

EXERCISES 16.4

Verifying Green's Theorem

In Exercises 1–4, verify the conclusion of Green's Theorem by evaluating both sides of Equations (3) and (4) for the field $\mathbf{F} = M\mathbf{i} + N\mathbf{j}$. Take the domains of integration in each case to be the disk $R: x^2 + y^2 \leq a^2$ and its bounding circle $C: \mathbf{r} = (a \cos t)\mathbf{i} + (a \sin t)\mathbf{j}$, $0 \leq t \leq 2\pi$.

1. $\mathbf{F} = -y\mathbf{i} + x\mathbf{j}$
2. $\mathbf{F} = y\mathbf{i}$
3. $\mathbf{F} = 2x\mathbf{i} - 3y\mathbf{j}$
4. $\mathbf{F} = -x^2y\mathbf{i} + xy^2\mathbf{j}$

Counterclockwise Circulation and Outward Flux

In Exercises 5–10, use Green's Theorem to find the counterclockwise circulation and outward flux for the field \mathbf{F} and curve C .

5. $\mathbf{F} = (x - y)\mathbf{i} + (y - x)\mathbf{j}$
 C : The square bounded by $x = 0, x = 1, y = 0, y = 1$
6. $\mathbf{F} = (x^2 + 4y)\mathbf{i} + (x + y^2)\mathbf{j}$
 C : The square bounded by $x = 0, x = 1, y = 0, y = 1$
7. $\mathbf{F} = (y^2 - x^2)\mathbf{i} + (x^2 + y^2)\mathbf{j}$
 C : The triangle bounded by $y = 0, x = 3$, and $y = x$
8. $\mathbf{F} = (x + y)\mathbf{i} - (x^2 + y^2)\mathbf{j}$
 C : The triangle bounded by $y = 0, x = 1$, and $y = x$
9. $\mathbf{F} = (x + e^x \sin y)\mathbf{i} + (x + e^x \cos y)\mathbf{j}$
 C : The right-hand loop of the lemniscate $r^2 = \cos 2\theta$
10. $\mathbf{F} = \left(\tan^{-1} \frac{y}{x}\right)\mathbf{i} + \ln(x^2 + y^2)\mathbf{j}$
 C : The boundary of the region defined by the polar coordinate inequalities $1 \leq r \leq 2, 0 \leq \theta \leq \pi$
11. Find the counterclockwise circulation and outward flux of the field $\mathbf{F} = xy\mathbf{i} + y^2\mathbf{j}$ around and over the boundary of the region enclosed by the curves $y = x^2$ and $y = x$ in the first quadrant.

12. Find the counterclockwise circulation and the outward flux of the field $\mathbf{F} = (-\sin y)\mathbf{i} + (x \cos y)\mathbf{j}$ around and over the square cut from the first quadrant by the lines $x = \pi/2$ and $y = \pi/2$.
13. Find the outward flux of the field

$$\mathbf{F} = \left(3xy - \frac{x}{1 + y^2}\right)\mathbf{i} + (e^x + \tan^{-1} y)\mathbf{j}$$

across the cardioid $r = a(1 + \cos \theta)$, $a > 0$.

14. Find the counterclockwise circulation of $\mathbf{F} = (y + e^x \ln y)\mathbf{i} + (e^x/y)\mathbf{j}$ around the boundary of the region that is bounded above by the curve $y = 3 - x^2$ and below by the curve $y = x^4 + 1$.

Work

In Exercises 15 and 16, find the work done by \mathbf{F} in moving a particle once counterclockwise around the given curve.

15. $\mathbf{F} = 2xy^3\mathbf{i} + 4x^2y^2\mathbf{j}$
 C : The boundary of the "triangular" region in the first quadrant enclosed by the x -axis, the line $x = 1$, and the curve $y = x^3$
16. $\mathbf{F} = (4x - 2y)\mathbf{i} + (2x - 4y)\mathbf{j}$
 C : The circle $(x - 2)^2 + (y - 2)^2 = 4$

Evaluating Line Integrals in the Plane

Apply Green's Theorem to evaluate the integrals in Exercises 17–20.

