\Big[\frac{r^2}{2} - \frac{r^4}{4}\Big]_0^1 = 2\pi(1/2 - 1/4) = \pi/2.
\end{aligned}$$

F8 A dummy funnel on a passenger steamer is to be used as a water tank. The tank is to have vertical sides, a horizontal base and slanting plane top. Find the volume of the tank if the base is the plane $z = 0$, the top is the plane $x + 3z = 24$ and the sides are determined by the circular cylinder $x^2 + y^2 = 9$.

Solution



$$\begin{aligned}
\text{Volume } &= \int\int_A z\,dxdy \quad (\text{where } A \text{ is the interior of the circle } x^2+y^2=9) \\
&= \int\int_A \frac{1}{3}(24-x)\,dxdy = \int\int_A 8\,dxdy - \frac{1}{3}\int\int_A x\,dxdy \\
&= 8\int\int_A 1\,dxdy \quad (\text{the last integral is zero due to symmetry of cosine}) \\
&= 8(\text{Area of the disc } x^2+y^2 \le 9) = 8\pi 3^2 = 72\pi.
\end{aligned}$$

Harder challenge problems [1]

[1] Only attempt these if you have been able to do all the other problems successfully.

F9 Evaluate the integral

$$\int_0^1 dy \int_{\sin^{-1} y}^{\pi/2} \cos x \sqrt{1+\cos^2 x}\, dx.$$

Solution

Reverse the order of integration and use integration by substitution to calculate the resulting integrals,

$$\int_0^{\pi/2} dx \int_0^{\sin x} \cos x \sqrt{1+\cos^2 x}\, dy = \frac{1}{3}(2\sqrt{2}-1).$$

F10 (a) A cylindrical drill with radius r_1 is used to bore a hole through the center of a sphere of radius r_2. Find the volume of the ring shaped solid that remains.
(b) Express the volume in part (a) in terms of the height h of the ring. Notice that the volume depends only on h not on r_1 or r_2.

Solution

(a) The volume of sphere is $(4/3)\pi r_2^3$. We use the symmetry of the problem and calculate the volume of the cylinder is which is removed from the top hemisphere. This volume is bounded by the surface the sphere, namely by $z = \sqrt{r_2^2 - x^2 - y^2}$ and the domain of integration is a circle of radius r_1. Thus the following integral gives the portion of the top hemisphere which removed,

$$\int_0^{2\pi} \int_0^{r_1} \sqrt{(r_2^2 - r^2)}\, r\, dr\, d\theta = \frac{2\pi}{3} \left((r_2^3 - (r_2^2 - r_1^2)^{3/2} \right).$$

By symmetry the same amount is removed from the lower hemisphere. Thus the volume remaining after removing the cylindrical region is $\frac{4\pi}{3} \left(r_2^2 - r_1^2\right)^{3/2}$.
(b) The height of the ring h, is found by calculating when the cylinder $(x^2 + y^2 = r_1^2)$ and sphere $(z^2 = r_2^2 - x^2 - y^2)$ intersect. We find this be substituting the equation of the cylinder into the equation for the sphere, giving $z^2 = (r_2^2 - r_1^2) = h^2$. Substituting this definition for h into our solution for part (a) gives the volume is $\frac{4\pi}{3} h^3$, which is independent of the radii as required.