

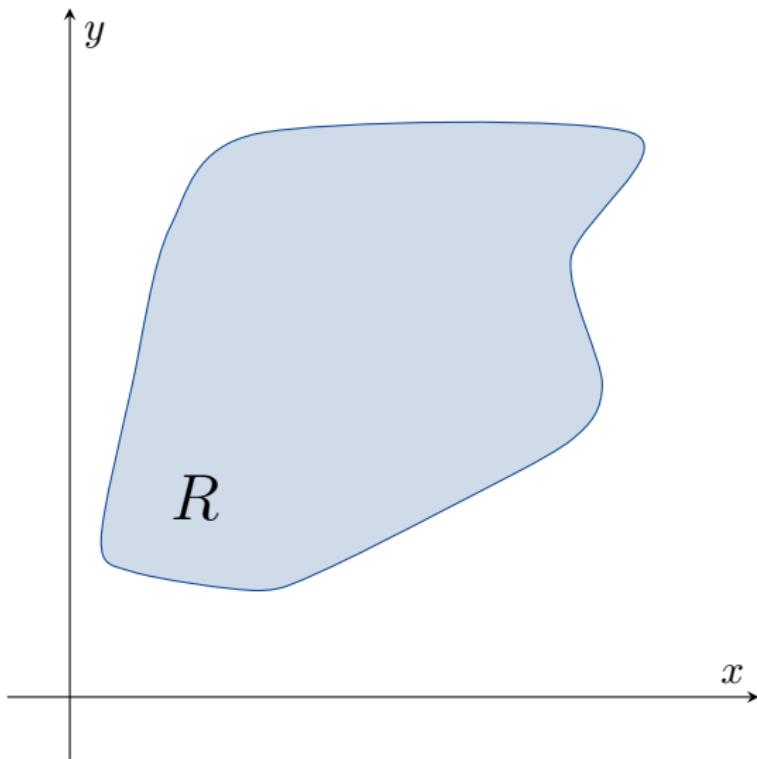
Lecture 8

- 14.4 Double Integrals in Polar Form
- 14.5 Triple Integrals in Rectangular Coordinates
- 14.7 Triple Integrals in Cylindrical and Spherical Coordinates
- 14.8 Substitutions in Multiple Integrals

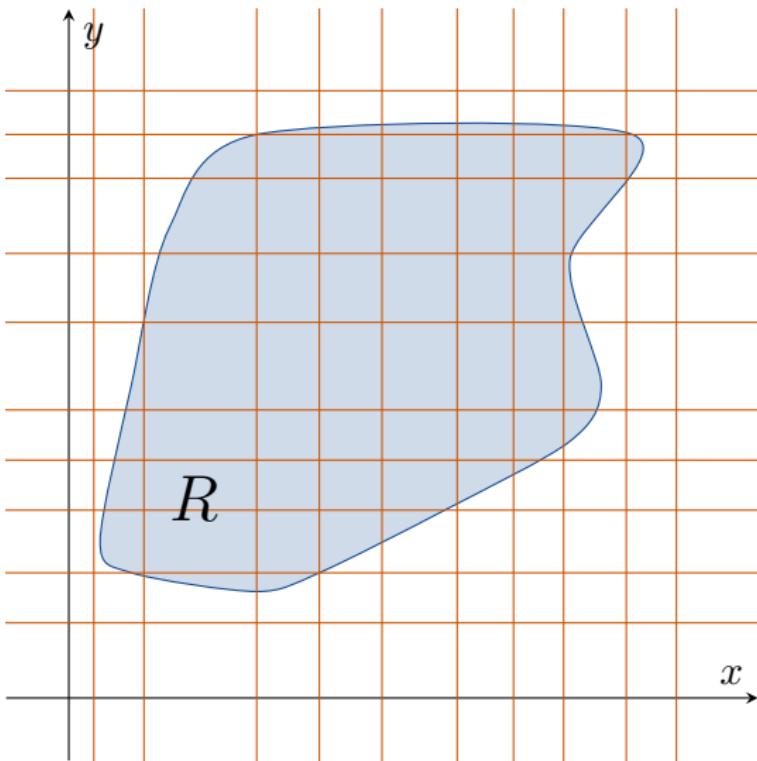


11 Double Integrals in Polar Form

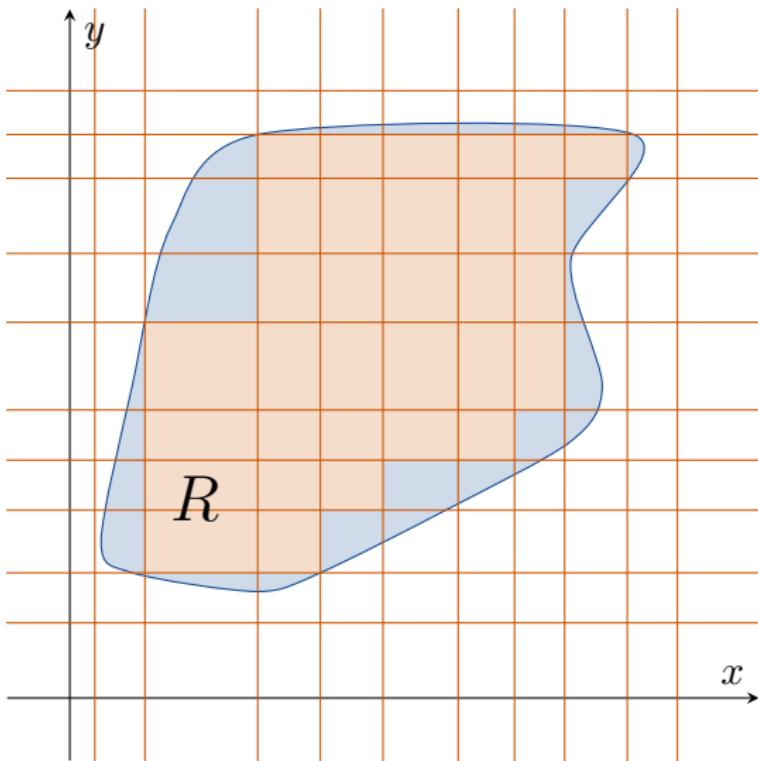
14.4 Double Integrals in Polar Form



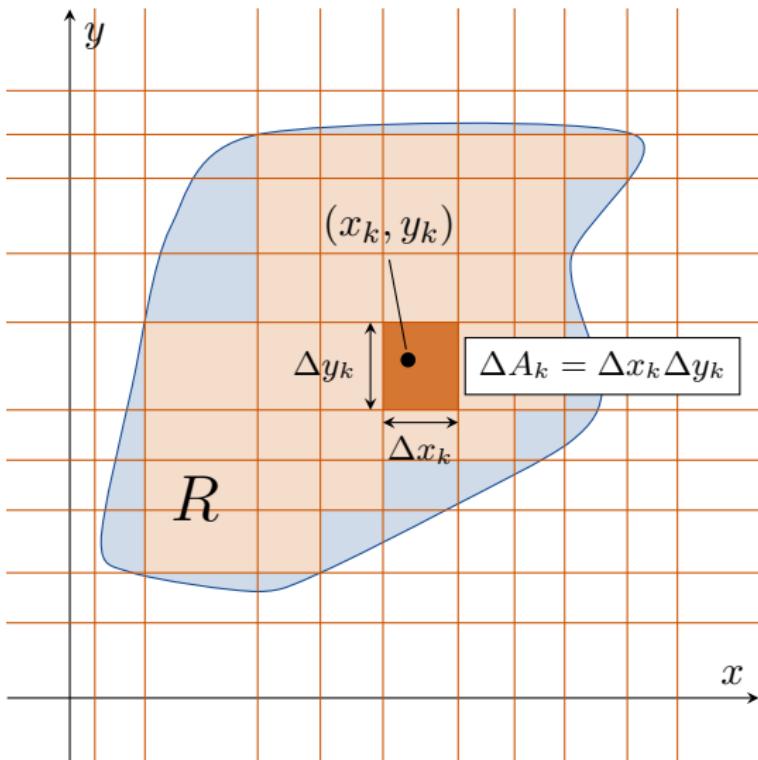
14.4 Double Integrals in Polar Form



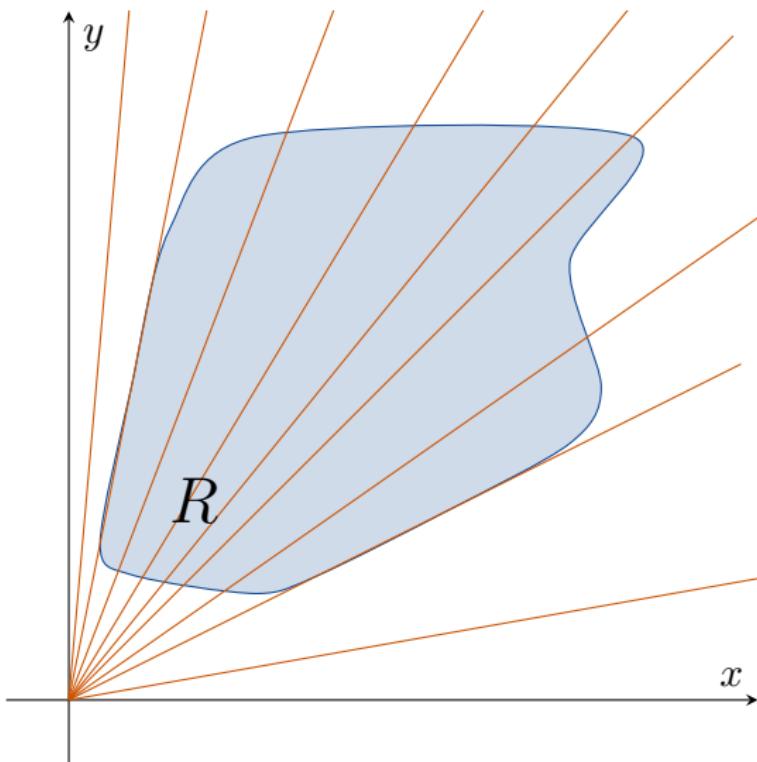
14.4 Double Integrals in Polar Form



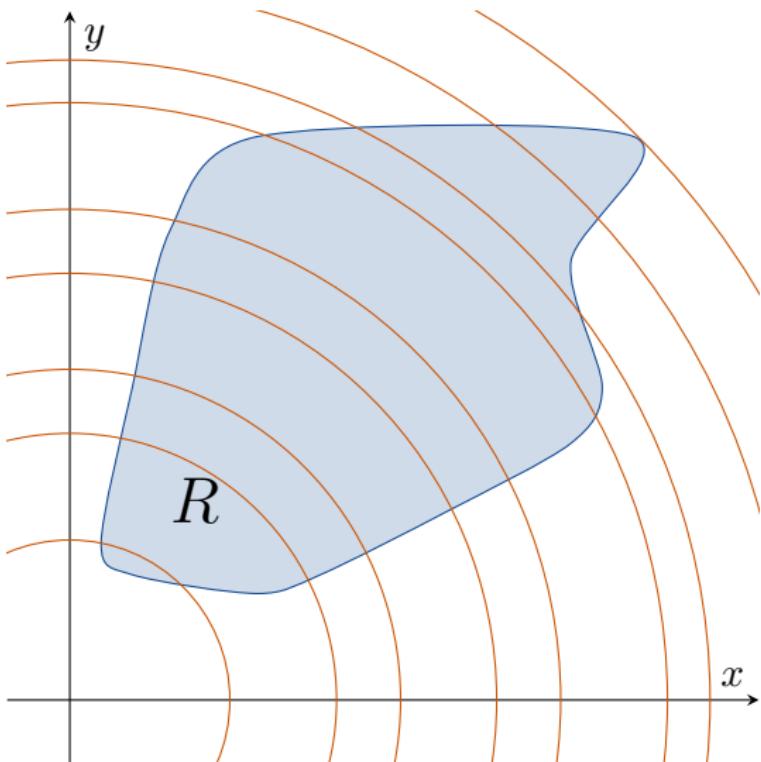
14.4 Double Integrals in Polar Form



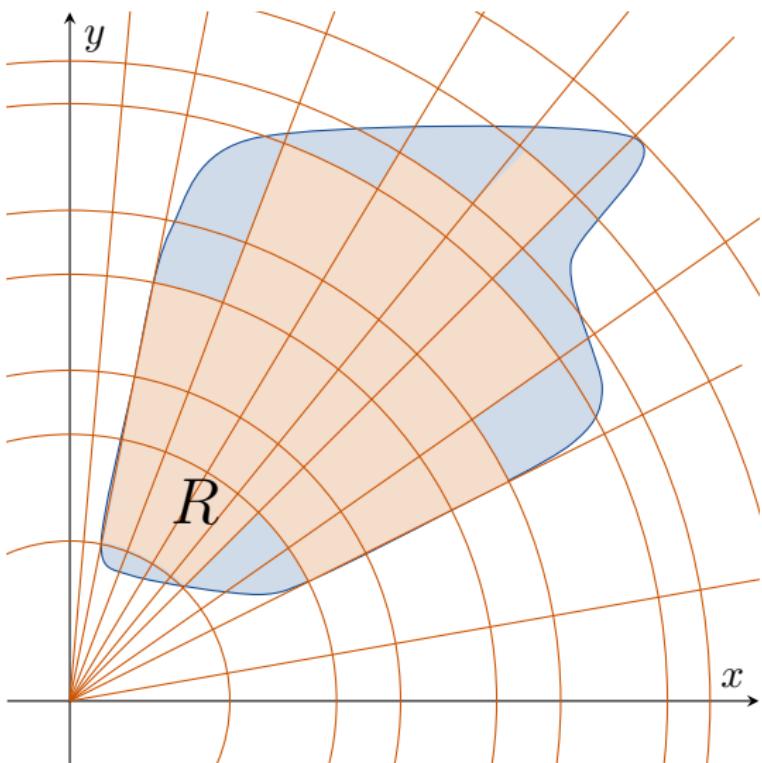
14.4 Double Integrals in Polar Form



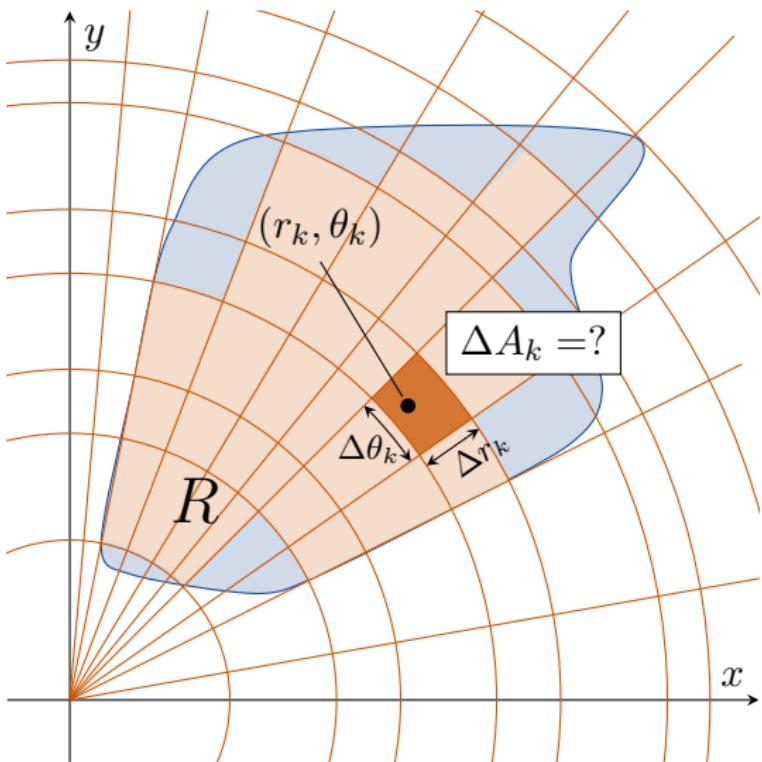
14.4 Double Integrals in Polar Form



14.4 Double Integrals in Polar Form



14.4 Double Integrals in Polar Form



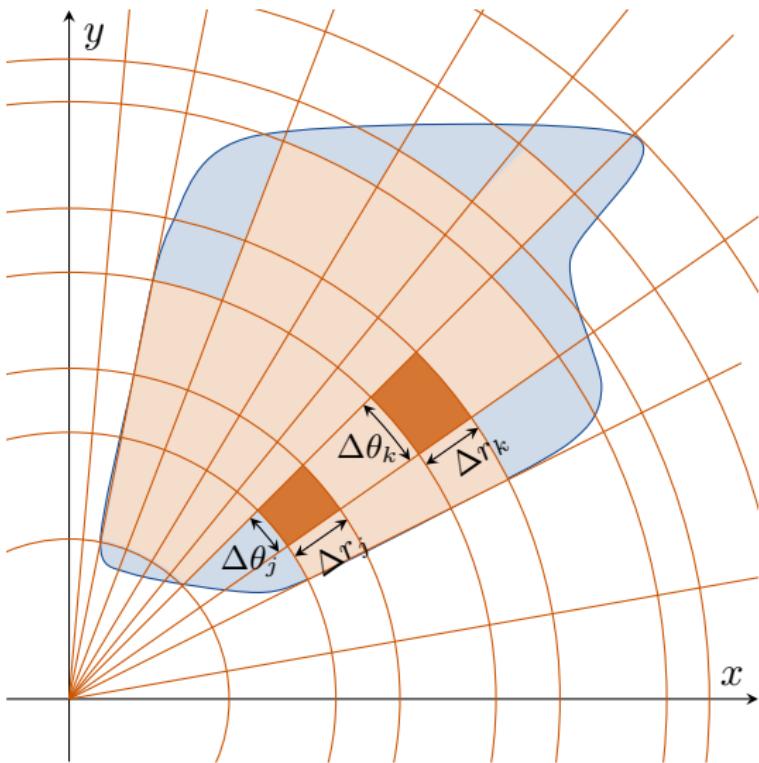
14.4 Double Integrals in Polar Form



$$\iint_R f(r, \theta) dA = \lim_{\|P\| \rightarrow 0} \sum_k f(r_k, \theta_k) \Delta A_k$$

But what is ΔA_k ?

14.4 Double Integrals in Polar Form



Note that

$$\Delta A_k = \Delta x_k \Delta y_k$$

but

$$\Delta A_k \neq \Delta r_k \Delta \theta_k.$$

14.4 Double Integrals in Polar Form

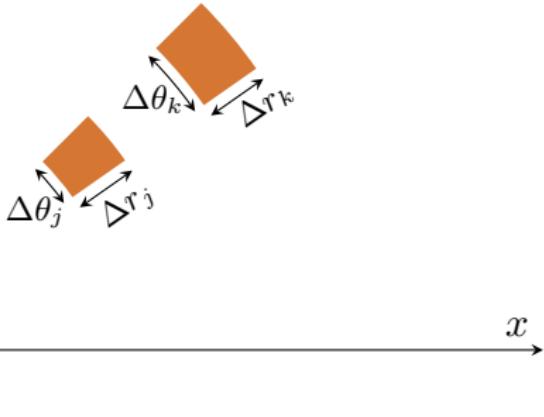
y

Note that

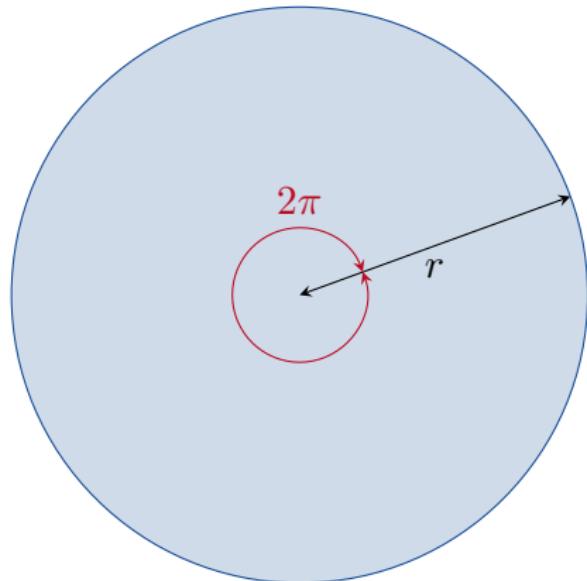
$$\Delta A_k = \Delta x_k \Delta y_k$$

but

$$\Delta A_k \neq \Delta r_k \Delta \theta_k.$$

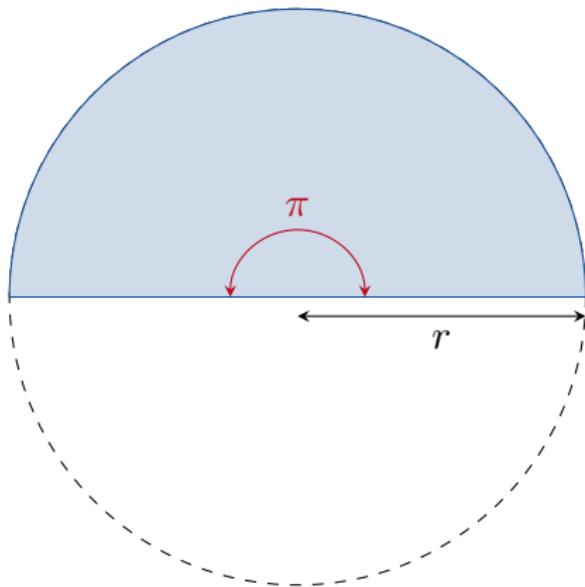


14.4 Double Integrals in Polar Form



$$\text{area of a circle} = \pi r^2 = \frac{1}{2}(2\pi)r^2$$

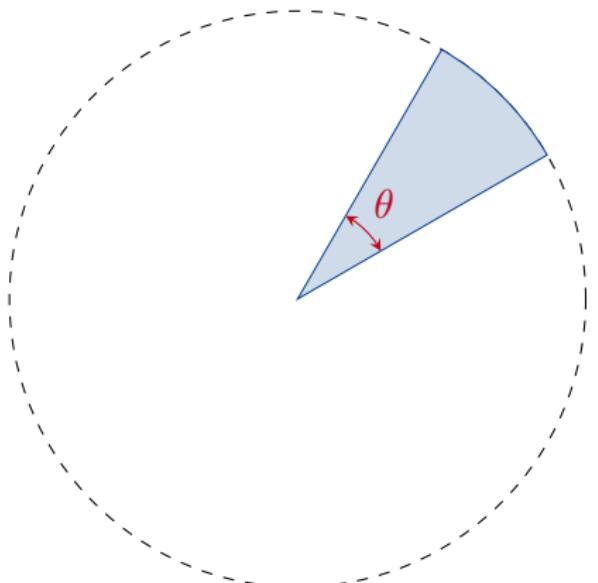
14.4 Double Integrals in Polar Form



$$\text{area of a circle} = \pi r^2 = \frac{1}{2}(2\pi)r^2$$

$$\text{area of a semicircle} = \frac{1}{2}\pi r^2$$

14.4 Double Integrals in Polar Form

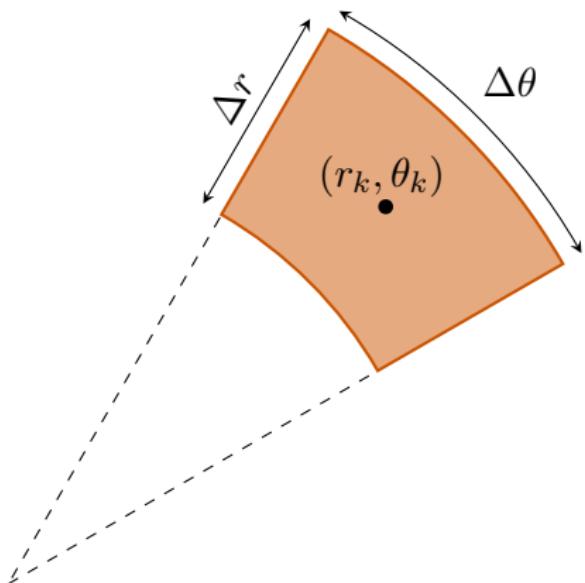


$$\begin{aligned}\text{area of a circle} &= \pi r^2 = \frac{1}{2}(2\pi)r^2\end{aligned}$$

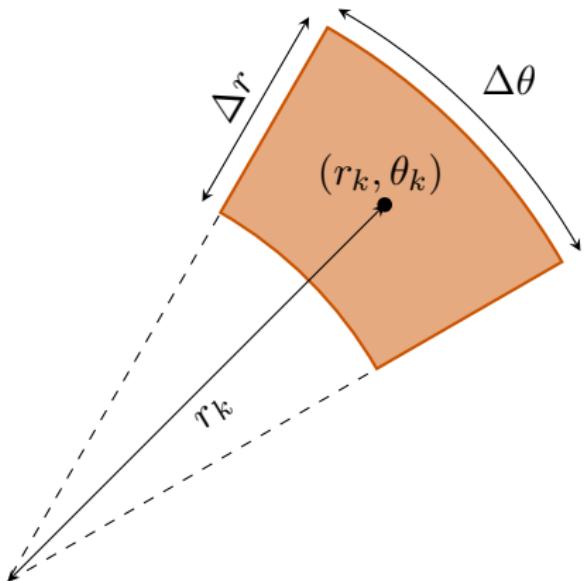
$$\begin{aligned}\text{area of a semicircle} &= \frac{1}{2}\pi r^2\end{aligned}$$

$$\begin{aligned}\text{area of a sector} &= \frac{1}{2}\theta r^2\end{aligned}$$

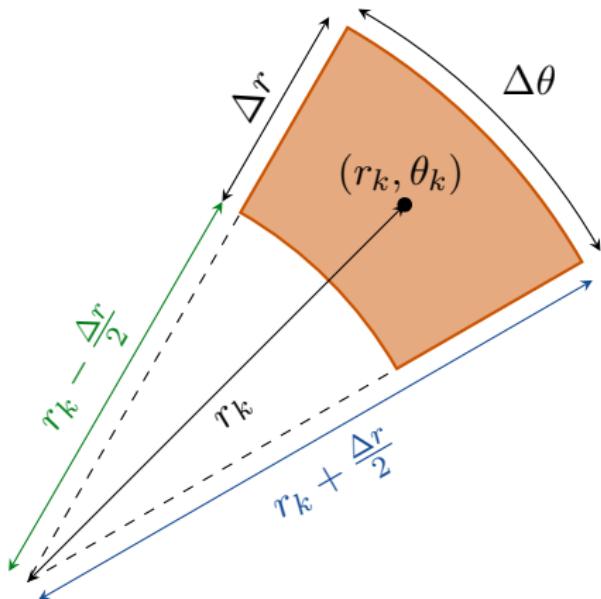
14.4 Double Integrals in Polar Form



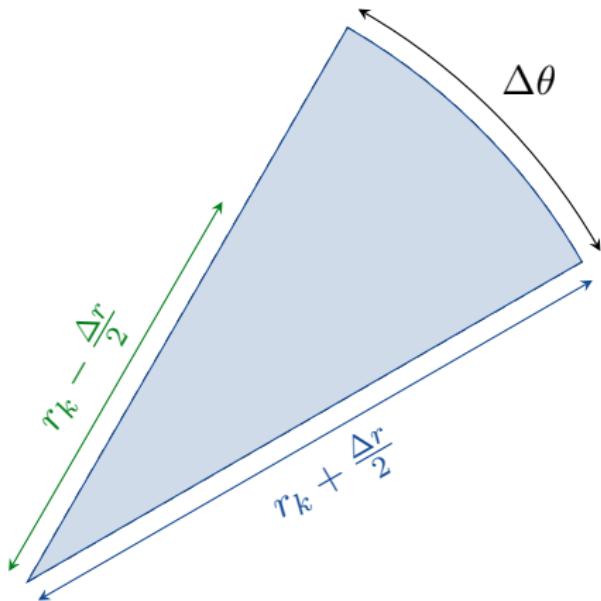
14.4 Double Integrals in Polar Form



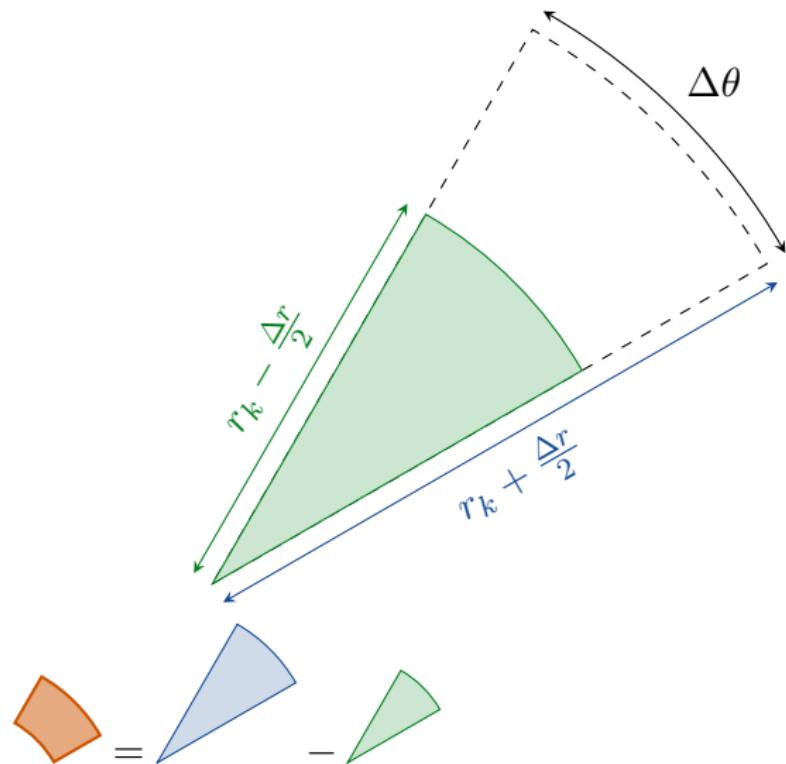
14.4 Double Integrals in Polar Form



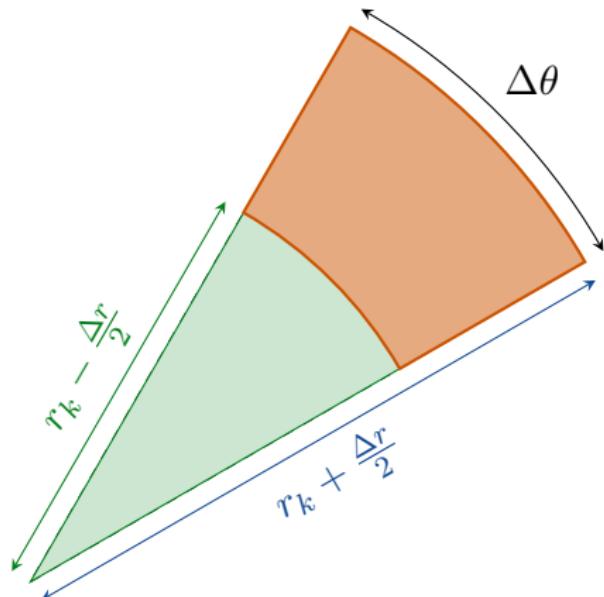
14.4 Double Integrals in Polar Form



14.4 Double Integrals in Polar Form



14.4 Double Integrals in Polar Form



$$\text{orange sector} = \text{blue sector} - \text{green sector} = \frac{1}{2}\Delta\theta \left(r_k + \frac{\Delta r}{2}\right)^2 - \frac{1}{2}\Delta\theta \left(r_k - \frac{\Delta r}{2}\right)^2$$

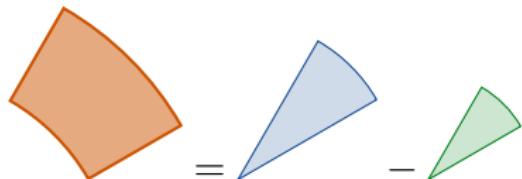
14.4 Double Integrals in Polar Form



A diagram illustrating the subtraction of two sectors from a larger orange sector. The orange sector is divided into two smaller sectors by a radial line. A blue sector is subtracted from the right side, and a green sector is subtracted from the left side. This visualizes the formula for the area of a sector in polar coordinates.

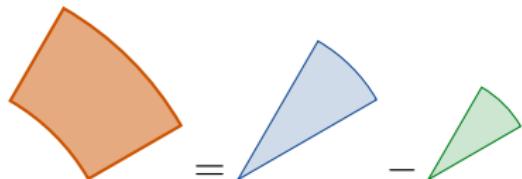
$$= \frac{1}{2} \Delta\theta \left(r_k + \frac{\Delta r}{2} \right)^2 - \frac{1}{2} \Delta\theta \left(r_k - \frac{\Delta r}{2} \right)^2$$

14.4 Double Integrals in Polar Form



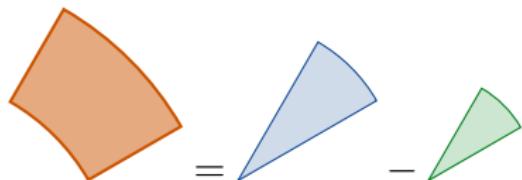
$$\begin{aligned}&= \frac{1}{2} \Delta\theta \left(r_k + \frac{\Delta r}{2} \right)^2 - \frac{1}{2} \Delta\theta \left(r_k - \frac{\Delta r}{2} \right)^2 \\&= \frac{1}{2} \Delta\theta \left(r_k^2 + 2r_k \frac{\Delta r}{2} + \frac{(\Delta r)^2}{4} - r_k^2 + 2r_k \frac{\Delta r}{2} - \frac{(\Delta r)^2}{4} \right)\end{aligned}$$

14.4 Double Integrals in Polar Form



$$\begin{aligned}&= \frac{1}{2} \Delta\theta \left(r_k + \frac{\Delta r}{2} \right)^2 - \frac{1}{2} \Delta\theta \left(r_k - \frac{\Delta r}{2} \right)^2 \\&= \frac{1}{2} \Delta\theta \left(r_k^2 + 2r_k \frac{\Delta r}{2} + \frac{(\Delta r)^2}{4} - r_k^2 + 2r_k \frac{\Delta r}{2} - \frac{(\Delta r)^2}{4} \right) \\&= \frac{1}{2} \Delta\theta (2r_k \Delta r)\end{aligned}$$

14.4 Double Integrals in Polar Form



$$\begin{aligned}&= \frac{1}{2} \Delta\theta \left(r_k + \frac{\Delta r}{2} \right)^2 - \frac{1}{2} \Delta\theta \left(r_k - \frac{\Delta r}{2} \right)^2 \\&= \frac{1}{2} \Delta\theta \left(r_k^2 + 2r_k \frac{\Delta r}{2} + \frac{(\Delta r)^2}{4} - r_k^2 + 2r_k \frac{\Delta r}{2} - \frac{(\Delta r)^2}{4} \right) \\&= \frac{1}{2} \Delta\theta (2r_k \Delta r) \\&= r_k \Delta r \Delta\theta.\end{aligned}$$

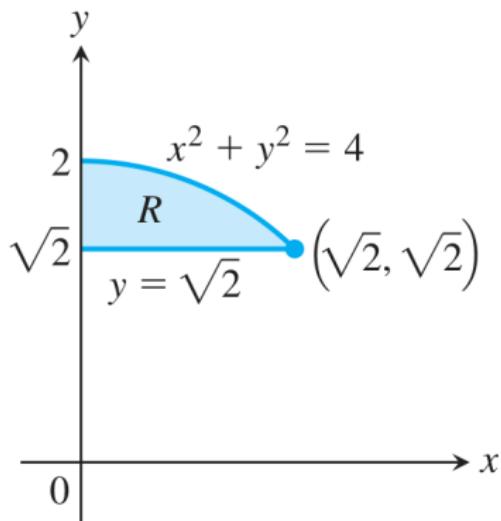
14.4 Double Integrals in Polar Form



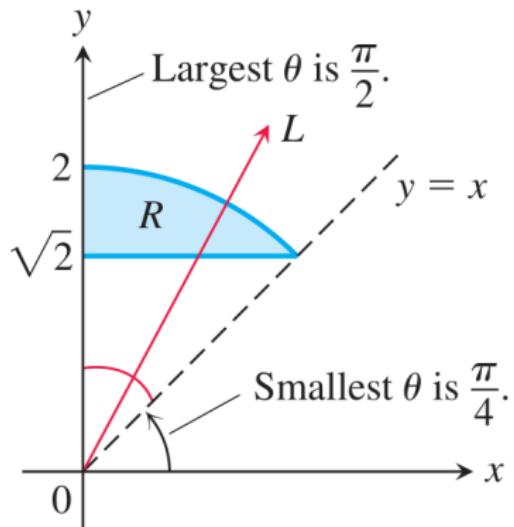
Theorem

$$dA = dx dy = r dr d\theta.$$

14.4 Double Integrals in Polar Form



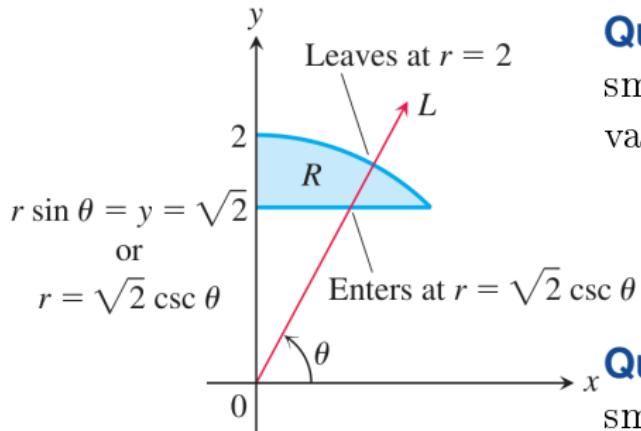
14.4 Double Integrals in Polar Form



Question: What are the smallest and biggest possible values of θ in R ?

$$\frac{\pi}{4} \leq \theta \leq \frac{\pi}{2}$$

14.4 Double Integrals in Polar Form



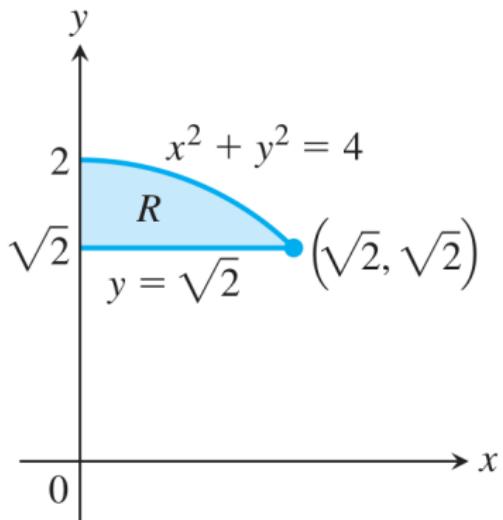
Question: What are the smallest and biggest possible values of θ in R ?

$$\frac{\pi}{4} \leq \theta \leq \frac{\pi}{2}$$

Question: What are the smallest and biggest possible values of r in R ?

$$\sqrt{2} \operatorname{cosec} \theta \leq r \leq 2$$

14.4 Double Integrals in Polar Form



Question: What are the smallest and biggest possible values of θ in R ?

