

Lecture 7

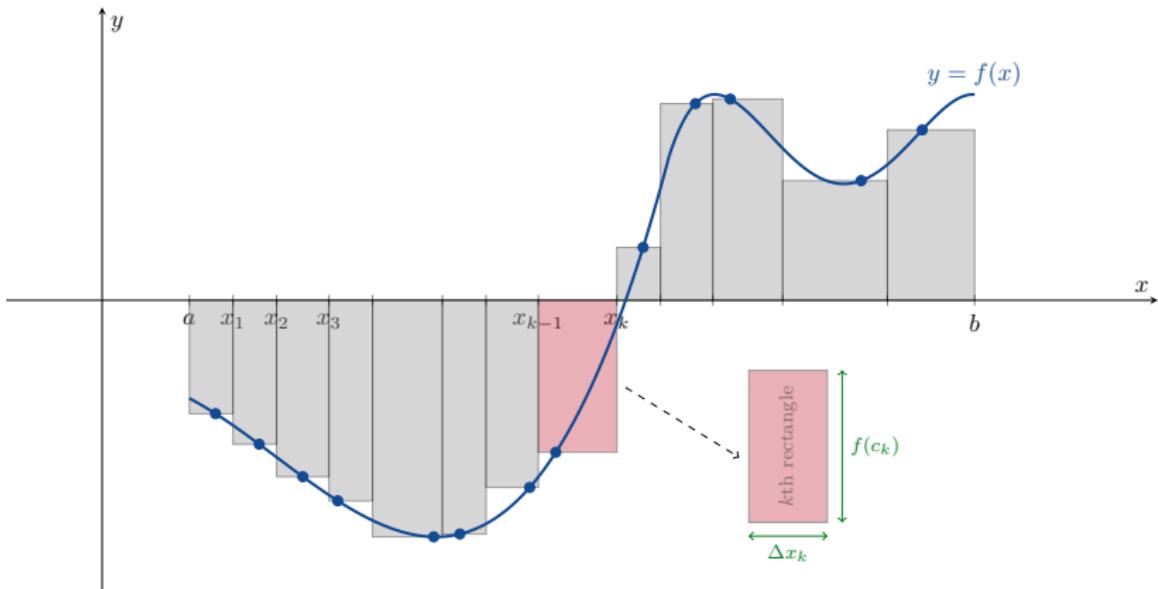
- 14.1 Double and Iterated Integrals over Rectangles
- 14.2 Double Integrals over General Regions

(no break this week)



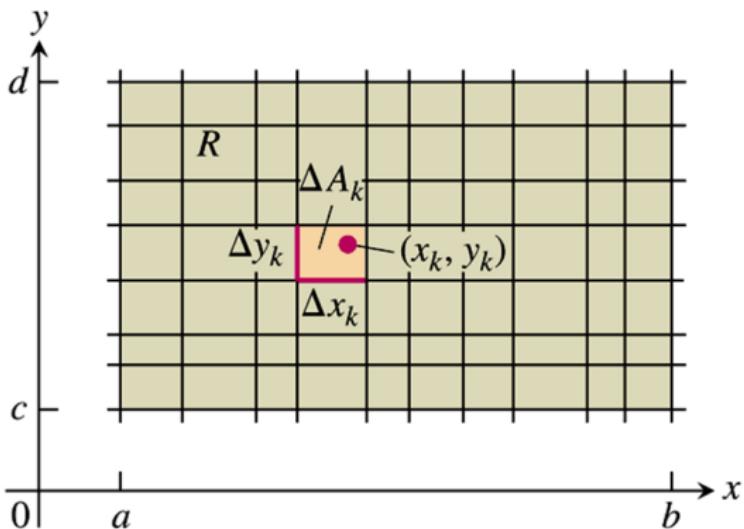
Double and Iterated Integrals over Rectangles

Riemann Sums



$$\int_a^b f(x) dx = \lim_{\|P\| \rightarrow 0} \sum_{k=1}^n f(c_k) \Delta x_k.$$

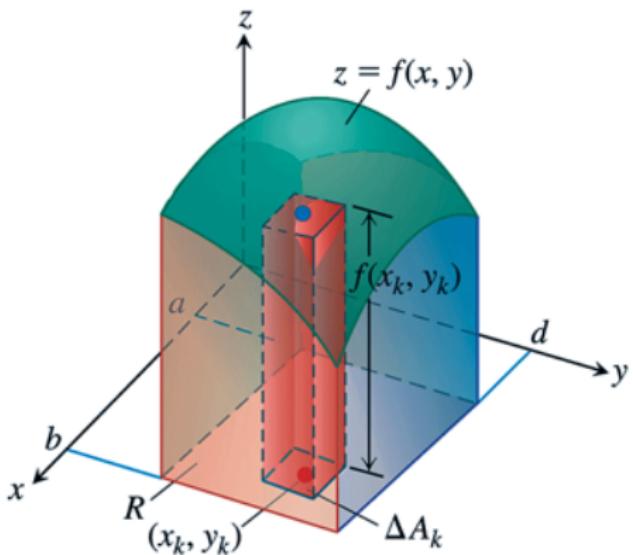
Riemann Sums for Double Integrals



Partition a rectangle R into small rectangles of area

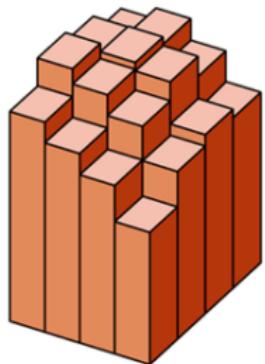
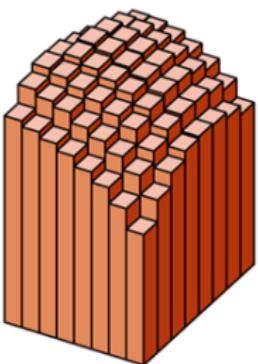
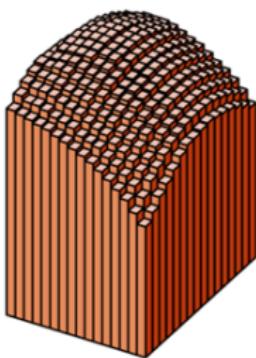
$$\Delta A_k = \Delta x_k \Delta y_k.$$

Riemann Sums for Double Integrals



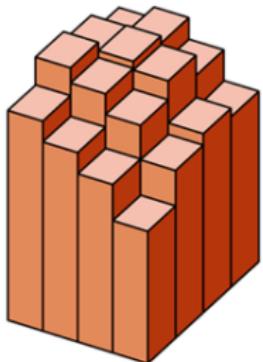
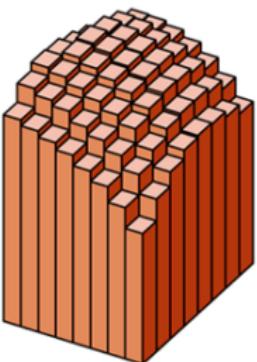
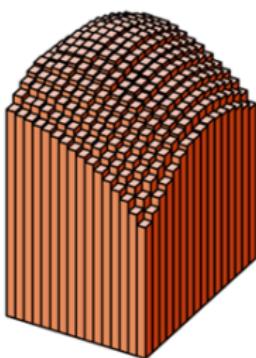
Then approximate the graph of $z = f(x, y)$ by drawing a cuboid on each small rectangle.

Riemann Sums for Double Integrals

(a) $n = 16$ (b) $n = 64$ (c) $n = 256$

$$\sum_k f(x_k, y_k) \Delta A_k.$$

Riemann Sums for Double Integrals

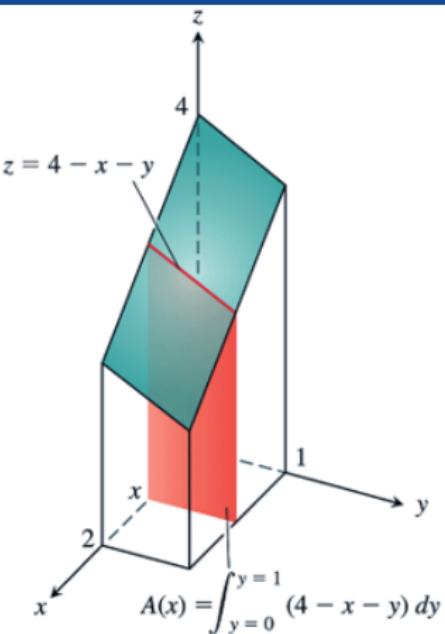
(a) $n = 16$ (b) $n = 64$ (c) $n = 256$

Then take the limit,

$$\iint_R f \, dA = \lim_{\|P\| \rightarrow 0} \sum_k f(x_k, y_k) \Delta A_k.$$

14.1 Double and

Volume by Rectangl



Example

Calculate the volume under the plane $z = 4 - x - y$ over the rectangle $R = \{(x, y) \mid 0 \leq x \leq 2, 0 \leq y \leq 1\}$.

