

## **Chapter 14 - Problem Set 2**

### **Calculus 3**

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## Section 5: The Chain Rule

### 3-7 (odd)

Use The Chain Rule to find  $\frac{dz}{dt}$  or  $\frac{dw}{dt}$ .

3.  $z = xy^3 - x^2y, \quad x = t^2 + 1, \quad y = t^2 - 1$

*Solution*

$$\begin{aligned}\frac{dz}{dt} &= \frac{dz}{dx} \left( \frac{dx}{dt} \right) + \frac{dz}{dy} \left( \frac{dy}{dt} \right) \\ \frac{dz}{dt} &= [y^3 - 2xy](2t) + [3xy^2 - x^2](2t) \\ \boxed{\frac{dz}{dt} &= 2t[y^3 - 2xy + 3xy^2 - x^2]}\end{aligned}$$

5.  $z = \sin x \cos y, \quad x = \sqrt{t}, \quad y = 1/t$

*Solution*

$$\begin{aligned}\frac{dz}{dt} &= \frac{dz}{dx} \left( \frac{dx}{dt} \right) + \frac{dz}{dy} \left( \frac{dy}{dt} \right) \\ \frac{dz}{dt} &= [\cos x \cos y] \left( \frac{1}{2} t^{-\frac{1}{2}} \right) + [-\sin x \sin y] (-t^{-2}) \\ \boxed{\frac{dz}{dt} &= \frac{1}{2\sqrt{t}} \cos x \cos y + \frac{1}{t^2} \sin x \sin y}\end{aligned}$$

7.  $w = xe^{y/z}, \quad x = t^2, \quad y = 1 - t, \quad z = 1 + 2t$

*Solution*

$$\begin{aligned}\frac{dw}{dt} &= \frac{dw}{dx} \left( \frac{dx}{dt} \right) + \frac{dw}{dy} \left( \frac{dy}{dt} \right) + \frac{dw}{dz} \left( \frac{dz}{dt} \right) \\ \frac{dw}{dt} &= [e^{y/z}] (2t) + \left[ \frac{x}{z} e^{y/z} \right] (-1) + \left[ -\frac{xy}{z^2} e^{y/z} \right] (2) \\ \boxed{\frac{dw}{dt} &= e^{y/z} \left[ 2t - \frac{x}{z} - \frac{2xy}{z^2} \right]}\end{aligned}$$

**11-15 (odd)**

Use the Chain Rule to find  $\frac{\partial z}{\partial s}$  and  $\frac{\partial z}{\partial t}$

11.  $z = (x - y)^5, \quad x = s^2t, \quad y = st^2$

*Solution*

$$\begin{aligned}\frac{\partial z}{\partial s} &= \frac{\partial z}{\partial x} \left( \frac{\partial x}{\partial s} \right) + \frac{\partial z}{\partial y} \left( \frac{\partial y}{\partial s} \right) \\ \frac{\partial z}{\partial s} &= [5(x - y)^4] (2st) + [-5(x - y)^4] (t^2)\end{aligned}$$

$$\boxed{\frac{\partial z}{\partial s} = 5(x - y)^4 [2st - t^2]}$$

$$\begin{aligned}\frac{\partial z}{\partial t} &= \frac{\partial z}{\partial x} \left( \frac{\partial x}{\partial t} \right) + \frac{\partial z}{\partial y} \left( \frac{\partial y}{\partial t} \right) \\ \frac{\partial z}{\partial t} &= [5(x - y)^4] (s^2) + [-5(x - y)^4] (2st)\end{aligned}$$

$$\boxed{\frac{\partial z}{\partial t} = 5(x - y)^4 [s^2 - 2st]}$$

13.  $z = \ln(3x + 2y), \quad x = s \sin t, \quad y = t \cos s$

*Solution*

$$\begin{aligned}\frac{\partial z}{\partial s} &= \frac{\partial z}{\partial x} \left( \frac{\partial x}{\partial s} \right) + \frac{\partial z}{\partial y} \left( \frac{\partial y}{\partial s} \right) \\ \frac{\partial z}{\partial s} &= \left[ \frac{3}{3x + 2y} \right] (\sin t) + \left[ \frac{2}{3x + 2y} \right] (-t \sin s)\end{aligned}$$