17. $\oint_C (y^2 dx + x^2 dy)$
 C : The triangle bounded by $x = 0, x + y = 1, y = 0$
18. $\oint_C (3y dx + 2x dy)$
 C : The boundary of $0 \leq x \leq \pi, 0 \leq y \leq \sin x$

19. $\oint_C (6y + x) dx + (y + 2x) dy$
 C : The circle $(x - 2)^2 + (y - 3)^2 = 4$

20. $\oint_C (2x + y^2) dx + (2xy + 3y) dy$
 C : Any simple closed curve in the plane for which Green's Theorem holds

Calculating Area with Green's Theorem

If a simple closed curve C in the plane and the region R it encloses satisfy the hypotheses of Green's Theorem, the area of R is given by

Green's Theorem Area Formula

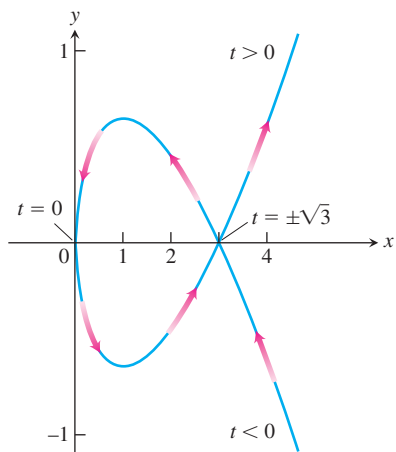
$$\text{Area of } R = \frac{1}{2} \oint_C x dy - y dx \quad (13)$$

The reason is that by Equation (3), run backward,

$$\begin{aligned} \text{Area of } R &= \iint_R dy dx = \iint_R \left(\frac{1}{2} + \frac{1}{2} \right) dy dx \\ &= \oint_C \frac{1}{2} x dy - \frac{1}{2} y dx. \end{aligned}$$

Use the Green's Theorem area formula (Equation 13) to find the areas of the regions enclosed by the curves in Exercises 21–24.

21. The circle $\mathbf{r}(t) = (a \cos t)\mathbf{i} + (a \sin t)\mathbf{j}$, $0 \leq t \leq 2\pi$
 22. The ellipse $\mathbf{r}(t) = (a \cos t)\mathbf{i} + (b \sin t)\mathbf{j}$, $0 \leq t \leq 2\pi$
 23. The astroid $\mathbf{r}(t) = (\cos^3 t)\mathbf{i} + (\sin^3 t)\mathbf{j}$, $0 \leq t \leq 2\pi$
 24. The curve $\mathbf{r}(t) = t^2\mathbf{i} + ((t^3/3) - t)\mathbf{j}$, $-\sqrt{3} \leq t \leq \sqrt{3}$ (see accompanying figure).



Theory and Examples

25. Let C be the boundary of a region on which Green's Theorem holds. Use Green's Theorem to calculate

a. $\oint_C f(x) dx + g(y) dy$

b. $\oint_C ky dx + hx dy$ (k and h constants).

26. **Integral dependent only on area** Show that the value of

$$\oint_C xy^2 dx + (x^2y + 2x) dy$$

around any square depends only on the area of the square and not on its location in the plane.

27. What is special about the integral

$$\oint_C 4x^3y dx + x^4 dy?$$

Give reasons for your answer.

28. What is special about the integral

$$\oint_C -y^3 dy + x^3 dx?$$

Give reasons for your answer.

29. **Area as a line integral** Show that if R is a region in the plane bounded by a piecewise-smooth simple closed curve C , then

$$\text{Area of } R = \oint_C x dy = - \oint_C y dx.$$

30. **Definite integral as a line integral** Suppose that a nonnegative function $y = f(x)$ has a continuous first derivative on $[a, b]$. Let C be the boundary of the region in the xy -plane that is bounded below by the x -axis, above by the graph of f , and on the sides by the lines $x = a$ and $x = b$. Show that

$$\int_a^b f(x) dx = - \oint_C y dx.$$

31. **Area and the centroid** Let A be the area and \bar{x} the x -coordinate of the centroid of a region R that is bounded by a piecewise-smooth simple closed curve C in the xy -plane. Show that

$$\frac{1}{2} \oint_C x^2 dy = - \oint_C xy dx = \frac{1}{3} \oint_C x^2 dy - xy dx = A\bar{x}.$$

32. **Moment of inertia** Let I_y be the moment of inertia about the y -axis of the region in Exercise 31. Show that

$$\frac{1}{3} \oint_C x^3 dy = - \oint_C x^2y dx = \frac{1}{4} \oint_C x^3 dy - x^2y dx = I_y.$$

- 33. Green's Theorem and Laplace's equation** Assuming that all the necessary derivatives exist and are continuous, show that if $f(x, y)$ satisfies the Laplace equation

$$\frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2} = 0,$$

then

$$\oint_C \frac{\partial f}{\partial y} dx - \frac{\partial f}{\partial x} dy = 0$$

for all closed curves C to which Green's Theorem applies. (The converse is also true: If the line integral is always zero, then f satisfies the Laplace equation.)