14.1 Double and Iterated Integrals over Rectangles

Since $R = \{(x, y) \mid 0 \leq x \leq 2, 0 \leq y \leq 1\}$, we calculate that

$$\iint_R (4 - x - y) dA = \int_{x=0}^{x=2} \int_{y=0}^{y=1} (4 - x - y) dy dx$$

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14.1 Double and Iterated Integrals over Rectangles

Since $R = \{(x, y) \mid 0 \leq x \leq 2, 0 \leq y \leq 1\}$, we calculate that

$$\begin{aligned} \iint_R (4 - x - y) dA &= \int_{x=0}^{x=2} \int_{y=0}^{y=1} (4 - x - y) dy dx \\ &= \int_{x=0}^{x=2} \left(\int_{y=0}^{y=1} (4 - x - y) dy \right) dx \end{aligned}$$

=

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14.1 Double and Iterated Integrals over Rectangles

Since $R = \{(x, y) \mid 0 \leq x \leq 2, 0 \leq y \leq 1\}$, we calculate that

$$\begin{aligned}
 \iint_R (4 - x - y) dA &= \int_{x=0}^{x=2} \int_{y=0}^{y=1} (4 - x - y) dy dx \\
 &= \int_{x=0}^{x=2} \left(\int_{y=0}^{y=1} (4 - x - y) dy \right) dx \\
 &= \int_{x=0}^{x=2} \left[4y - xy - \frac{y^2}{2} \right]_{y=0}^{y=1} dx \\
 &= \\
 &=
 \end{aligned}$$

14.1 Double and Iterated Integrals over Rectangles

Since $R = \{(x, y) \mid 0 \leq x \leq 2, 0 \leq y \leq 1\}$, we calculate that

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 &= \int_{x=0}^{x=2} \left[4y - xy - \frac{y^2}{2} \right]_{y=0}^{y=1} dx \\
 &= \int_{x=0}^{x=2} \left(\frac{7}{2} - x \right) dx \\
 &=
 \end{aligned}$$

14.1 Double and Iterated Integrals over Rectangles

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 &= \int_{x=0}^{x=2} \left(\int_{y=0}^{y=1} (4 - x - y) dy \right) dx \\
 &= \int_{x=0}^{x=2} \left[4y - xy - \frac{y^2}{2} \right]_{y=0}^{y=1} dx \\
 &= \int_{x=0}^{x=2} \left(\frac{7}{2} - x \right) dx \\
 &= \left[\frac{7}{2}x - \frac{x^2}{2} \right]_{x=0}^{x=2} = 5.
 \end{aligned}$$

14.1 Double and Iterated Integrals over Rectangl

Remark

You don't need to write " $x =$ " and " $y =$ " if understand which integral is which:

$$\int_{x=0}^{x=2} \int_{y=0}^{y=1} (4 - x - y) dy dx = \int_0^2 \int_0^1 (4 - x - y) dy dx.$$

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14.1 Double and Iterated Integrals over Rectangl

Previously we did

$$\int_0^2 \int_0^1 (4 - x - y) \, dy \, dx = 5.$$

14.1 Double and Iterated Integrals over Rectangles

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$$\int_0^2 \int_0^1 (4 - x - y) \, dy \, dx = 5.$$

But note that

$$\begin{aligned} \int_0^1 \int_0^2 (4 - x - y) \, dx \, dy &= \int_0^1 \left(\int_0^2 (4 - x - y) \, dx \right) \, dy \\ &= \int_0^1 \left[4x - \frac{x^2}{2} - xy \right]_0^2 \, dy \\ &= \int_0^1 (6 - 2y) \, dy \\ &= [6y - y^2]_0^1 = 5 \end{aligned}$$

also.

14.1 Double and Iterated Integrals over Rectangles



Guido Fubini

BORN

19 January 1879

DECEASED

6 June 1943

NATIONALITY

Italian

Theorem (Fubini's Theorem)

If $f(x, y)$ is continuous on the rectangle

$$R = \{(x, y) \mid a \leq x \leq b, c \leq y \leq d\} = [a, b] \times [c, d],$$

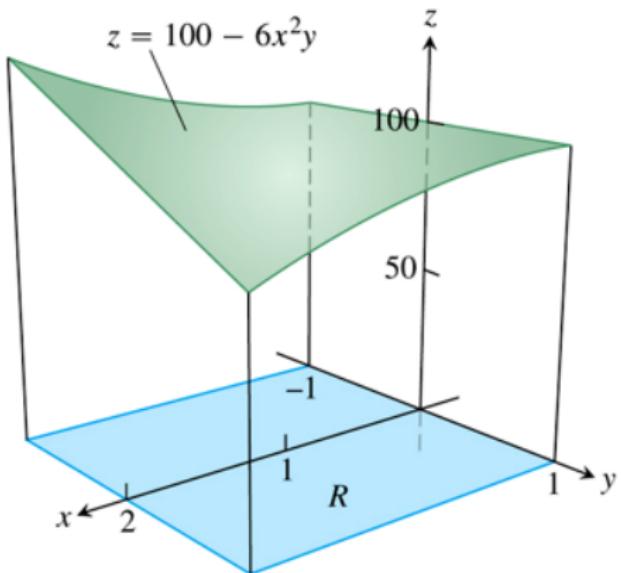
then

$$\iint_R f(x, y) dA = \int_a^b \int_c^d f(x, y) dy dx = \int_c^d \int_a^b f(x, y) dx dy.$$

14.1 Double and Iterated Integrals over Rectangular Regions

EXAMPLE 1 Calculate $\iint_R f(x, y) dA$ for

$$f(x, y) = 100 - 6x^2y \quad \text{and} \quad R: 0 \leq x \leq 2, -1 \leq y \leq 1.$$



Solution Figure 15.6 displays the volume beneath the surface. By Fubini's Theorem,

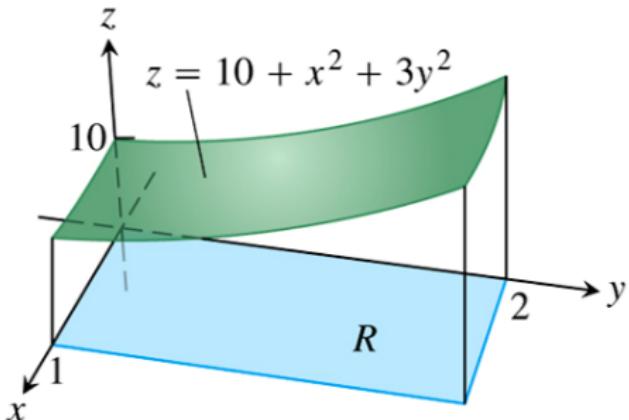
$$\begin{aligned}\iint_R f(x, y) dA &= \int_{-1}^1 \int_0^2 (100 - 6x^2y) dx dy = \int_{-1}^1 \left[100x - 2x^3y \right]_{x=0}^{x=2} dy \\ &= \int_{-1}^1 (200 - 16y) dy = \left[200y - 8y^2 \right]_{-1}^1 = 400.\end{aligned}$$

Reversing the order of integration gives the same answer:

$$\begin{aligned}\int_0^2 \int_{-1}^1 (100 - 6x^2y) dy dx &= \int_0^2 \left[100y - 3x^2y^2 \right]_{y=-1}^{y=1} dx \\ &= \int_0^2 [(100 - 3x^2) - (-100 - 3x^2)] dx \\ &= \int_0^2 200 dx = 400.\end{aligned}$$



14.1 Double and



EXAMPLE 2 Find the volume of the region bounded above by the elliptical paraboloid $z = 10 + x^2 + 3y^2$ and below by the rectangle $R: 0 \leq x \leq 1, 0 \leq y \leq 2$.

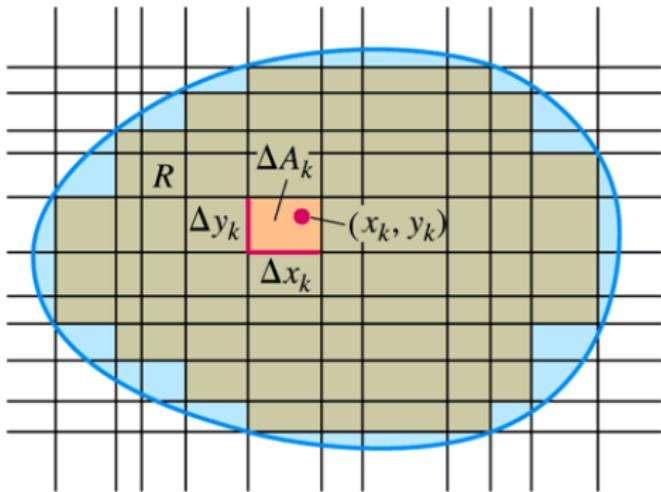
Solution The surface and volume are shown in Figure 15.7. The volume is given by the double integral

$$\begin{aligned}
 V &= \iint_R (10 + x^2 + 3y^2) dA = \int_0^1 \int_0^2 (10 + x^2 + 3y^2) dy dx \\
 &= \int_0^1 \left[10y + x^2y + y^3 \right]_{y=0}^{y=2} dx \\
 &= \int_0^1 (20 + 2x^2 + 8) dx = \left[20x + \frac{2}{3}x^3 + 8x \right]_0^1 = \frac{86}{3}.
 \end{aligned}$$



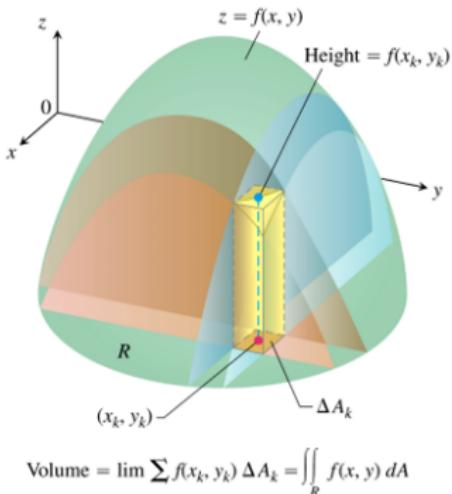
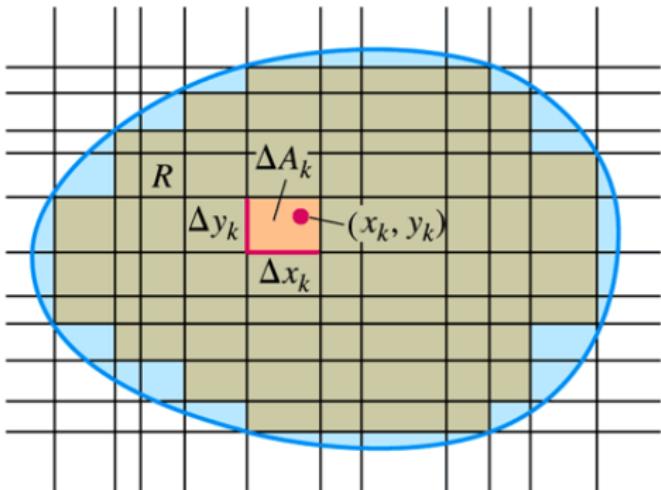
Double Integrals over General Regions

14.2 Double Integrals over General Regions



We only use rectangles that are completely inside R .

14.2 Double Integrals over General Regions



$$\text{Volume} = \lim \sum f(x_k, y_k) \Delta A_k = \iint_R f(x, y) dA$$

We only use rectangles that are completely inside R .

$$\iint_R f dA = \lim_{\|P\| \rightarrow 0} \sum_k f(x_k, y_k) \Delta A_k.$$

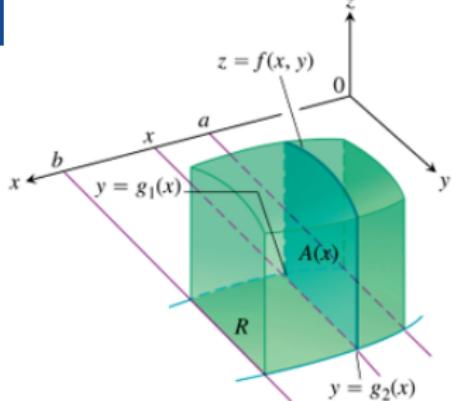
14.2 Double Integrals over General Regions



Theorem (Fubini's Theorem)

Let $f(x, y)$ be continuous on R . Let g_1, g_2, h_1 and h_2 be continuous.