$$\boxed{\frac{\partial z}{\partial s} = \frac{3 \sin t - 2t \sin s}{3x + 2y}}$$

$$\begin{aligned}\frac{\partial z}{\partial t} &= \frac{\partial z}{\partial x} \left( \frac{\partial x}{\partial t} \right) + \frac{\partial z}{\partial y} \left( \frac{\partial y}{\partial t} \right) \\ \frac{\partial z}{\partial t} &= \left[ \frac{3}{3x + 2y} \right] (s \cos t) + \left[ \frac{2}{3x + 2y} \right] (\cos s)\end{aligned}$$

$$\boxed{\frac{\partial z}{\partial t} = \frac{3s \cos t + 2 \cos s}{3x + 2y}}$$

15.  $z = (\sin \theta)/r, \quad r = st, \quad \theta = s^2 + t^2$

*Solution*

$$\frac{\partial z}{\partial s} = \frac{\partial z}{\partial r} \left( \frac{\partial r}{\partial s} \right) + \frac{\partial z}{\partial \theta} \left( \frac{\partial \theta}{\partial s} \right)$$

$$\frac{\partial z}{\partial s} = \left[ -\frac{\sin \theta}{r^2} \right] (t) + \left[ \frac{\cos \theta}{r} \right] (2s)$$

$$\boxed{\frac{\partial z}{\partial s} = -\frac{t \sin \theta}{r^2} + \frac{2s \cos \theta}{r}}$$

$$\frac{\partial z}{\partial t} = \frac{\partial z}{\partial r} \left( \frac{\partial r}{\partial t} \right) + \frac{\partial z}{\partial \theta} \left( \frac{\partial \theta}{\partial t} \right)$$

$$\frac{\partial z}{\partial t} = \left[ -\frac{\sin \theta}{r^2} \right] (s) + \left[ \frac{\cos \theta}{r} \right] (2t)$$

$$\boxed{\frac{\partial z}{\partial t} = -\frac{s \sin \theta}{r^2} + \frac{2t \cos \theta}{r}}$$

### 25-29 (odd)

Use the Chain Rule to find the indicated partial derivatives.

25.  $z = x^4 + x^2y, \quad x = s + 2t - u, \quad y = stu^2;$

$\frac{\partial z}{\partial s}, \frac{\partial z}{\partial t}, \frac{\partial z}{\partial u}$  when  $s = 4, t = 2, u = 1$

*Solution*

When  $s = 4, t = 2$ , and  $u = 1 \Rightarrow x = 7, y = 8$

$$\frac{\partial z}{\partial s} = [4x^3 + 2xy] (1) + [x^2] (tu^2) = 4x^3 + 2xy + x^2tu^2$$

$$\frac{\partial z}{\partial s} = 4(7)^3 + 2(7)(8) + (7)^2(2)(1)^2$$

$$\boxed{\frac{\partial z}{\partial s} = 1582}$$

$$\frac{\partial z}{\partial t} = [4x^3 + 2xy] (2) + [x^2] (su^2) = 8x^3 + 4xy + x^2su^2$$

$$\frac{\partial z}{\partial t} = 8(7)^3 + 4(7)(8) + (7)^2(4)(1)^2$$

$$\boxed{\frac{\partial z}{\partial t} = 3164}$$

$$\frac{\partial z}{\partial u} = [4x^3 + 2xy] (-1) + [x^2] (2stu) = -4x^3 - 2xy + 2x^2stu$$

$$\frac{\partial z}{\partial u} = -4(7)^3 - 2(7)(8) + 2(7)^2(4)(2)(1)$$

$$\boxed{\frac{\partial z}{\partial u} = -700}$$

**27.**  $w = xy + yz + zx, \quad x = r \cos \theta, \quad y = r \sin \theta, \quad z = r\theta;$

$$\frac{\partial w}{\partial r}, \frac{\partial w}{\partial \theta} \quad \text{when } r = 2, \theta = \pi/2$$