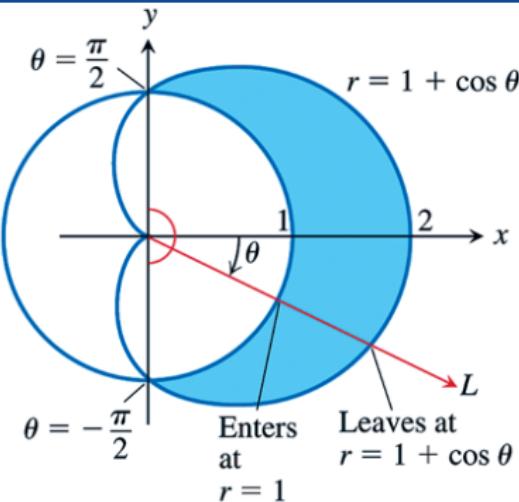
$$\frac{\pi}{4} \leq \theta \leq \frac{\pi}{2}$$

Question: What are the smallest and biggest possible values of r in R ?

$$\sqrt{2} \operatorname{cosec} \theta \leq r \leq 2$$

$$\iint_R f \, dA = \int_{\frac{\pi}{4}}^{\frac{\pi}{2}} \int_{\sqrt{2} \operatorname{cosec} \theta}^{\frac{\pi}{2}} f(r, \theta) \, r \, dr \, d\theta.$$

14.4 Double Integrals



EXAMPLE 1 Find the limits of integration for integrating $f(r, \theta)$ over the region R that lies inside the cardioid $r = 1 + \cos \theta$ and outside the circle $r = 1$.

Solution

1. We first sketch the region and label the bounding curves (Figure 15.25).
2. Next we find the *r-limits of integration*. A typical ray from the origin enters R where $r = 1$ and leaves where $r = 1 + \cos \theta$.
3. Finally we find the *θ -limits of integration*. The rays from the origin that intersect R run from $\theta = -\pi/2$ to $\theta = \pi/2$. The integral is

$$\int_{-\pi/2}^{\pi/2} \int_1^{1+\cos\theta} f(r, \theta) r dr d\theta.$$

■

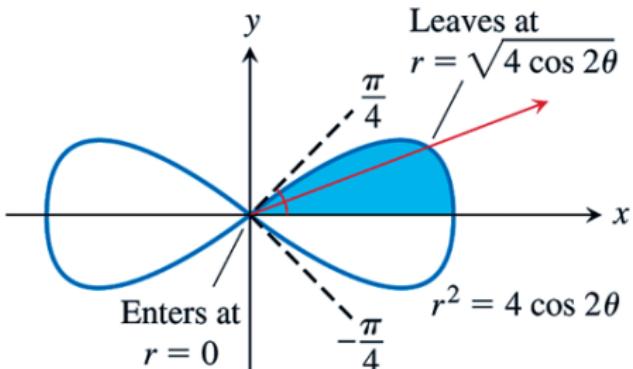
14.4 Double Integrals in Polar Form



The area of a closed, bounded region R is

$$A = \iint_R dA = \iint_R r dr d\theta.$$

14.4 Double Integrals in Polar Form



EXAMPLE 2 Find the area enclosed by the lemniscate $r^2 = 4 \cos 2\theta$.

Solution We graph the lemniscate to determine the limits of integration (Figure 15.26) and see from the symmetry of the region that the total area is 4 times the first-quadrant portion.

$$\begin{aligned} A &= 4 \int_0^{\pi/4} \int_0^{\sqrt{4 \cos 2\theta}} r dr d\theta = 4 \int_0^{\pi/4} \left[\frac{r^2}{2} \right]_{r=0}^{r=\sqrt{4 \cos 2\theta}} d\theta \\ &= 4 \int_0^{\pi/4} 2 \cos 2\theta d\theta = 4 \sin 2\theta \Big|_0^{\pi/4} = 4. \end{aligned}$$

■

14.4 Double Integrals in Polar Form



Cartesian Integral \longrightarrow Polar Integral

$$x = r \cos \theta \quad x^2 + y^2 = r^2$$

$$y = r \sin \theta \quad \tan \theta = \frac{y}{x}$$

14.4 Double Integrals in Polar Form



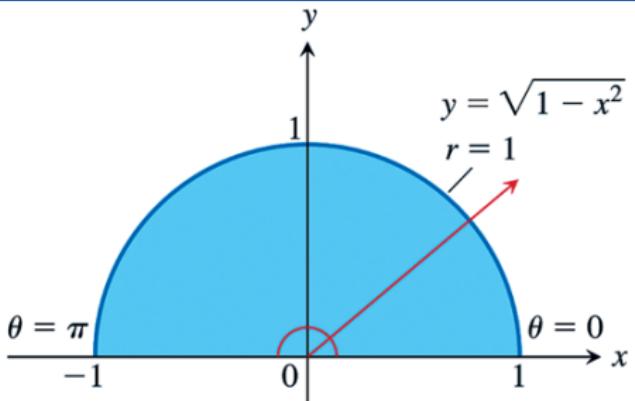
Cartesian Integral \longrightarrow Polar Integral

$$x = r \cos \theta \quad x^2 + y^2 = r^2$$

$$dxdy = r dr d\theta$$

$$y = r \sin \theta \quad \tan \theta = \frac{y}{x}$$

14.4 Double Integrals



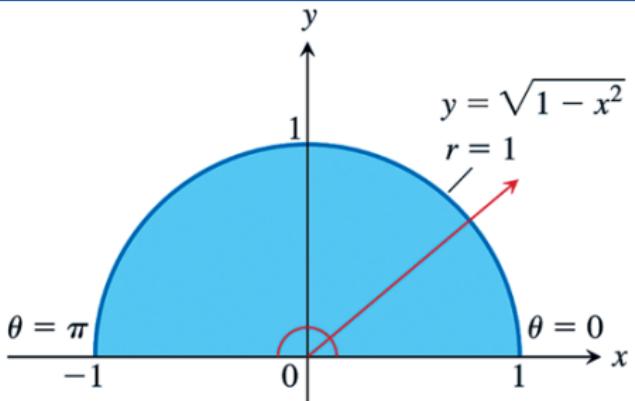
Example

Calculate

$$\iint_R e^{x^2+y^2} dy dx$$

where R is the region under $y = \sqrt{1 - x^2}$.

14.4 Double Integrals



Example

Calculate

$$\iint_R e^{x^2+y^2} dy dx$$

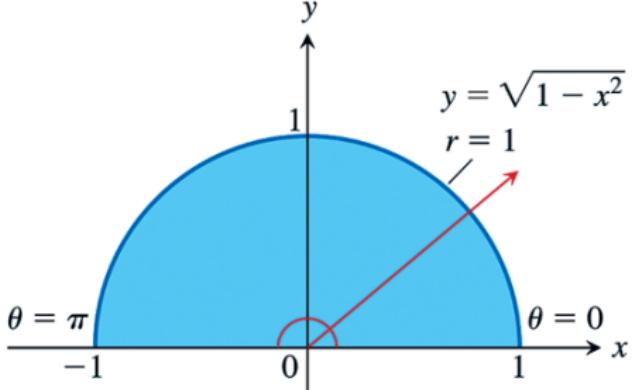
where R is the region under $y = \sqrt{1 - x^2}$.

difficult
Cartesian
integral



easy polar
integral

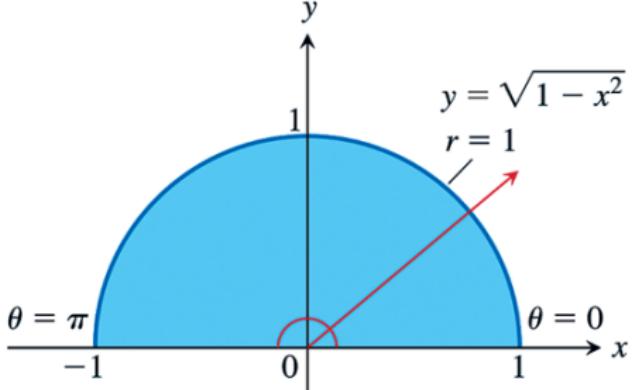
14.4 Double Integrals in Polar Form



$$\iint_R e^{x^2+y^2} dy dx = \int \int r dr d\theta$$

=

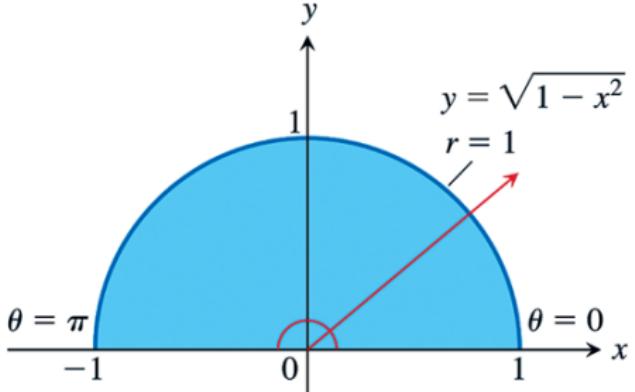
14.4 Double Integrals in Polar Form



$$\iint_R e^{x^2+y^2} dy dx = \int \int e^{r^2} r dr d\theta$$

=

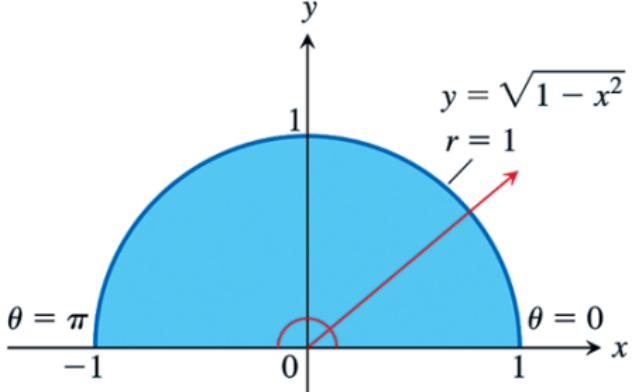
14.4 Double Integrals in Polar Form



$$\iint_R e^{x^2+y^2} dy dx = \int_0^{\pi} \int r e^{r^2} r dr d\theta$$

=

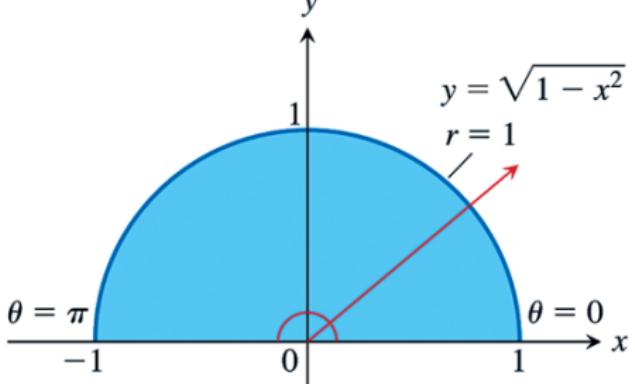
14.4 Double Integrals in Polar Form



$$\iint_R e^{x^2+y^2} dy dx = \int_0^\pi \int_0^1 e^{r^2} r dr d\theta$$

=

14.4 Double Integrals in Polar Form



$$\begin{aligned}\iint_R e^{x^2+y^2} dy dx &= \int_0^\pi \int_0^1 e^{r^2} r dr d\theta \\ &= \int_0^\pi \left[\frac{1}{2} e^{r^2} \right]_0^1 d\theta = \int_0^\pi \frac{1}{2} (e - 1) d\theta = \frac{\pi}{2} (e - 1).\end{aligned}$$

14.4 Double Integrals in Polar Form

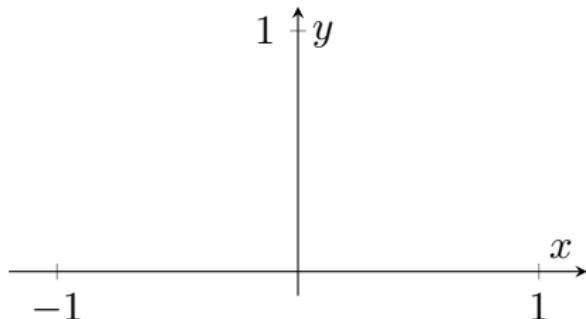
Example

$$\text{Calculate } \int_0^1 \int_0^{\sqrt{1-x^2}} (x^2 + y^2) dy dx.$$

Note that

$$\int_0^1 \int_0^{\sqrt{1-x^2}} (x^2 + y^2) dy dx = \int_0^1 \left(x^2 \sqrt{1-x^2} + \frac{(1-x^2)^{\frac{3}{2}}}{3} \right) dx,$$

which is not easy to calculate. So let's change to polar coordinates.



14.4 Double Integrals in Polar Form

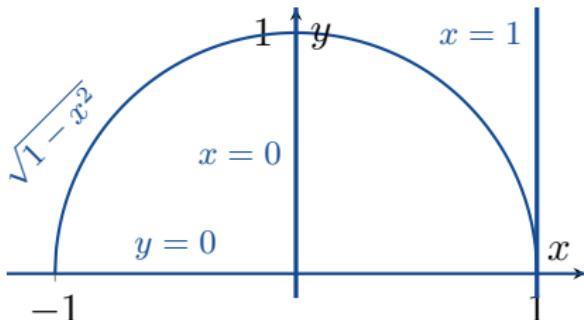
Example

$$\text{Calculate } \int_0^1 \int_0^{\sqrt{1-x^2}} (x^2 + y^2) dy dx.$$

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which is not easy to calculate. So let's change to polar coordinates.



14.4 Double Integrals in Polar Form

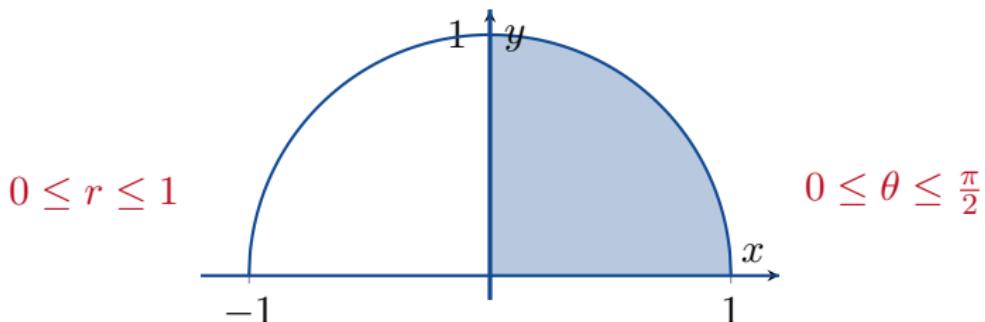
Example

$$\text{Calculate } \int_0^1 \int_0^{\sqrt{1-x^2}} (x^2 + y^2) dy dx.$$

Note that

$$\int_0^1 \int_0^{\sqrt{1-x^2}} (x^2 + y^2) dy dx = \int_0^1 \left(x^2 \sqrt{1-x^2} + \frac{(1-x^2)^{\frac{3}{2}}}{3} \right) dx,$$

which is not easy to calculate. So let's change to polar coordinates.



14.4 Double Integrals in Polar Form



$$\int_0^1 \int_0^{\sqrt{1-x^2}} (x^2 + y^2) dy dx = \int \int r dr d\theta$$
A diagram illustrating the transformation of a double integral from Cartesian coordinates to polar coordinates. On the left, a Cartesian double integral is shown with limits: the outer integral is from 0 to 1, and the inner integral is from 0 to $\sqrt{1-x^2}$. The integrand is $(x^2 + y^2)$, with $dy dx$ written in orange. An orange arrow points from this expression to the right. On the right, a polar double integral is shown with the same limits, but the integrand is $r dr d\theta$, also in orange. Another orange arrow points from the original expression to this polar form.

14.4 Double Integrals in Polar Form



$$\int_0^1 \int_0^{\sqrt{1-x^2}} (x^2 + y^2) dy dx = \int_0^{\frac{\pi}{2}} \int_0^1 r dr d\theta$$
A red curved arrow starts from the origin (0,0) and points towards the point (1,0) on the positive x-axis, forming a quarter-circle arc in the first quadrant. The arc is labeled with a red arrow pointing from the origin to the point (1,0).

14.4 Double Integrals in Polar Form



$$\int_0^1 \int_0^{\sqrt{1-x^2}} (x^2 + y^2) dy dx = \int_0^{\frac{\pi}{2}} \int_0^1 r^2 r dr d\theta$$
A green curved arrow points from the left integral to the right one, indicating a transformation or comparison between the two forms of the double integral.

14.4 Double Integrals in Polar Form



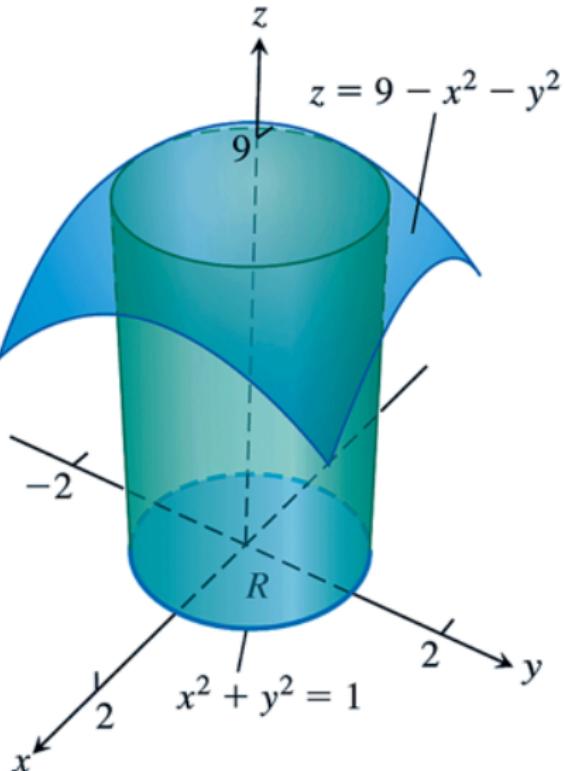
$$\int_0^1 \int_0^{\sqrt{1-x^2}} (x^2 + y^2) dy dx = \int_0^{\frac{\pi}{2}} \int_0^1 r^2 r dr d\theta$$
$$= \dots$$
$$= \frac{\pi}{8}.$$

14.4 Double Integrals in Polar Form

EXAMPLE 5 Find the volume of the solid region bounded above by the paraboloid $z = 9 - x^2 - y^2$ and below by the unit circle in the xy -plane.

Solution The region of integration R is bounded by the unit circle $x^2 + y^2 \leq 1$. It is described in polar coordinates by $r = 1$, $0 \leq \theta \leq 2\pi$. Figure 15.28. The volume is given by the double integral

$$\begin{aligned} \iint_R (9 - x^2 - y^2) dA &= \int_0^{2\pi} \int_0^1 (9 - r^2) r dr d\theta \\ &= \int_0^{2\pi} \int_0^1 (9r - r^3) dr d\theta \\ &= \int_0^{2\pi} \left[\frac{9}{2}r^2 - \frac{1}{4}r^4 \right]_0^1 d\theta \\ &= \frac{17}{4} \int_0^{2\pi} d\theta = \frac{17\pi}{2} \end{aligned}$$



14.4 Double Integrals in Polar Form

EXAMPLE 5 Find the volume of the solid region bounded above by the paraboloid $z = 9 - x^2 - y^2$ and below by the unit circle in the xy -plane.

Solution The region of integration R is bounded by the unit circle $x^2 + y^2 = 1$, which is described in polar coordinates by $r = 1, 0 \leq \theta \leq 2\pi$. The solid region is shown in Figure 15.28. The volume is given by the double integral

$$\begin{aligned}
 \iint_R (9 - x^2 - y^2) dA &= \int_0^{2\pi} \int_0^1 (9 - r^2) r dr d\theta && r^2 = x^2 + y^2, \quad dA = r dr d\theta. \\
 &= \int_0^{2\pi} \int_0^1 (9r - r^3) dr d\theta \\
 &= \int_0^{2\pi} \left[\frac{9}{2}r^2 - \frac{1}{4}r^4 \right]_{r=0}^{r=1} d\theta \\
 &= \frac{17}{4} \int_0^{2\pi} d\theta = \frac{17\pi}{2}.
 \end{aligned}$$



14.4 Double Integrals in Polar Form



Please read Example 6 in the textbook.



Triple Integrals in Rectangular Coordinates

14.5 Triple Integrals in Rectangular Coordinates



In the last two lectures we have been studying

$$\iint_R f(x, y) dA.$$

14.5 Triple Integrals in Rectangular Coordinates



In the last two lectures we have been studying

$$\iint_R f(x, y) \, dA.$$

Today we will consider

$$\iiint_D f(x, y, z) \, dV.$$

14.5 Triple Integrals in Rectangular Coordinates



Definition

The *volume* of a closed, bounded region D in space is

$$V = \iiint_R dV.$$



Finding Limits of Integration

$$\int \int \int F(x, y, z) dz dy dx.$$



Finding Limits of Integration

$$\int_{x=a}^{x=b} \int \int F(x, y, z) dz dy d\textcolor{brown}{x}.$$

only numbers

Finding Limits of Integration

$$\int_{x=a}^{x=b} \int_{y=g_1(x)}^{y=g_2(x)} \int F(x, y, z) dz dy dx.$$

functions of x
only numbers



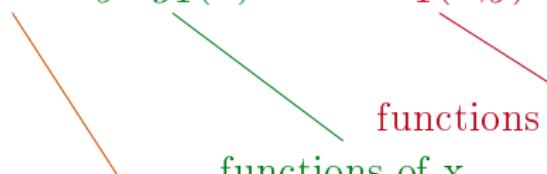
Finding Limits of Integration

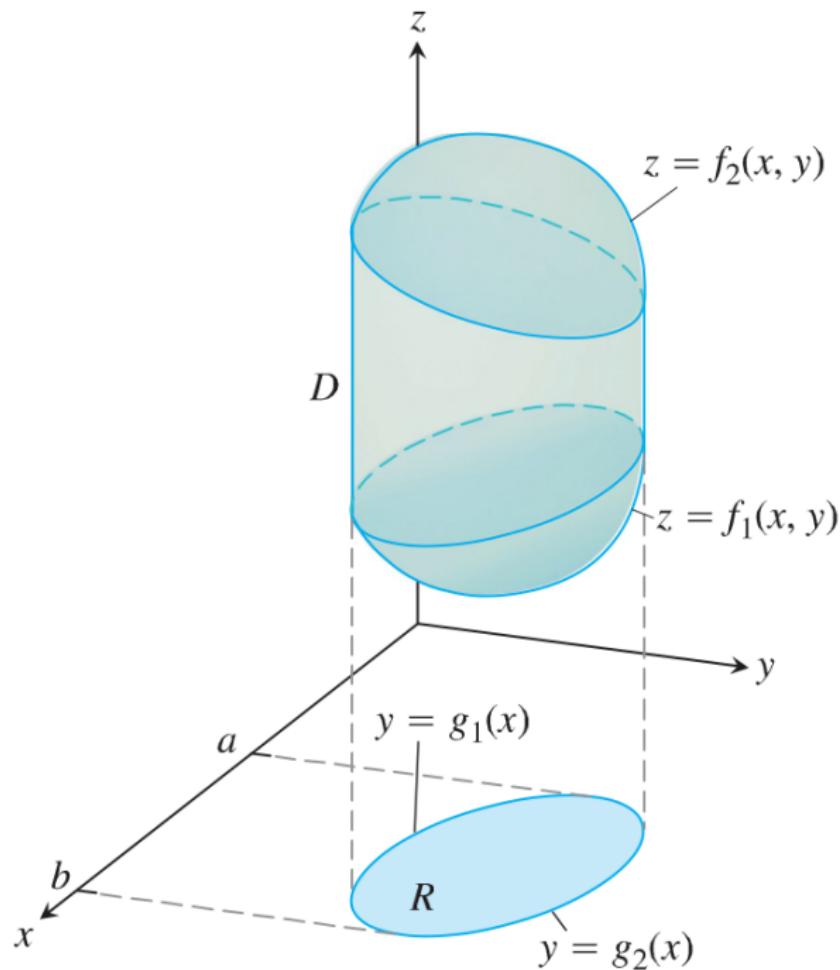
$$\int_{x=a}^{x=b} \int_{y=g_1(x)}^{y=g_2(x)} \int_{z=h_1(x,y)}^{z=h_2(x,y)} F(x, y, z) dz dy dx.$$

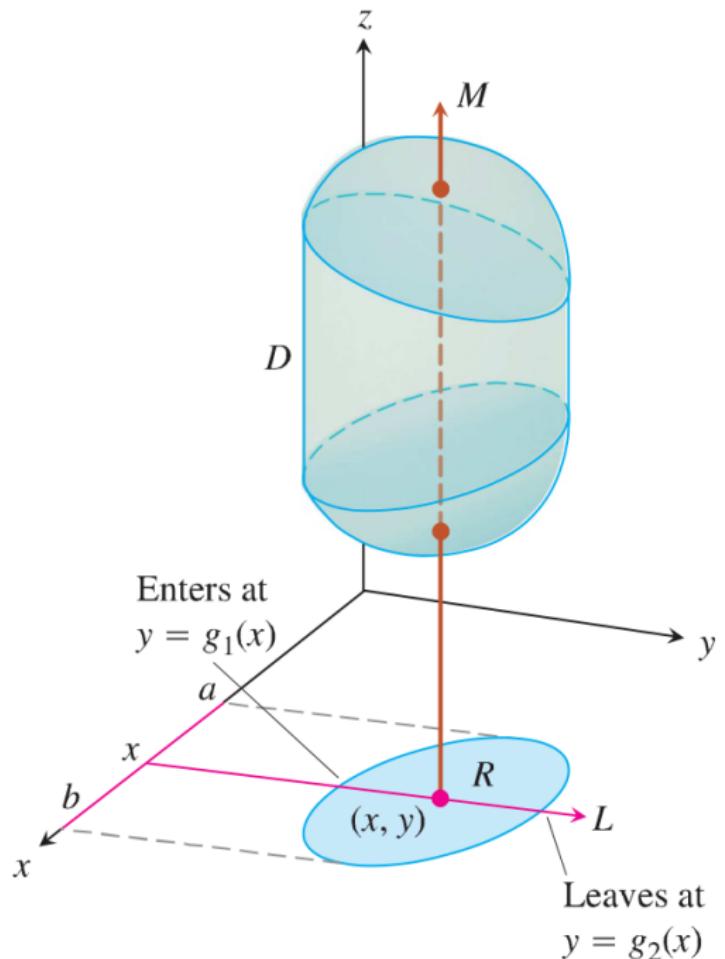
only numbers

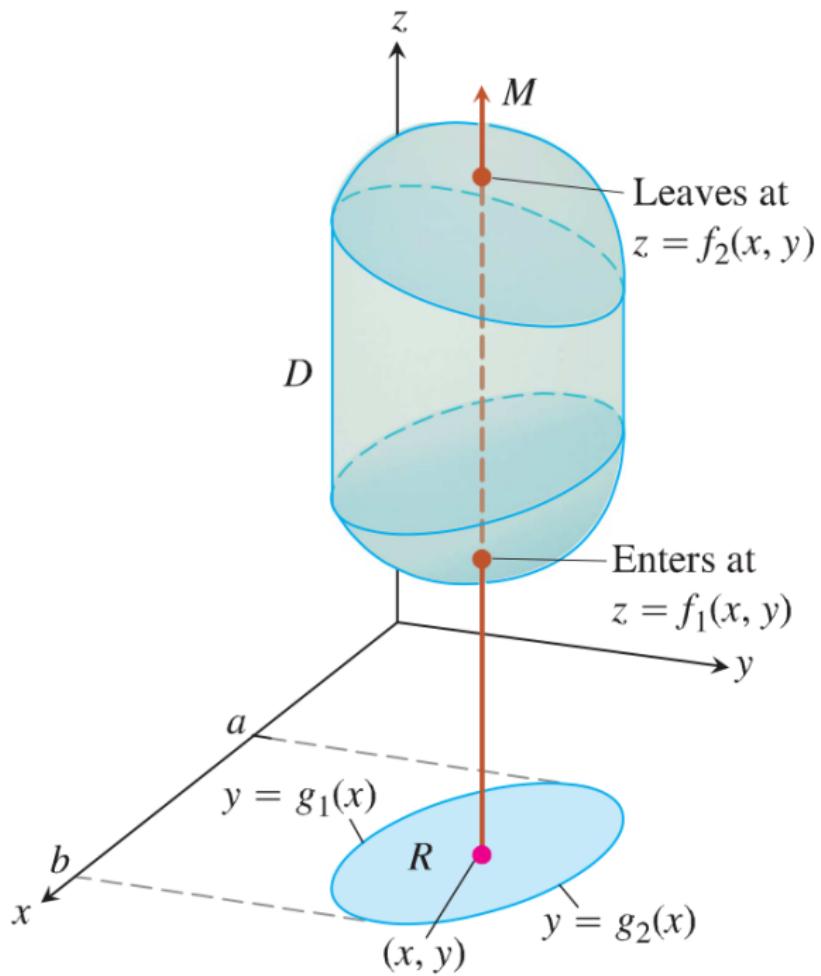
functions of x

functions of x and y

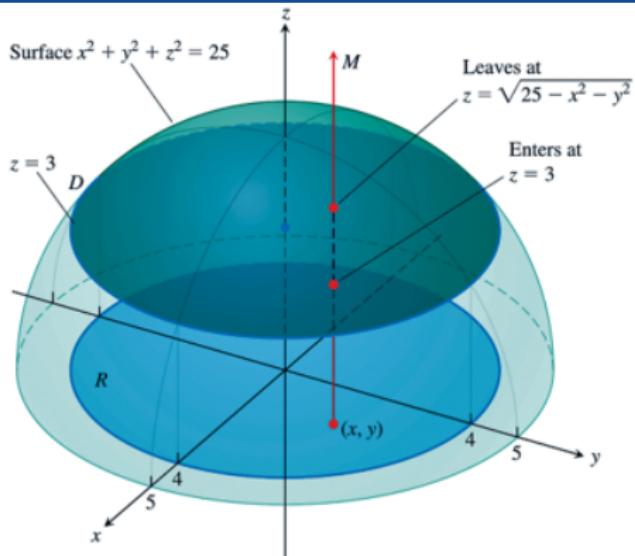








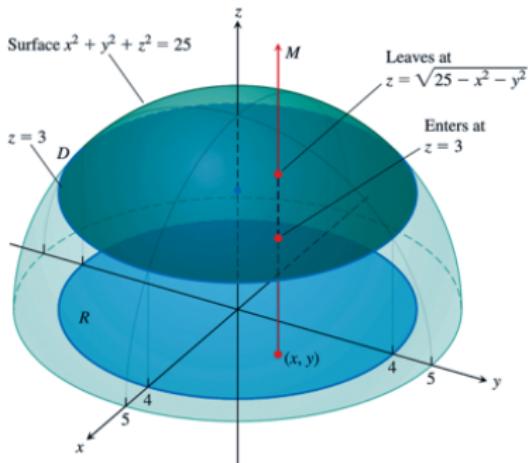
14.5 Triple Integrals in Rectangular Coordinates



Example

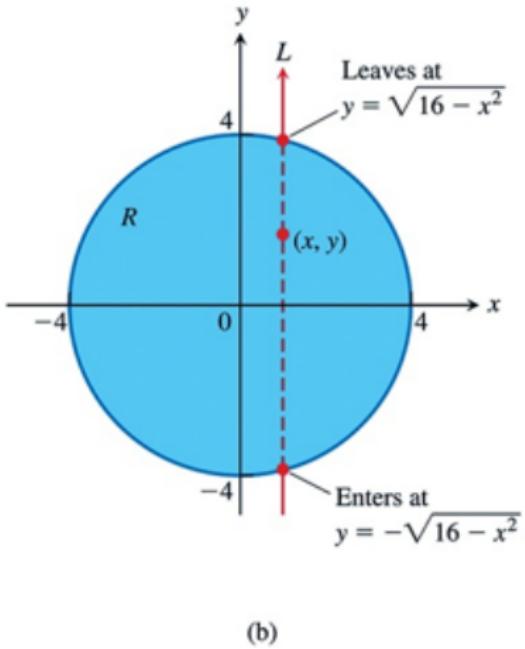
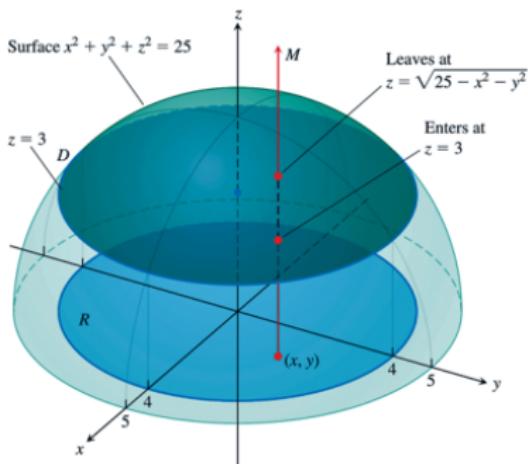
Let S be the sphere of radius 5 centred at the origin. Let D be the region under the sphere and above the plane $z = 3$. Set up the limits of integration over D .