14.2 Double Integrals over General Regions



Theorem (Fubini's Theorem)

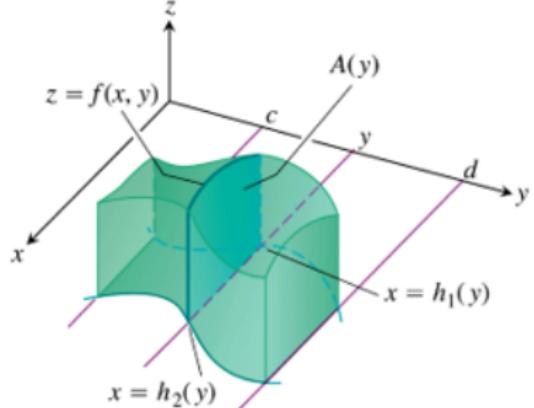
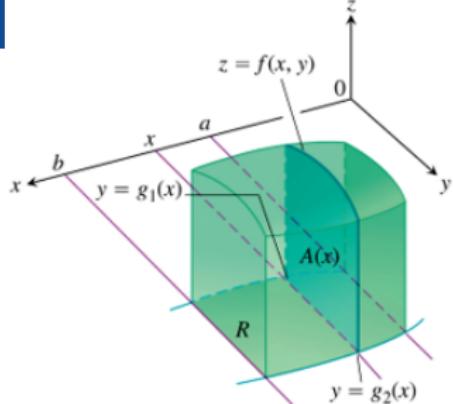
- 1 If R is defined by $a \leq x \leq b$ and $g_1(x) \leq y \leq g_2(x)$, then

$$\iint_R f \, dA = \int_a^b \int_{y=g_1(x)}^{y=g_2(x)} f(x, y) \, dy \, dx$$

only numbers

you can have functions here

14.2 Double Integrals over General Regions



Theorem (Fubini's Theorem)

- 2 If R is defined by $a \leq x \leq b$ and $g_1(x) \leq y \leq g_2(x)$, then

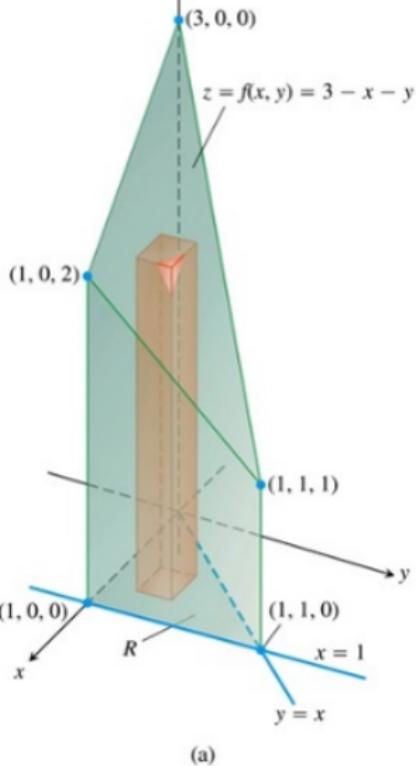
$$\iint_R f \, dA = \int_c^d \int_{x=h_1(x)}^{x=h_2(x)} f(x, y) \, dx \, dy$$

only numbers

you can have functions here

14.2 Double Integrals

regions

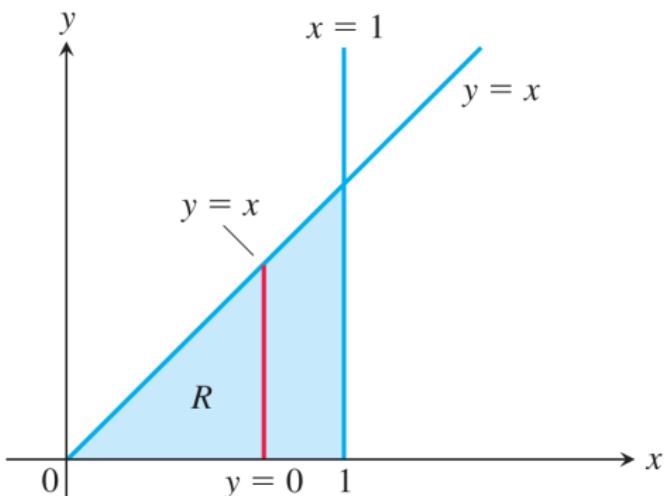


(a)

EXAMPLE 1 Find the volume of the prism whose base is the triangle in the xy -plane bounded by the x -axis and the lines $y = x$ and $x = 1$ and whose top lies in the plane

$$z = f(x, y) = 3 - x - y.$$

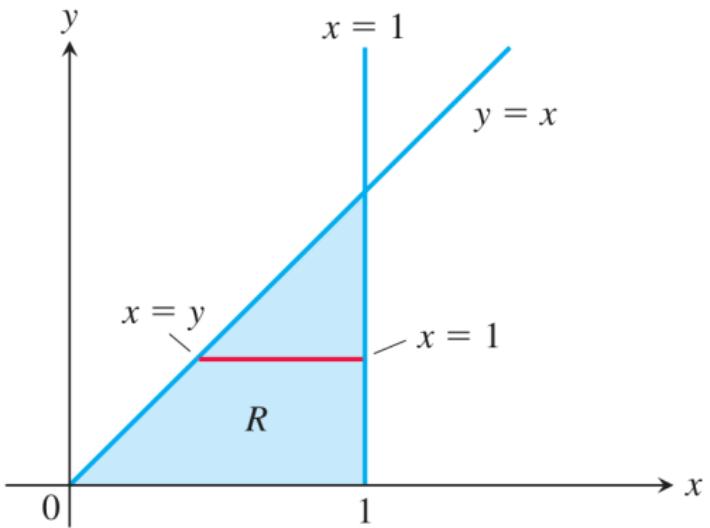
14.2 Double



Solution See Figure 15.12. For any x between 0 and 1, y may vary from $y = 0$ to $y = x$ (Figure 15.12b). Hence,

$$\begin{aligned} V &= \int_0^1 \int_0^x (3 - x - y) dy dx = \int_0^1 \left[3y - xy - \frac{y^2}{2} \right]_{y=0}^{y=x} dx \\ &= \int_0^1 \left(3x - \frac{3x^2}{2} \right) dx = \left[\frac{3x^2}{2} - \frac{x^3}{2} \right]_{x=0}^{x=1} = 1. \end{aligned}$$

14.2 Double



When the order of integration is reversed (Figure 15.12c), the integral for the volume is

$$\begin{aligned}
 V &= \int_0^1 \int_y^1 (3 - x - y) \, dx \, dy = \int_0^1 \left[3x - \frac{x^2}{2} - xy \right]_{x=y}^{x=1} dy \\
 &= \int_0^1 \left(3 - \frac{1}{2} - y - 3y + \frac{y^2}{2} + y^2 \right) dy \\
 &= \int_0^1 \left(\frac{5}{2} - 4y + \frac{3}{2}y^2 \right) dy = \left[\frac{5}{2}y - 2y^2 + \frac{y^3}{2} \right]_{y=0}^{y=1} = 1.
 \end{aligned}$$

The two integrals are equal, as they should be.

14.2 Double Integrals over General Regions



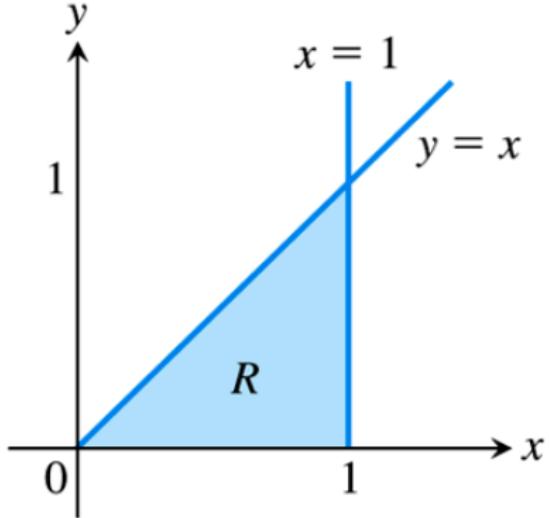
Remark

Fubini's Theorem tells us that

$$\iint f \, dxdy = \iint f \, dydx.$$

But sometimes one is easier to calculate than the other.

14.2 Double Integrals over General Regions



EXAMPLE 2 Calculate

$$\iint_R \frac{\sin x}{x} dA,$$

where R is the triangle in the xy -plane bounded by the x -axis, the line $y = x$, and the line $x = 1$.

Solution The region of integration is shown in Figure 15.13. If we integrate first with respect to y and next with respect to x , then because x is held fixed in the first integration, we find

$$\int_0^1 \left(\int_0^x \frac{\sin x}{x} dy \right) dx = \int_0^1 \left[y \frac{\sin x}{x} \right]_{y=0}^{y=x} dx = \int_0^1 \sin x dx = -\cos(1) + 1 \approx 0.46.$$

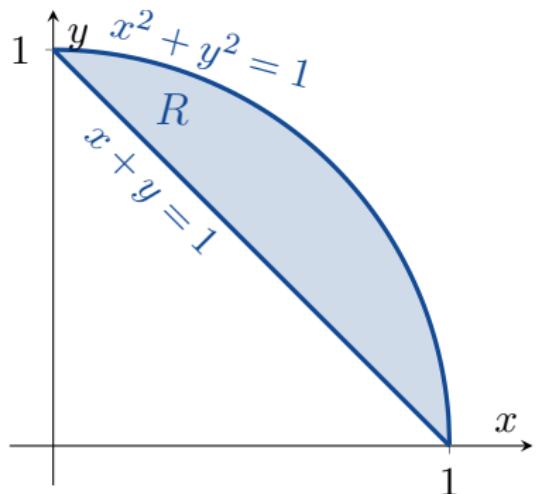
If we reverse the order of integration and attempt to calculate

$$\int_0^1 \int_y^1 \frac{\sin x}{x} dx dy,$$

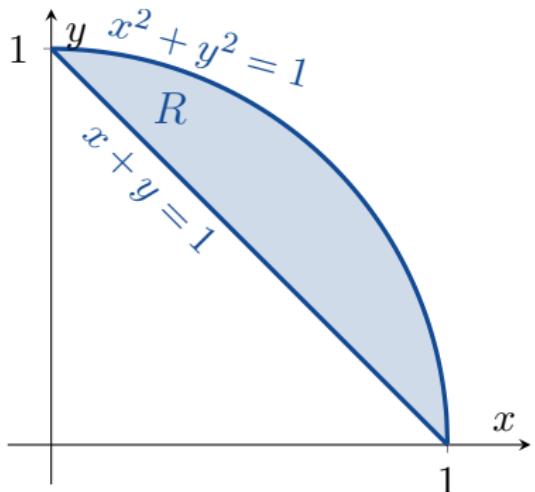
we run into a problem because $\int ((\sin x)/x) dx$ cannot be expressed in terms of elementary functions (there is no simple antiderivative).