- 34. Maximizing work** Among all smooth simple closed curves in the plane, oriented counterclockwise, find the one along which the work done by

$$\mathbf{F} = \left(\frac{1}{4}x^2y + \frac{1}{3}y^3 \right) \mathbf{i} + xy \mathbf{j}$$

is greatest. (*Hint:* Where is $(\text{curl } \mathbf{F}) \cdot \mathbf{k}$ positive?)

- 35. Regions with many holes** Green's Theorem holds for a region R with any finite number of holes as long as the bounding curves are smooth, simple, and closed and we integrate over each component of the boundary in the direction that keeps R on our immediate left as we go along (Figure 16.37).

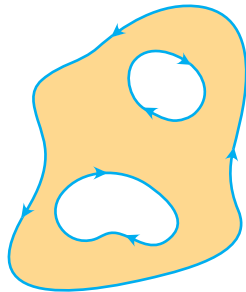


FIGURE 16.37 Green's Theorem holds for regions with more than one hole (Exercise 35).

- a. Let $f(x, y) = \ln(x^2 + y^2)$ and let C be the circle $x^2 + y^2 = a^2$. Evaluate the flux integral

$$\oint_C \nabla f \cdot \mathbf{n} \, ds.$$

- b. Let K be an arbitrary smooth simple closed curve in the plane

that does not pass through $(0, 0)$. Use Green's Theorem to show that

$$\oint_K \nabla f \cdot \mathbf{n} \, ds$$

has two possible values, depending on whether $(0, 0)$ lies inside K or outside K .

- 36. Bendixson's criterion** The *streamlines* of a planar fluid flow are the smooth curves traced by the fluid's individual particles. The vectors $\mathbf{F} = M(x, y)\mathbf{i} + N(x, y)\mathbf{j}$ of the flow's velocity field are the tangent vectors of the streamlines. Show that if the flow takes place over a simply connected region R (no holes or missing points) and that if $M_x + N_y \neq 0$ throughout R , then none of the streamlines in R is closed. In other words, no particle of fluid ever has a closed trajectory in R . The criterion $M_x + N_y \neq 0$ is called **Bendixson's criterion** for the nonexistence of closed trajectories.
- 37.** Establish Equation (7) to finish the proof of the special case of Green's Theorem.
- 38.** Establish Equation (10) to complete the argument for the extension of Green's Theorem.
- 39. Curl component of conservative fields** Can anything be said about the curl component of a conservative two-dimensional vector field? Give reasons for your answer.
- 40. Circulation of conservative fields** Does Green's Theorem give any information about the circulation of a conservative field? Does this agree with anything else you know? Give reasons for your answer.

COMPUTER EXPLORATIONS

Finding Circulation

In Exercises 41–44, use a CAS and Green's Theorem to find the counterclockwise circulation of the field \mathbf{F} around the simple closed curve C . Perform the following CAS steps.

- Plot C in the xy -plane.
 - Determine the integrand $(\partial N/\partial x) - (\partial M/\partial y)$ for the curl form of Green's Theorem.
 - Determine the (double integral) limits of integration from your plot in part (a) and evaluate the curl integral for the circulation.
- 41.** $\mathbf{F} = (2x - y)\mathbf{i} + (x + 3y)\mathbf{j}$, C : The ellipse $x^2 + 4y^2 = 4$
- 42.** $\mathbf{F} = (2x^3 - y^3)\mathbf{i} + (x^3 + y^3)\mathbf{j}$, C : The ellipse $\frac{x^2}{4} + \frac{y^2}{9} = 1$
- 43.** $\mathbf{F} = x^{-1}e^y\mathbf{i} + (e^y \ln x + 2x)\mathbf{j}$,
 C : The boundary of the region defined by $y = 1 + x^4$ (below) and $y = 2$ (above)
- 44.** $\mathbf{F} = xe^y\mathbf{i} + 4x^2 \ln y \mathbf{j}$,
 C : The triangle with vertices $(0, 0)$, $(2, 0)$, and $(0, 4)$