14.5 Triple Integrals in Rectangular Coordinates



$$z = 3 \implies x^2 + y^2 + 9 = 25 \implies x^2 + y^2 = 16$$

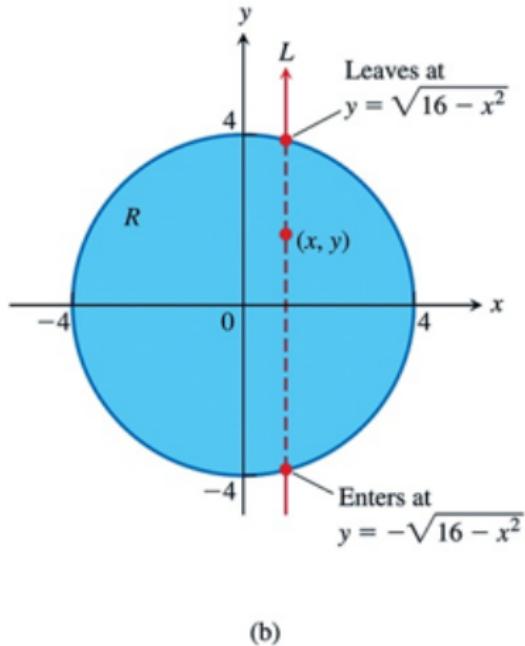
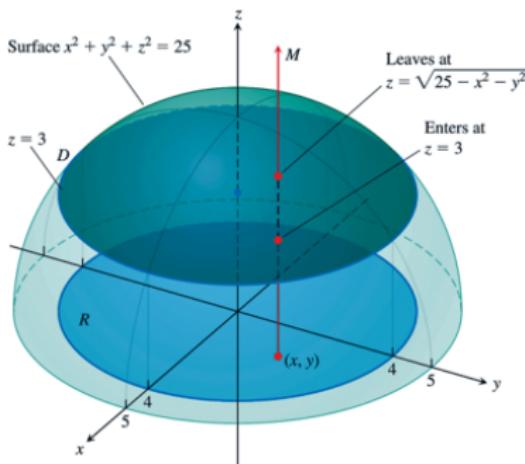
14.5 Triple Integrals in Rectangular



$$z = 3 \implies x^2 + y^2 + 9 = 25 \implies x^2 + y^2 = 16$$

$$-4 \leq x \leq 4$$

14.5 Triple Integrals in Rectangular

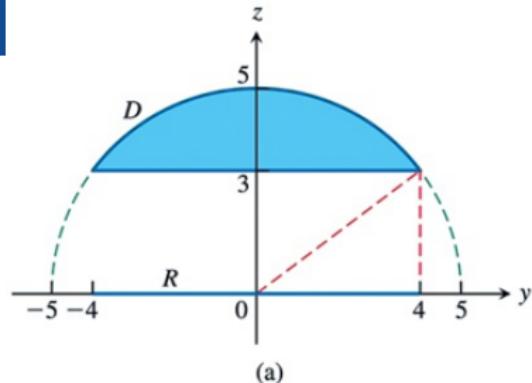
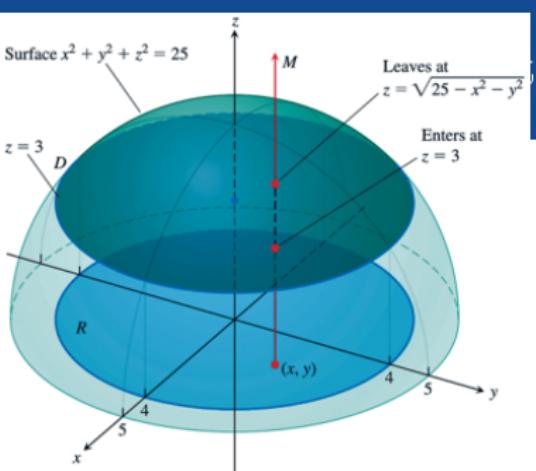


$$z = 3 \implies x^2 + y^2 + 9 = 25 \implies x^2 + y^2 = 16$$

$$-4 \leq x \leq 4 \quad -\sqrt{16 - x^2} \leq y \leq \sqrt{16 - x^2}$$

14.5

Spherical Coordinates

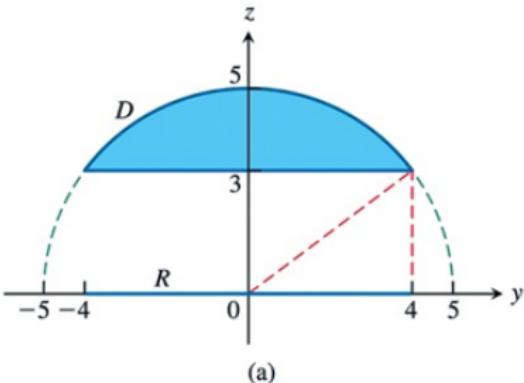
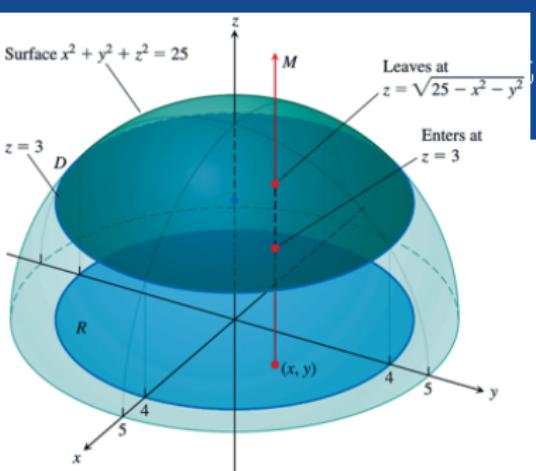


$$-4 \leq x \leq 4$$

$$-\sqrt{16 - x^2} \leq y \leq \sqrt{16 - x^2}$$

14.5

Spherical Coordinates



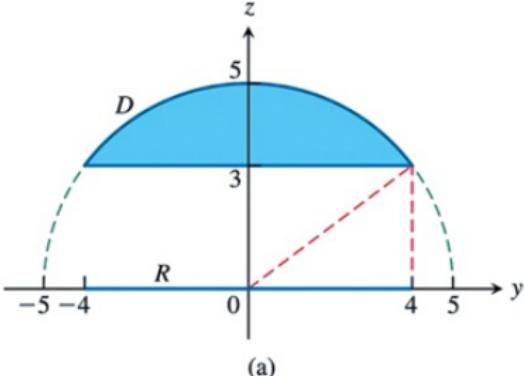
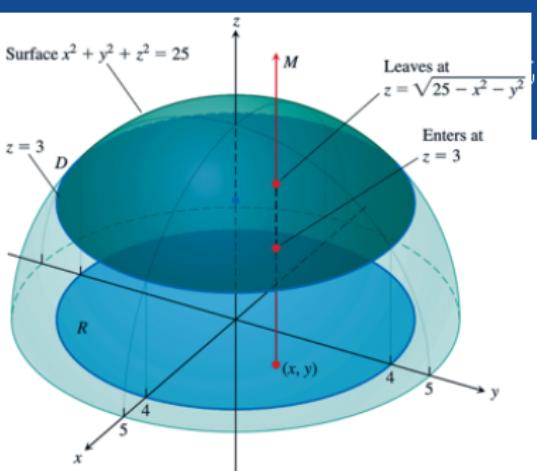
$$-4 \leq x \leq 4$$

$$-\sqrt{16 - x^2} \leq y \leq \sqrt{16 - x^2}$$

$$3 \leq z \leq \sqrt{25 - x^2 - y^2}$$

14.5

Spherical Coordinates



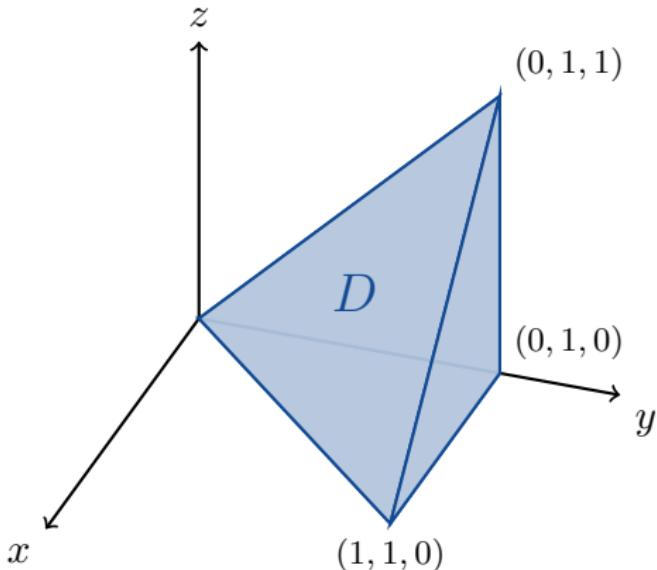
$$-4 \leq x \leq 4$$

$$-\sqrt{16 - x^2} \leq y \leq \sqrt{16 - x^2}$$

$$3 \leq z \leq \sqrt{25 - x^2 - y^2}$$

$$\int_{-4}^4 \int_{-\sqrt{16-x^2}}^{\sqrt{16-x^2}} \int_3^{\sqrt{25-x^2-y^2}} F(x, y, z) dz dy dx.$$

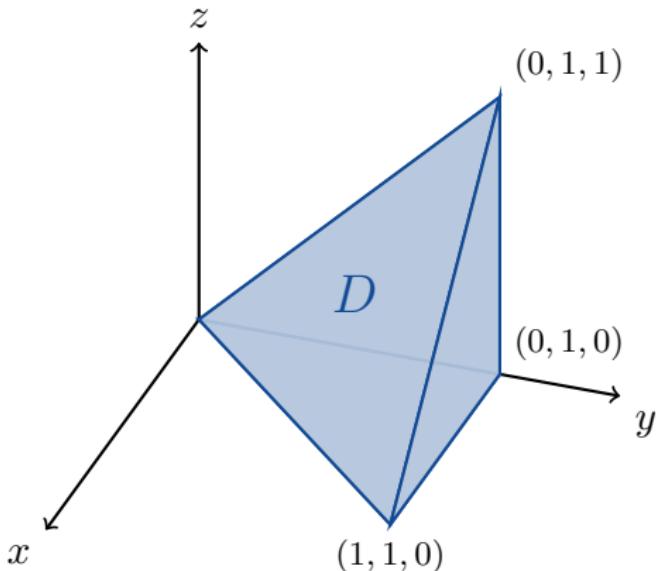
14.5 Triple Integrals in Rectangular Coordinates



Example

Let D be the tetrahedron whose vertices are $(0,0,0)$, $(1,1,0)$, $(0,1,0)$ and $(0,1,1)$.

14.5 Triple Integrals in Rectangular Coordinates



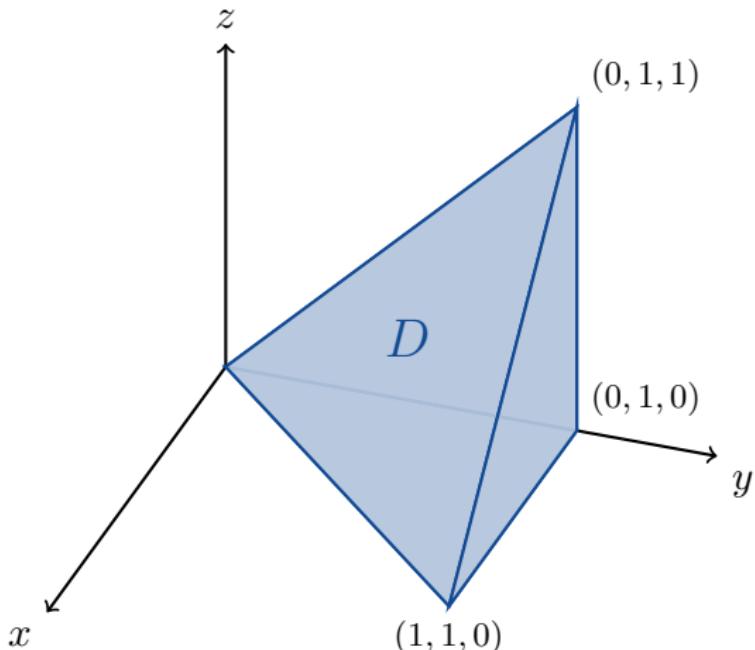
Example

Let D be the tetrahedron whose vertices are $(0, 0, 0)$, $(1, 1, 0)$, $(0, 1, 0)$ and $(0, 1, 1)$. Set up the limits of integration over D using the order $dxdydz$.

14.5 Triple Integrals in Rectangular Coordinates

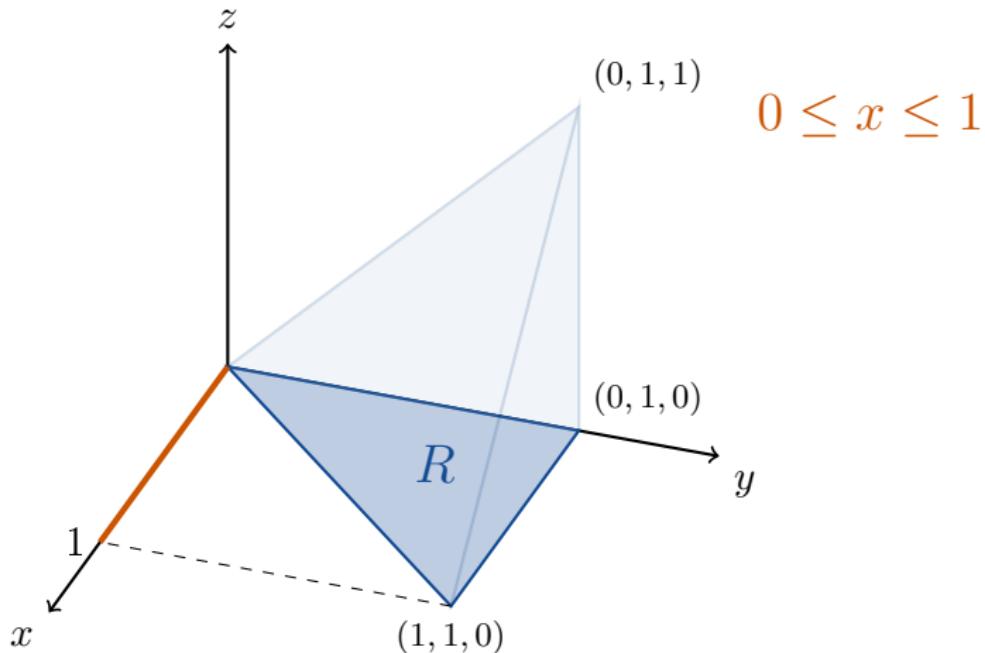


$$\iiint_D F(x, y, z) dz dy dx =$$



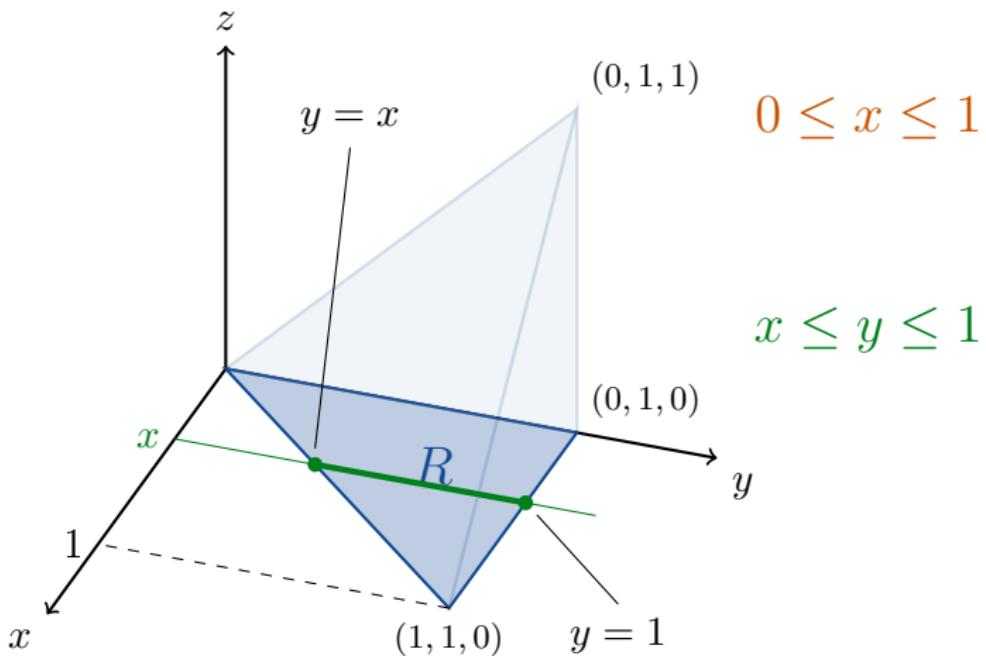
14.5 Triple Integrals in Rectangular Coordinates

$$\iiint_D F(x, y, z) dz dy dx =$$



14.5 Triple Integrals in Rectangular Coordinates

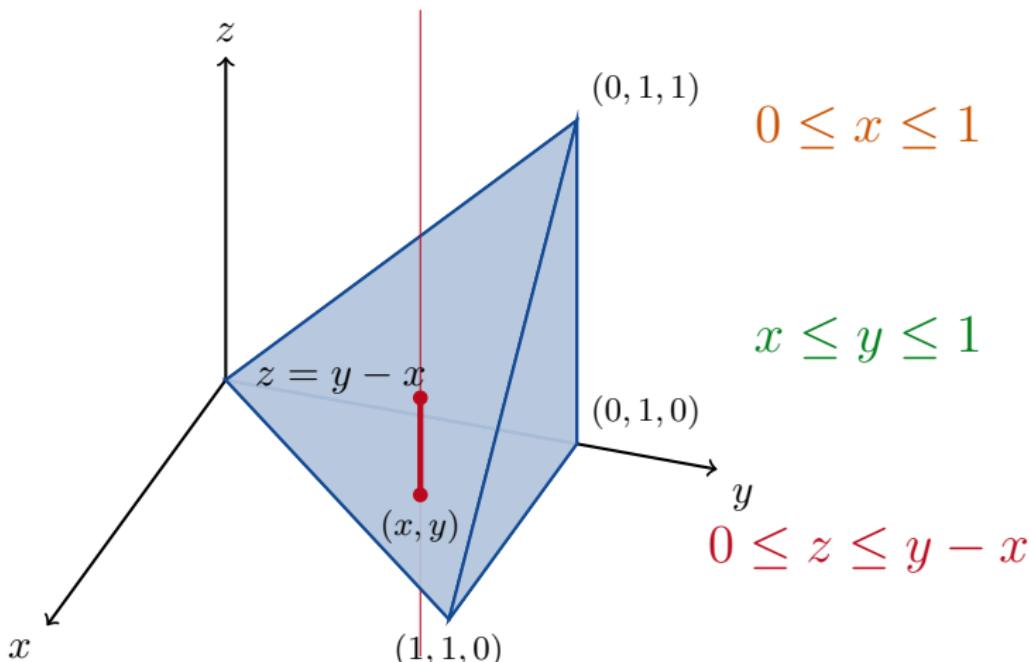
$$\iiint_D F(x, y, z) dz dy dx =$$



14.5 Triple Integrals in Rectangular Coordinates



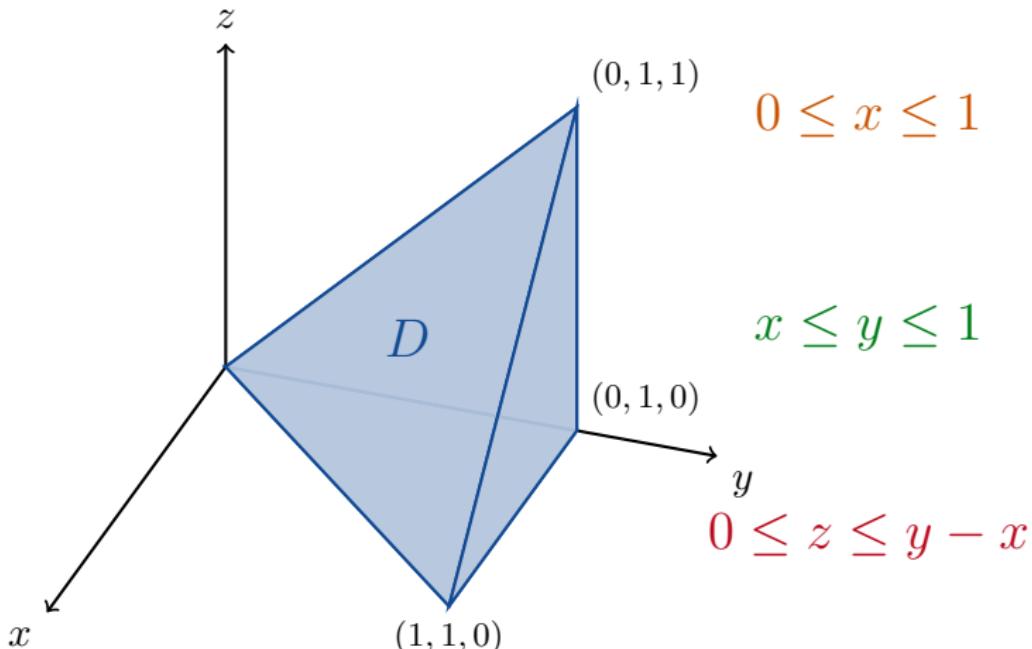
$$\iiint_D F(x, y, z) dz dy dx =$$



14.5 Triple Integrals in Rectangular Coordinates



$$\iiint_D F(x, y, z) dz dy dx = \int_0^1 \int_x^1 \int_0^{y-x} F(x, y, z) dz dy dx.$$

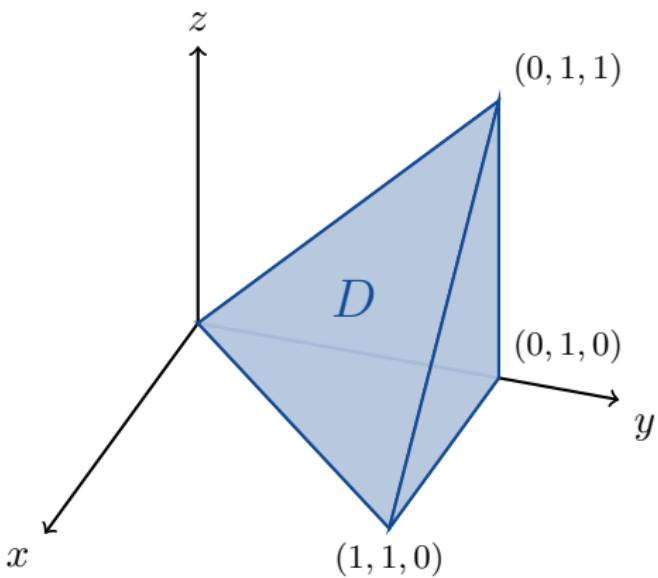


14.5 Triple Integrals in Rectangular Coordinates



Example

Find the volume of this tetrahedron by integrating the function $F(x, y, z) = 1$ over D using the order $dzdydx$.



14.5 Triple Integrals in Rectangular Coordinates



Example

Find the volume of this tetrahedron by integrating the function $F(x, y, z) = 1$ over D using the order $dzdydx$.

$$V = \iiint_D dzdydx = \int_0^1 \int_x^1 \int_0^{y-x} dzdydx$$

14.5 Triple Integrals in Rectangular Coordinates

Example

Find the volume of this tetrahedron by integrating the function $F(x, y, z) = 1$ over D using the order $dzdydx$.

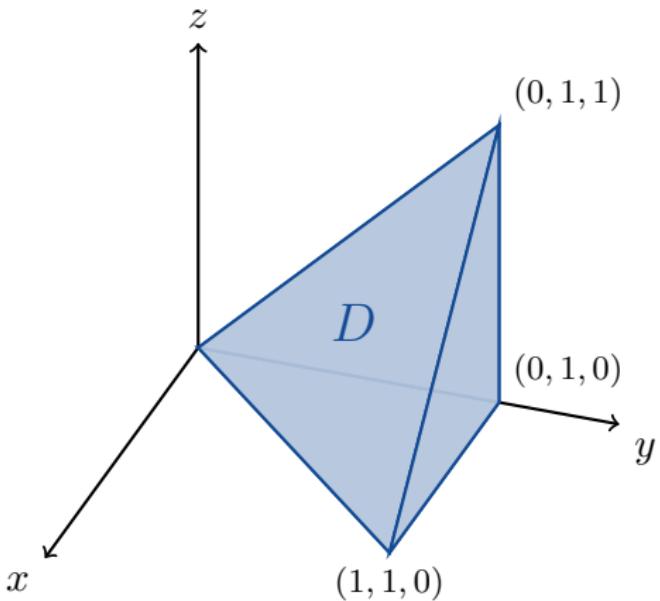
$$\begin{aligned} V &= \iiint_D dz dy dx = \int_0^1 \int_x^1 \int_0^{y-x} dz dy dx \\ &= \int_0^1 \int_x^1 (y - x) dy dx = \int_0^1 \left[\frac{1}{2}y^2 - xy \right]_{y=x}^{y=1} dx \\ &= \int_0^1 \left(\frac{1}{2} - x + \frac{1}{2}x^2 \right) dx = \left[\frac{1}{2}x - \frac{1}{2}x^2 + \frac{1}{6}x^3 \right]_0^1 = \frac{1}{6}. \end{aligned}$$

14.5 Triple Integrals in Rectangular Coordinates



Example

Find the volume of this tetrahedron by integrating the function $F(x, y, z) = 1$ over D using the order $\textcolor{red}{dydzdx}$.

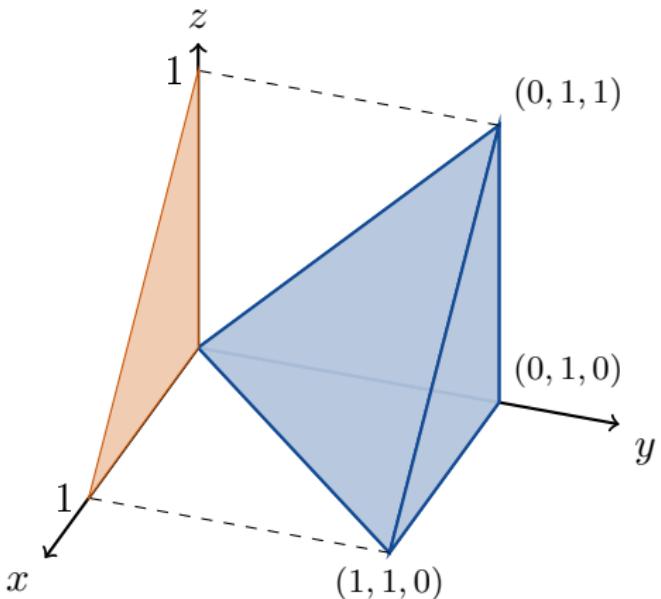


14.5 Triple Integrals in Rectangular Coordinates



Example

Find the volume of this tetrahedron by integrating the function $F(x, y, z) = 1$ over D using the order $dydzdx$.

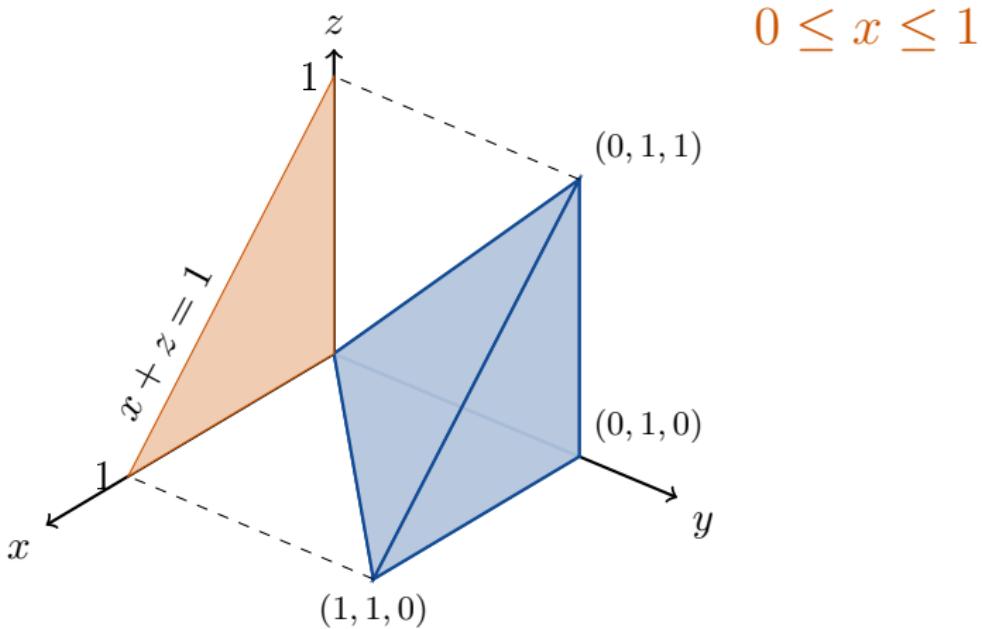


14.5 Triple Integrals in Rectangular Coordinates



Example

Find the volume of this tetrahedron by integrating the function $F(x, y, z) = 1$ over D using the order dydzdx .

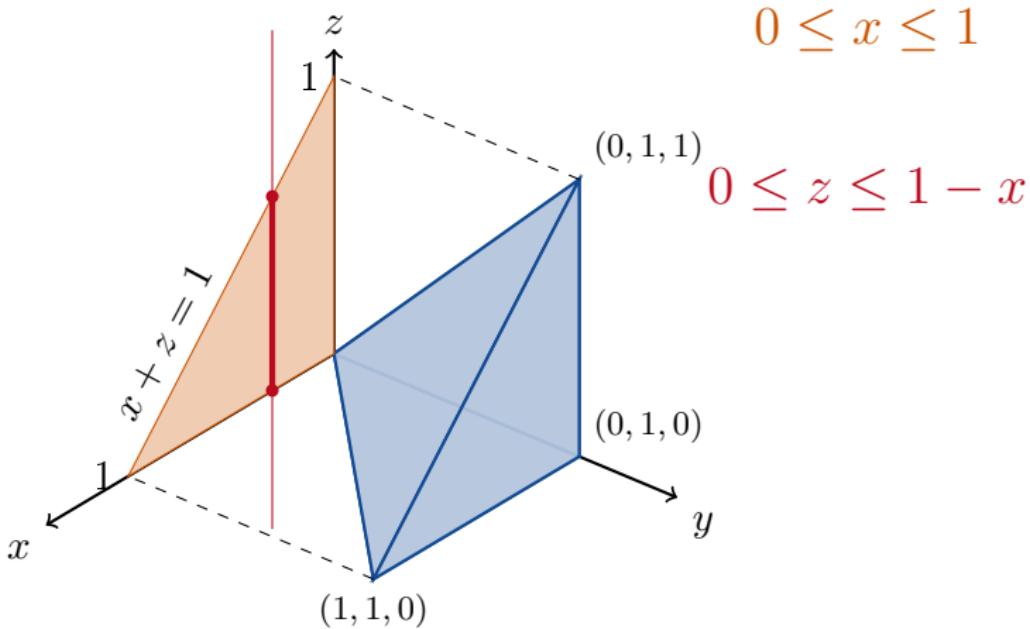


14.5 Triple Integrals in Rectangular Coordinates



Example

Find the volume of this tetrahedron by integrating the function $F(x, y, z) = 1$ over D using the order dydzdx .

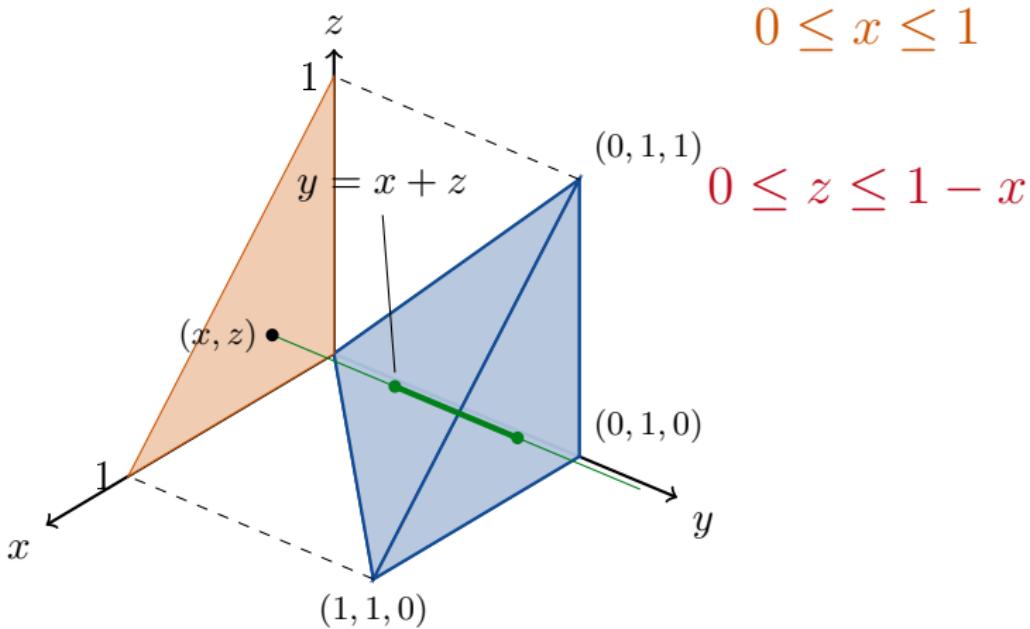


14.5 Triple Integrals in Rectangular Coordinates



Example

Find the volume of this tetrahedron by integrating the function $F(x, y, z) = 1$ over D using the order dydzdx .

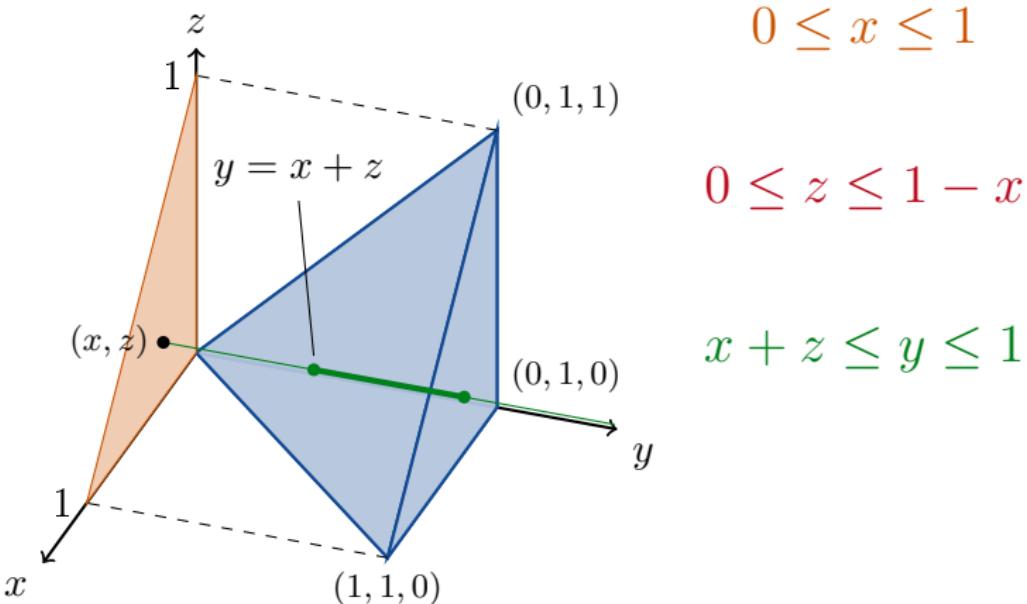


14.5 Triple Integrals in Rectangular Coordinates



Example

Find the volume of this tetrahedron by integrating the function $F(x, y, z) = 1$ over D using the order dydzdx .



14.5 Triple Integrals in Rectangular Coordinates



$$0 \leq x \leq 1 \quad 0 \leq z \leq 1 - x \quad x + z \leq y \leq 1$$

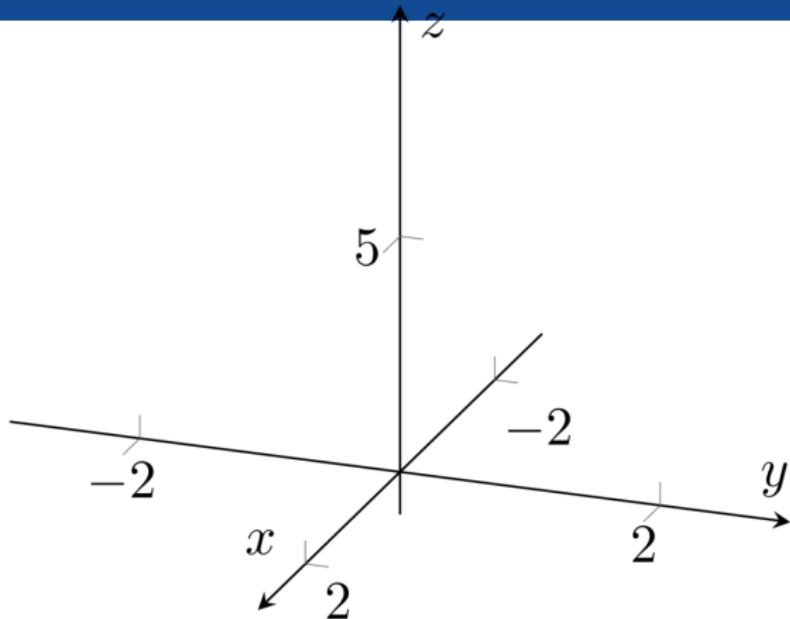
$$V = \iiint_D dz dy dx = \int_0^1 \int_0^{1-x} \int_{x+z}^1 dy dz dx$$

14.5 Triple Integrals in Rectangular Coordinates

$$0 \leq x \leq 1 \quad 0 \leq z \leq 1 - x \quad x + z \leq y \leq 1$$

$$\begin{aligned}
 V &= \iiint_D dz dy dx = \int_0^1 \int_0^{1-x} \int_{x+z}^1 dy dz dx \\
 &= \int_0^1 \int_0^{1-x} (1 - x - z) dz dx = \int_0^1 \left[z - xz - \frac{1}{2}z^2 \right]_{z=0}^{z=1-x} dx \\
 &= \int_0^1 \left(1 - x - x - x^2 - \frac{1}{2}(1-x)^2 \right) dx \\
 &= \frac{1}{2} \int_0^1 (1-x)^2 dx = \frac{1}{2} \left[-\frac{1}{3}(1-x)^3 \right]_0^1 = \frac{1}{6}.
 \end{aligned}$$

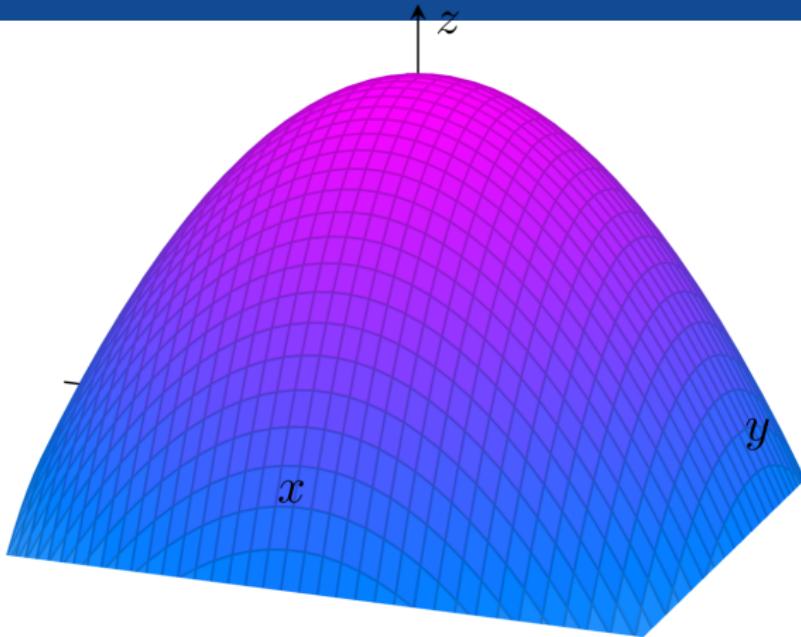
14.5 Triple Integrals in Rectangular Coordinates



Example

Find the volume of the region D enclosed by the surfaces $z = x^2 + 3y^2$ and $z = 8 - x^2 - y^2$.