There is no general rule for predicting which order of integration will be the good one in circumstances like these. If the order you first choose doesn't work, try the other. Sometimes neither order will work, and then we may need to use numerical approximations. ■

Finding Limits of Integration



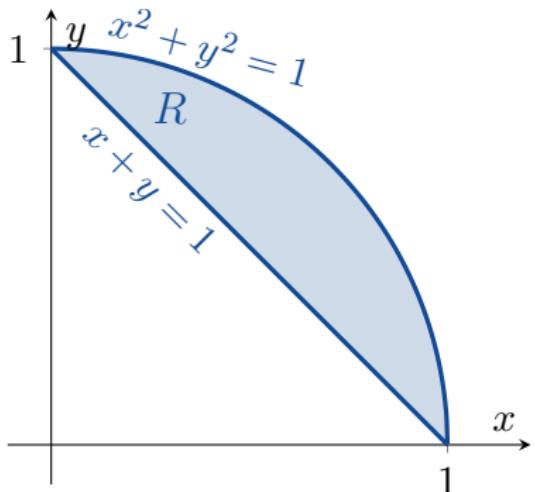
Finding Limits of Integration



Question 1: Shall we do $dxdy$ or $dydx$?

$$\int \int f(x, y)$$

Finding Limits of Integration

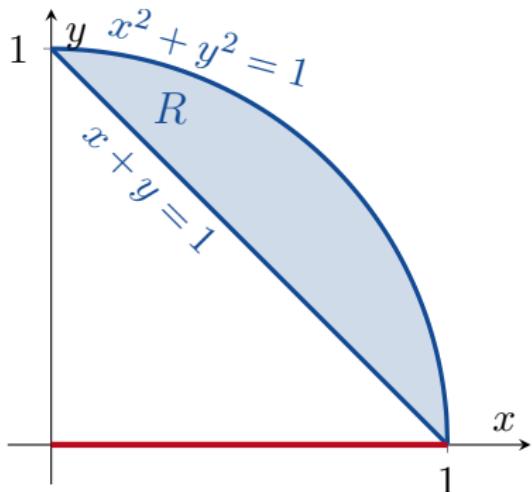


Question 1: Shall we do $dxdy$ or $dydx$?

$dydx$

$$\int \int f(x, y) dydx$$

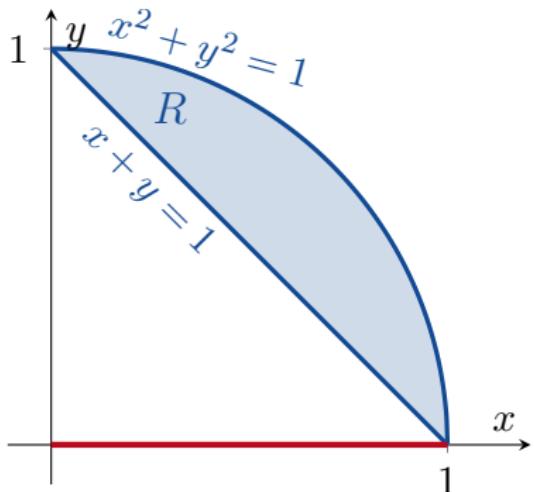
Finding Limits of Integration



Question 2: What are the smallest and biggest possible values of x in R ?

$$\int \int f(x, y) dy dx$$

Finding Limits of Integration

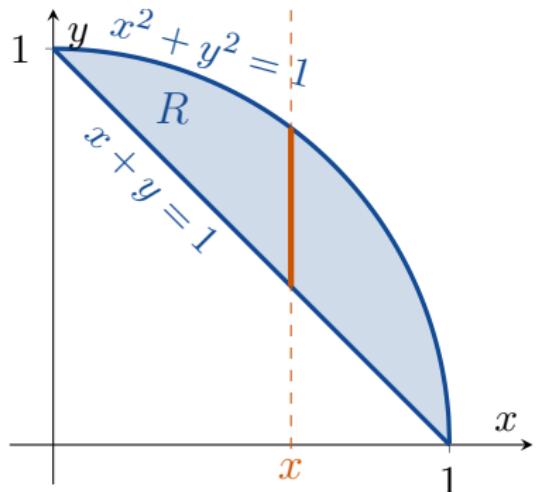


Question 2: What are the smallest and biggest possible values of x in R ?

$$0 \leq x \leq 1$$

$$\int_0^1 \int f(x, y) dy dx$$

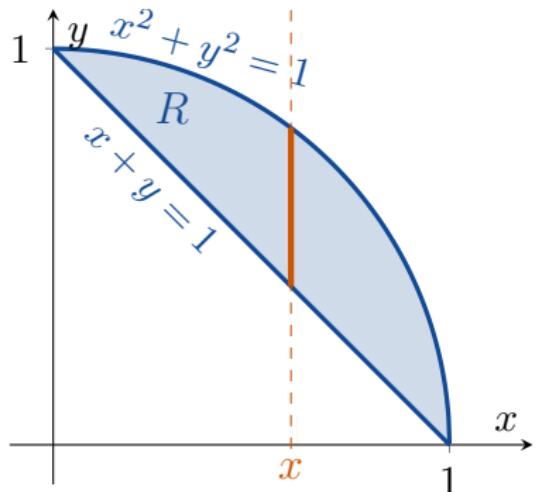
Finding Limits of Integration



Now choose an x between 0 and 1 and draw the **vertical** line through x .

$$\int_0^1 \int f(x, y) dy dx$$

Finding Limits of Integration



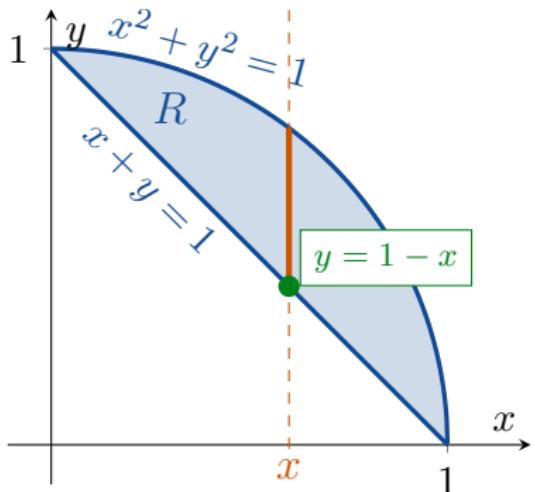
Now choose an x between 0 and 1 and draw the **vertical** line through x .

Question 3: What are the smallest and biggest possible values of y (on this **line**) in R ?

$$\leq y \leq$$

$$\int_0^1 \int f(x, y) dy dx$$

Finding Limits of Integration



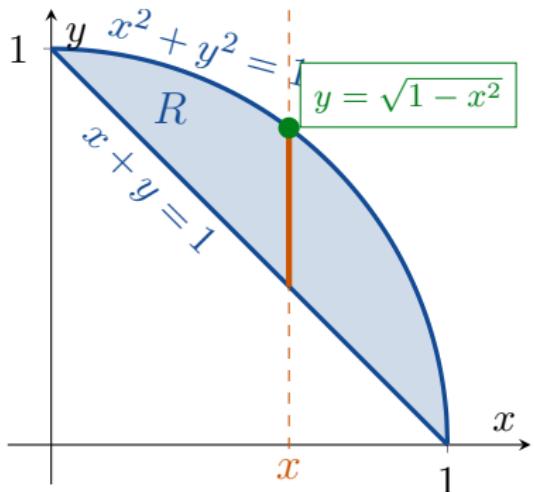
Now choose an x between 0 and 1 and draw the **vertical** line through x .

Question 3: What are the smallest and biggest possible values of y (on this **line**) in R ?

$$1 - x \leq y \leq$$

$$\int_0^1 \int_{1-x}^{\sqrt{1-x^2}} f(x, y) dy dx$$

Finding Limits of Integration



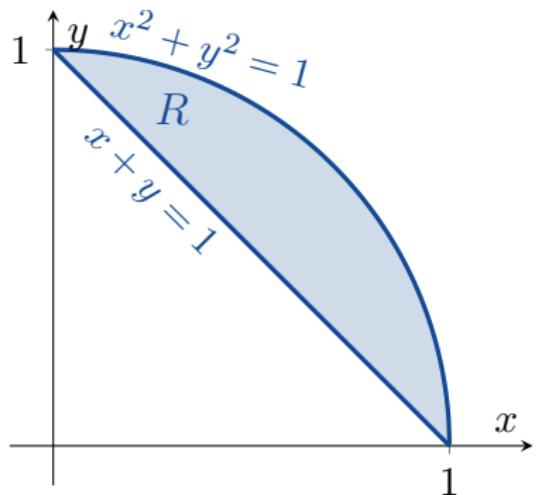
Now choose an x between 0 and 1 and draw the **vertical** line through x .

Question 3: What are the smallest and biggest possible values of y (on this **line**) in R ?