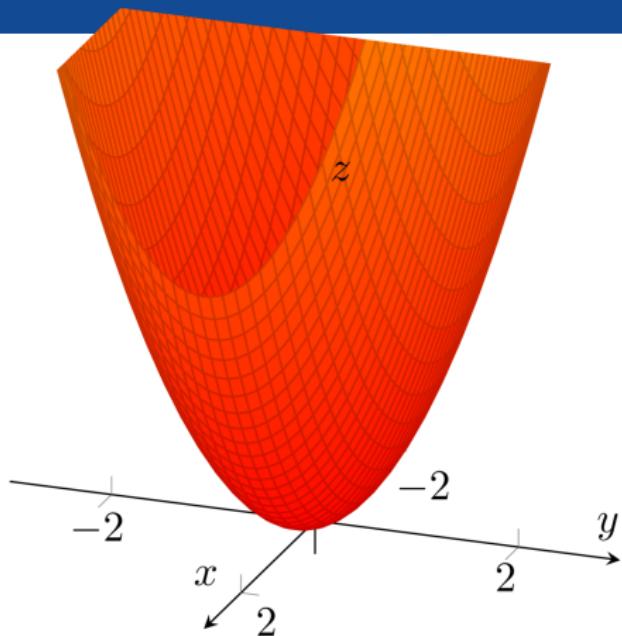
14.5 Triple Integrals in Rectangular Coordinates



Example

Find the volume of the region D enclosed by the surfaces $z = x^2 + 3y^2$ and $z = 8 - x^2 - y^2$.

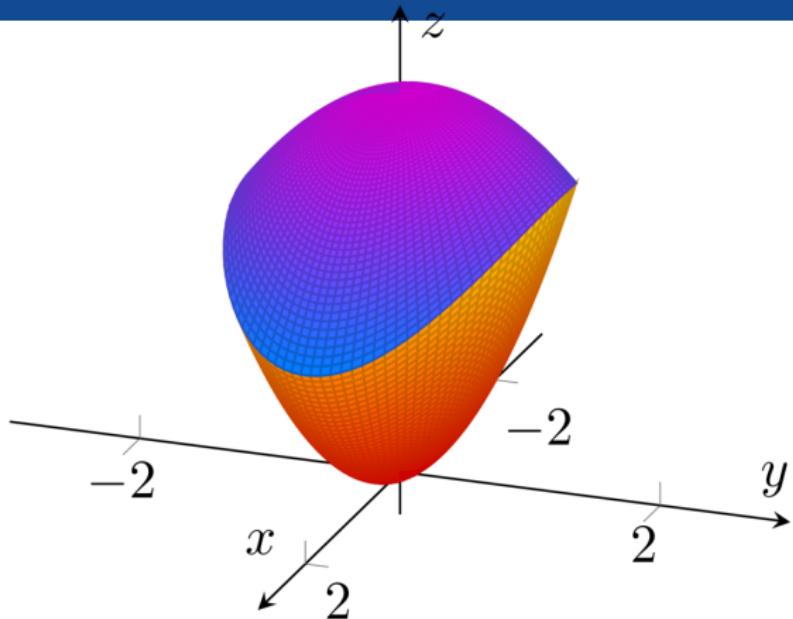
14.5 Triple Integrals in Rectangular Coordinates



Example

Find the volume of the region D enclosed by the surfaces $z = x^2 + 3y^2$ and $z = 8 - x^2 - y^2$.

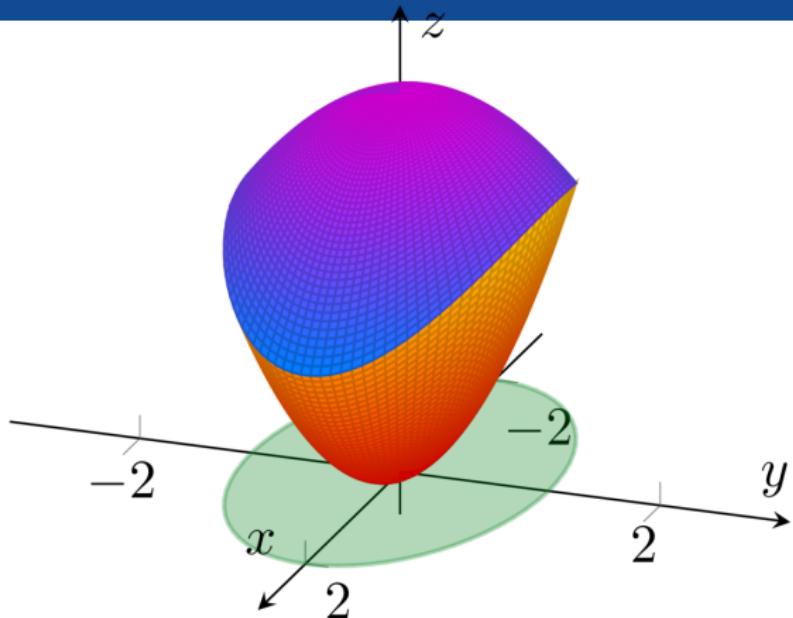
14.5 Triple Integrals in Rectangular Coordinates



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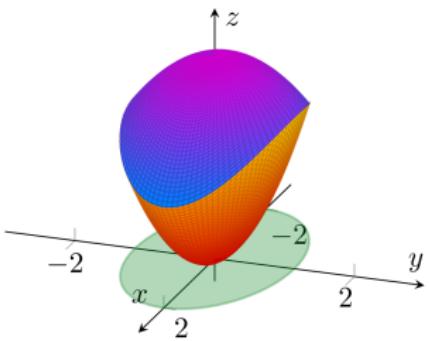
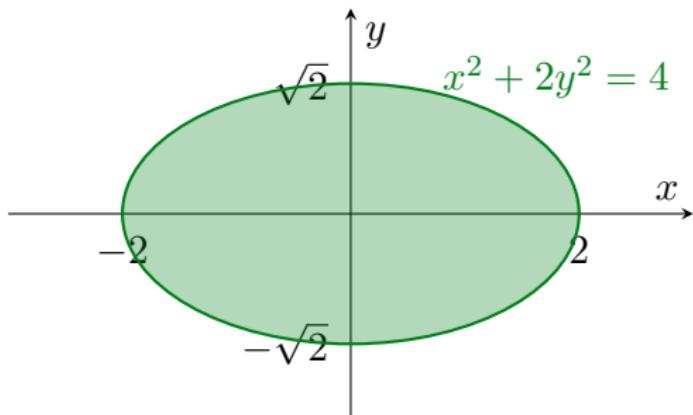
14.5 Triple Integrals in Rectangular Coordinates



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Find the volume of the region D enclosed by the surfaces $z = x^2 + 3y^2$ and $z = 8 - x^2 - y^2$.

14.5 Triple Integrals in Rectangular Coordinates

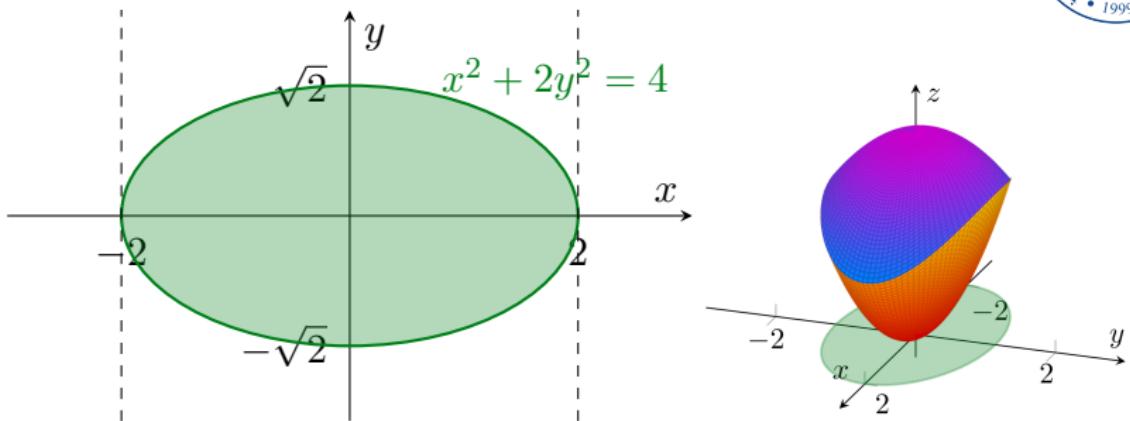


$$x^2 + 3y^2 = z = 8 - x^2 - y^2$$

$$2x^2 + 4y^2 = 8$$

$$x^2 + 2y^2 = 4.$$

14.5 Triple Integrals in Rectangular Coordinates



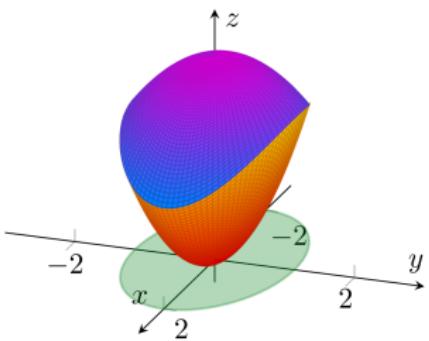
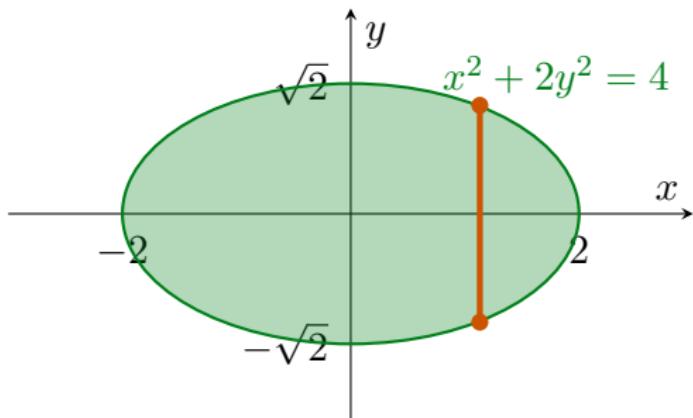
$$-2 \leq x \leq 2$$

$$x^2 + 3y^2 = z = 8 - x^2 - y^2$$

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14.5 Triple Integrals in Rectangular Coordinates



$$-2 \leq x \leq 2$$

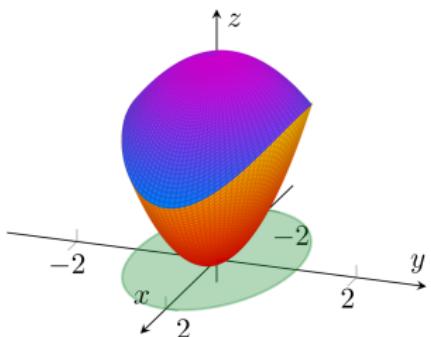
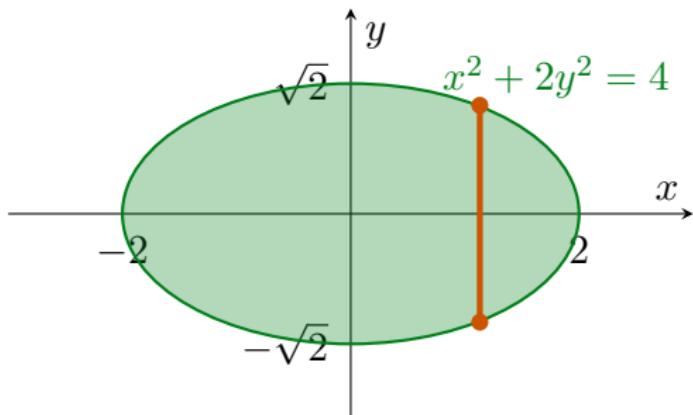
$$x^2 + 3y^2 = z = 8 - x^2 - y^2$$

$$2x^2 + 4y^2 = 8$$

$$x^2 + 2y^2 = 4.$$

$$-\sqrt{\frac{4-x^2}{2}} \leq y \leq \sqrt{\frac{4-x^2}{2}}$$

14.5 Triple Integrals in Rectangular Coordinates



$$-2 \leq x \leq 2$$

$$x^2 + 3y^2 = z = 8 - x^2 - y^2$$

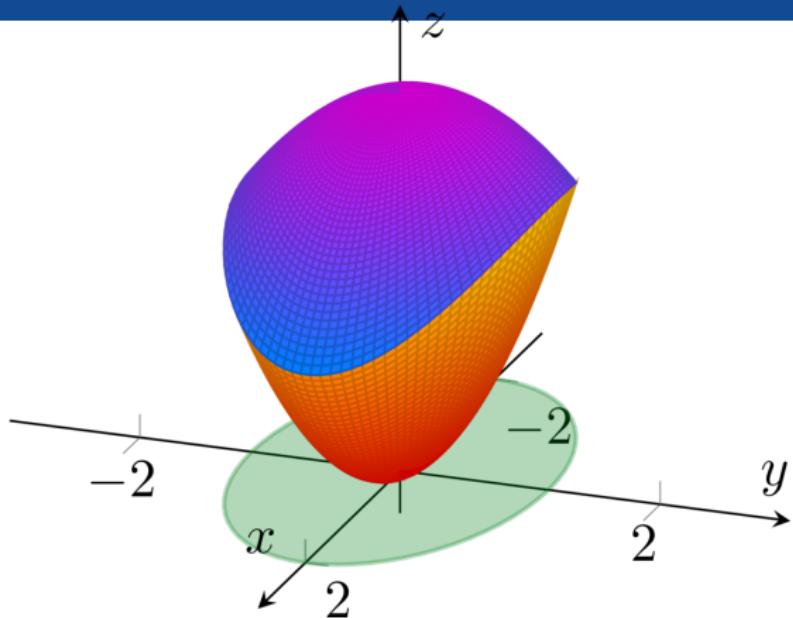
$$2x^2 + 4y^2 = 8$$

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$$-\sqrt{\frac{4-x^2}{2}} \leq y \leq \sqrt{\frac{4-x^2}{2}}$$

$$x^2 + 3y^2 \leq z \leq 8 - x^2 - y^2$$

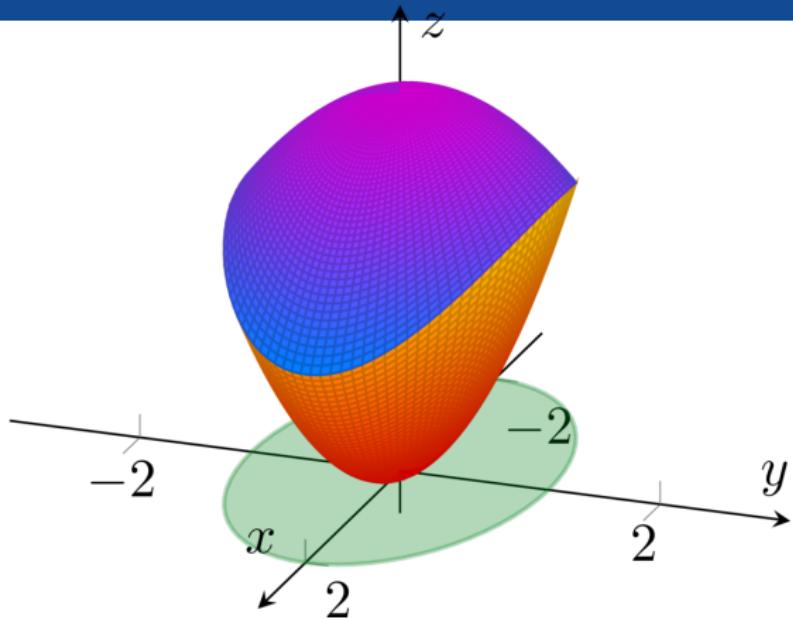
14.5 Triple Integrals in Rectangular Coordinates



The volume of D is

$$V = \int_{-2}^2 \int_{-\sqrt{\frac{4-x^2}{2}}}^{\sqrt{\frac{4-x^2}{2}}} \int_{x^2+3y^2}^{8-x^2-y^2} dz dy dx =$$

14.5 Triple Integrals in Rectangular Coordinates



The volume of D is

$$V = \int_{-2}^2 \int_{-\sqrt{\frac{4-x^2}{2}}}^{\sqrt{\frac{4-x^2}{2}}} \int_{x^2+3y^2}^{8-x^2-y^2} dz dy dx = \dots = 8\pi\sqrt{2}.$$



Average Value of a Function

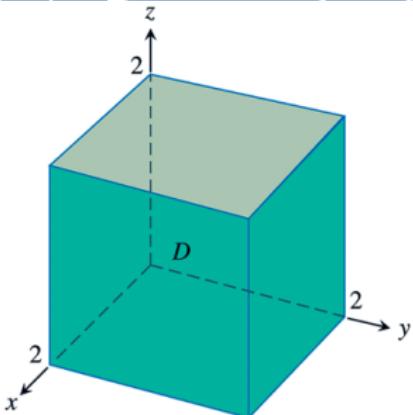
Definition

The *average value* of a function F over a region D is

$$\text{av}(F) = \frac{1}{\text{volume of } D} \iiint_D F \, dV.$$

14.5 Triple Integrals

Coordinates

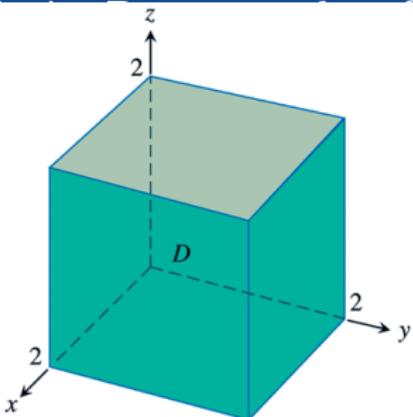


Example

Find the average value of $F(x, y, z) = xyz$ over the cube $[0, 2] \times [0, 2] \times [0, 2]$.

14.5 Triple Integrals

Coordinates



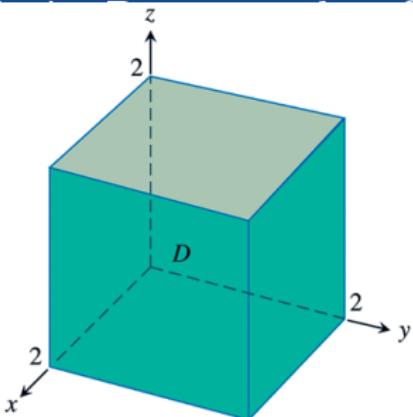
Example

Find the average value of $F(x, y, z) = xyz$ over the cube $[0, 2] \times [0, 2] \times [0, 2]$.

$$\text{av}(F) = \frac{1}{\text{volume of the cube}} \iiint_{\text{cube}} xyz \, dxdydz$$

14.5 Triple Integrals

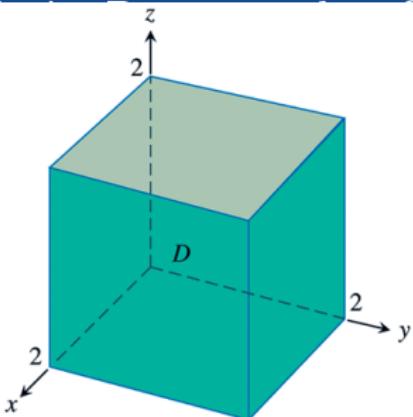
Coordinates



Example

Find the average value of $F(x, y, z) = xyz$ over the cube $[0, 2] \times [0, 2] \times [0, 2]$.

$$\begin{aligned}\text{av}(F) &= \frac{1}{\text{volume of the cube}} \iiint_{\text{cube}} xyz \, dxdydz \\ &= \frac{1}{8} \int_0^2 \int_0^2 \int_0^2 xyz \, dxdydz\end{aligned}$$



Example

Find the average value of $F(x, y, z) = xyz$ over the cube $[0, 2] \times [0, 2] \times [0, 2]$.

$$\begin{aligned}\text{av}(F) &= \frac{1}{\text{volume of the cube}} \iiint_{\text{cube}} xyz \, dxdydz \\ &= \frac{1}{8} \int_0^2 \int_0^2 \int_0^2 xyz \, dxdydz = \dots = 1.\end{aligned}$$



Properties of Triple Integrals



Properties of Triple Integrals

The same as for double integrals.



Break

We will continue at 2pm

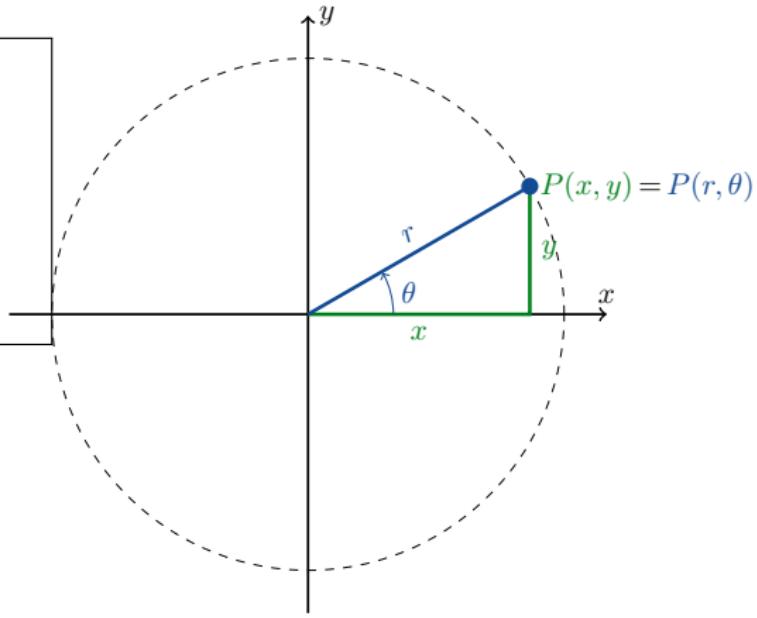




Triple Integrals in Cylindrical and Spherical Coordinates

Polar Coordinates in \mathbb{R}^2

$$\begin{array}{ll} x = r \cos \theta & x^2 + y^2 = r^2 \\ y = r \sin \theta & \tan \theta = \frac{y}{x} \end{array}$$



14.7 Triple Integrals in Cylindrical and Spherical Coordinates



Cylindrical Coordinates in \mathbb{R}^3

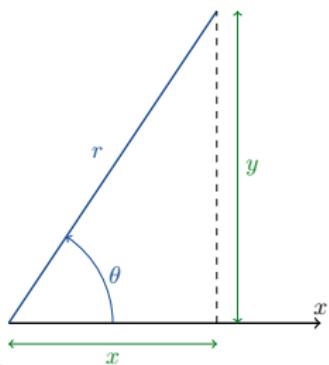
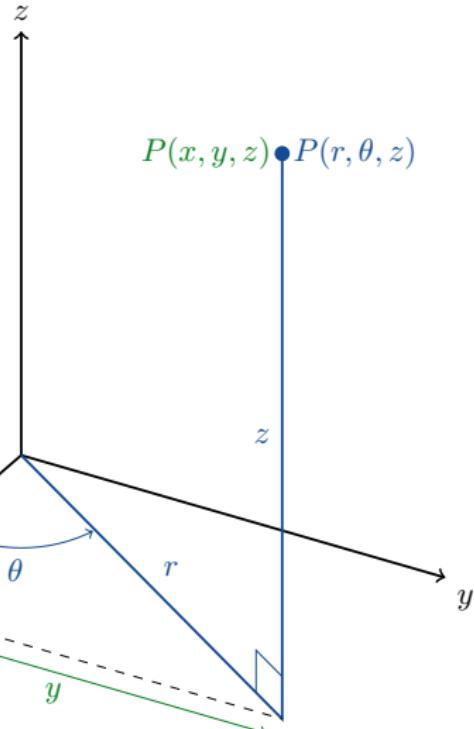
$$x = r \cos \theta$$

$$x^2 + y^2 = r^2$$

$$y = r \sin \theta$$

$$\tan \theta = \frac{y}{x}$$

$$z = z$$



$$x = r \cos \theta \quad y = r \sin \theta \quad z = z$$

Example

Find cylindrical coordinates for the Cartesian coordinates $(x, y, z) = (1, 1, 1)$.

$$x = r \cos \theta \quad y = r \sin \theta \quad z = z$$

Example

Find cylindrical coordinates for the Cartesian coordinates $(x, y, z) = (1, 1, 1)$.

$$\begin{aligned}(r, \theta, z) &= \left(\sqrt{x^2 + y^2}, \tan^{-1} \frac{y}{x}, z \right) \\&= \left(\sqrt{1^2 + 1^2}, \tan^{-1} 1, 1 \right) = \left(\sqrt{2}, \frac{\pi}{4}, 1 \right).\end{aligned}$$

$$x = r \cos \theta \quad y = r \sin \theta \quad z = z$$

Example

Find cylindrical coordinates for the Cartesian coordinates $(x, y, z) = (1, 1, 1)$.

$$\begin{aligned}(r, \theta, z) &= \left(\sqrt{x^2 + y^2}, \tan^{-1} \frac{y}{x}, z \right) \\ &= \left(\sqrt{1^2 + 1^2}, \tan^{-1} 1, 1 \right) = \left(\sqrt{2}, \frac{\pi}{4}, 1 \right).\end{aligned}$$

Example

Convert the cylindrical coordinates $(r, \theta, z) = \left(2, \frac{\pi}{2}, 2\right)$ to Cartesian coordinates.

$$x = r \cos \theta \quad y = r \sin \theta \quad z = z$$

Example

Find cylindrical coordinates for the Cartesian coordinates $(x, y, z) = (1, 1, 1)$.

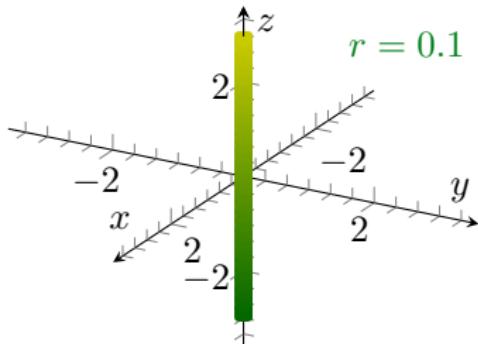
$$\begin{aligned} (r, \theta, z) &= \left(\sqrt{x^2 + y^2}, \tan^{-1} \frac{y}{x}, z \right) \\ &= \left(\sqrt{1^2 + 1^2}, \tan^{-1} 1, 1 \right) = \left(\sqrt{2}, \frac{\pi}{4}, 1 \right). \end{aligned}$$

Example

Convert the cylindrical coordinates $(r, \theta, z) = \left(2, \frac{\pi}{2}, 2\right)$ to Cartesian coordinates.

$$\begin{aligned} (x, y, z) &= (x \cos \theta, y \sin \theta, z) \\ &= \left(2 \cos \frac{\pi}{2}, 2 \sin \frac{\pi}{2}, 2 \right) = (0, 2, 2). \end{aligned}$$

14.7 Triple Integrals in Cylindrical and Spherical Coordinates

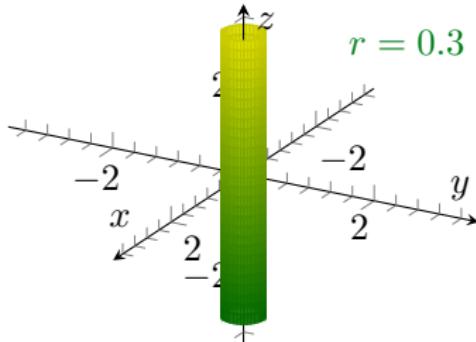


Remark

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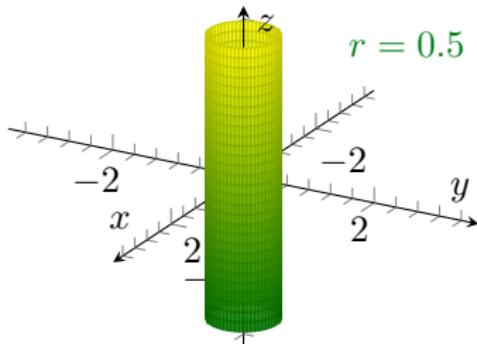


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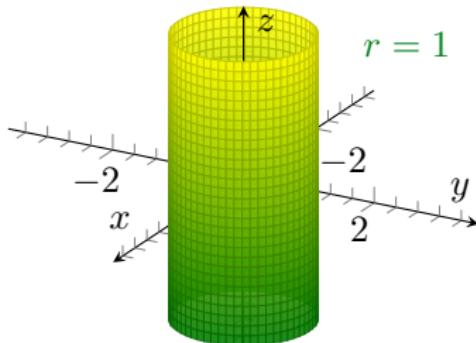


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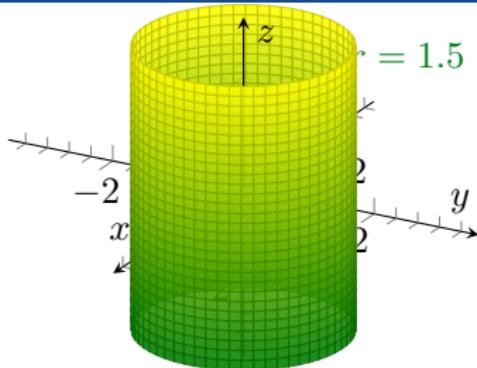


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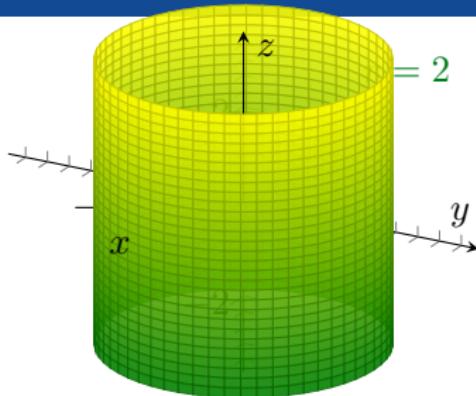


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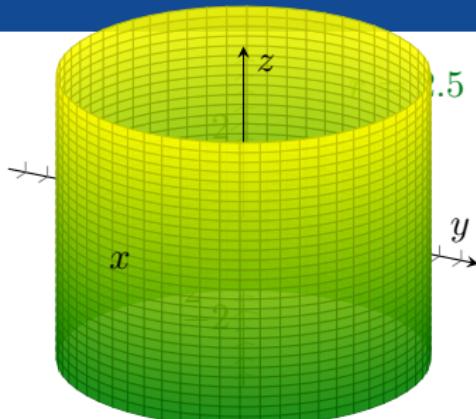


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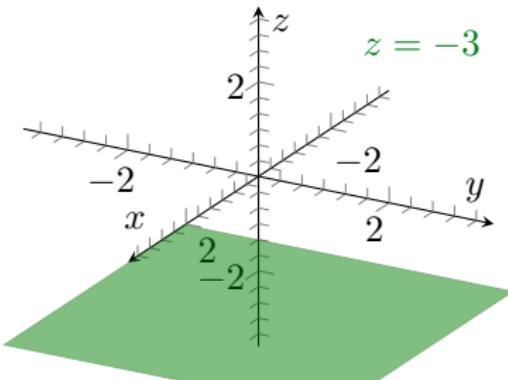


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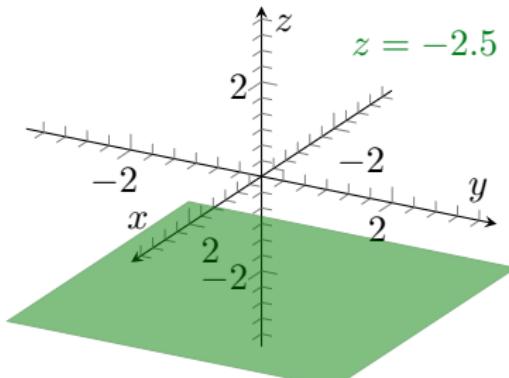


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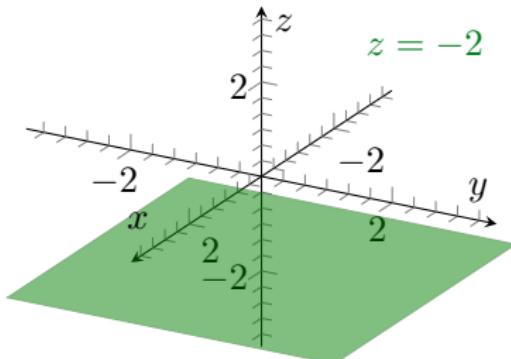


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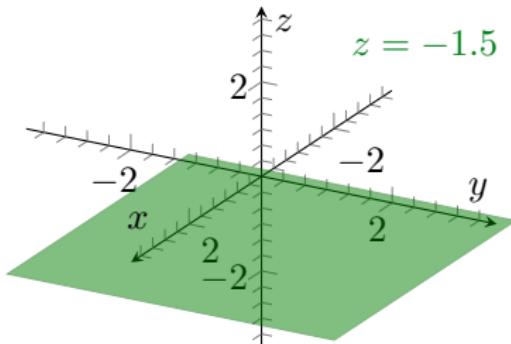


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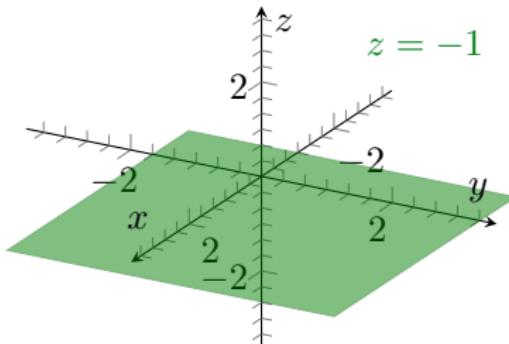


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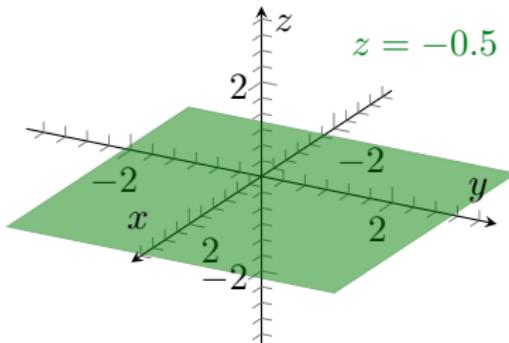


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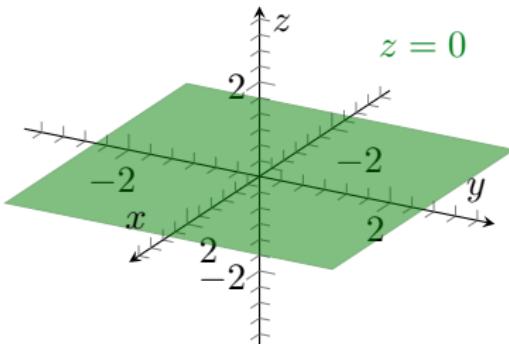


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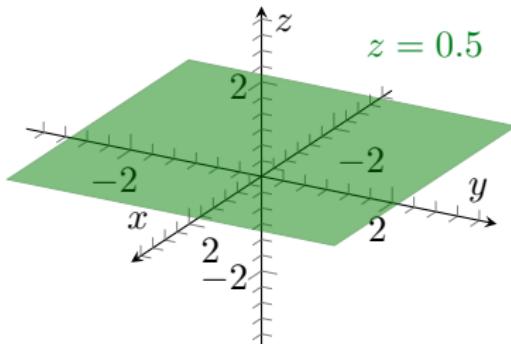


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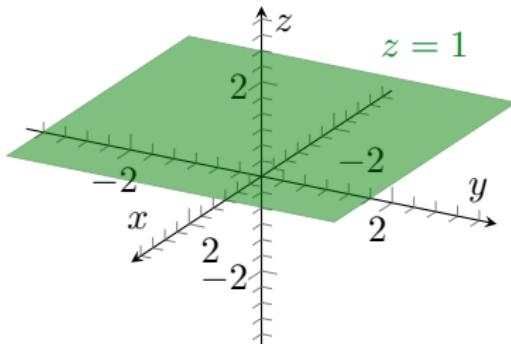


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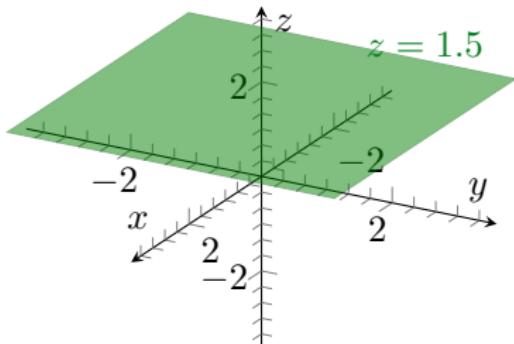


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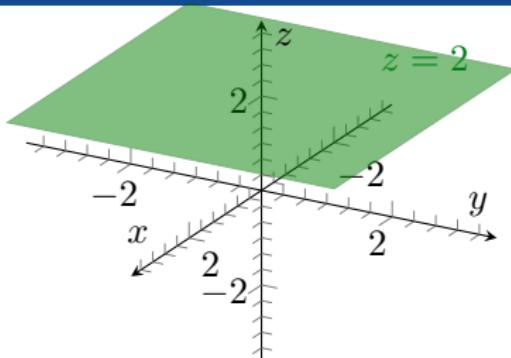


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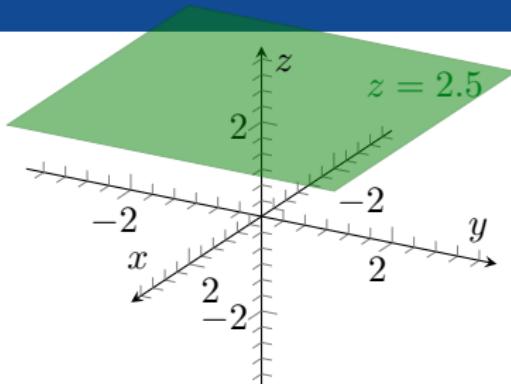


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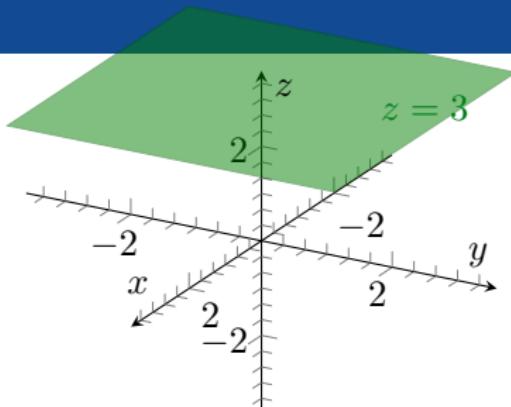


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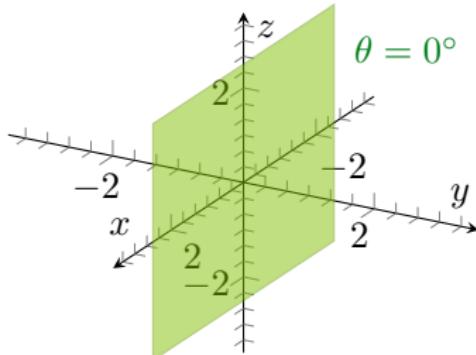


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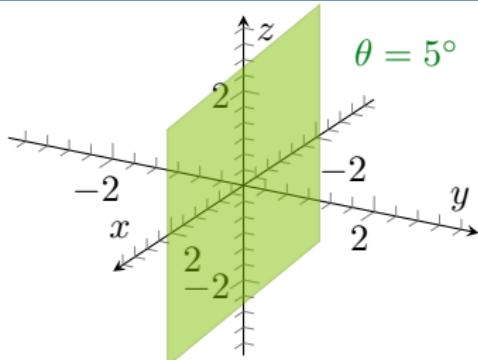


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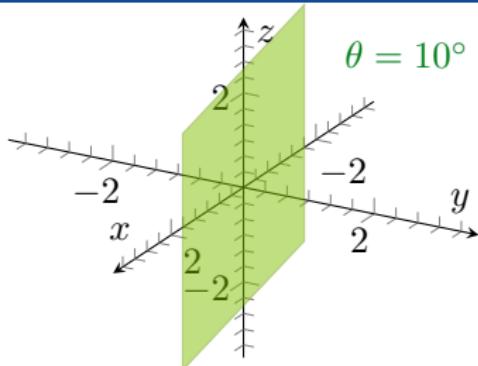


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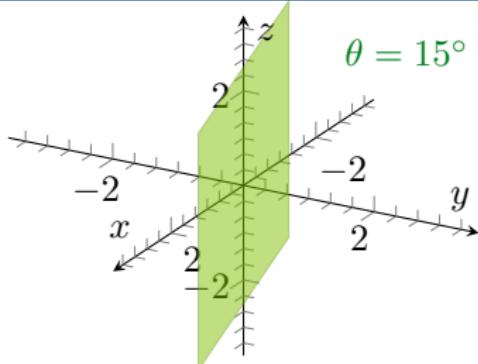


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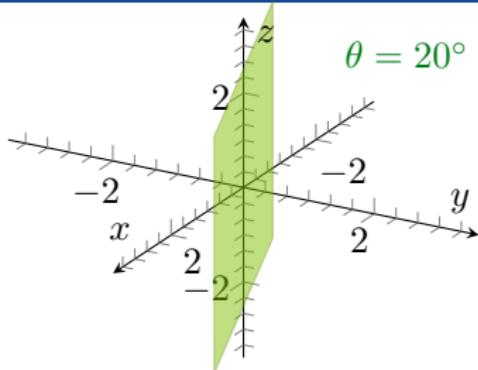


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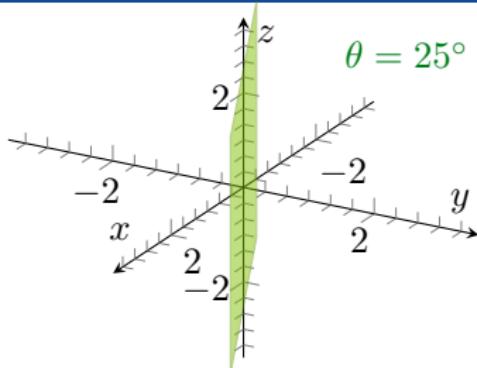


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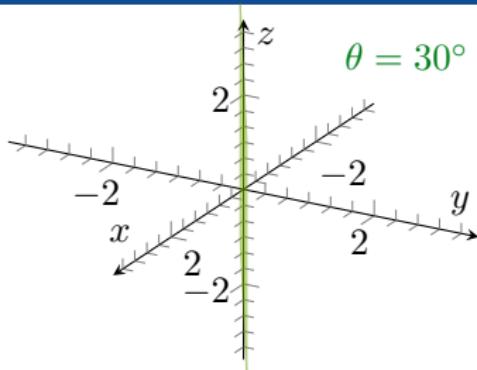


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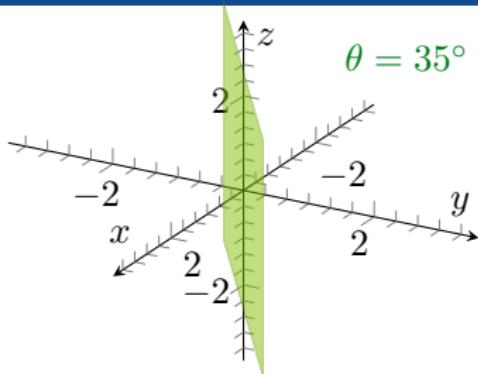


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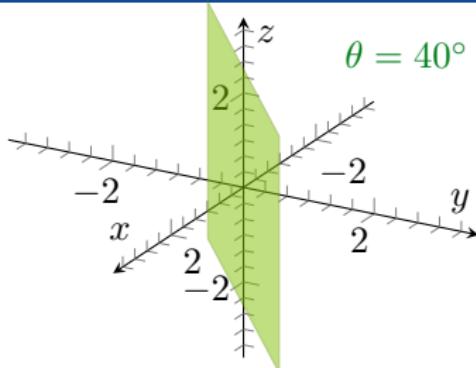


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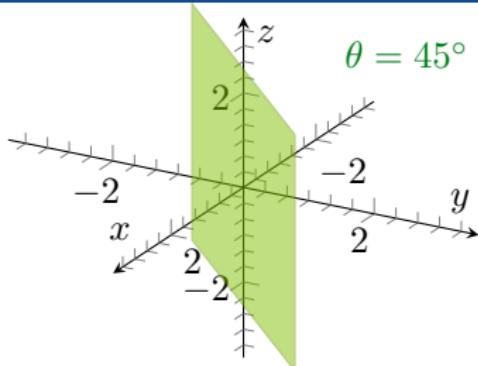


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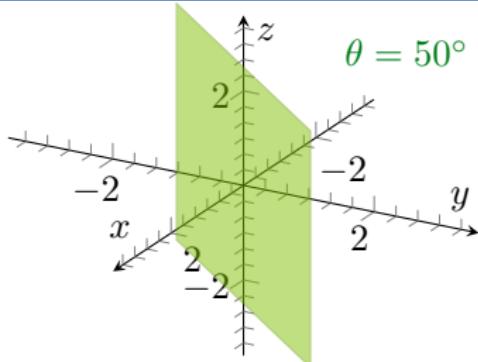


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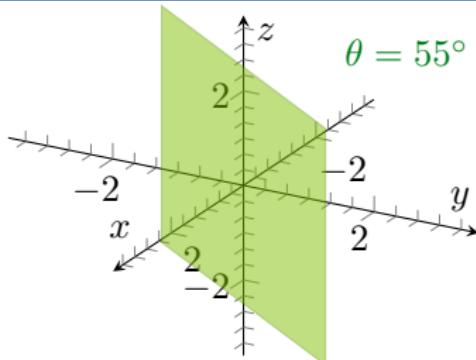


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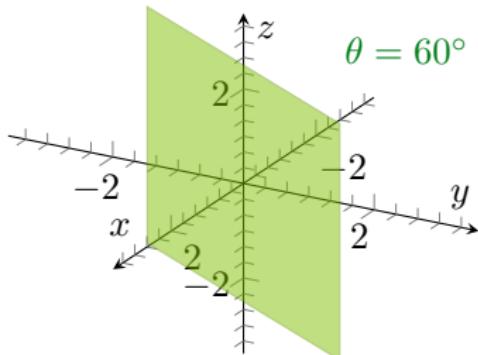


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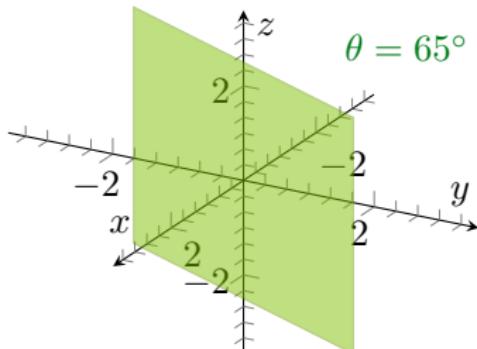


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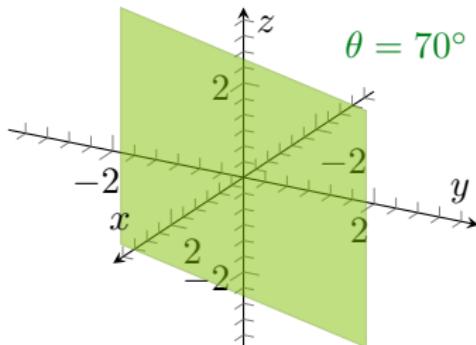


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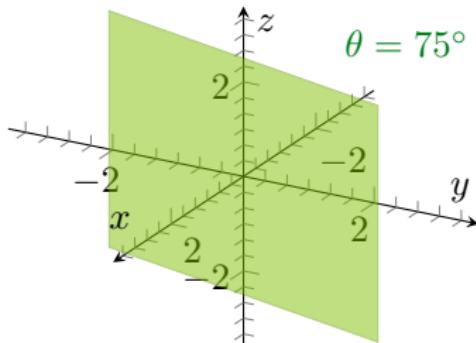


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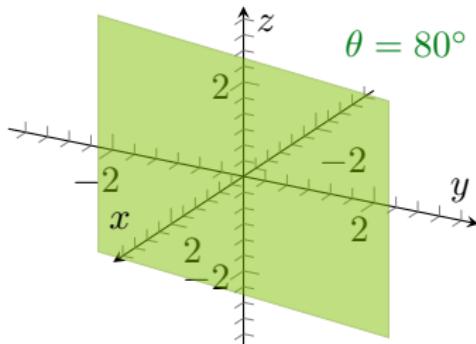


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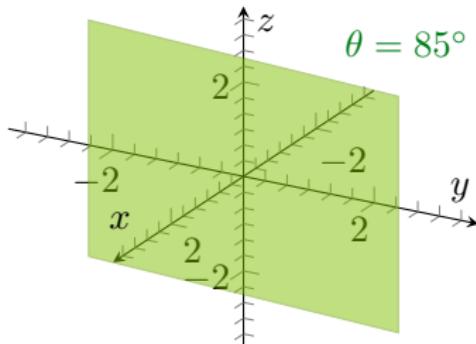


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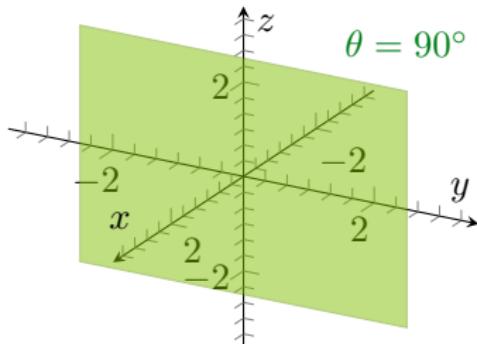


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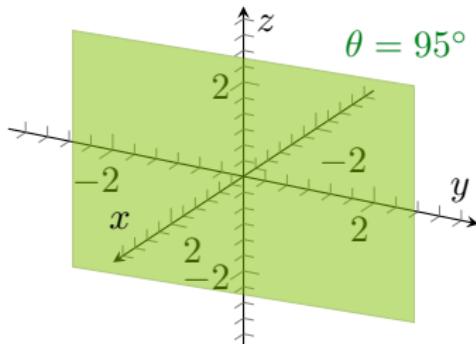


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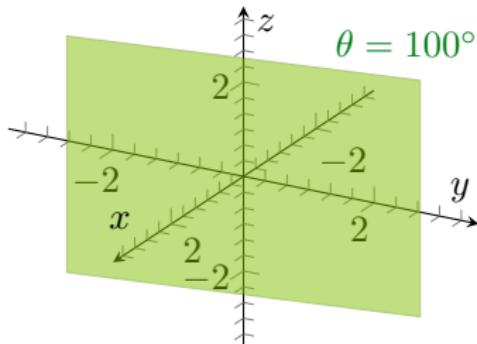


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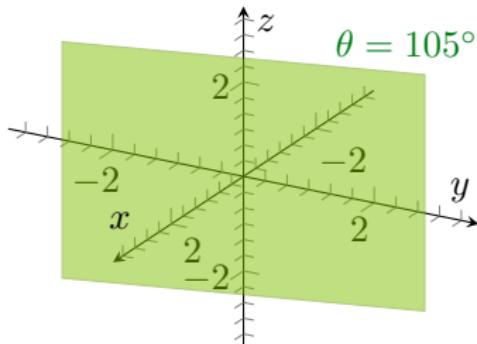


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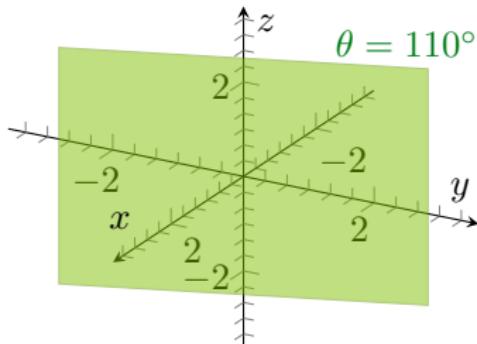


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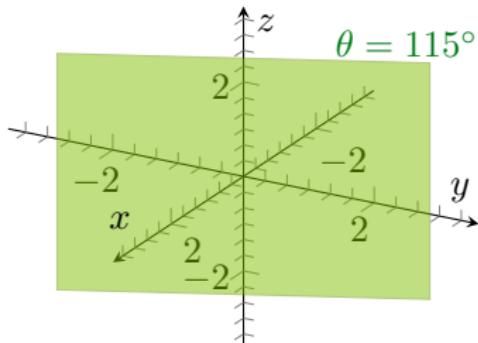


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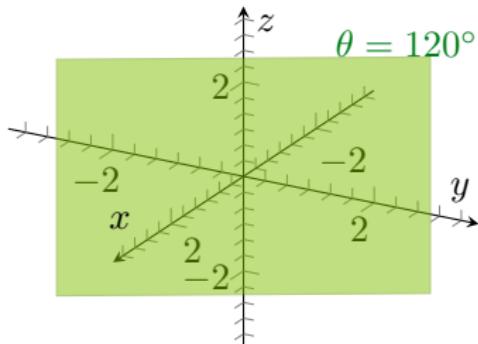


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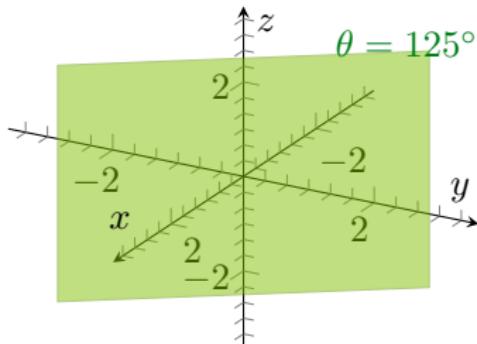


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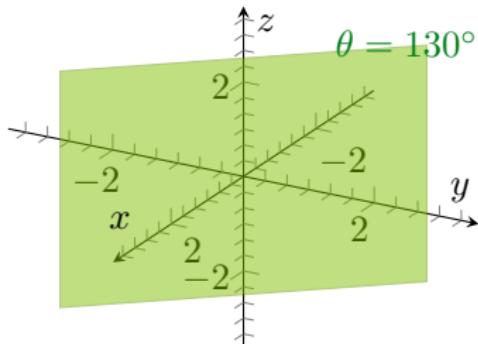


Remark

Cylindrical coordinates are good for describing:

- vertical cylinders with axis on the z -axis ($r = r_0$);
- horizontal planes ($z = z_0$); and
- planes containing the z -axis ($\theta = \theta_0$).

14.7 Triple Integrals in Cylindrical and Spherical Coordinates

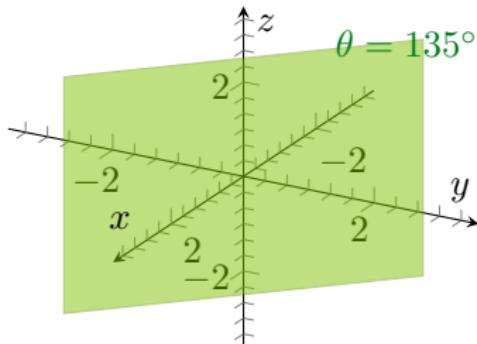


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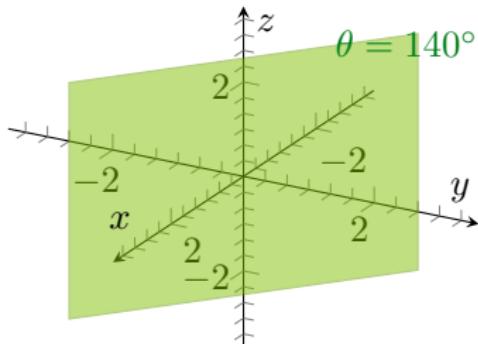


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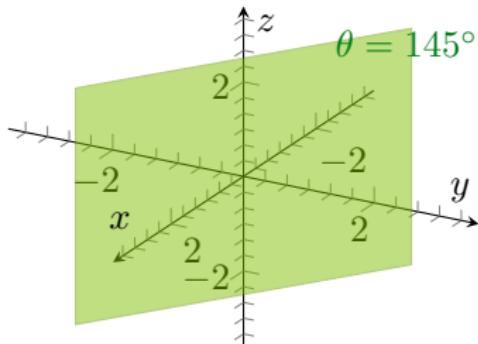


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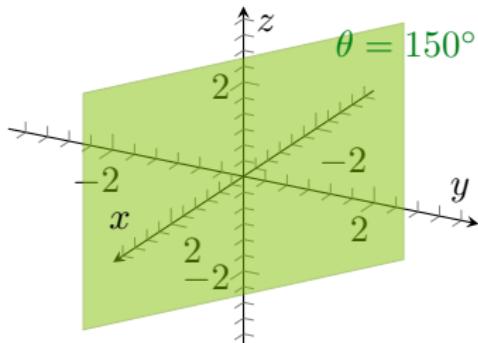


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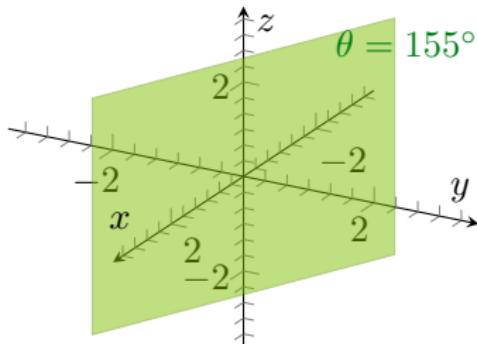


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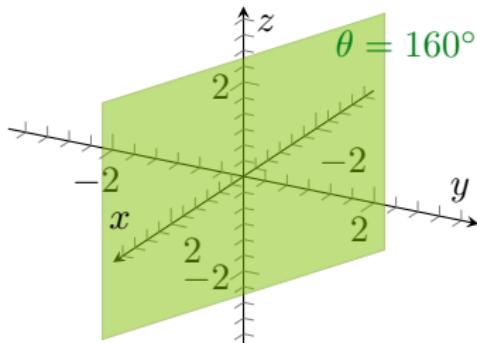


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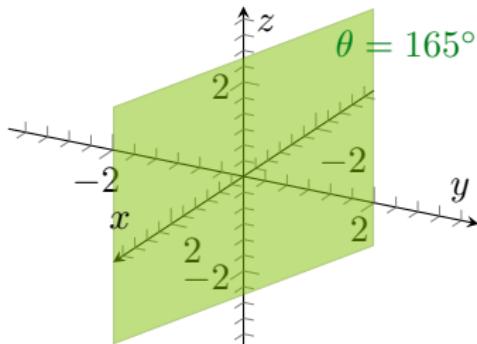


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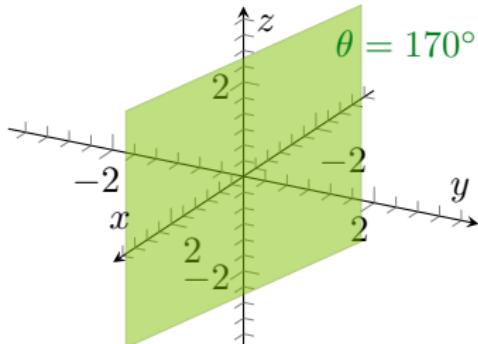


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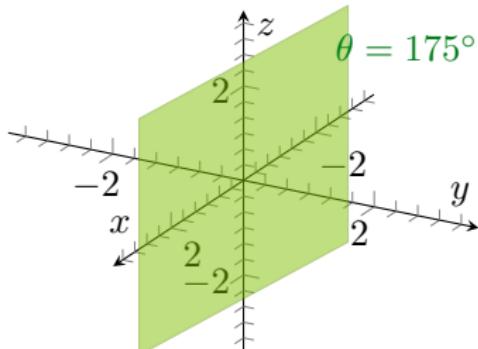


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14.7 Triple Integrals in Cylindrical and Spherical Coordinates



Recall that

$$dA = dx dy = r dr d\theta.$$

14.7 Triple Integrals in Cylindrical and Spherical Coordinates



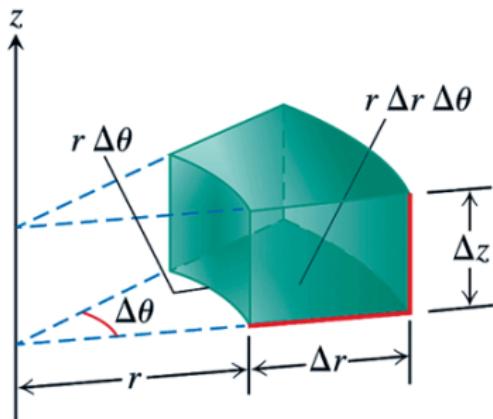
Recall that

$$dA = dx dy = r dr d\theta.$$

Now we have

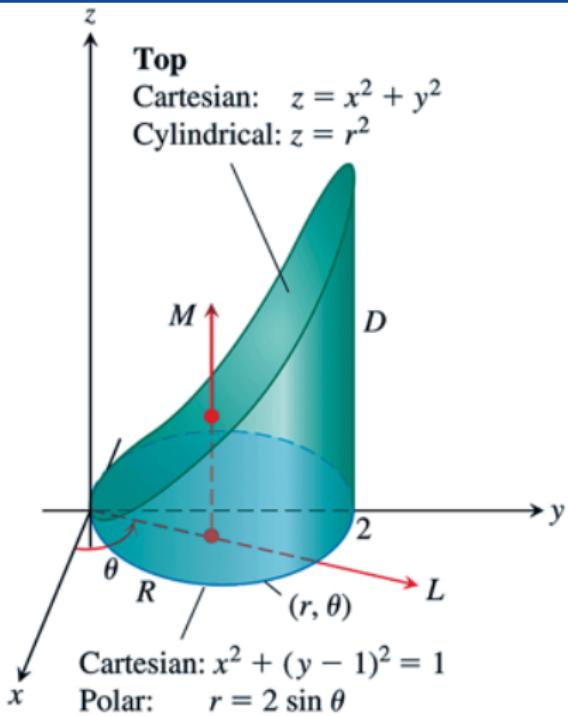
Theorem

$$dV = dx dy dz = r dr d\theta dz.$$



14.7 Triple Integrals in Cylindrical Coordinates

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Example

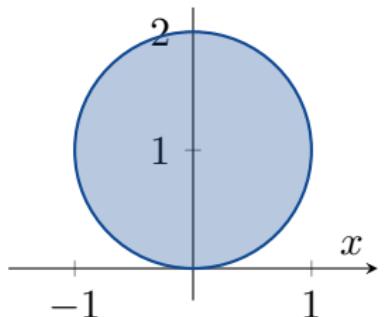
Let D be the region bounded by $z = 0$, $x^2 + (y - 1)^2 = 1$ and $z = x^2 + y^2$. Find the limits of integration in cylindrical coordinates.

14.7

$$x = r \cos \theta \quad y = r \sin \theta \quad z = z$$



$$x^2 + (y - 1)^2 = 1$$



First note that

$$x^2 + (y - 1)^2 = 1$$

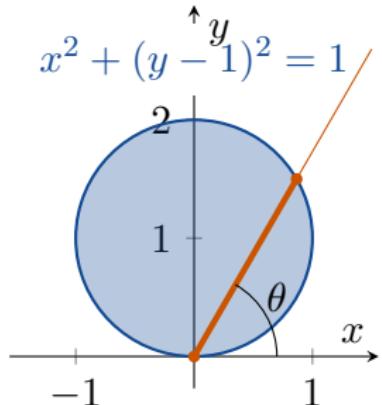
$$x^2 + y^2 - 2y + 1 = 1$$

$$r^2 - 2r \sin \theta = 0$$

$$r = 2 \sin \theta.$$

14.7

$$x = r \cos \theta \quad y = r \sin \theta \quad z = z$$



So

$$0 \leq \theta \leq \pi$$

$$0 \leq r \leq 2 \sin \theta$$

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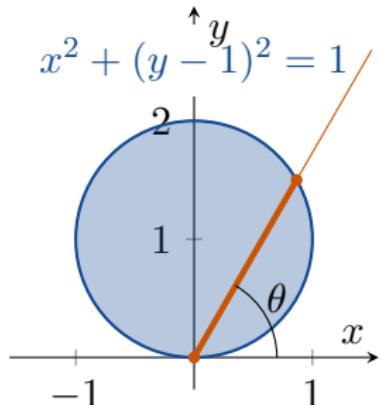
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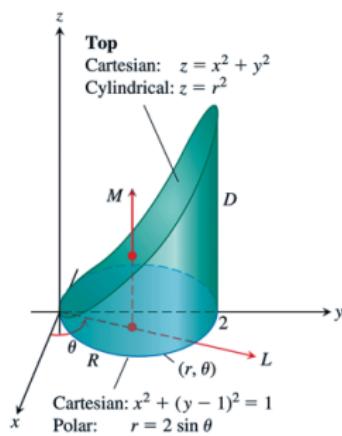
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$$x^2 + y^2 - 2y + 1 = 1$$

$$r^2 - 2r \sin \theta = 0$$

$$r = 2 \sin \theta.$$



$$0 \leq z \leq x^2 + y^2 = r^2$$

14.7

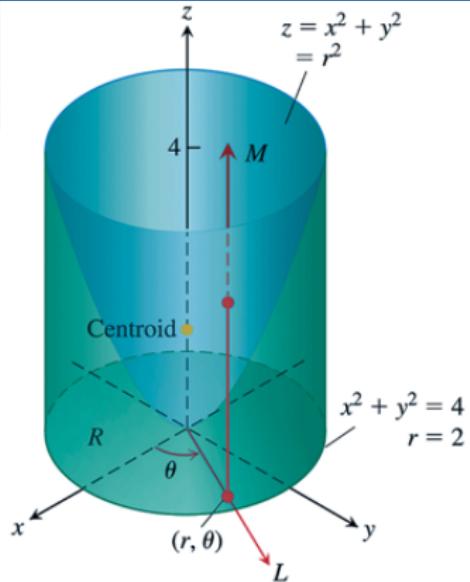
$$dV = dx dy dz = r dr d\theta dz$$



$$0 \leq \theta \leq \pi \quad 0 \leq r \leq 2 \sin \theta \quad 0 \leq z \leq r^2$$

Therefore

$$\iiint_D F(r, \theta, z) dV = \int_0^\pi \int_0^{2 \sin \theta} \int_0^{r^2} F(r, \theta, z) \textcolor{red}{r} dz dr d\theta.$$

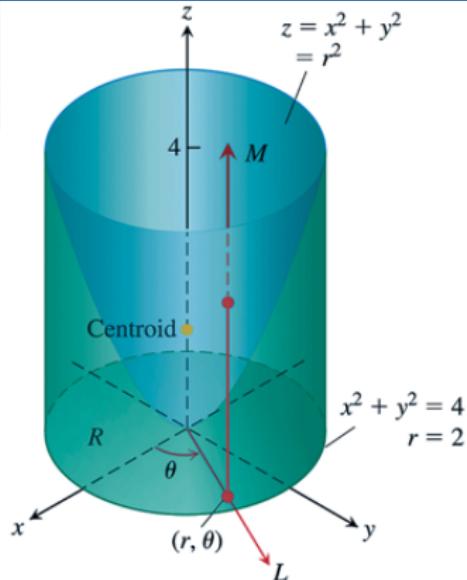


Example

Calculate

$$\iiint_D z \, dV$$

where D is the region enclosed by the cylinder $x^2 + y^2 = 4$, the xy -plane and the paraboloid $z = x^2 + y^2$.



$$0 \leq \theta \leq 2\pi$$

$$0 \leq r \leq 2$$

$$0 \leq z \leq r^2.$$

Example

Calculate

$$\iiint_D z \, dV$$

where D is the region enclosed by the cylinder $x^2 + y^2 = 4$, the xy -plane and the paraboloid $z = x^2 + y^2$.

14.7

$$dV = dx dy dz = r dr d\theta dz$$



$$0 \leq \theta \leq 2\pi \quad 0 \leq r \leq 2 \quad 0 \leq z \leq r^2$$

Therefore

$$\iiint_D z \, dV = \int_0^{2\pi} \int_0^2 \int_0^{r^2} z \, r \, dz \, dr \, d\theta$$

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14.7

$$dV = dx dy dz = r dr d\theta dz$$



$$0 \leq \theta \leq 2\pi \quad 0 \leq r \leq 2 \quad 0 \leq z \leq r^2$$

Therefore

$$\begin{aligned} \iiint_D z \, dV &= \int_0^{2\pi} \int_0^2 \int_0^{r^2} zr \, dz dr d\theta \\ &= \int_0^{2\pi} \int_0^2 \left[\frac{1}{2}z^2 r \right]_{z=0}^{z=r^2} dr d\theta \\ &= \end{aligned}$$

 $=$
 $=$
 $=$
 $= \quad .$

14.7

$$dV = dx dy dz = r dr d\theta dz$$



$$0 \leq \theta \leq 2\pi \quad 0 \leq r \leq 2 \quad 0 \leq z \leq r^2$$

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$$= \quad = \quad .$$

14.7

$$dV = dx dy dz = r dr d\theta dz$$



$$0 \leq \theta \leq 2\pi \quad 0 \leq r \leq 2 \quad 0 \leq z \leq r^2$$

Therefore

$$\begin{aligned}
 \iiint_D z \, dV &= \int_0^{2\pi} \int_0^2 \int_0^{r^2} zr \, dz dr d\theta \\
 &= \int_0^{2\pi} \int_0^2 \left[\frac{1}{2}z^2 r \right]_{z=0}^{z=r^2} dr d\theta \\
 &= \int_0^{2\pi} \int_0^2 \frac{1}{2}r^5 dr d\theta \\
 &= \int_0^{2\pi} \left[\frac{1}{12}r^6 \right]_0^2 d\theta \\
 &= \dots
 \end{aligned}$$

14.7

$$dV = dx dy dz = r dr d\theta dz$$



$$0 \leq \theta \leq 2\pi \quad 0 \leq r \leq 2 \quad 0 \leq z \leq r^2$$

Therefore

$$\begin{aligned}
 \iiint_D z \, dV &= \int_0^{2\pi} \int_0^2 \int_0^{r^2} zr \, dz dr d\theta \\
 &= \int_0^{2\pi} \int_0^2 \left[\frac{1}{2}z^2 r \right]_{z=0}^{z=r^2} dr d\theta \\
 &= \int_0^{2\pi} \int_0^2 \frac{1}{2}r^5 dr d\theta \\
 &= \int_0^{2\pi} \left[\frac{1}{12}r^6 \right]_0^2 d\theta \\
 &= \int_0^{2\pi} \frac{16}{3} d\theta = .
 \end{aligned}$$

14.7

$$dV = dx dy dz = r dr d\theta dz$$



$$0 \leq \theta \leq 2\pi \quad 0 \leq r \leq 2 \quad 0 \leq z \leq r^2$$

Therefore

$$\begin{aligned} \iiint_D z \, dV &= \int_0^{2\pi} \int_0^2 \int_0^{r^2} zr \, dz dr d\theta \\ &= \int_0^{2\pi} \int_0^2 \left[\frac{1}{2}z^2 r \right]_{z=0}^{z=r^2} dr d\theta \\ &= \int_0^{2\pi} \int_0^2 \frac{1}{2}r^5 dr d\theta \\ &= \int_0^{2\pi} \left[\frac{1}{12}r^6 \right]_0^2 d\theta \\ &= \int_0^{2\pi} \frac{16}{3} d\theta = \frac{32\pi}{3}. \end{aligned}$$

14.7 Triple Integrals in Cylindrical and Spherical Coordinates



Spherical Coordinates in \mathbb{R}^3

$$x = r \cos \theta = \rho \sin \phi \cos \theta$$

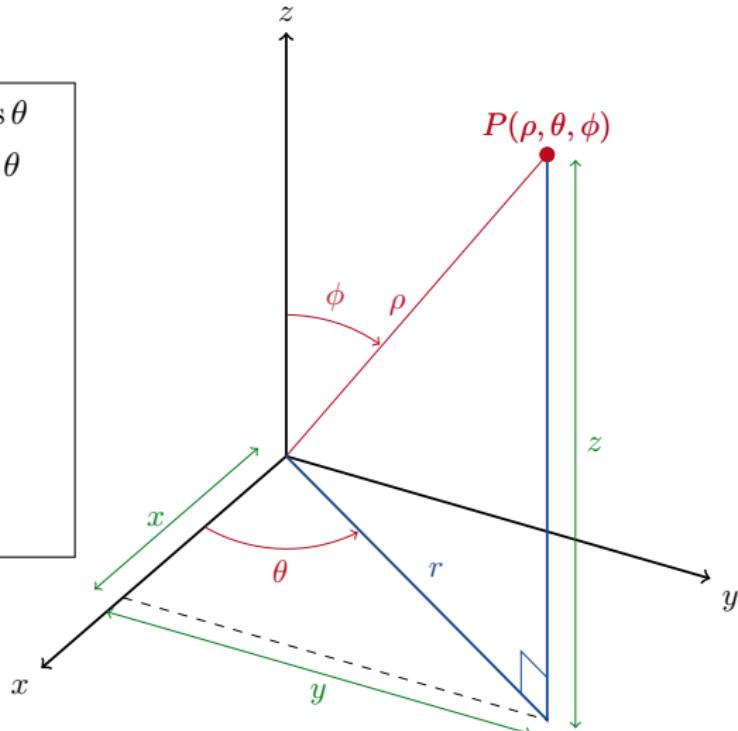
$$y = r \sin \theta = \rho \sin \phi \sin \theta$$

$$z = \rho \cos \phi$$

$$r = \rho \sin \phi$$

$$\tan \theta = \frac{y}{x}$$

$$\begin{aligned}\rho &= \sqrt{x^2 + y^2 + z^2} \\ &= \sqrt{r^2 + z^2}\end{aligned}$$



14.7 Triple Integrals in Cylindrical and Spherical Coordinates



Spherical Coordinates in \mathbb{R}^3

$$x = r \cos \theta = \rho \sin \phi \cos \theta$$

$$y = r \sin \theta = \rho \sin \phi \sin \theta$$

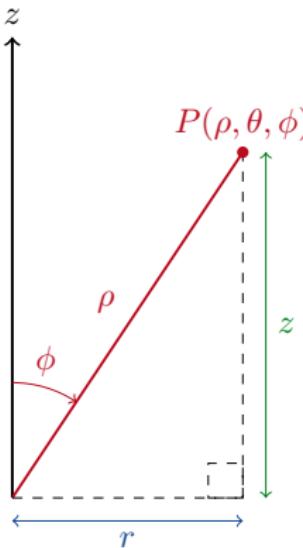
$$z = \rho \cos \phi$$

$$r = \rho \sin \phi$$

$$\tan \theta = \frac{y}{x}$$

$$\rho = \sqrt{x^2 + y^2 + z^2}$$

$$= \sqrt{r^2 + z^2}$$



Typically, we require that $\rho \geq 0$ and $0 \leq \phi \leq \pi$. As before, θ can be any number.

14.7

$$\rho = \sqrt{r^2 + z^2} \quad \theta = \theta \quad z = \rho \cos \phi$$



Example

Convert the point $P(\sqrt{6}, \frac{\pi}{4}, \sqrt{2})$ from cylindrical to spherical coordinates.

14.7

$$\rho = \sqrt{r^2 + z^2} \quad \theta = \theta \quad z = \rho \cos \phi$$



Example

Convert the point $P(\sqrt{6}, \frac{\pi}{4}, \sqrt{2})$ from cylindrical to spherical coordinates.