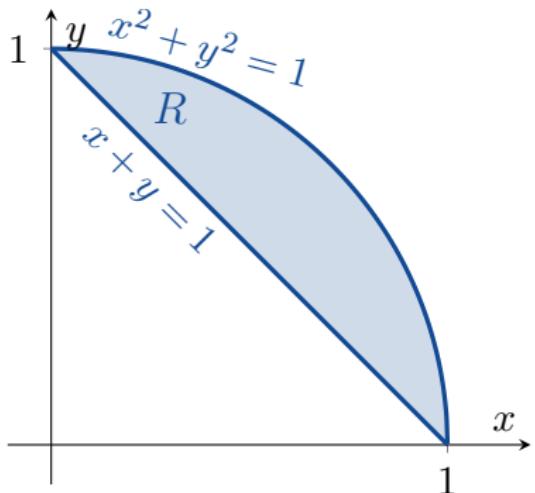
$$1 - x \leq y \leq \sqrt{1 - x^2}$$

$$\int_0^1 \int_{1-x}^{\sqrt{1-x^2}} f(x, y) dy dx$$

Finding Limits of Integration (again)



Finding Limits of Integration (again)

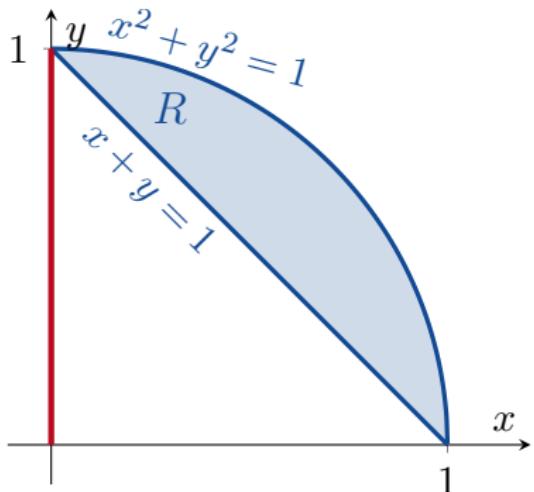


Question 1: Shall we do $dxdy$ or $dydx$?

$dxdy$

$$\int \int f(x, y) \, dxdy$$

Finding Limits of Integration (again)

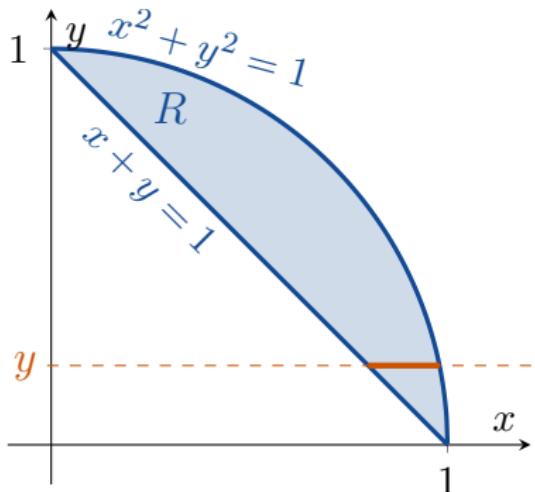


Question 2: What are the smallest and biggest possible values of y in R ?

$$0 \leq y \leq 1$$

$$\int_0^1 \int f(x, y) dx dy$$

Finding Limits of Integration (again)

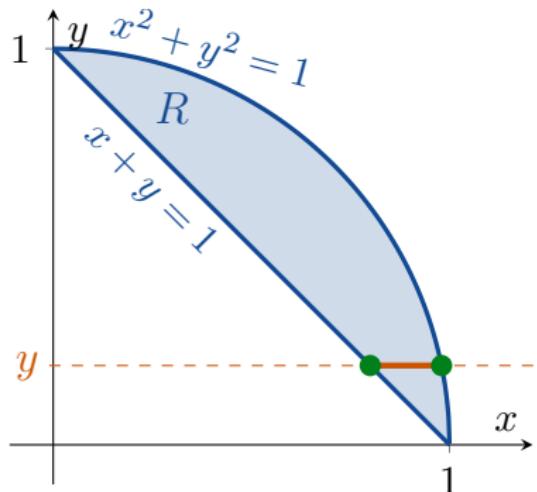


Now choose an y between 0 and 1 and draw the **horizontal** line through y .

Question 3: What are the smallest and biggest possible values of x (on this **line**) in R ?

$$\int_0^1 \int f(x, y) \, dx \, dy$$

Finding Limits of Integration (again)



Now choose an y between 0 and 1 and draw the **horizontal** line through y .

Question 3: What are the smallest and biggest possible values of x (on this **line**) in R ?

$$1 - y \leq x \leq \sqrt{1 - y^2}$$

$$\int_0^1 \int_{1-y}^{\sqrt{1-y^2}} f(x, y) \, dx \, dy$$

14.2 Double Integrals over General Regions



Example

Sketch the region of integration for the integral

$$\int_0^2 \int_{x^2}^{2x} (4x + 2) dy dx.$$

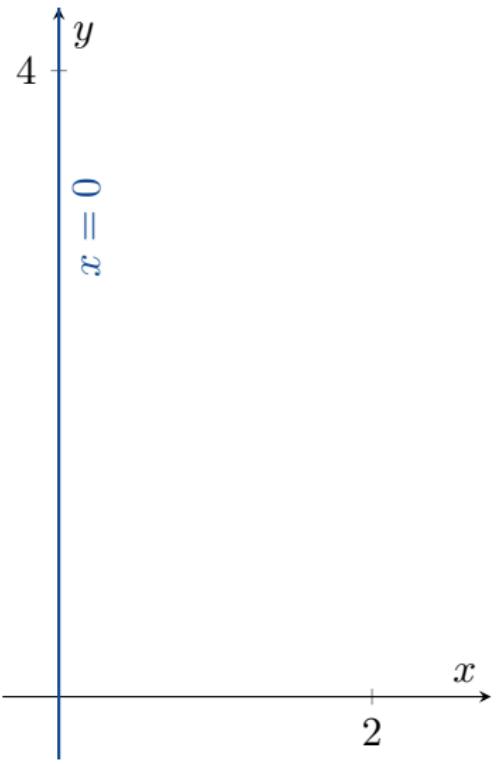
Then write an equivalent integral with $dxdy$.

14.2 Double Integrals over General Regions



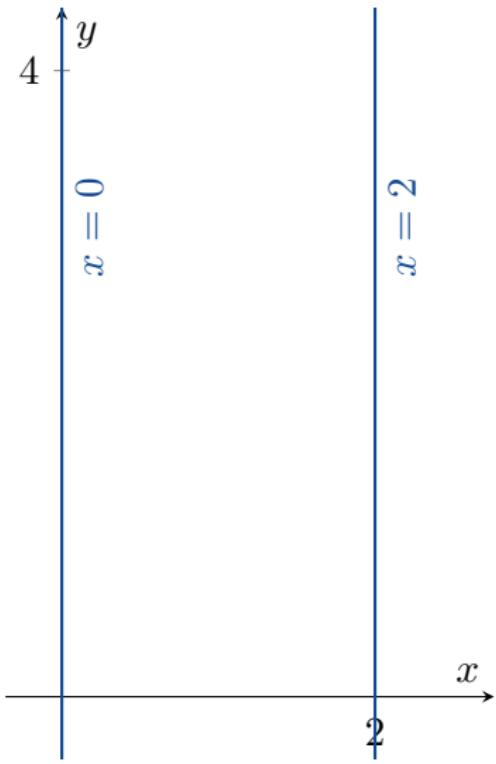
$$\int_0^2 \int_{x^2}^{2x} (4x + 2) dy dx$$

14.2 Double Integrals over General Regions



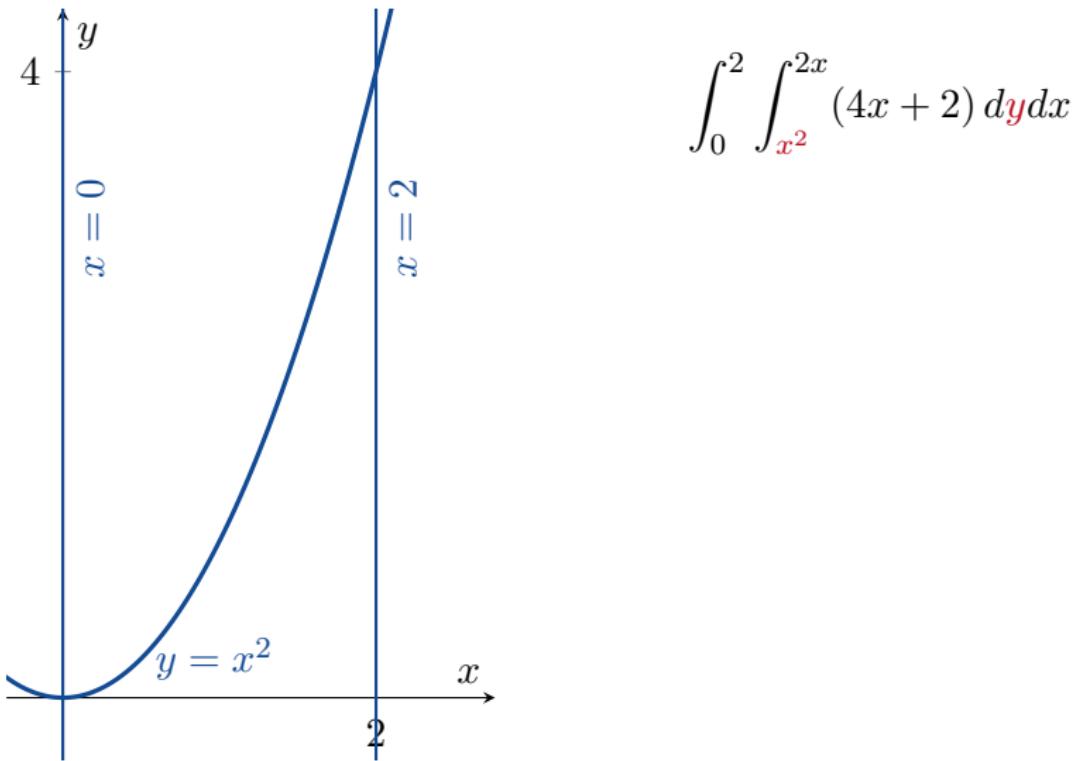
$$\int_0^2 \int_{x^2}^{2x} (4x + 2) dy dx$$