We have that $r = \sqrt{6}$, $\theta = \frac{\pi}{4}$ and $z = \sqrt{2}$. Therefore

$$\begin{aligned} (\rho, \theta, \phi) &= \left(\sqrt{r^2 + z^2}, \theta, \cos^{-1} \frac{z}{\rho} \right) \\ &= \left(\sqrt{6+2}, \frac{\pi}{4}, \cos^{-1} \frac{\sqrt{2}}{\rho} \right) \\ &= \left(2\sqrt{2}, \frac{\pi}{4}, \cos^{-1} \frac{\sqrt{2}}{2\sqrt{2}} \right) \\ &= \left(2\sqrt{2}, \frac{\pi}{4}, \cos^{-1} \frac{1}{2} \right) = \left(2\sqrt{2}, \frac{\pi}{4}, \frac{\pi}{3} \right). \end{aligned}$$

14.7

$$\rho = \sqrt{x^2 + y^2 + z^2} \quad y = \rho \sin \phi \sin \theta \quad z = \rho \cos \phi$$



Example

Convert the point $P(-1, 1, -\sqrt{2})$ from Cartesian to spherical polar coordinates.

$$\rho = \sqrt{x^2 + y^2 + z^2} \quad y = \rho \sin \phi \sin \theta \quad z = \rho \cos \phi$$

Example

Convert the point $P(-1, 1, -\sqrt{2})$ from Cartesian to spherical polar coordinates.

First we calculate that

$$\rho = \sqrt{x^2 + y^2 + z^2} = \sqrt{(-1)^2 + 1^2 + (-\sqrt{2})^2} = \sqrt{4} = 2.$$

Next we calculate that

$$\phi = \cos^{-1} \frac{z}{\rho} = \cos^{-1} \frac{-\sqrt{2}}{2} = \frac{3\pi}{4}$$

because we want $\phi \in [0, \pi]$.

14.7

$$\rho = \sqrt{x^2 + y^2 + z^2} \quad y = \rho \sin \phi \sin \theta \quad z = \rho \cos \phi$$



Finally we need a θ .

$$\sin \theta = \frac{y}{\rho \sin \phi} = \frac{1}{2 \left(\frac{\sqrt{2}}{2} \right)} = \frac{1}{\sqrt{2}}.$$

There are infinitely many θ that satisfy this equation. Two possible θ are $\theta = \frac{\pi}{4}$ and $\theta = \frac{3\pi}{4}$.

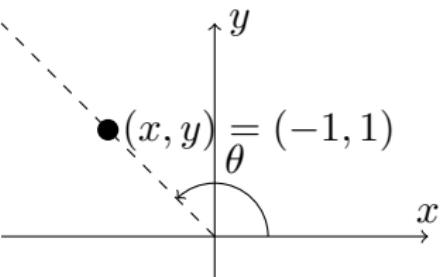
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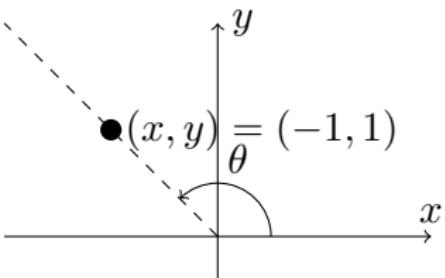
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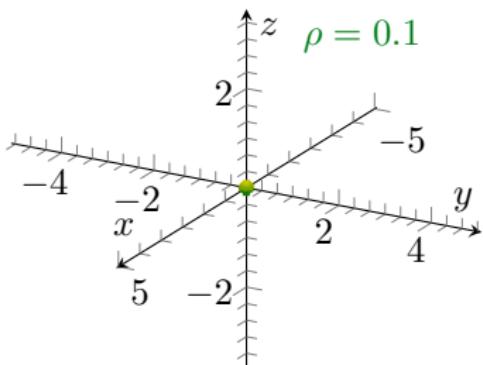
There are infinitely many θ that satisfy this equation. Two possible θ are $\theta = \frac{\pi}{4}$ and $\theta = \frac{3\pi}{4}$. Only one of these can be correct.



Therefore the answer is

$$(\rho, \theta, \phi) = \left(2, \frac{3\pi}{4}, \frac{3\pi}{4} \right).$$

14.7 Triple Integrals in Cylindrical and Spherical Coordinates

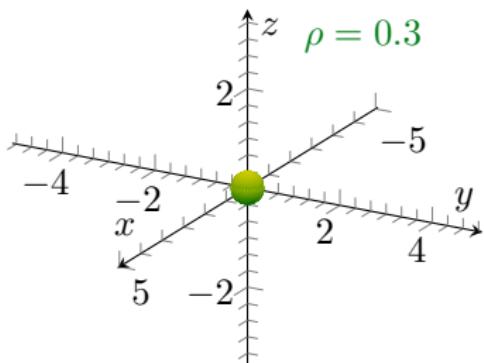


Remark

Spherical coordinates are good for describing:

- spheres centred at the origin ($\rho = \rho_0$);
- cones (with vertex at the origin and axis on the z -axis) ($\phi = \phi_0$); and
- half planes containing the z -axis ($\theta = \theta_0$).

14.7 Triple Integrals in Cylindrical and Spherical Coordinates

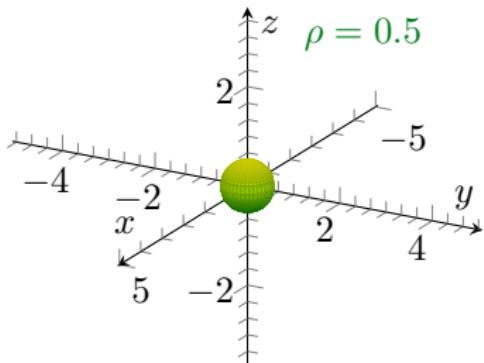


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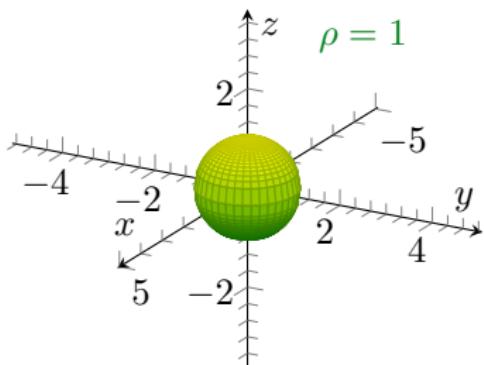


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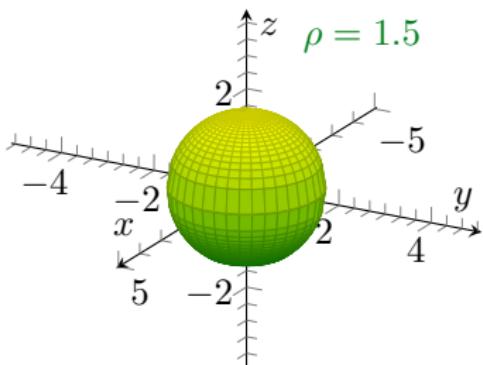


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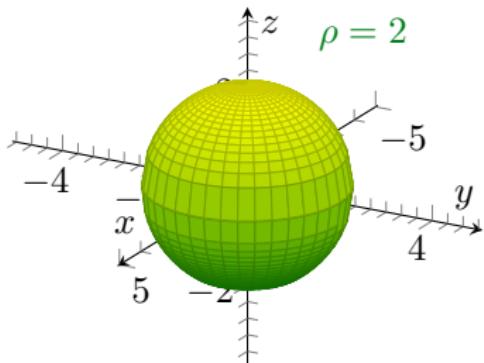


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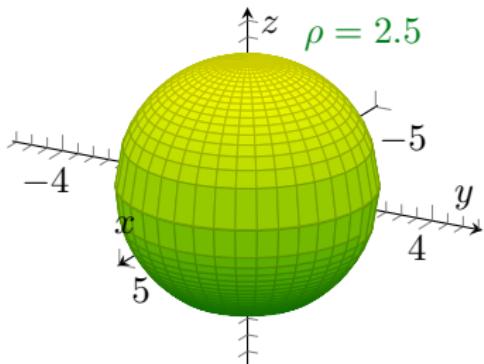


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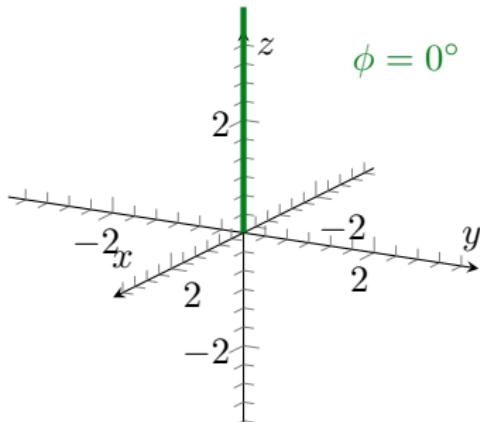


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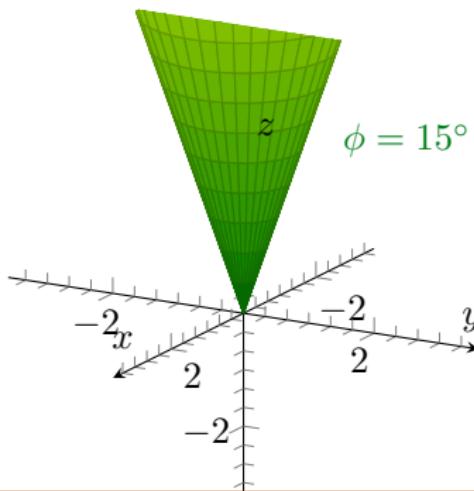


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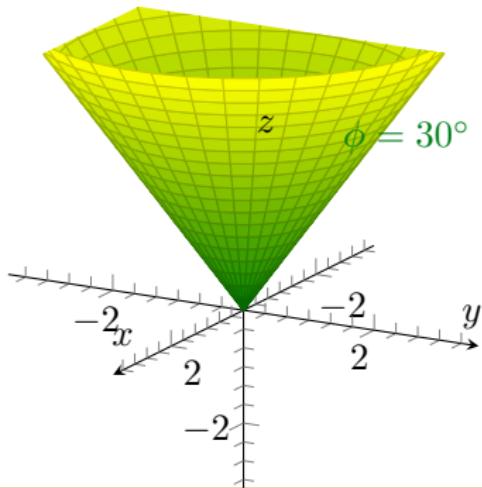


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14.7 Triple Integrals in Cylindrical and Spherical Coordinates

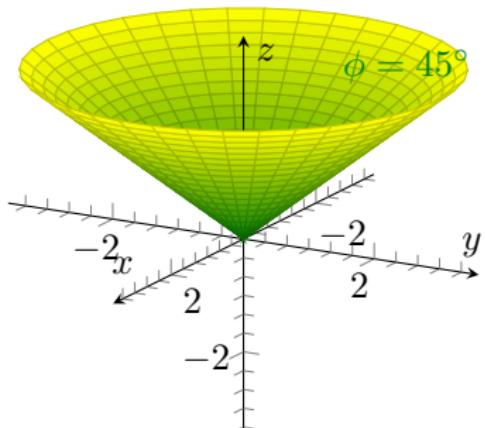


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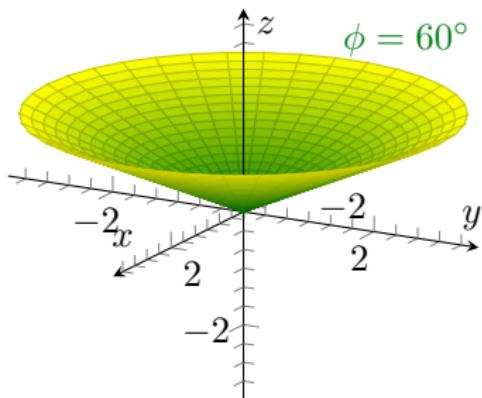


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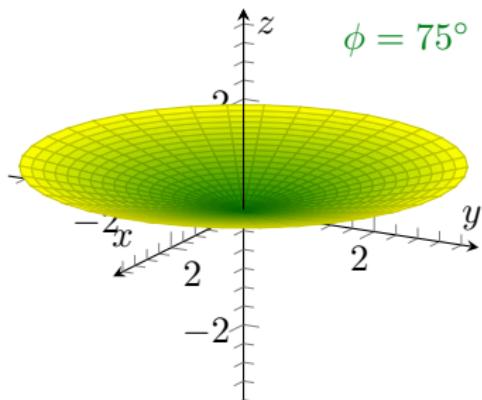


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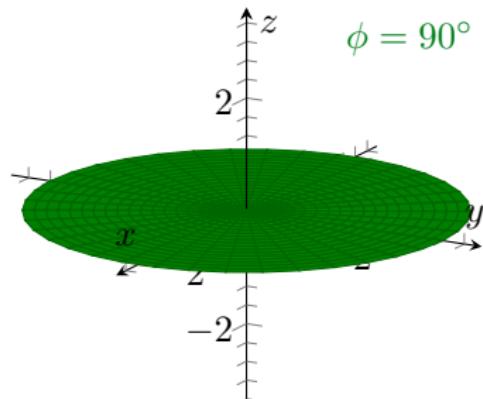


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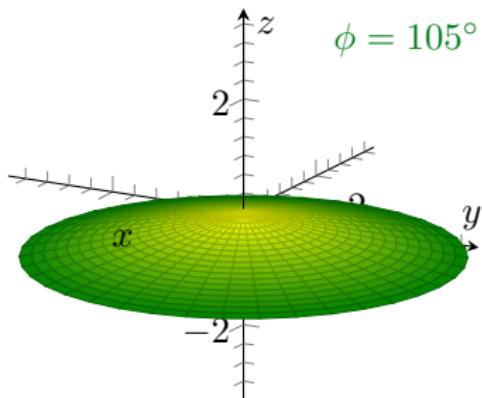


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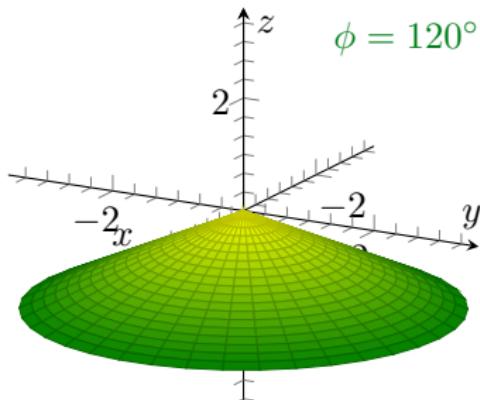


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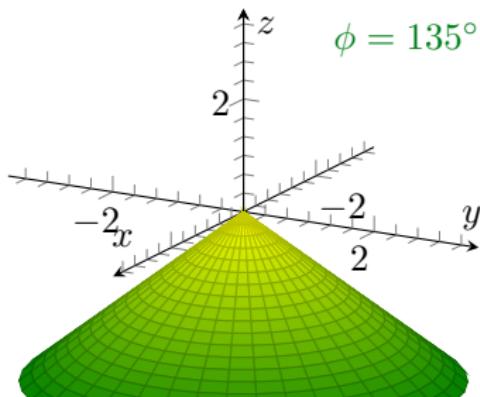


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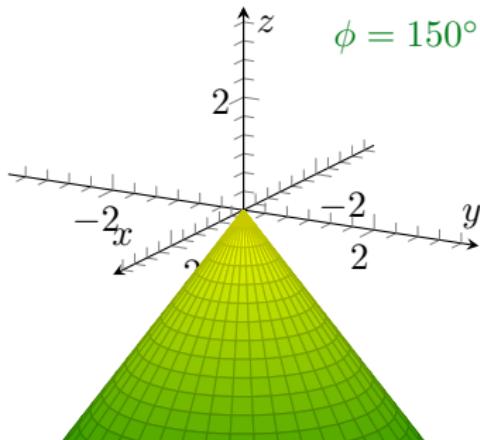


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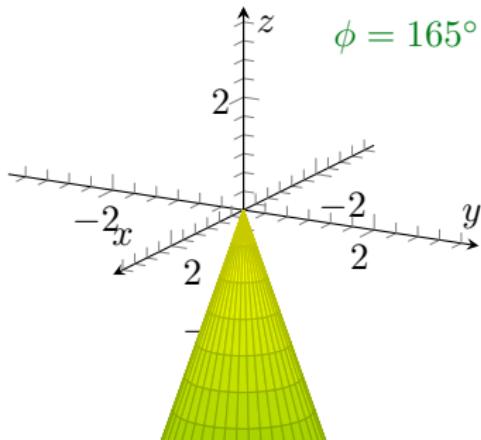


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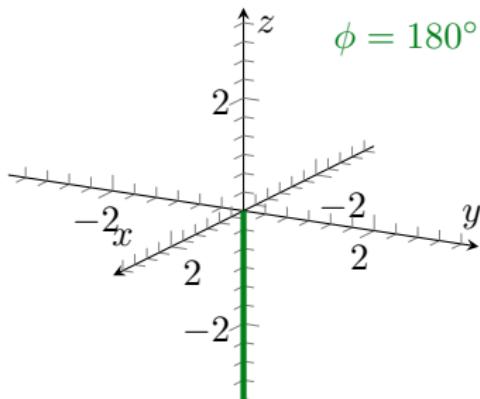


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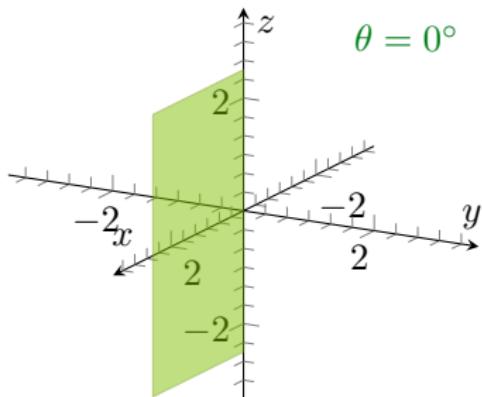


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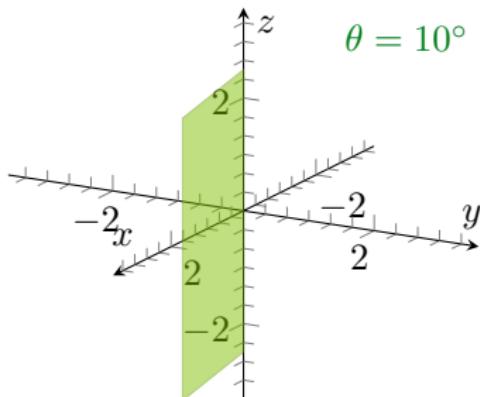


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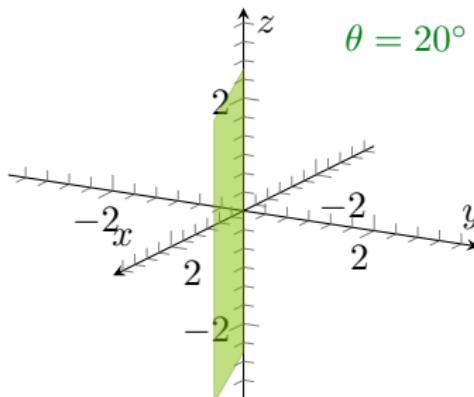


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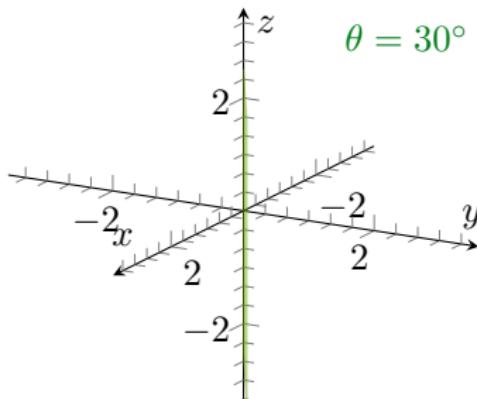


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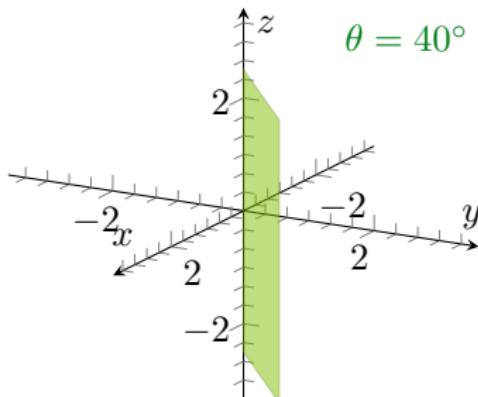


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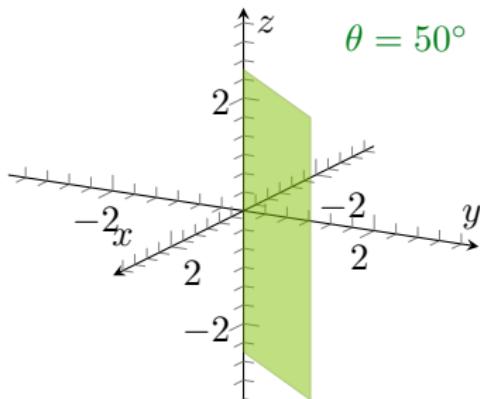


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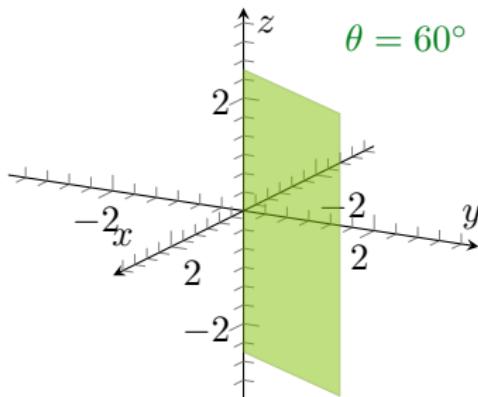


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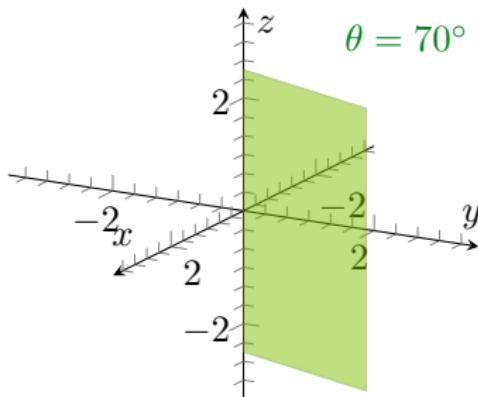


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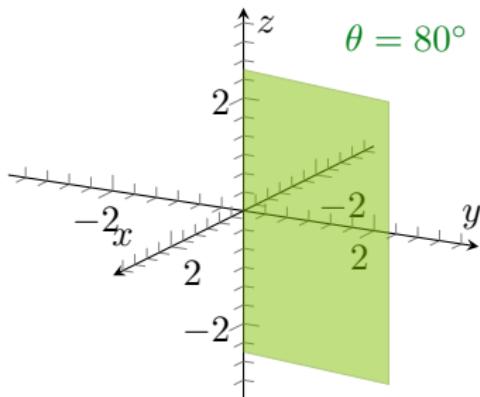


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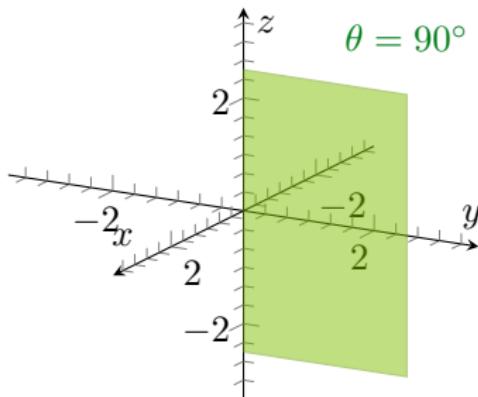


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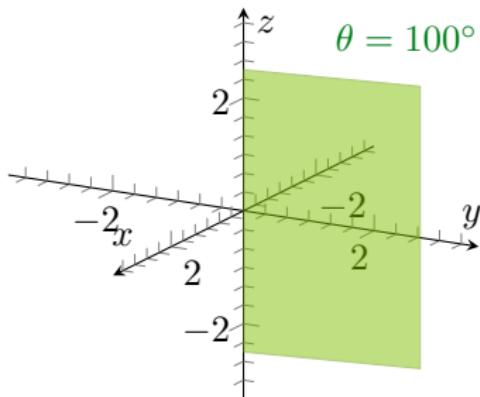


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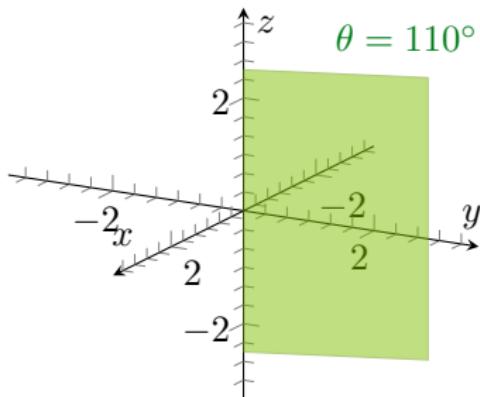


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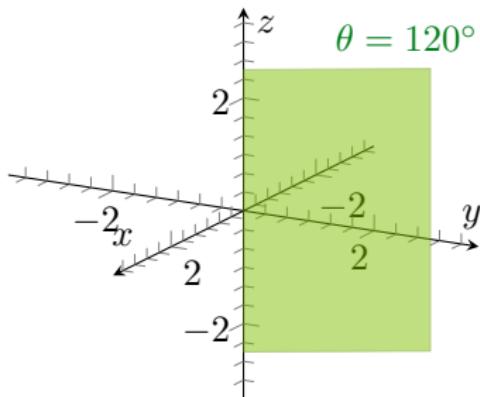


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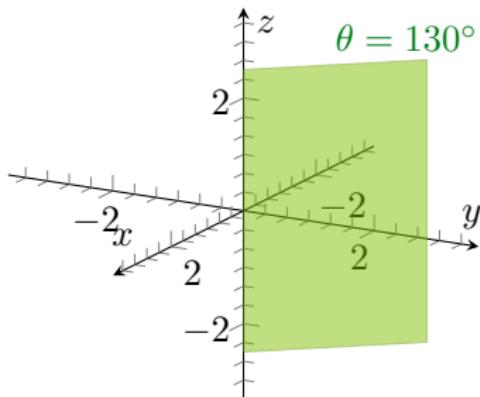


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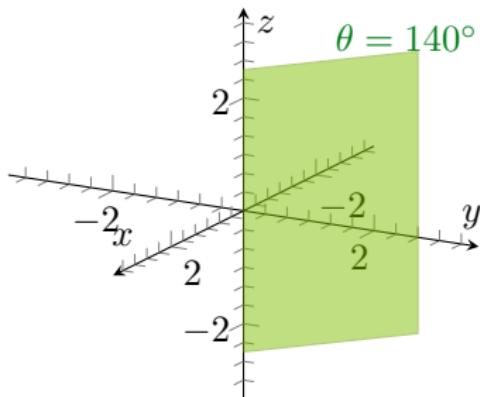


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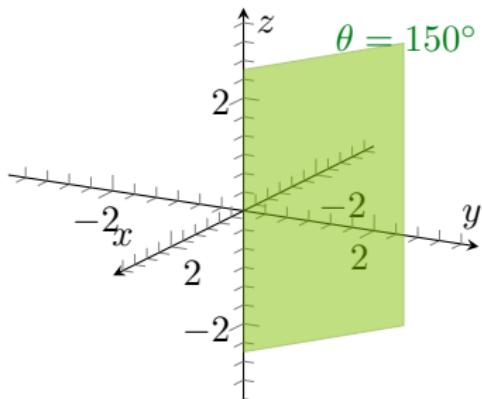


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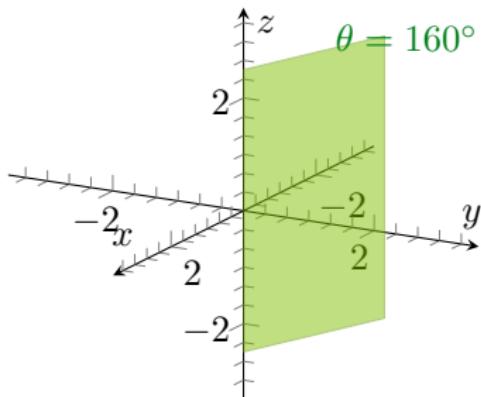


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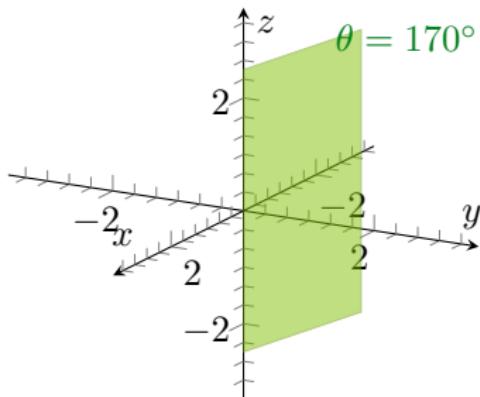


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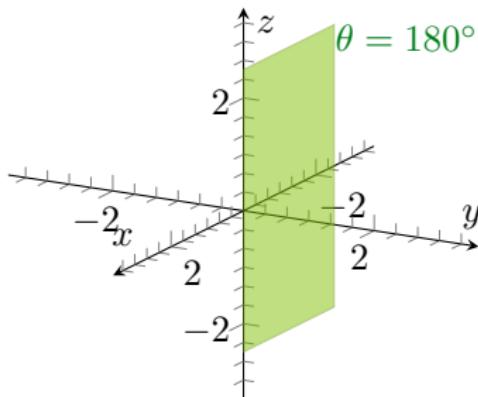


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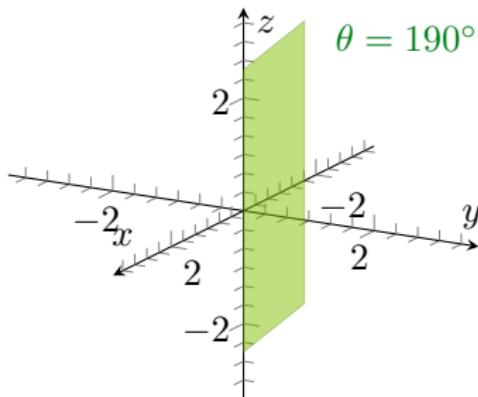


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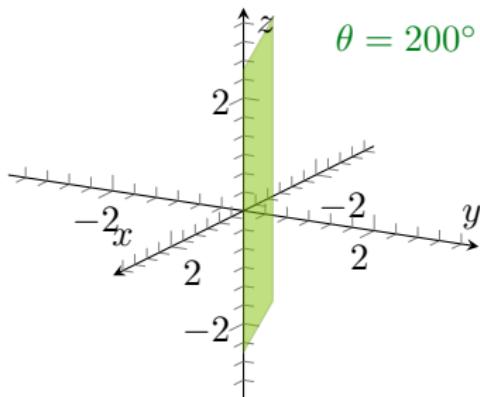


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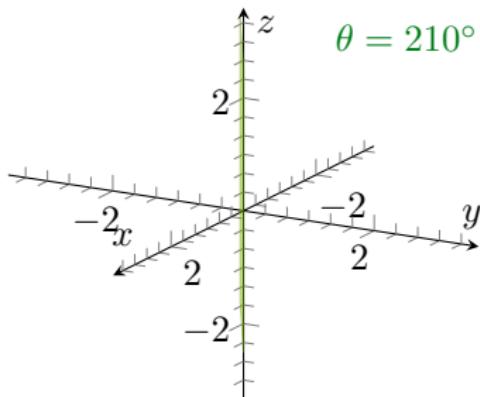


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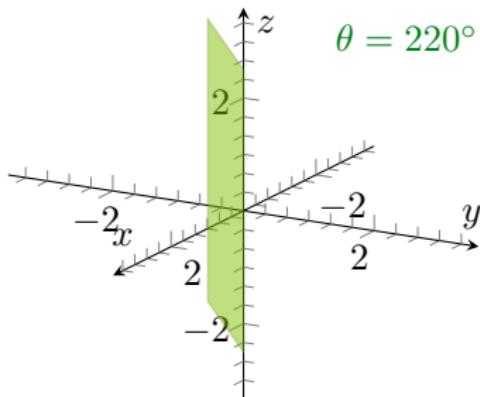


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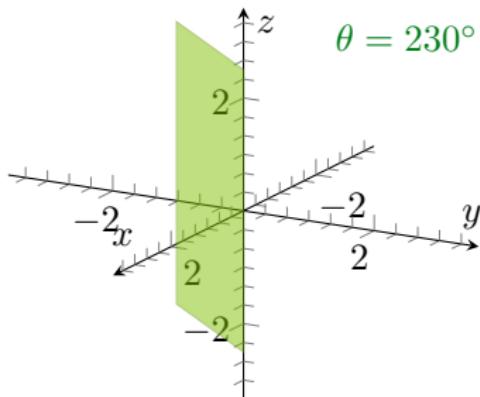


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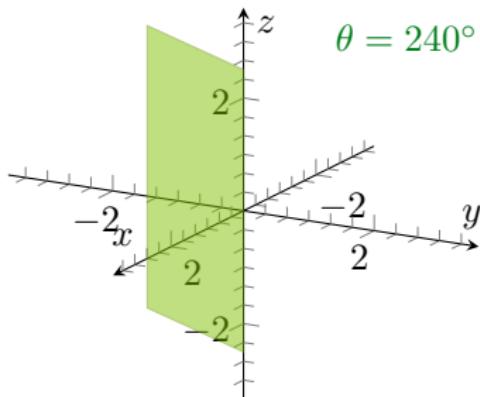


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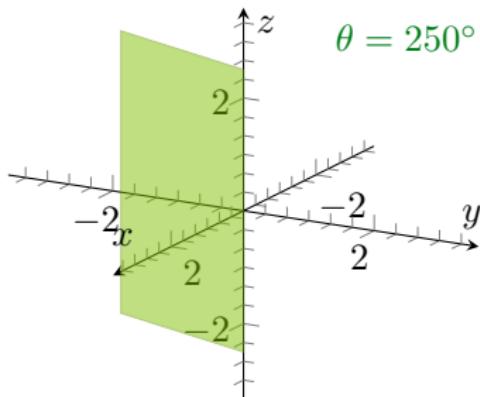


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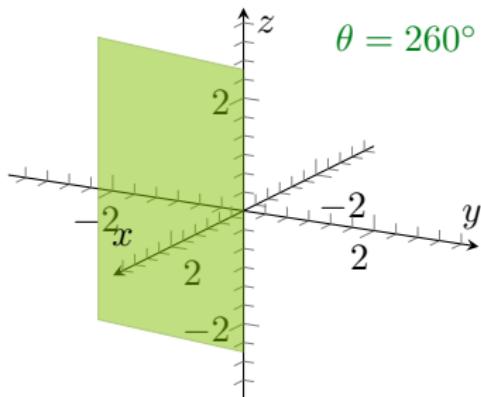


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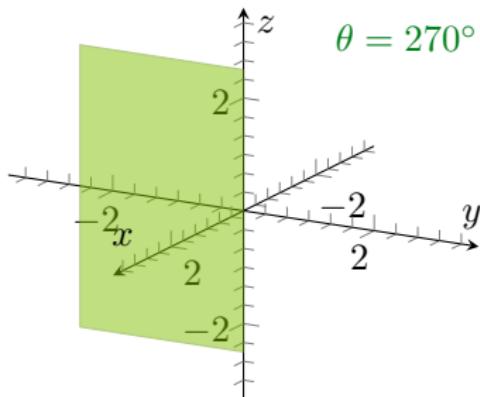


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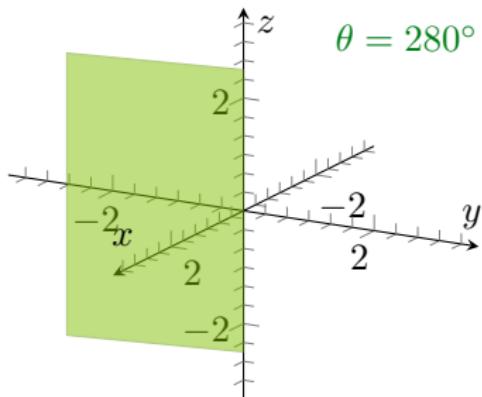


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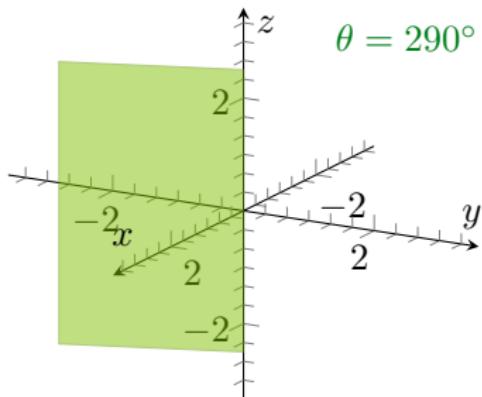


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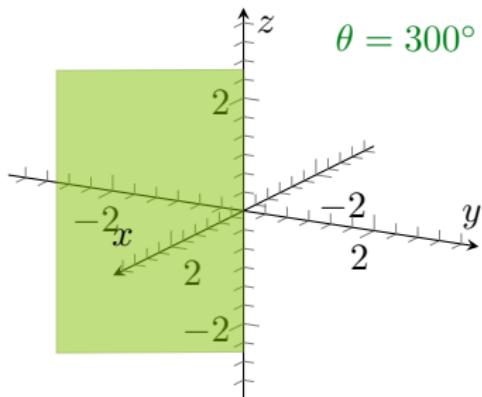


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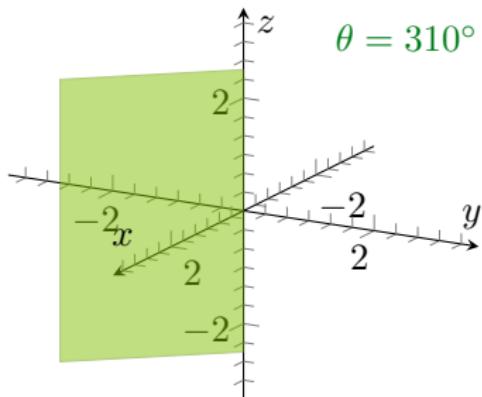


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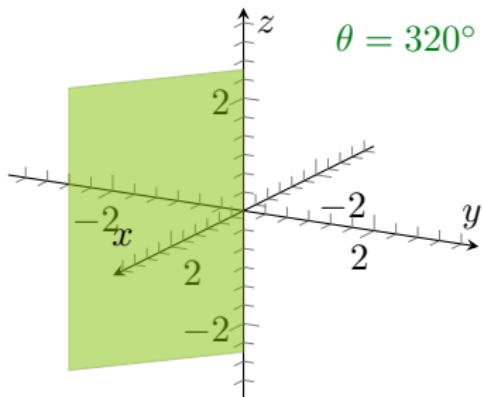


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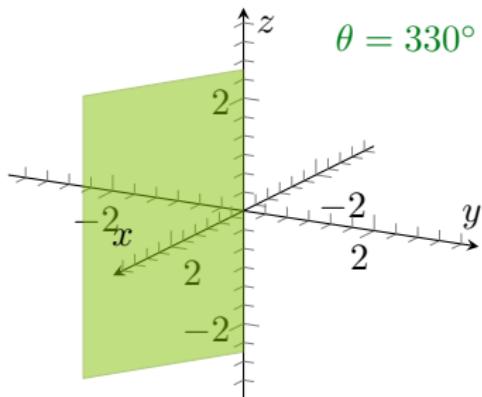


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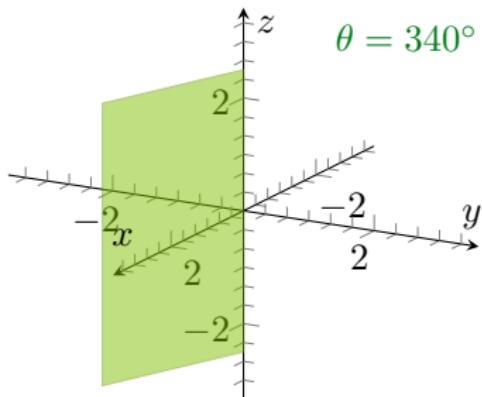


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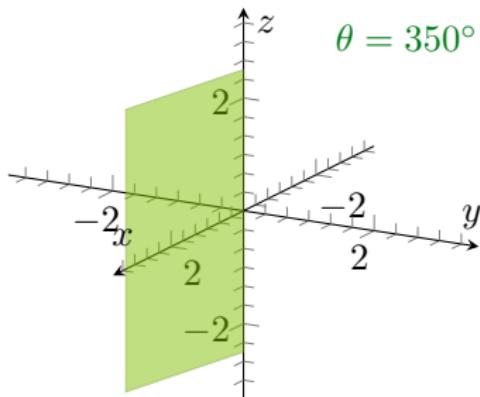


Remark

Spherical coordinates are good for describing:

- spheres centred at the origin ($\rho = \rho_0$);
- cones (with vertex at the origin and axis on the z -axis) ($\phi = \phi_0$); and
- half planes containing the z -axis ($\theta = \theta_0$).