14.2 Double Integrals over General Regions

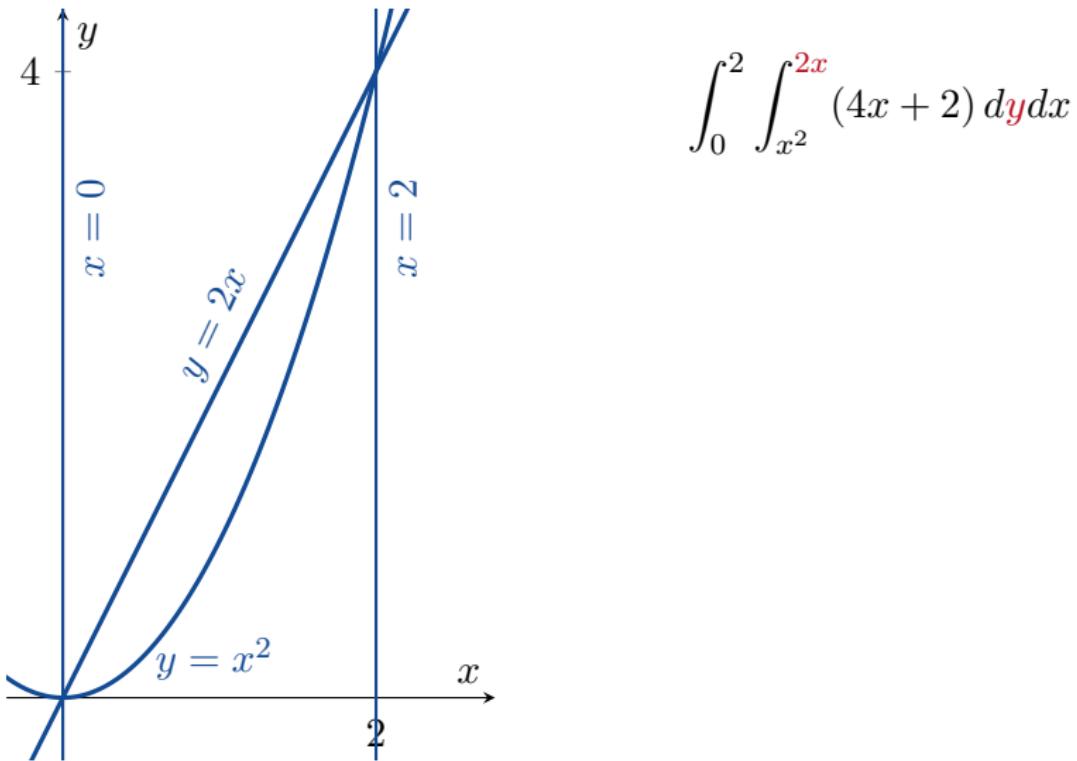


$$\int_0^2 \int_{x^2}^{2x} (4x + 2) dy dx$$

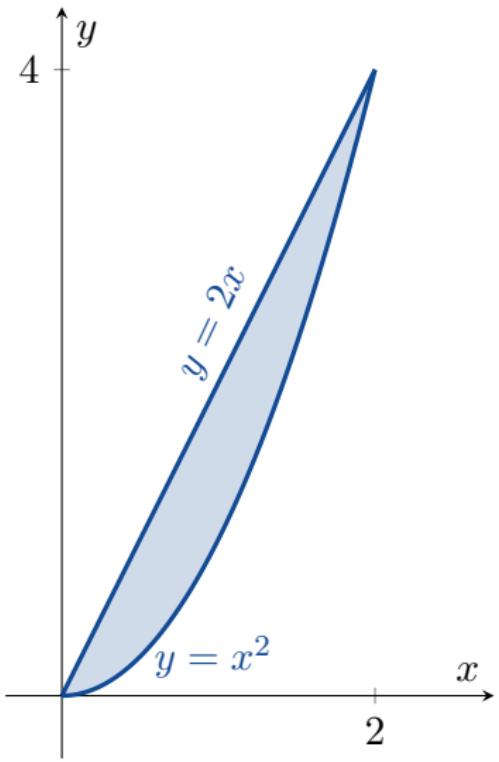
14.2 Double Integrals over General Regions



14.2 Double Integrals over General Regions

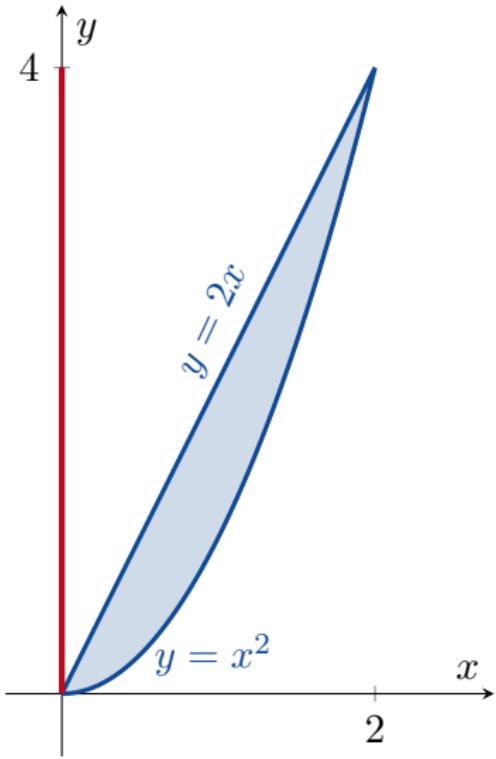


14.2 Double Integrals over General Regions



$$\int_0^2 \int_{x^2}^{2x} (4x + 2) \, dy \, dx \\ = \int \int (4x + 2) \, dx \, dy.$$

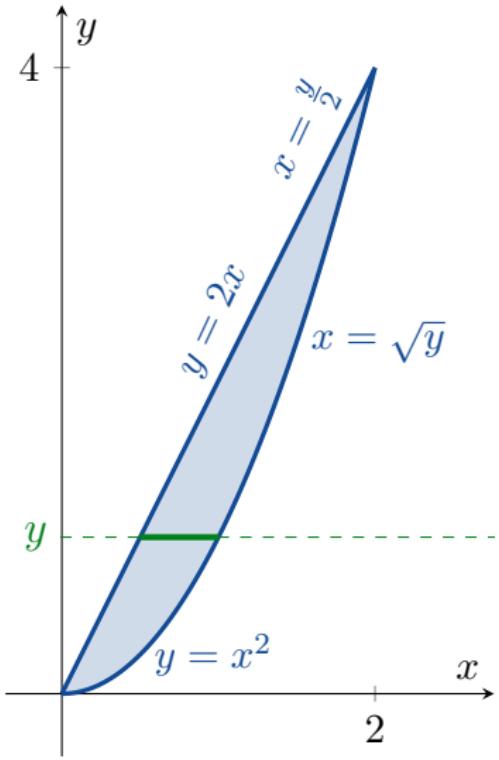
14.2 Double Integrals over General Regions



$$\int_0^2 \int_{x^2}^{2x} (4x + 2) \, dy \, dx$$

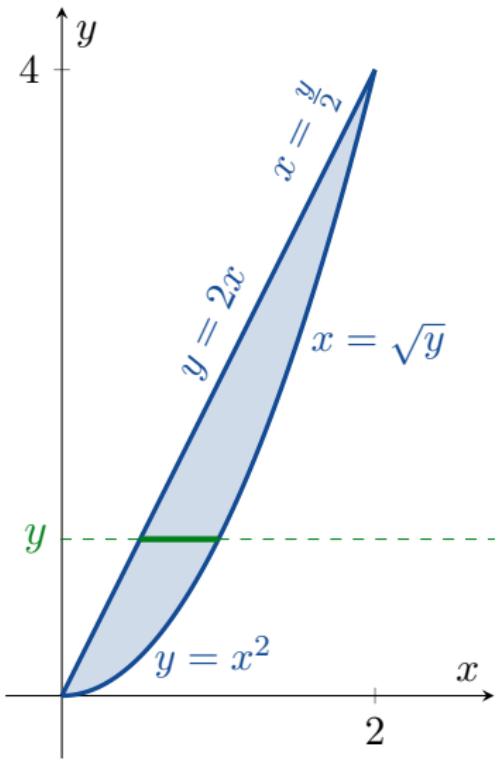
$$= \int_0^4 \int \quad (4x + 2) \, dx \, dy.$$

14.2 Double Integrals over General Regions



$$\int_0^2 \int_{x^2}^{2x} (4x + 2) \, dy \, dx \\ = \int_0^4 \int \quad (4x + 2) \, d\textcolor{green}{x} \, dy.$$

14.2 Double Integrals over General Regions



$$\int_0^2 \int_{x^2}^{2x} (4x + 2) \, dy \, dx$$

$$= \int_0^4 \int_{\frac{y}{2}}^{\sqrt{y}} (4x + 2) \, d\text{x} \, dy.$$



Properties of Double Integrals

Suppose that $f(x, y)$ and $g(x, y)$ are continuous on the bounded region R .

Theorem



Properties of Double Integrals

Suppose that $f(x, y)$ and $g(x, y)$ are continuous on the bounded region R .

Theorem

$$\iint_R cf \, dA = c \iint_R f \, dA$$

for any number c .



Properties of Double Integrals

Suppose that $f(x, y)$ and $g(x, y)$ are continuous on the bounded region R .

Theorem

$$\iint_R (f + g) \, dA = \iint_R f \, dA + \iint_R g \, dA.$$



Properties of Double Integrals

Suppose that $f(x, y)$ and $g(x, y)$ are continuous on the bounded region R .

Theorem

$$f \geq 0 \text{ on } R \implies \iint_R f \, dA \geq 0.$$



Properties of Double Integrals

Suppose that $f(x, y)$ and $g(x, y)$ are continuous on the bounded region R .

Theorem

$$f \geq g \text{ on } R \implies \iint_R f \, dA \geq \iint_R g \, dA.$$

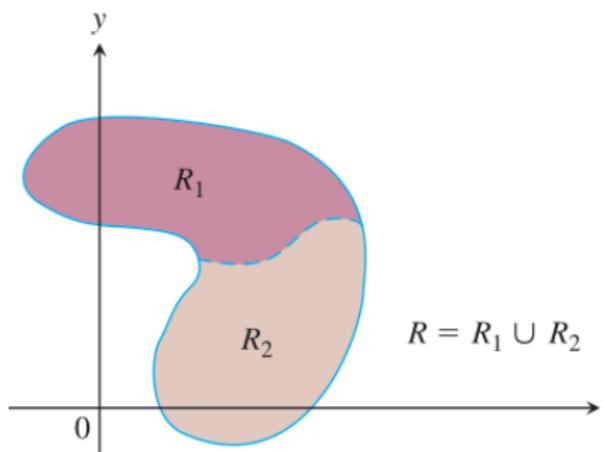
Properties of Double Integrals

Suppose that $f(x, y)$ and $g(x, y)$ are continuous on the bounded region R .

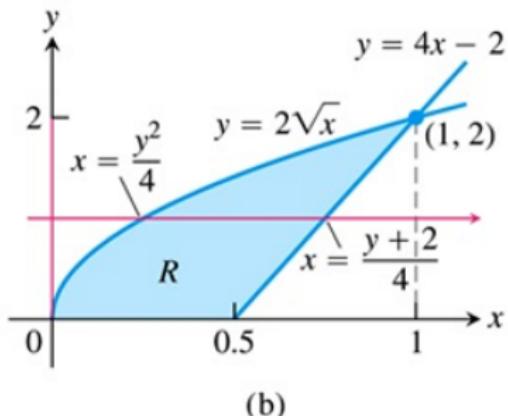
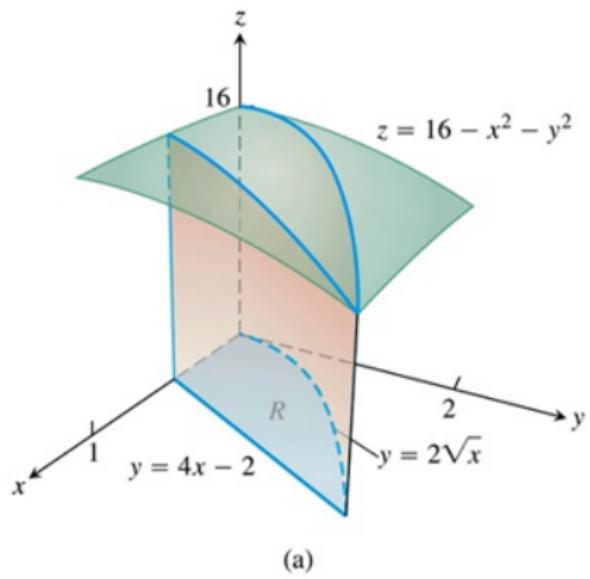
Theorem

If $R = R_1 \cup R_2$ where R_1 and R_2 don't overlay, then

$$\iint_R f \, dA = \iint_{R_1} f \, dA + \iint_{R_2} f \, dA.$$

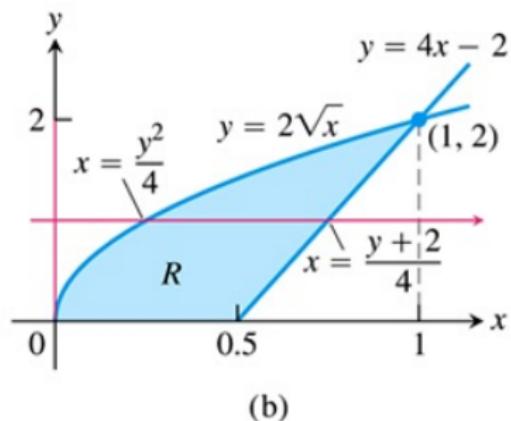
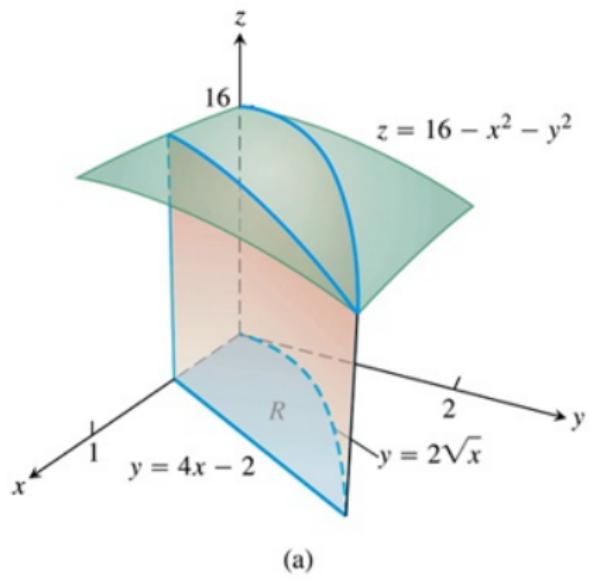


14.2 Double Integrals over General Regions



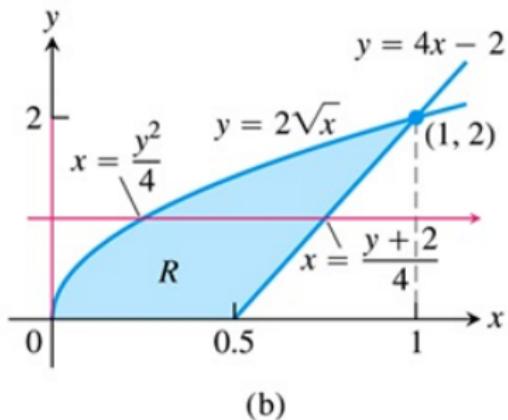
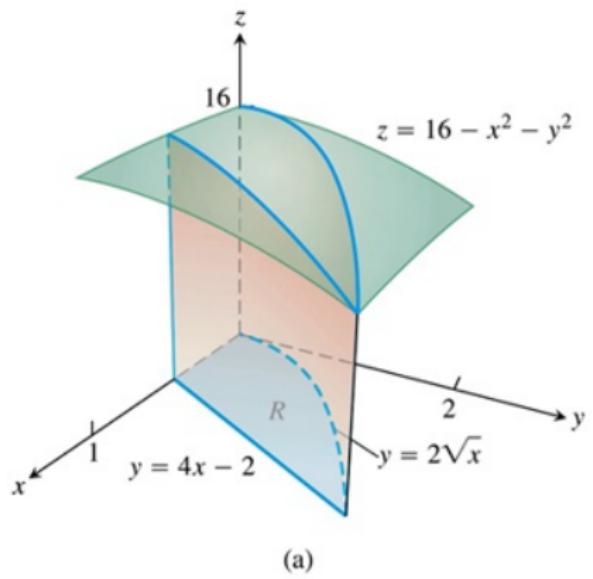
EXAMPLE 4 Find the volume of the wedgelike solid that lies beneath the surface $z = 16 - x^2 - y^2$ and above the region R bounded by the curve $y = 2\sqrt{x}$, the line $y = 4x - 2$, and the x -axis.

14.2 Double Integrals over General Regions



$$0 \leq y \leq 2$$

14.2 Double Integrals over General Regions



$$0 \leq y \leq 2$$

$$\frac{y^2}{4} \leq x \leq \frac{y+2}{4}$$

Solution Figure 15.18a shows the surface and the “wedgelike” solid whose volume we want to calculate. Figure 15.18b shows the region of integration in the xy -plane. If we integrate in the order $dy\,dx$ (first with respect to y and then with respect to x), two integrations will be required because y varies from $y = 0$ to $y = 2\sqrt{x}$ for $0 \leq x \leq 0.5$, and then varies from $y = 4x - 2$ to $y = 2\sqrt{x}$ for $0.5 \leq x \leq 1$. So we choose to integrate in the order $dx\,dy$, which requires only one double integral whose limits of integration are indicated in Figure 15.18b. The volume is then calculated as the iterated integral:

$$\begin{aligned}
 & \iint_R (16 - x^2 - y^2) \, dA \\
 &= \int_0^2 \int_{y^2/4}^{(y+2)/4} (16 - x^2 - y^2) \, dx \, dy \\
 &= \int_0^2 \left[16x - \frac{x^3}{3} - xy^2 \right]_{x=y^2/4}^{x=(y+2)/4} \, dx \\
 &= \int_0^2 \left[4(y+2) - \frac{(y+2)^3}{3 \cdot 64} - \frac{(y+2)y^2}{4} - 4y^2 + \frac{y^6}{3 \cdot 64} + \frac{y^4}{4} \right] dy \\
 &= \left[\frac{191y}{24} + \frac{63y^2}{32} - \frac{145y^3}{96} - \frac{49y^4}{768} + \frac{y^5}{20} + \frac{y^7}{1344} \right]_0^2 = \frac{20803}{1680} \approx 12.4.
 \end{aligned}$$

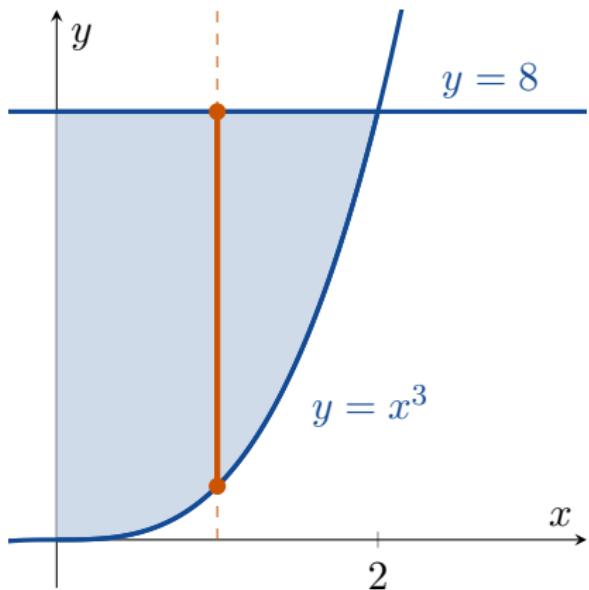


14.2 Double Integrals over General Regions



Now some problems for you.

14.2 Double Integrals over General Regions



Which is correct?

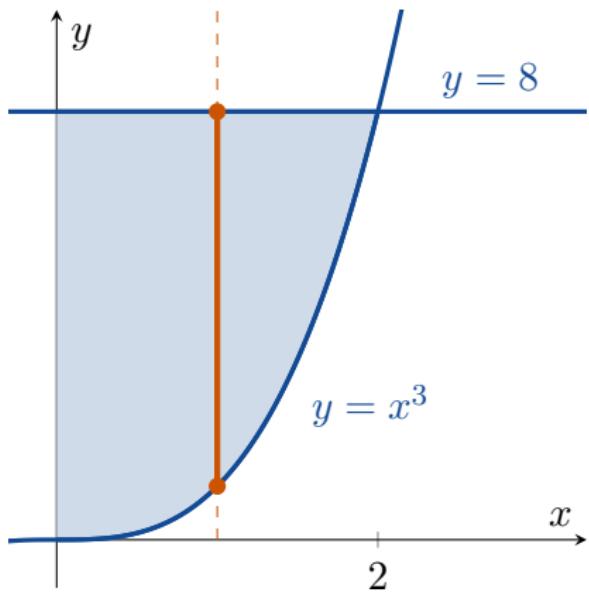
A $\int_0^2 \int_0^8 f(x, y) dy dx$

B $\int_0^2 \int_{x^3}^8 f(x, y) dy dx$

C $\int_{x^3}^8 \int_0^2 f(x, y) dy dx$

D $\int_0^1 \int_0^{x^3} f(x, y) dy dx$

14.2 Double Integrals over General Regions



Which is correct?