14.7 Triple Integrals in Cylindrical and Spherical Coordinates



Remark

Spherical coordinates are good for describing:

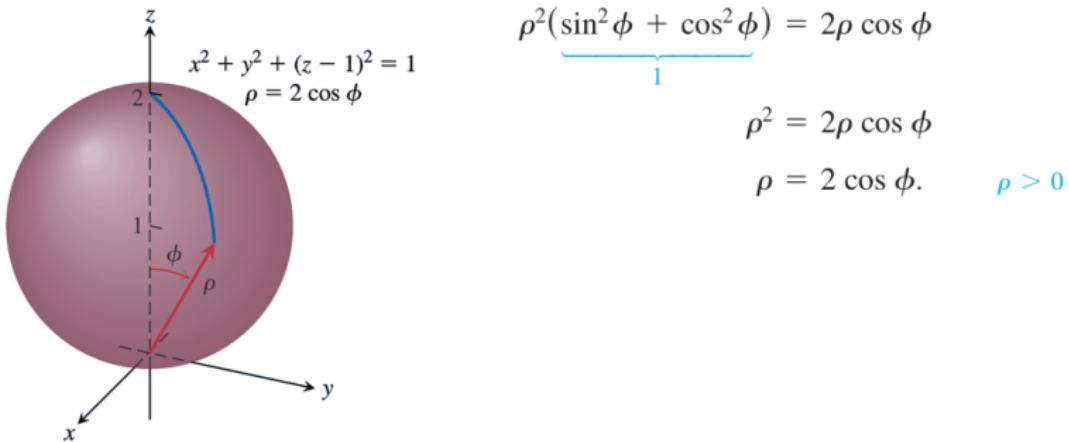
- spheres centred at the origin ($\rho = \rho_0$);
- cones (with vertex at the origin and axis on the z -axis) ($\phi = \phi_0$); and
- half planes containing the z -axis ($\theta = \theta_0$).

$$x = \rho \sin \phi \cos \theta \quad y = \rho \sin \phi \sin \theta \quad z = \rho \cos \phi$$

EXAMPLE 3 Find a spherical coordinate equation for the sphere $x^2 + y^2 + (z - 1)^2 = 1$.

Solution We use Equations (1) to substitute for x , y , and z :

$$\begin{aligned} x^2 + y^2 + (z - 1)^2 &= 1 \\ \rho^2 \sin^2 \phi \cos^2 \theta + \rho^2 \sin^2 \phi \sin^2 \theta + (\rho \cos \phi - 1)^2 &= 1 && \text{Eqs. (1)} \\ \underbrace{\rho^2 \sin^2 \phi (\cos^2 \theta + \sin^2 \theta) + \rho^2 \cos^2 \phi - 2\rho \cos \phi + 1}_{1} &= 1 \end{aligned}$$



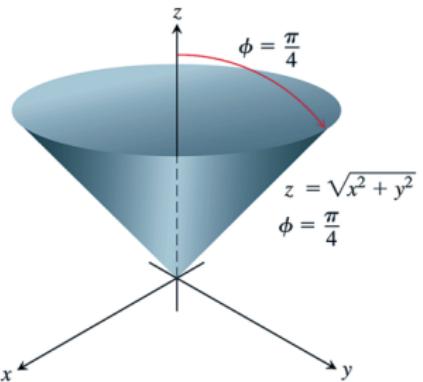
$$\begin{aligned} \rho^2 (\sin^2 \phi + \cos^2 \phi) &= 2\rho \cos \phi \\ \underbrace{\rho^2}_{1} &= 2\rho \cos \phi \\ \rho &= 2 \cos \phi. && \rho > 0 \end{aligned}$$

$$x = \rho \sin \phi \cos \theta \quad y = \rho \sin \phi \sin \theta \quad z = \rho \cos \phi$$

EXAMPLE 4 Find a spherical coordinate equation for the cone $z = \sqrt{x^2 + y^2}$.

Solution 1 *Use geometry.* The cone is symmetric with respect to the z -axis and cuts the first quadrant of the yz -plane along the line $z = y$. The angle between the cone and the positive z -axis is therefore $\pi/4$ radians. The cone consists of the points whose spherical coordinates have ϕ equal to $\pi/4$, so its equation is $\phi = \pi/4$. (See Figure 15.54.)

Solution 2 *Use algebra.* If we use Equations (1) to substitute for x , y , and z we obtain the same result:



$$z = \sqrt{x^2 + y^2}$$

$$\rho \cos \phi = \sqrt{\rho^2 \sin^2 \phi}$$

$$\rho \cos \phi = \rho \sin \phi$$

$$\cos \phi = \sin \phi$$

Example 3

$\rho > 0, \sin \phi \geq 0$

$$\phi = \frac{\pi}{4}.$$

$0 \leq \phi \leq \pi$



14.7 Triple Integrals in Cylindrical and Spherical Coordinates



Theorem

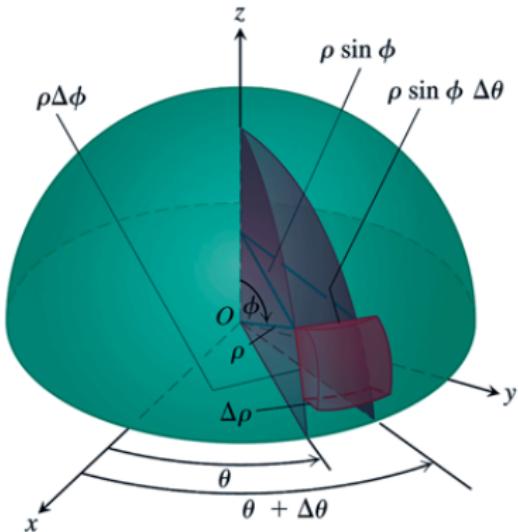
$$dV = dx dy dz = r dr d\theta dz = .$$

14.7 Triple Integrals in Cylindrical and Spherical Coordinates



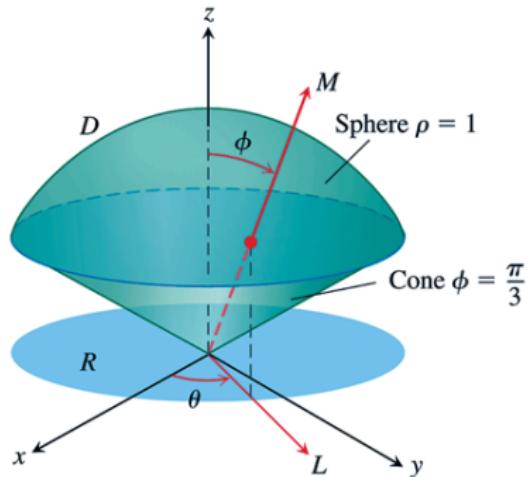
Theorem

$$dV = dxdydz = r \, dr d\theta dz = \rho^2 \sin \phi \, d\rho d\phi d\theta.$$



14.7

$$dV = \rho^2 \sin \phi \, d\rho d\phi d\theta$$

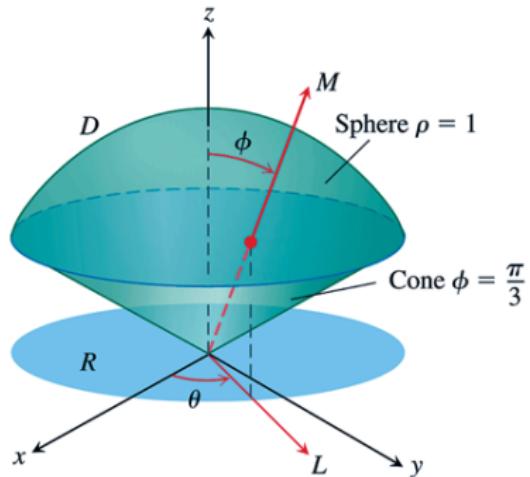


Example

Calculate the volume of the region enclosed by the sphere $\phi = 1$ and the cone $\phi = \frac{\pi}{3}$.

14.7

$$dV = \rho^2 \sin \phi \, d\rho d\phi d\theta$$



$$0 \leq \theta \leq 2\pi$$

$$0 \leq \phi \leq \frac{\pi}{3}$$

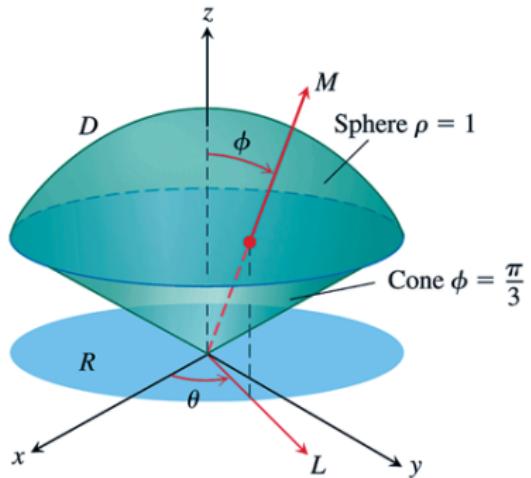
$$0 \leq \rho \leq 1.$$

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14.7

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$$0 \leq \theta \leq 2\pi$$

$$0 \leq \phi \leq \frac{\pi}{3}$$

$$0 \leq \rho \leq 1.$$

Example

Calculate the volume of the region enclosed by the sphere $\phi = 1$ and the cone $\phi = \frac{\pi}{3}$.

$$\iiint_D dV = \int_0^{2\pi} \int_0^{\frac{\pi}{3}} \int_0^1 \rho^2 \sin \phi \, d\rho d\phi d\theta = \dots = \frac{\pi}{3}.$$

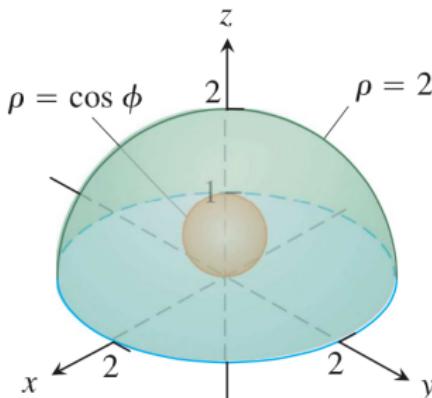
14.7 Triple Integrals in Cylindrical and Spherical Coordinates

Example

Find the limits of integration for the region shown below: The region is bounded by $\rho = 2$ and the xy -plane, but the sphere $\rho = \cos \phi$ has been removed from this large hemisphere.

A $0 \leq \theta \leq 2\pi$
 $0 \leq \phi \leq \pi$
 $0 \leq \rho \leq 2$

B $0 \leq \theta \leq 2\pi$
 $0 \leq \phi \leq \frac{\pi}{2}$
 $0 \leq \rho \leq 2$



C $0 \leq \theta \leq 2\pi$
 $0 \leq \phi \leq \frac{\pi}{2}$
 $\cos \phi \leq \rho \leq 2$

D $0 \leq \theta \leq \pi$
 $0 \leq \phi \leq 2$
 $2 \leq \rho \leq \cos \phi$

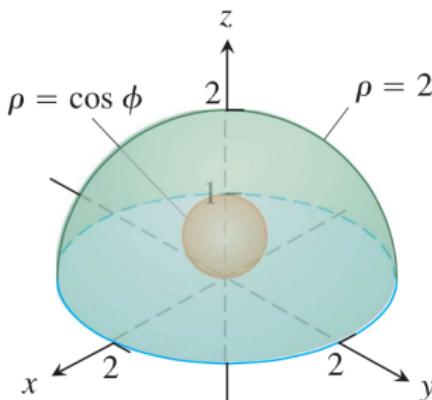
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 $\cos \phi \leq \rho \leq 2$

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 $0 \leq \phi \leq 2$
 $2 \leq \rho \leq \cos \phi$

Coordinate Conversion Formulas

CYLINDRICAL TO RECTANGULAR

$$x = r \cos \theta$$

$$y = r \sin \theta$$

$$z = z$$

SPHERICAL TO RECTANGULAR

$$x = \rho \sin \phi \cos \theta$$

$$y = \rho \sin \phi \sin \theta$$

$$z = \rho \cos \phi$$

SPHERICAL TO CYLINDRICAL

$$r = \rho \sin \phi$$

$$z = \rho \cos \phi$$

$$\theta = \theta$$

Corresponding formulas for dV in triple integrals:

$$\begin{aligned} dV &= dx \, dy \, dz \\ &= dz \, r \, dr \, d\theta \\ &= \rho^2 \sin \phi \, d\rho \, d\phi \, d\theta \end{aligned}$$



Substitutions in Multiple Integrals

Substitutions in Single Integrals

You know that if we write $u = 2x + 3$ then $du = 2 dx$ and

$$\int_0^1 2\sqrt{2x+3} dx = \int_3^5 \sqrt{u} du.$$

14.8 Substitutions in Multiple Integrals



Substitutions in Single Integrals

You know that if we write $u = 2x + 3$ then $du = 2 dx$ and

$$\int_0^1 2\sqrt{2x+3} dx = \int_3^5 \sqrt{u} du.$$

Substitutions in Double Integrals

We are going to do the same thing for substitutions in double integrals.

14.8 Substitutions in Multiple Integrals



Carl Gustav Jacob Jacobi

BORN

10 December 1804

DECEASED

18 February 1851

NATIONALITY

German

Definition

The *Jacobian* of the coordinate transformation $x = g(u, v)$, $y = h(u, v)$ is

$$J(u, v) = \frac{\partial(x, y)}{\partial(u, v)} = \begin{vmatrix} \frac{\partial x}{\partial u} & \frac{\partial x}{\partial v} \\ \frac{\partial y}{\partial u} & \frac{\partial y}{\partial v} \end{vmatrix} = \frac{\partial x}{\partial u} \frac{\partial y}{\partial v} - \frac{\partial x}{\partial v} \frac{\partial y}{\partial u}.$$

14.8

$$\frac{\partial(x, y)}{\partial(u, v)} = \frac{\partial x}{\partial u} \frac{\partial y}{\partial v} - \frac{\partial x}{\partial v} \frac{\partial y}{\partial u}$$



Example

Find the Jacobian of the polar coordinate transformation
 $x = r \cos \theta$ and $y = r \sin \theta$.

14.8

$$\frac{\partial(x, y)}{\partial(u, v)} = \frac{\partial x}{\partial u} \frac{\partial y}{\partial v} - \frac{\partial x}{\partial v} \frac{\partial y}{\partial u}$$



Example

Find the Jacobian of the polar coordinate transformation
 $x = r \cos \theta$ and $y = r \sin \theta$.

$$\frac{\partial(x, y)}{\partial(r, \theta)} = \frac{\partial x}{\partial r} \frac{\partial y}{\partial \theta} - \frac{\partial x}{\partial \theta} \frac{\partial y}{\partial r}$$

=

=

14.8

$$\frac{\partial(x, y)}{\partial(u, v)} = \frac{\partial x}{\partial u} \frac{\partial y}{\partial v} - \frac{\partial x}{\partial v} \frac{\partial y}{\partial u}$$



Example

Find the Jacobian of the polar coordinate transformation
 $x = r \cos \theta$ and $y = r \sin \theta$.

$$\begin{aligned}\frac{\partial(x, y)}{\partial(r, \theta)} &= \frac{\partial x}{\partial r} \frac{\partial y}{\partial \theta} - \frac{\partial x}{\partial \theta} \frac{\partial y}{\partial r} \\ &= (\cos \theta) (r \cos \theta) - (-r \sin \theta) (\sin \theta) \\ &= r.\end{aligned}$$

14.8

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Remark

Remember that

$$dxdy = r dr d\theta.$$

14.8 Substitutions in Multiple Integrals



Theorem

Suppose that $f(x, y)$ is continuous over the region R . Let G be the preimage of R under the transformation $x = g(u, v)$, $y = h(u, v)$, which is assumed to be one-to-one on the interior of G . If the functions g and h have continuous first partial derivatives within the interior of G , then

$$\iint_R f(x, y) \, dxdy = \iint_G f(g(u, v), h(u, v)) \left| \frac{\partial(x, y)}{\partial(u, v)} \right| \, dudv.$$

14.8 Substitutions in Multiple Integrals



Theorem

Suppose that $f(x, y)$ is continuous over the region R . Let G be the preimage of R under the transformation $x = g(u, v)$, $y = h(u, v)$, which is assumed to be one-to-one on the interior of G . If the functions g and h have continuous first partial derivatives within the interior of G , then

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14.8 Substitutions in Multiple Integrals



Example

Calculate

$$\int_0^4 \int_{\frac{y}{2}}^{\frac{y}{2}+1} \frac{2x - y}{2} dx dy$$

by applying the transformation

$$u = \frac{2x - y}{2}, \quad v = \frac{y}{2}$$

and integrating over an appropriate region in the uv -plane.

14.8 Substitutions in Multiple Integrals



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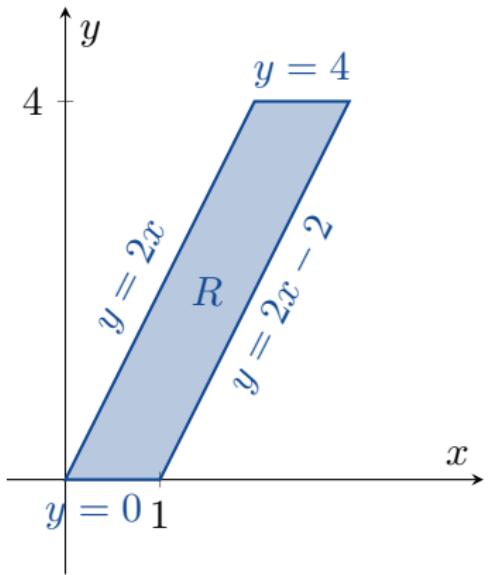
$$u = \frac{2x - y}{2}, \quad v = \frac{y}{2}$$

and integrating over an appropriate region in the uv -plane.

$$0 \leq y \leq 4 \quad \text{and} \quad \frac{y}{2} \leq x \leq \frac{y}{2} + 1$$

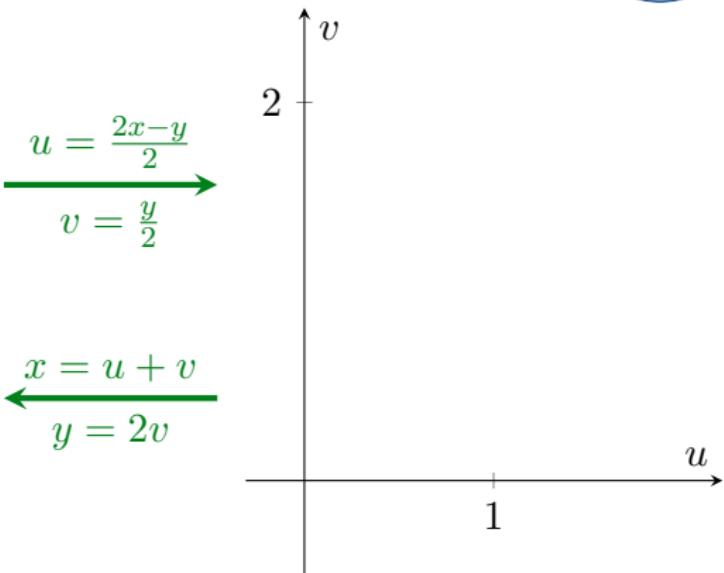
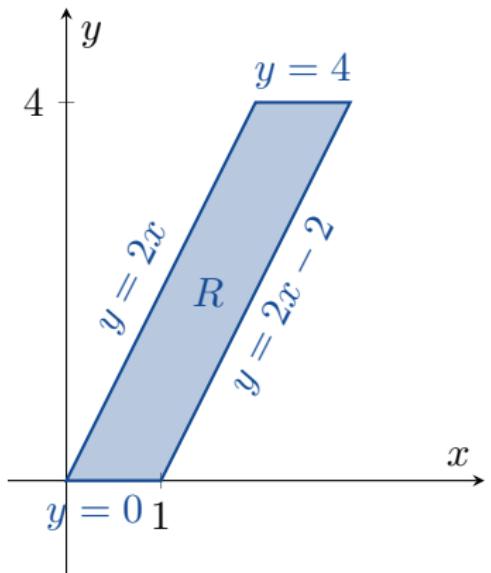
14.8

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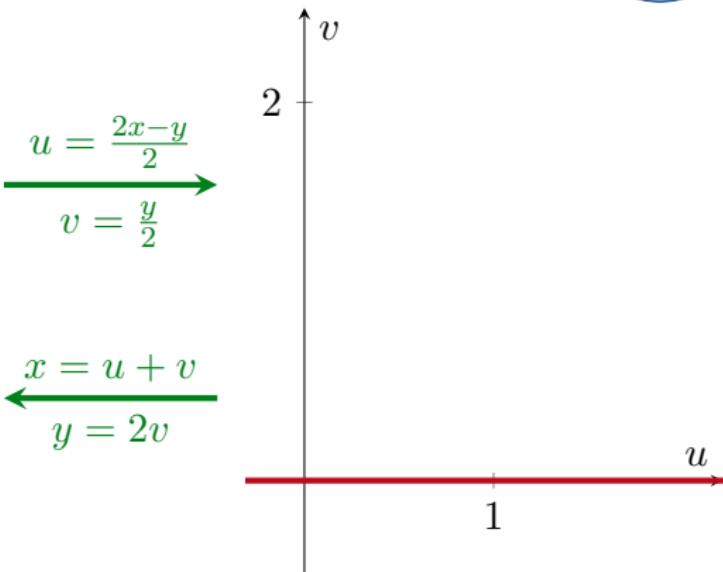
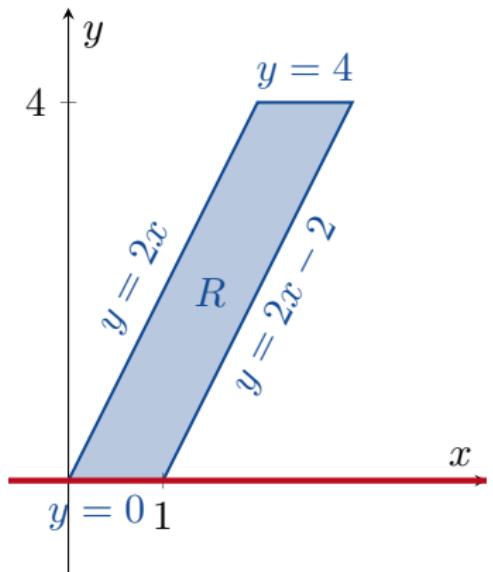
14.8

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14.8

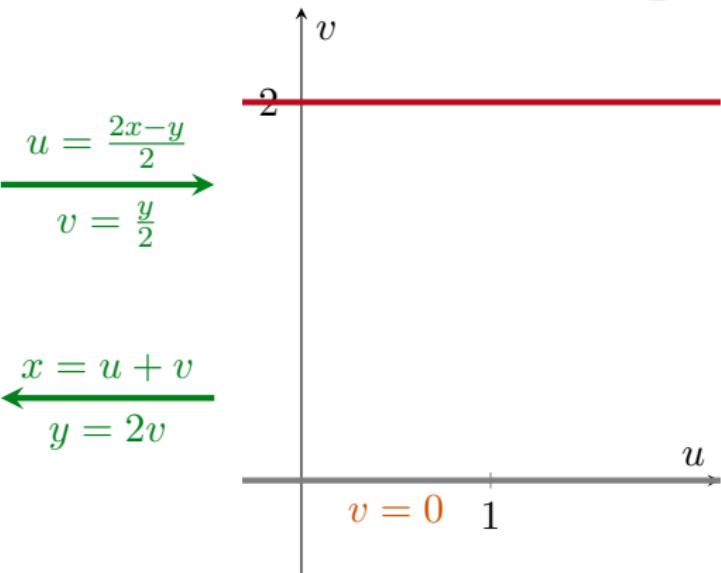
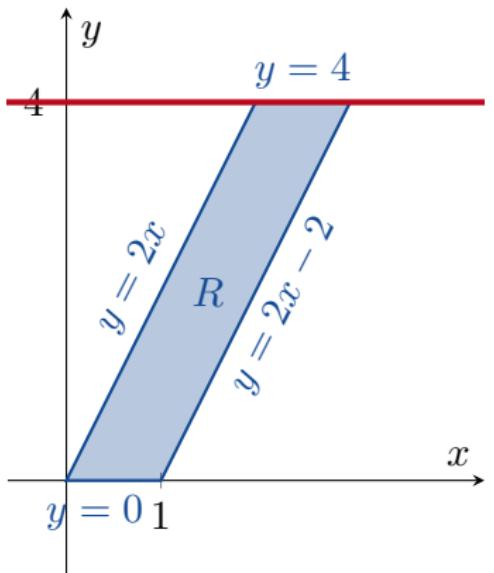
$$0 \leq y \leq 4 \quad \text{and} \quad \frac{y}{2} \leq x \leq \frac{y}{2} + 1$$



$$y = 0 \quad \Rightarrow \quad v = \frac{y}{2} = 0$$

14.8

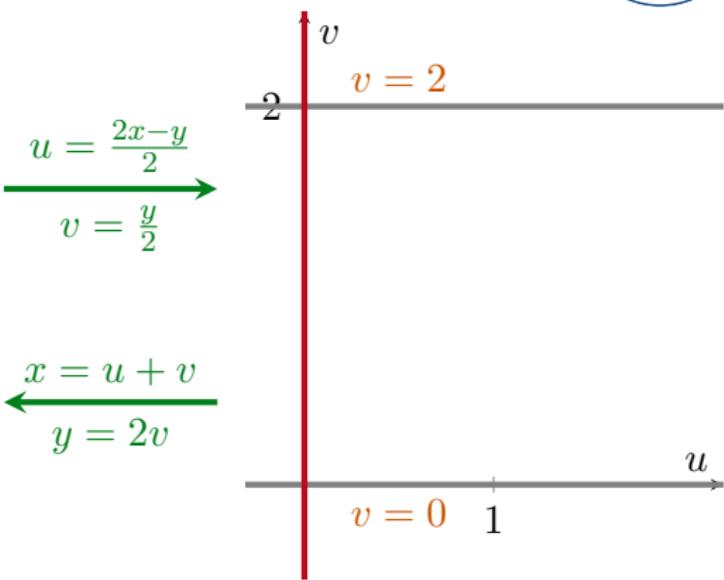
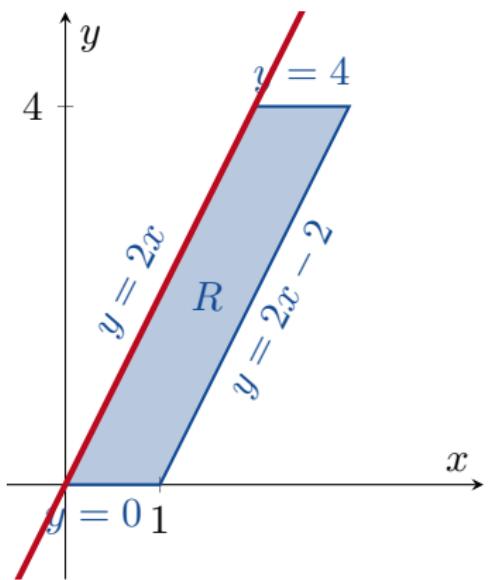
$$0 \leq y \leq 4 \quad \text{and} \quad \frac{y}{2} \leq x \leq \frac{y}{2} + 1$$



$$y = 4 \quad \Rightarrow \quad v = \frac{y}{2} = 2$$

14.8

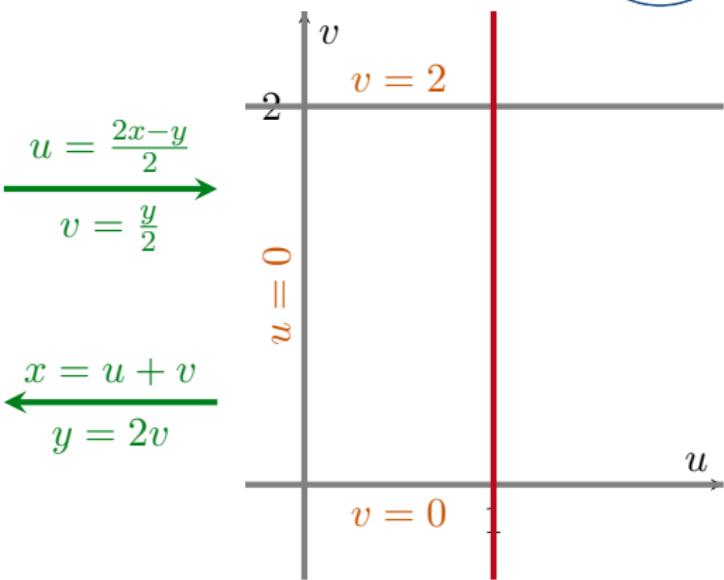
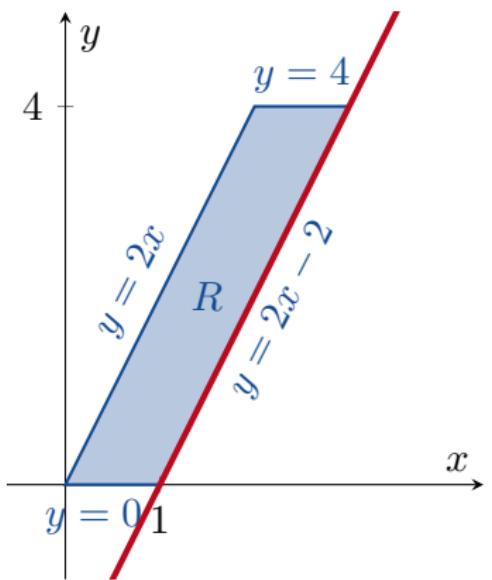
$$0 \leq y \leq 4 \quad \text{and} \quad \frac{y}{2} \leq x \leq \frac{y}{2} + 1$$



$$y = 2x \implies u = \frac{2x - y}{2} = \frac{2x - 2x}{2} = 0$$

14.8

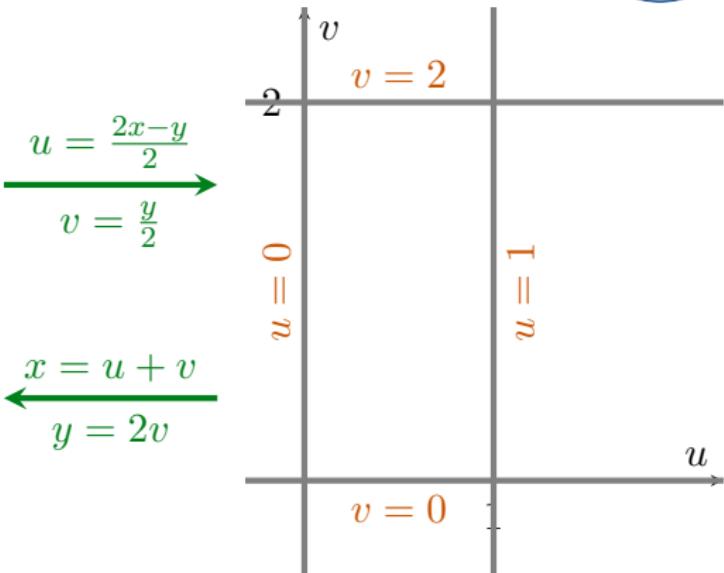
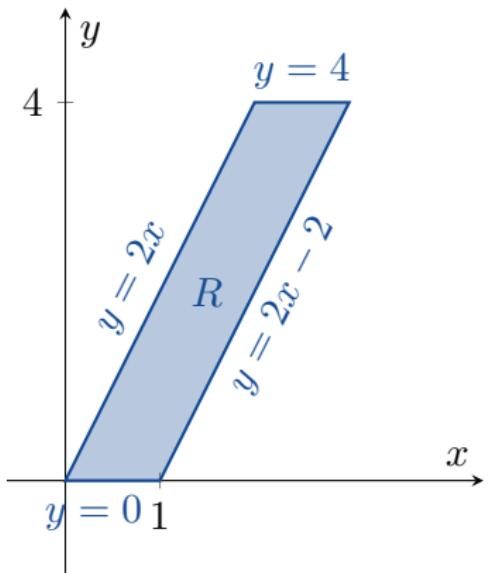
$$0 \leq y \leq 4 \quad \text{and} \quad \frac{y}{2} \leq x \leq \frac{y}{2} + 1$$



$$y = 2x - 2 \quad \Rightarrow \quad u = \frac{2x - y}{2} = \frac{2x - 2x + 2}{2} = 1$$

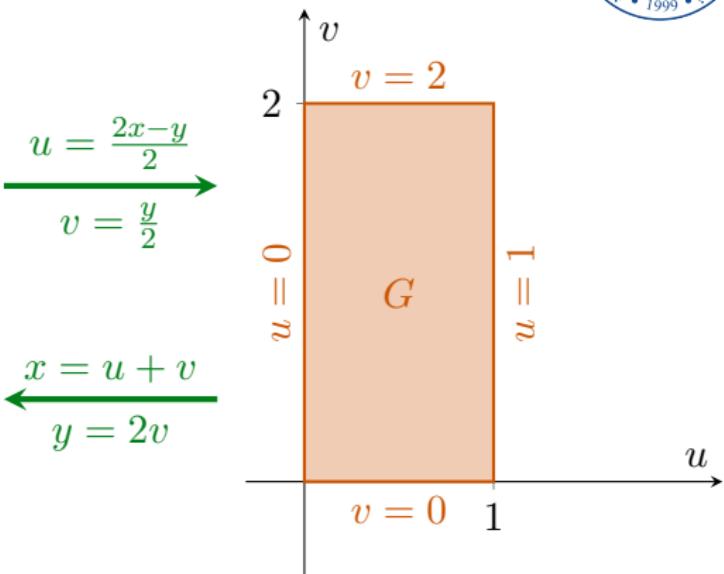
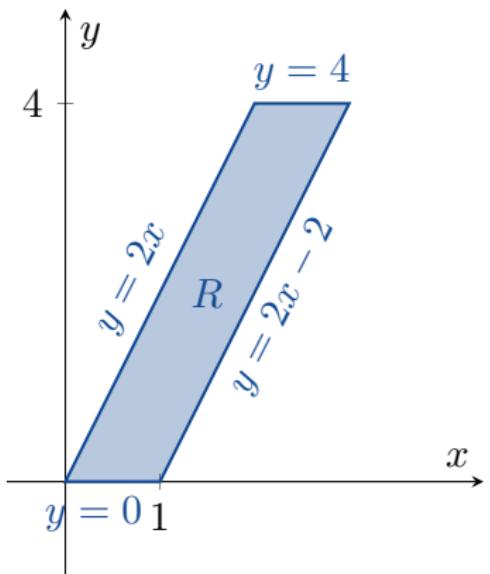
14.8

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14.8

$$0 \leq y \leq 4 \quad \text{and} \quad \frac{y}{2} \leq x \leq \frac{y}{2} + 1$$



$$0 \leq u \leq 1 \quad \text{and} \quad 0 \leq v \leq 2$$

14.8

$$\frac{\partial(x, y)}{\partial(u, v)} = \frac{\partial x}{\partial u} \frac{\partial y}{\partial v} - \frac{\partial x}{\partial v} \frac{\partial y}{\partial u}$$



$$x = u + v \quad \text{and} \quad y = 2v$$

Next we need the Jacobian of this coordinate transformation:

14.8

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Next we need the Jacobian of this coordinate transformation:

$$\begin{aligned}\frac{\partial(x, y)}{\partial(u, v)} &= \frac{\partial x}{\partial u} \frac{\partial y}{\partial v} - \frac{\partial x}{\partial v} \frac{\partial y}{\partial u} \\ &= (1)(2) - (1)(0) = 2.\end{aligned}$$

14.8 Substitutions in Multiple Integrals



$$u = \frac{2x - y}{2}, \quad v = \frac{y}{2}$$

$$0 \leq u \leq 1 \quad 0 \leq v \leq 2 \quad \frac{\partial(x, y)}{\partial(u, v)} = 2$$

Therefore

$$\int_0^4 \int_{\frac{y}{2}}^{\frac{y}{2}+1} \frac{2x - y}{2} dx dy =$$

14.8 Substitutions in Multiple Integrals



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Therefore

$$\int_0^4 \int_{\frac{y}{2}}^{\frac{y}{2}+1} \frac{2x - y}{2} dx dy = \int_0^2 \int_0^1 u \left| \frac{\partial(x, y)}{\partial(u, v)} \right| du dv$$

14.8 Substitutions in Multiple Integrals



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$$\begin{aligned} \int_0^4 \int_{\frac{y}{2}}^{\frac{y}{2}+1} \frac{2x - y}{2} dx dy &= \int_0^2 \int_0^1 u \left| \frac{\partial(x, y)}{\partial(u, v)} \right| du dv \\ &= \int_0^2 \int_0^1 2u du dv \end{aligned}$$

14.8 Substitutions in Multiple Integrals



$$u = \frac{2x - y}{2}, \quad v = \frac{y}{2}$$

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Therefore

$$\begin{aligned} \int_0^4 \int_{\frac{y}{2}}^{\frac{y}{2}+1} \frac{2x - y}{2} dx dy &= \int_0^2 \int_0^1 u \left| \frac{\partial(x, y)}{\partial(u, v)} \right| du dv \\ &= \int_0^2 \int_0^1 2u du dv = \dots = 2. \end{aligned}$$

14.8 Substitutions in Multiple Integrals



Remark

To do a substitution, we need to do two things:

- 1 Calculate the Jacobian and write $dxdy = \left| \frac{\partial(x, y)}{\partial(u, v)} \right| dudv;$

and

- 2 change the limits of integration.

14.8

$$\frac{\partial(x, y)}{\partial(u, v)} = \frac{\partial x}{\partial u} \frac{\partial y}{\partial v} - \frac{\partial x}{\partial v} \frac{\partial y}{\partial u}$$



Example

Calculate $\int_0^1 \int_0^{1-x} \sqrt{x+y}(y-2x)^2 dy dx$.

14.8

$$\frac{\partial(x, y)}{\partial(u, v)} = \frac{\partial x}{\partial u} \frac{\partial y}{\partial v} - \frac{\partial x}{\partial v} \frac{\partial y}{\partial u}$$



Example

Calculate $\int_0^1 \int_0^{1-x} \sqrt{x+y}(y-2x)^2 dy dx$.

First we need to choose u and v .

14.8

$$\frac{\partial(x, y)}{\partial(u, v)} = \frac{\partial x}{\partial u} \frac{\partial y}{\partial v} - \frac{\partial x}{\partial v} \frac{\partial y}{\partial u}$$



Example

Calculate $\int_0^1 \int_0^{1-x} \sqrt{x+y}(y-2x)^2 dydx.$

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Calculate $\int_0^1 \int_0^{1-x} \sqrt{x+y}(y-2x)^2 dy dx.$

First we need to choose u and v . I choose

$$u = x + y \quad \text{and} \quad v = y - 2x.$$

We can rearrange these to

$$x = \frac{u}{3} - \frac{v}{3} \quad \text{and} \quad y = \frac{2u}{3} + \frac{v}{3}.$$

14.8

$$\frac{\partial(x, y)}{\partial(u, v)} = \frac{\partial x}{\partial u} \frac{\partial y}{\partial v} - \frac{\partial x}{\partial v} \frac{\partial y}{\partial u}$$



Example

Calculate $\int_0^1 \int_0^{1-x} \sqrt{x+y}(y-2x)^2 dydx.$

First we need to choose u and v . I choose

$$u = x + y \quad \text{and} \quad v = y - 2x.$$

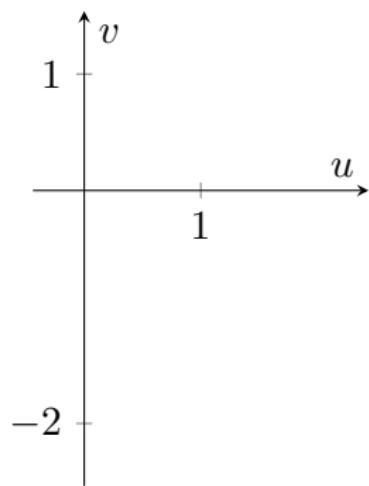
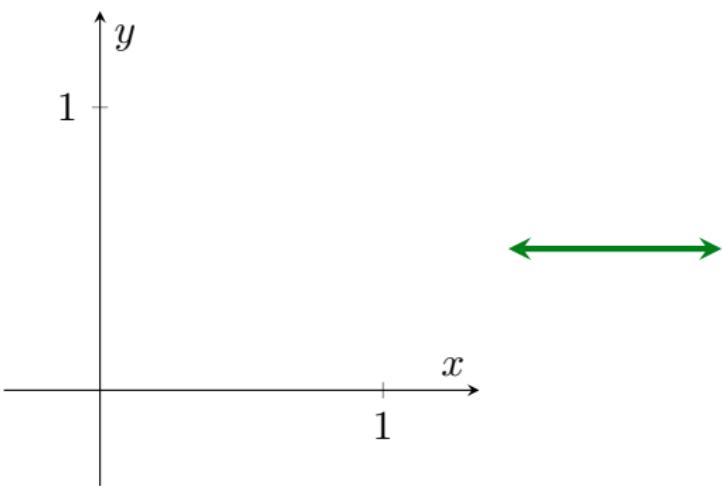
We can rearrange these to

$$x = \frac{u}{3} - \frac{v}{3} \quad \text{and} \quad y = \frac{2u}{3} + \frac{v}{3}.$$

Then the Jacobian is

$$\frac{\partial(x, y)}{\partial(u, v)} = \frac{\partial x}{\partial u} \frac{\partial y}{\partial v} - \frac{\partial x}{\partial v} \frac{\partial y}{\partial u} = \left(\frac{1}{3}\right) \left(\frac{1}{3}\right) - \left(-\frac{1}{3}\right) \left(\frac{2}{3}\right) = \frac{1}{3}.$$

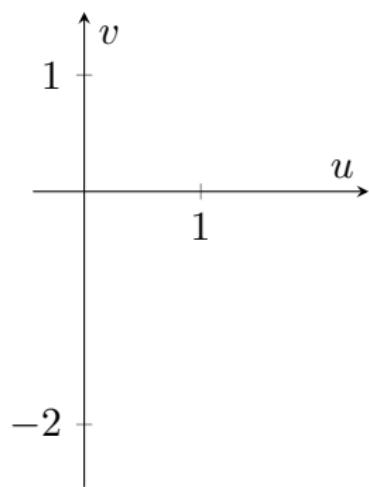
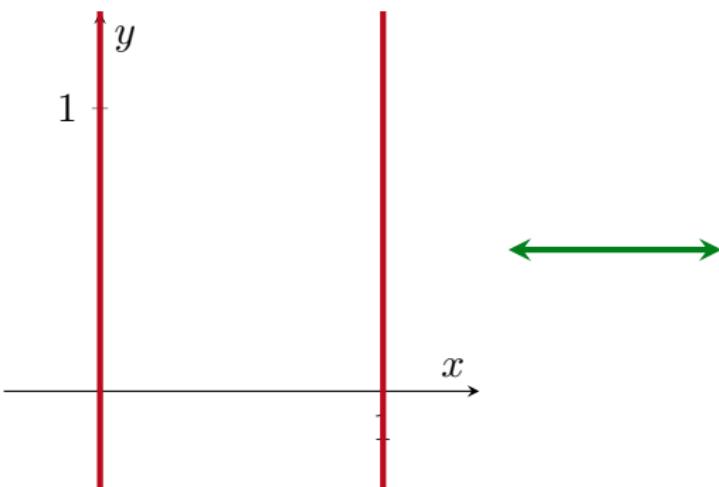
$$u = x + y \quad v = y - 2x \quad \int_0^1 \int_0^{1-x} \sqrt{x+y}(y-2x)^2 \, dy \, dx \quad \begin{aligned} x &= \frac{u}{3} - \frac{v}{3} \\ y &= \frac{2u}{3} + \frac{v}{3} \end{aligned}$$



$$u = x + y \quad v = y - 2x \quad \int_0^1 \int_0^{1-x} \sqrt{x+y}(y-2x)^2 dy dx \quad \begin{aligned} x &= \frac{u}{3} - \frac{v}{3} \\ y &= \frac{2u}{3} + \frac{v}{3} \end{aligned}$$

$$x = 0$$

$$x = 1$$



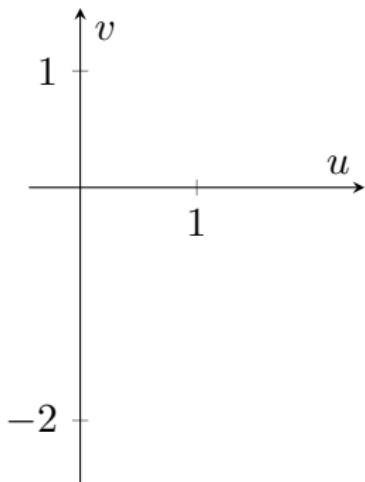
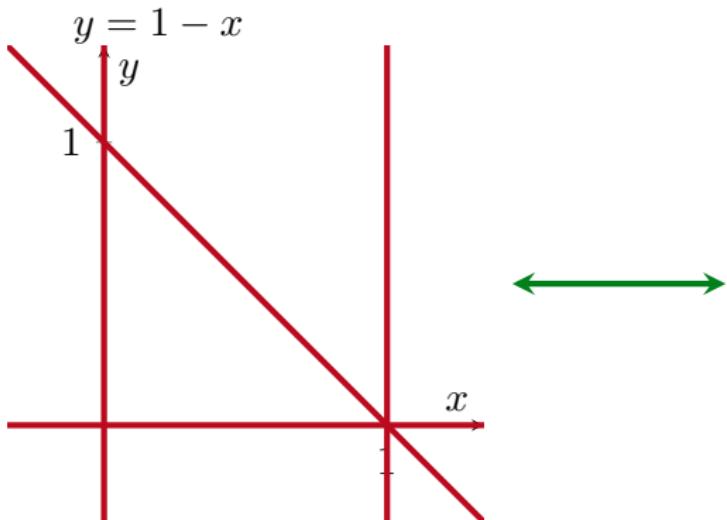
$$u = x + y \quad v = y - 2x \quad \int_0^1 \int_0^{1-x} \sqrt{x+y}(y-2x)^2 dy dx \quad x = \frac{u}{3} - \frac{v}{3}$$

$$y = \frac{2u}{3} + \frac{v}{3}$$

$$x = 0$$

$$x = 1$$

$$y = 0$$



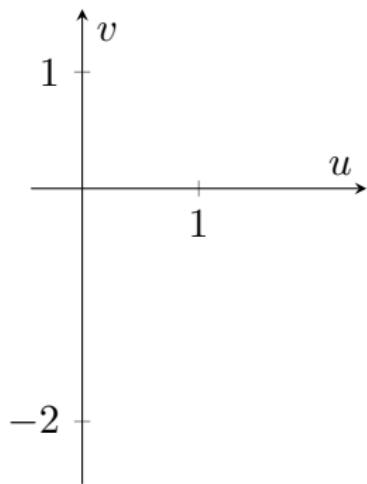
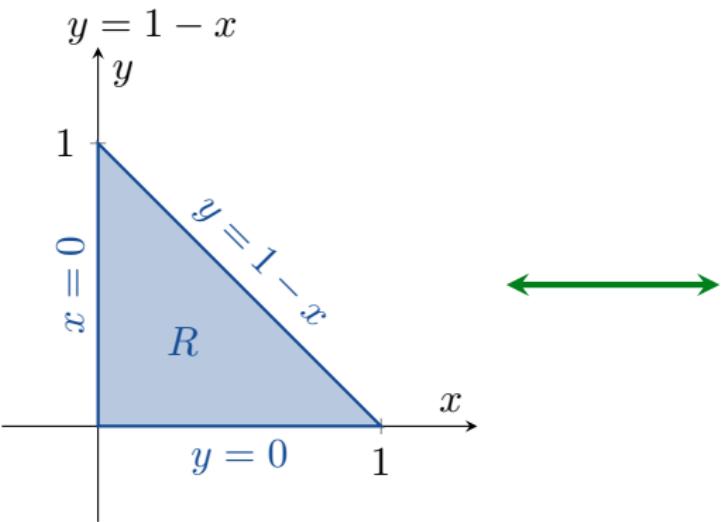
$$u = x + y \quad v = y - 2x \quad \int_0^1 \int_0^{1-x} \sqrt{x+y}(y-2x)^2 dy dx \quad x = \frac{u}{3} - \frac{v}{3}$$

$$y = \frac{2u}{3} + \frac{v}{3}$$

$$x = 0$$

~~$x = 1$~~

$$y = 0$$

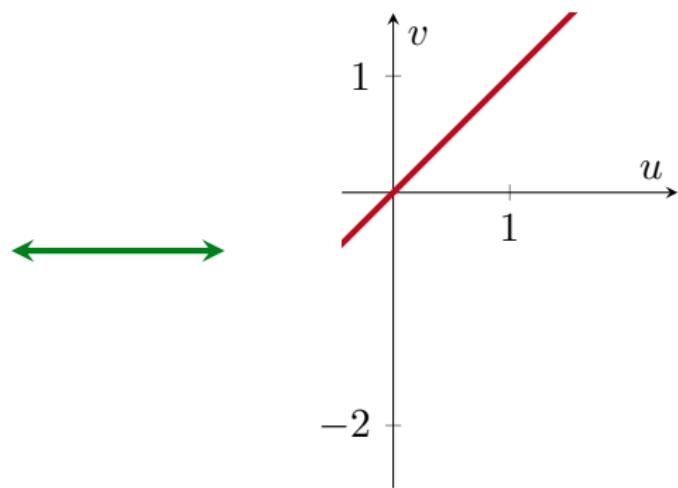
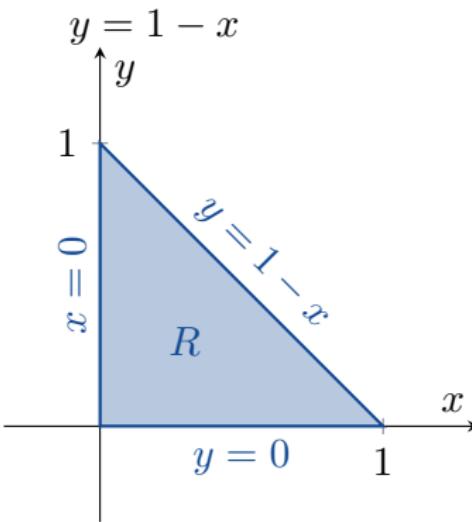


$$u = x + y \quad v = y - 2x \quad \int_0^1 \int_0^{1-x} \sqrt{x+y}(y-2x)^2 dy dx \quad \begin{aligned} x &= \frac{u}{3} - \frac{v}{3} \\ y &= \frac{2u}{3} + \frac{v}{3} \end{aligned}$$

$$x = 0 \implies 0 = \frac{u}{3} - \frac{v}{3} \implies u = v$$

$$\cancel{x=1}$$

$$y = 0$$

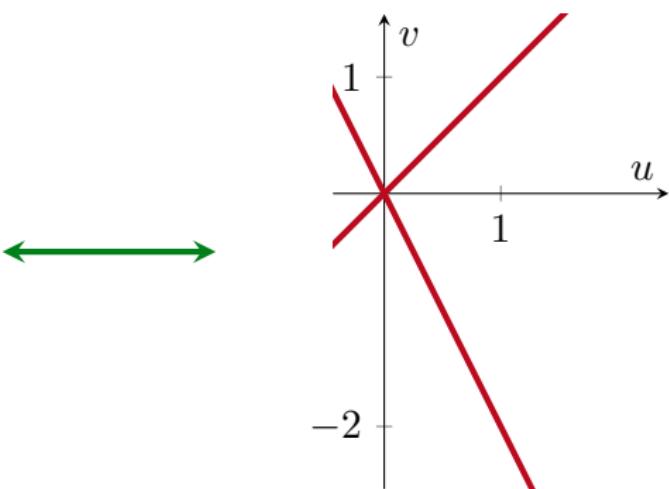
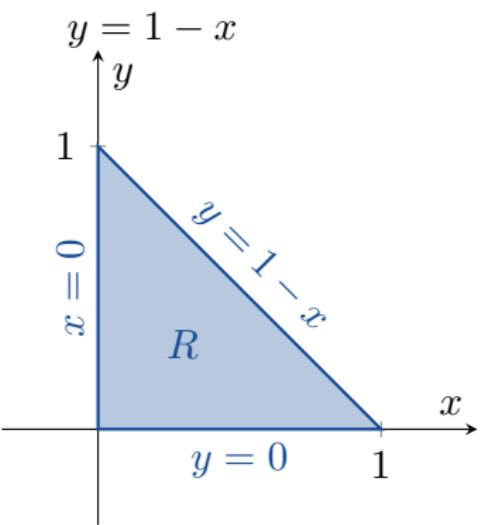


$$u = x + y \quad v = y - 2x \quad \int_0^1 \int_0^{1-x} \sqrt{x+y}(y-2x)^2 dy dx \quad x = \frac{u}{3} - \frac{v}{3} \\ y = \frac{2u}{3} + \frac{v}{3}$$

$$x = 0 \implies 0 = \frac{u}{3} - \frac{v}{3} \implies u = v$$

~~x = 1~~

$$y = 0 \implies 0 = \frac{2u}{3} + \frac{v}{3} \implies v = -2u$$



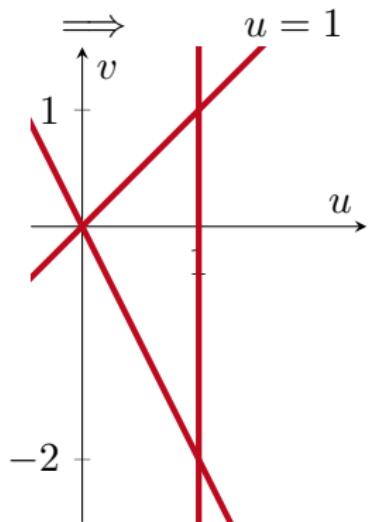
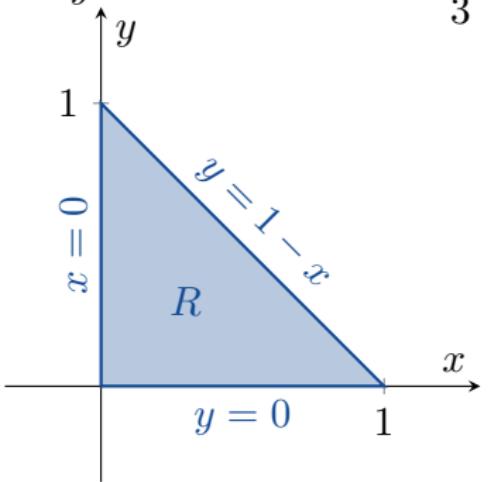
$$u = x + y \quad v = y - 2x \quad \int_0^1 \int_0^{1-x} \sqrt{x+y}(y-2x)^2 dy dx \quad x = \frac{u}{3} - \frac{v}{3} \quad y = \frac{2u}{3} + \frac{v}{3}$$

$$x = 0 \implies 0 = \frac{u}{3} - \frac{v}{3} \implies u = v$$

~~x = 1~~

$$y = 0 \implies 0 = \frac{2u}{3} + \frac{v}{3} \implies v = -2u$$

$$y = 1 - x \implies \frac{2u}{3} + \frac{v}{3} = 1 - \frac{u}{3} + \frac{v}{3} \implies u = 1$$



$$u = x + y \quad v = y - 2x \quad \int_0^1 \int_0^{1-x} \sqrt{x+y}(y-2x)^2 dy dx \quad x = \frac{u}{3} - \frac{v}{3} \quad y = \frac{2u}{3} + \frac{v}{3}$$

$$x = 0 \implies$$

$$0 = \frac{u}{3} - \frac{v}{3} \implies u = v$$

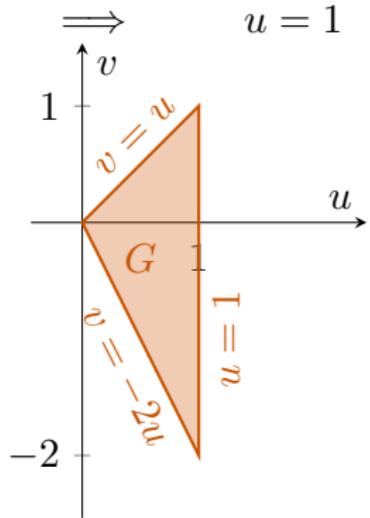
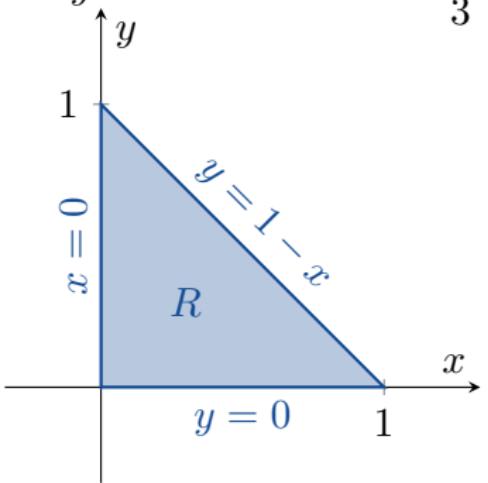
~~$x = 1$~~

$$y = 0 \implies$$

$$0 = \frac{2u}{3} + \frac{v}{3} \implies v = -2u$$

$$y = 1 - x \implies \frac{2u}{3} + \frac{v}{3} = 1 - \frac{u}{3} + \frac{v}{3}$$

$$\implies u = 1$$



$$\begin{aligned} u &= x + y \\ v &= y - 2x \end{aligned} \quad \int_0^1 \int_0^{1-x} \sqrt{x+y}(y-2x)^2 dy dx \quad \begin{aligned} x &= \frac{u}{3} - \frac{v}{3} \\ y &= \frac{2u}{3} + \frac{v}{3} \end{aligned}$$

$$x = 0 \implies 0 = \frac{u}{3} - \frac{v}{3} \implies u = v$$

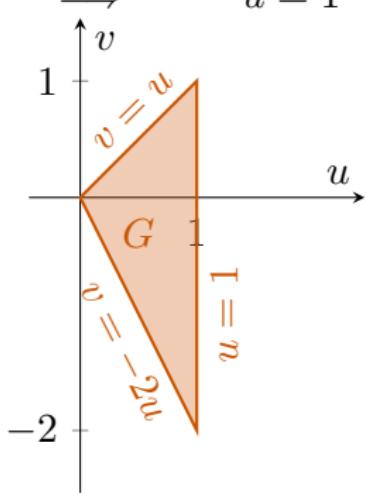
~~x = 1~~

$$y = 0 \implies 0 = \frac{2u}{3} + \frac{v}{3} \implies v = -2u$$

$$y = 1 - x \implies \frac{2u}{3} + \frac{v}{3} = 1 - \frac{u}{3} + \frac{v}{3} \implies u = 1$$

$$0 \leq u \leq 1$$

$$-2u \leq v \leq u$$



14

$$\begin{aligned} u &= x + y & \frac{\partial(x, y)}{\partial(u, v)} &= \frac{1}{3} & 0 \leq u \leq 1 & \quad -2u \leq v \leq u \\ v &= y - 2x \end{aligned}$$



Therefore

$$\int_0^1 \int_0^{1-x} \sqrt{x+y}(y-2x)^2 dy dx =$$

=

=

=

=

=

14

$$\begin{aligned} u &= x + y & \frac{\partial(x, y)}{\partial(u, v)} &= \frac{1}{3} & 0 \leq u \leq 1 & -2u \leq v \leq u \\ v &= y - 2x \end{aligned}$$



Therefore

$$\begin{aligned}
 \int_0^1 \int_0^{1-x} \sqrt{x+y}(y-2x)^2 dy dx &= \int_0^1 \int_{-2u}^u \sqrt{uv}^2 \frac{1}{3} dv du \\
 &= \\
 &= \\
 &= \\
 &= \\
 &=
 \end{aligned}$$

14

$$\begin{aligned} u &= x + y & \frac{\partial(x, y)}{\partial(u, v)} &= \frac{1}{3} & 0 \leq u \leq 1 & \quad -2u \leq v \leq u \\ v &= y - 2x \end{aligned}$$



Therefore

$$\begin{aligned} \int_0^1 \int_0^{1-x} \sqrt{x+y}(y-2x)^2 dy dx &= \int_0^1 \int_{-2u}^u \sqrt{uv}^2 \frac{1}{3} dv du \\ &= \dots \\ &= \dots \\ &= \dots \\ &= \dots \\ &= \frac{2}{9}. \end{aligned}$$

14.8 Substitutions in Multiple Integrals

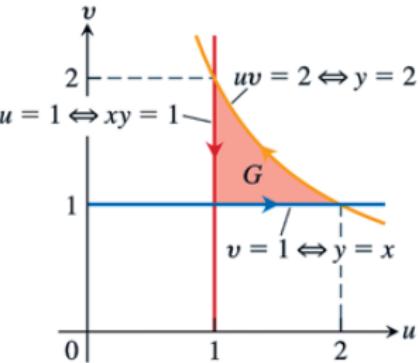
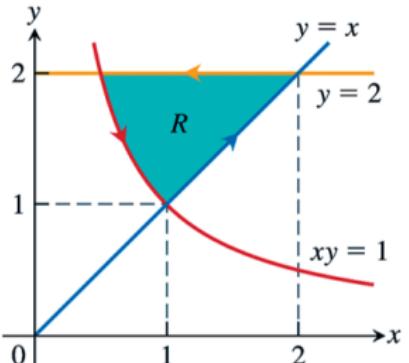
EXAMPLE 4 Evaluate the integral

$$\int_1^2 \int_{1/y}^y \sqrt{\frac{y}{x}} e^{\sqrt{xy}} dx dy.$$

Solution The square root terms in the integrand suggest that we might simplify the integration by substituting $u = \sqrt{xy}$ and $v = \sqrt{y/x}$. Squaring these equations gives $u^2 = xy$ and $v^2 = y/x$, which imply that $u^2v^2 = y^2$ and $u^2/v^2 = x^2$. So we obtain the transformation (in the same ordering of the variables as discussed before)

$$x = \frac{u}{v} \quad \text{and} \quad y = uv,$$

with $u > 0$ and $v > 0$.



Let's first see what happens to the integrand itself under this transformation. The Jacobian of the transformation is not constant:

$$J(u, v) = \begin{vmatrix} \frac{\partial x}{\partial u} & \frac{\partial x}{\partial v} \\ \frac{\partial y}{\partial u} & \frac{\partial y}{\partial v} \end{vmatrix} = \begin{vmatrix} \frac{1}{v} & -\frac{u}{v^2} \\ v & u \end{vmatrix} = \frac{2u}{v}.$$

If G is the region of integration in the uv -plane, then by Equation (2) the transformed double integral under the substitution is

$$\iint_R \sqrt{\frac{y}{x}} e^{\sqrt{xy}} dx dy = \iint_G ve^u \frac{2u}{v} du dv = \iint_G 2ue^u du dv.$$

The transformed integrand function is easier to integrate than the original one, so we proceed to determine the limits of integration for the transformed integral.

The region of integration R of the original integral in the xy -plane is shown in Figure 15.61. From the substitution equations $u = \sqrt{xy}$ and $v = \sqrt{y/x}$, we see that the image of the left-hand boundary $xy = 1$ for R is the vertical line segment $u = 1, 2 \geq v \geq 1$, in G (see Figure 15.62). Likewise, the right-hand boundary $y = x$ of R maps to the horizontal line segment $v = 1, 1 \leq u \leq 2$, in G . Finally, the horizontal top boundary $y = 2$ of R

maps to $uv = 2$, $1 \leq v \leq 2$, in G . As we move counterclockwise around the boundary of the region R , we also move counterclockwise around the boundary of G , as shown in Figure 15.62. Knowing the region of integration G in the uv -plane, we can now write equivalent iterated integrals:

$$\int_1^2 \int_{1/y}^y \sqrt{\frac{y}{x}} e^{\sqrt{xy}} dx dy = \int_1^2 \int_1^{2/u} 2ue^u dv du. \quad \text{Note the order of integration.}$$

We now evaluate the transformed integral on the right-hand side,

$$\begin{aligned} \int_1^2 \int_1^{2/u} 2ue^u dv du &= 2 \int_1^2 \left[vu e^u \right]_{v=1}^{v=2/u} du \\ &= 2 \int_1^2 (2e^u - ue^u) du \\ &= 2 \int_1^2 (2 - u)e^u du \\ &= 2 \left[(2 - u)e^u + e^u \right]_{u=1}^{u=2} \quad \text{Integrate by parts.} \\ &= 2(e^2 - (e + e)) = 2e(e - 2). \end{aligned}$$



Substitutions in Triple Integrals

We use

$$x = g(u, v, w) \quad y = h(u, v, w) \quad z = k(u, v, w)$$

for

$$\iiint_D F \, dx dy dz = \iiint_R F \left| \frac{\partial(x, y, z)}{\partial(u, v, w)} \right| du dv dw$$

Substitutions in Triple Integrals

We use

$$x = g(u, v, w) \quad y = h(u, v, w) \quad z = k(u, v, w)$$

for

$$\iiint_D F \, dxdydz = \iiint_R F \left| \frac{\partial(x, y, z)}{\partial(u, v, w)} \right| \, dudvdw$$

where the *Jacobian* is

$$J(u, v, w) = \frac{\partial(x, y, z)}{\partial(u, v, w)} = \begin{vmatrix} \frac{\partial x}{\partial u} & \frac{\partial x}{\partial v} & \frac{\partial x}{\partial w} \\ \frac{\partial y}{\partial u} & \frac{\partial y}{\partial v} & \frac{\partial y}{\partial w} \\ \frac{\partial z}{\partial u} & \frac{\partial z}{\partial v} & \frac{\partial z}{\partial w} \end{vmatrix}.$$

14.8 Substitutions in Multiple Integrals

Example

Cartesian coordinates \rightarrow Cylindrical coordinates.

$$x = r \cos \theta, y = r \sin \theta, z = z.$$

$$\frac{\partial(x, y, z)}{\partial(r, \theta, z)} = \begin{vmatrix} \frac{\partial x}{\partial r} & \frac{\partial x}{\partial \theta} & \frac{\partial x}{\partial z} \\ \frac{\partial y}{\partial r} & \frac{\partial y}{\partial \theta} & \frac{\partial y}{\partial z} \\ \frac{\partial z}{\partial r} & \frac{\partial z}{\partial \theta} & \frac{\partial z}{\partial z} \end{vmatrix} = \begin{vmatrix} \cos \theta & -r \sin \theta & 0 \\ \sin \theta & r \cos \theta & 0 \\ 0 & 0 & 1 \end{vmatrix}$$

$$= r \cos^2 \theta + r \sin^2 \theta = r.$$

14.8 Substitutions in Multiple Integrals



Example

Cartesian coordinates \rightarrow Spherical coordinates.

$$x = \rho \sin \phi \cos \theta, y = \rho \sin \phi \sin \theta, z = \rho \cos \phi.$$

$$\frac{\partial(x, y, z)}{\partial(\rho, \phi, \theta)} = \begin{vmatrix} \frac{\partial x}{\partial \rho} & \frac{\partial x}{\partial \phi} & \frac{\partial x}{\partial \theta} \\ \frac{\partial y}{\partial \rho} & \frac{\partial y}{\partial \phi} & \frac{\partial y}{\partial \theta} \\ \frac{\partial z}{\partial \rho} & \frac{\partial z}{\partial \phi} & \frac{\partial z}{\partial \theta} \end{vmatrix} = \begin{vmatrix} \sin \phi \cos \theta & \rho \cos \phi \cos \theta & -\rho \sin \phi \sin \theta \\ \sin \phi \sin \theta & \rho \cos \phi \sin \theta & \rho \sin \phi \cos \theta \\ \cos \phi & -\rho \sin \phi & 0 \end{vmatrix}$$
$$= \rho^2 \sin \phi.$$

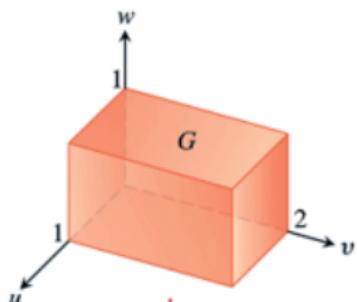
EXAMPLE 5 Evaluate

$$\int_0^3 \int_0^4 \int_{x=y/2}^{x=(y/2)+1} \left(\frac{2x - y}{2} + \frac{z}{3} \right) dx dy dz$$

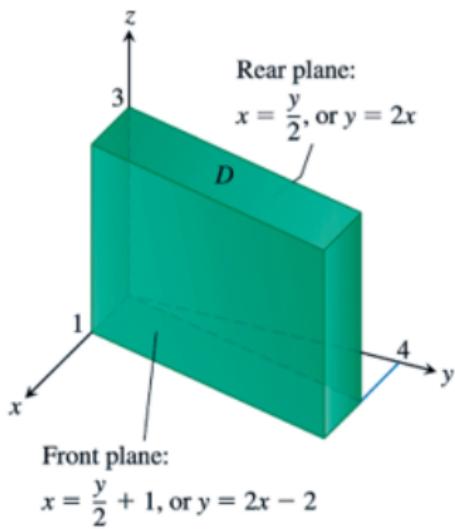
by applying the transformation

$$u = (2x - y)/2, \quad v = y/2, \quad w = z/3 \tag{8}$$

and integrating over an appropriate region in uvw -space.



$$\begin{aligned}x &= u + v \\y &= 2v \\z &= 3w\end{aligned}$$



Solution We sketch the region D of integration in xyz -space and identify its boundaries (Figure 15.66). In this case, the bounding surfaces are planes.

To apply Equation (7), we need to find the corresponding uvw -region G and the Jacobian of the transformation. To find them, we first solve Equations (8) for x , y , and z in terms of u , v , and w . Routine algebra gives

$$x = u + v, \quad y = 2v, \quad z = 3w. \quad (9)$$

We then find the boundaries of G by substituting these expressions into the equations for the boundaries of D :

xyz-equations for the boundary of D	Corresponding uvw -equations for the boundary of G	Simplified uvw -equations
$x = y/2$	$u + v = 2v/2 = v$	$u = 0$
$x = (y/2) + 1$	$u + v = (2v/2) + 1 = v + 1$	$u = 1$
$y = 0$	$2v = 0$	$v = 0$
$y = 4$	$2v = 4$	$v = 2$
$z = 0$	$3w = 0$	$w = 0$
$z = 3$	$3w = 3$	$w = 1$

The Jacobian of the transformation, again from Equations (9), is

$$J(u, v, w) = \begin{vmatrix} \frac{\partial x}{\partial u} & \frac{\partial x}{\partial v} & \frac{\partial x}{\partial w} \\ \frac{\partial y}{\partial u} & \frac{\partial y}{\partial v} & \frac{\partial y}{\partial w} \\ \frac{\partial z}{\partial u} & \frac{\partial z}{\partial v} & \frac{\partial z}{\partial w} \end{vmatrix} = \begin{vmatrix} 1 & 1 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 3 \end{vmatrix} = 6.$$

We now have everything we need to apply Equation (7):

$$\begin{aligned} & \int_0^3 \int_0^4 \int_{x=y/2}^{x=(y/2)+1} \left(\frac{2x - y}{2} + \frac{z}{3} \right) dx dy dz \\ &= \int_0^1 \int_0^2 \int_0^1 (u + w) |J(u, v, w)| du dv dw \\ &= \int_0^1 \int_0^2 \int_0^1 (u + w)(6) du dv dw = 6 \int_0^1 \int_0^2 \left[\frac{u^2}{2} + uw \right]_0^1 dv dw \\ &= 6 \int_0^1 \int_0^2 \left(\frac{1}{2} + w \right) dv dw = 6 \int_0^1 \left[\frac{v}{2} + vw \right]_0^2 dw = 6 \int_0^1 (1 + 2w) dw \\ &= 6 \left[w + w^2 \right]_0^1 = 6(2) = 12. \end{aligned}$$



Next Time

- 9.1 Sequences