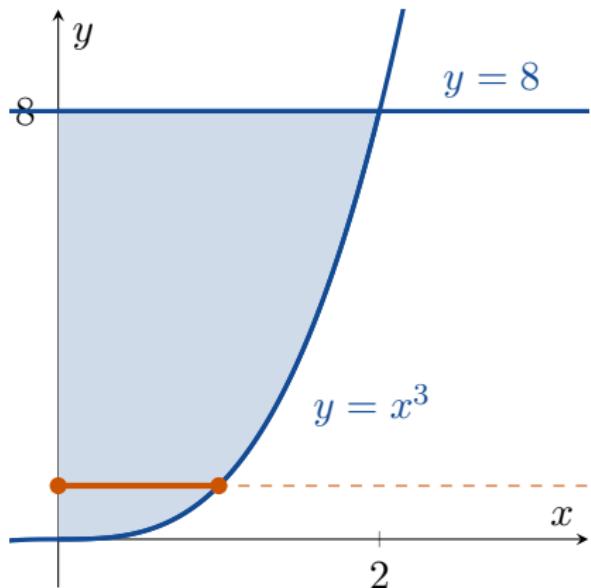
A $\int_0^2 \int_0^8 f(x, y) dy dx$

B $\int_0^2 \int_{x^3}^8 f(x, y) dy dx$

C $\int_{x^3}^8 \int_0^2 f(x, y) dy dx$

D $\int_0^1 \int_0^{x^3} f(x, y) dy dx$

14.2 Double Integrals over General Regions



Which is correct?

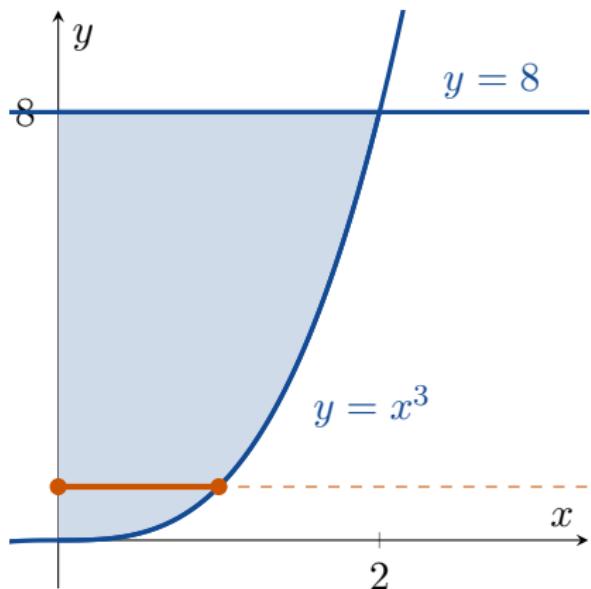
A $\int_0^8 \int_0^{y^{\frac{1}{3}}} f(x, y) dx dy$

B $\int_0^8 \int_0^{y^{\frac{1}{3}}} f(x, y) dy dx$

C $\int_0^8 \int_0^{x^3} f(x, y) dx dy$

D $\int_0^8 \int_0^3 f(x, y) dy dx$

14.2 Double Integrals over General Regions



Which is correct?

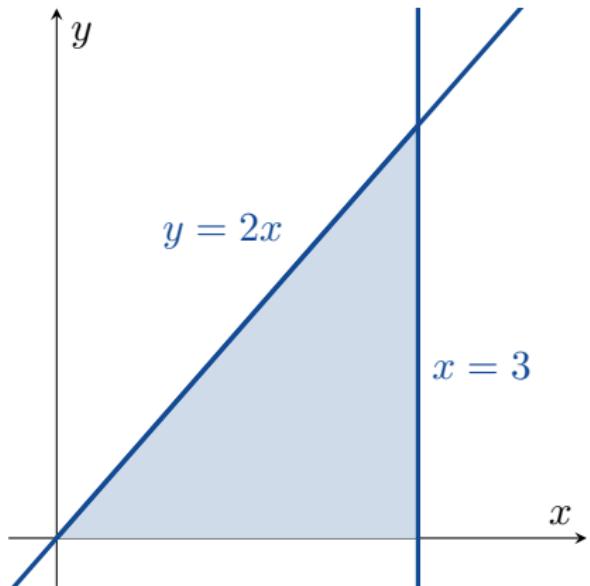
A $\int_0^8 \int_0^{y^{\frac{1}{3}}} f(x, y) dx dy$

B $\int_0^8 \int_0^{y^{\frac{1}{3}}} f(x, y) dy dx$

C $\int_0^8 \int_0^{x^3} f(x, y) dx dy$

D $\int_0^8 \int_0^3 f(x, y) dy dx$

14.2 Double Integrals over General Regions



Which is correct?

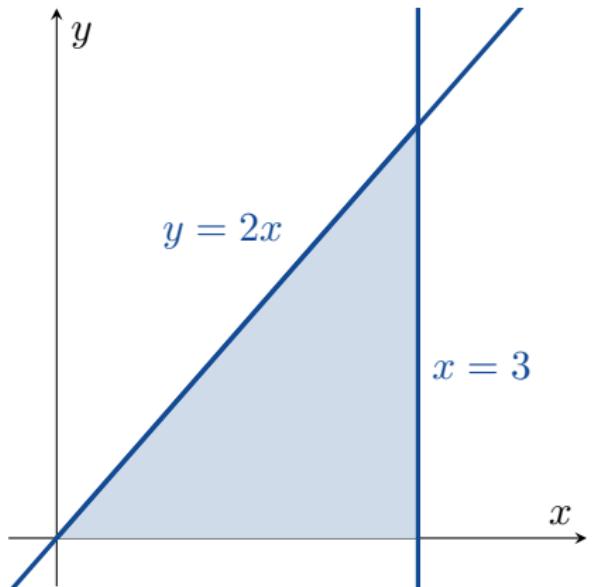
A $\int_0^6 \int_0^{\frac{y}{2}} f(x, y) \, dxdy$

B $\int_0^3 \int_0^{2x} f(x, y) \, dxdy$

C $\int_0^3 \int_0^{2x} f(x, y) \, dydx$

D $\int_0^6 \int_{\frac{y}{2}}^3 f(x, y) \, dxdy$

14.2 Double Integrals over General Regions



Which is correct?

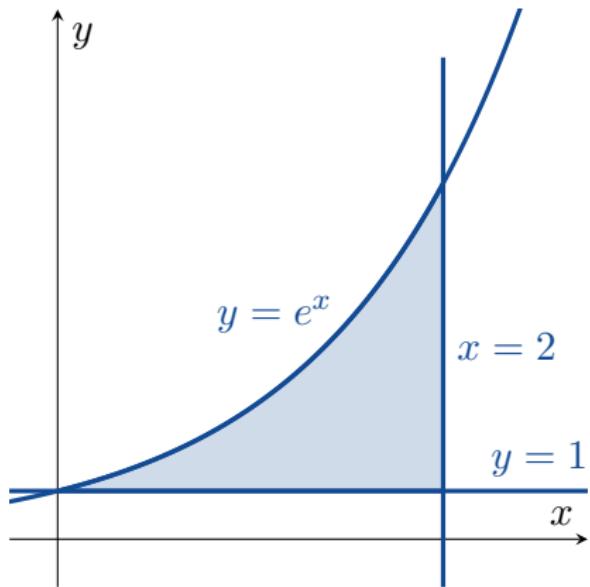
A $\int_0^6 \int_0^{\frac{y}{2}} f(x, y) \, dxdy$

B $\int_0^3 \int_0^{2x} f(x, y) \, dxdy$

C $\int_0^3 \int_0^{2x} f(x, y) \, dydx$

D $\int_0^6 \int_{\frac{y}{2}}^3 f(x, y) \, dxdy$

14.2 Double Integrals over General Regions



Which is correct?

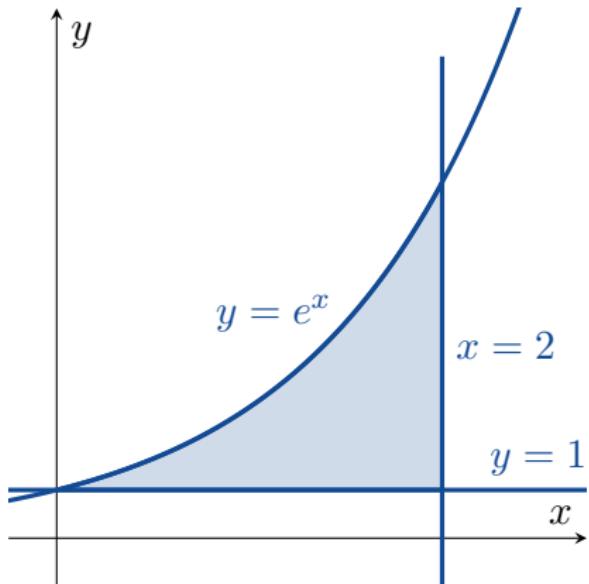
A $\int_1^{e^x} \int_0^2 f(x, y) \, dxdy$

B $\int_0^2 \int_0^{e^x} f(x, y) \, dxdy$

C $\int_0^2 \int_0^{e^x} f(x, y) \, dydx$

D $\int_0^2 \int_1^{e^x} f(x, y) \, dydx$

14.2 Double Integrals over General Regions



Which is correct?

A $\int_1^{e^x} \int_0^2 f(x, y) \, dxdy$

B $\int_0^2 \int_0^{e^x} f(x, y) \, dxdy$

C $\int_0^2 \int_0^{e^x} f(x, y) \, dydx$

D $\int_0^2 \int_1^{e^x} f(x, y) \, dydx$



Next Time

- 14.3 Area by Double Integration
- 10.3 Polar Coordinates
- 14.4 Double Integrals in Polar Form