*Solution*

When  $r = 2$  and  $\theta = \pi/2 \Rightarrow x = 0, y = 2, z = \pi$

$$\frac{\partial w}{\partial r} = [y + z](\cos \theta) + [x + z](\sin \theta) + [x + y](\theta)$$

$$\frac{\partial w}{\partial r} = [2 + \pi](0) + [0 + \pi](1) + [0 + 2](\pi/2) = 0 + \pi + \pi$$

$$\boxed{\frac{\partial w}{\partial r} = 2\pi}$$

$$\frac{\partial w}{\partial \theta} = [y + z](-r \sin \theta) + [x + z](r \cos \theta) + [x + y](r)$$

$$\frac{\partial w}{\partial \theta} = [2 + \pi](-2 \cdot 1) + [0 + \pi](0) + [0 + 2](2) = -4 - 2\pi + 0 + 4$$

$$\boxed{\frac{\partial w}{\partial \theta} = -2\pi}$$

$$29. N = \frac{p+q}{p+r}, \quad p = u + vw, \quad q = v + uw, \quad r = w + uv$$

$$\frac{\partial N}{\partial u}, \frac{\partial N}{\partial v}, \frac{\partial N}{\partial w} \quad \text{when } u = 2, v = 3, w = 4$$

*Solution*

$$\text{When } u = 2, v = 3, \text{ and } w = 4 \Rightarrow p = 14, q = 11, r = 10$$

$$\frac{\partial N}{\partial u} = \left[ \frac{(p+r) - (p+q)}{(p+r)^2} \right] (1) + \left[ \frac{1}{p+r} \right] (w) + \left[ -\frac{p+q}{(p+r)^2} \right] (v)$$

$$\frac{\partial N}{\partial u} = \frac{r-q}{(p+r)^2} + \frac{w}{p+r} - \frac{v(p+q)}{(p+r)^2}$$

$$\frac{\partial N}{\partial u} = \frac{10-11}{(14+10)^2} + \frac{4}{14+10} - \frac{3(14+11)}{(14+10)^2}$$

$$\frac{\partial N}{\partial u} = \frac{-1}{576} + \frac{4}{24} - \frac{75}{576} = \frac{-1+96-75}{576} = \frac{20}{576}$$

$$\boxed{\frac{\partial N}{\partial u} = \frac{5}{144}}$$

$$\frac{\partial N}{\partial v} = \left[ \frac{r-q}{(p+r)^2} \right] (w) + \left[ \frac{1}{p+r} \right] (1) + \left[ -\frac{p+q}{(p+r)^2} \right] (u)$$

$$\frac{\partial N}{\partial v} = \frac{w(r-q)}{(p+r)^2} + \frac{1}{p+r} - \frac{u(p+q)}{(p+r)^2}$$

$$\frac{\partial N}{\partial v} = \frac{4(10-11)}{(14+10)^2} + \frac{1}{14+10} - \frac{2(14+11)}{(14+10)^2}$$

$$\frac{\partial N}{\partial v} = \frac{-4}{576} + \frac{1}{24} - \frac{50}{576} = \frac{-4+24-50}{576} = \frac{-30}{576}$$

$$\boxed{\frac{\partial N}{\partial v} = -\frac{5}{96}}$$

$$\frac{\partial N}{\partial w} = \left[ \frac{r-q}{(p+r)^2} \right] (v) + \left[ \frac{1}{p+r} \right] (u) + \left[ -\frac{p+q}{(p+r)^2} \right] (1)$$

$$\frac{\partial N}{\partial w} = \frac{v(r-q)}{(p+r)^2} + \frac{u}{p+r} - \frac{p+q}{(p+r)^2}$$

$$\frac{\partial N}{\partial w} = \frac{3(10-11)}{(14+10)^2} + \frac{2}{(14+10)} - \frac{14+11}{(14+10)^2}$$

$$\frac{\partial N}{\partial w} = \frac{-3}{576} + \frac{2}{24} - \frac{25}{576} = \frac{-3+48-25}{576} = \frac{20}{576}$$

$$\boxed{\frac{\partial N}{\partial w} = \frac{5}{144}}$$

Use Equation 5 to find  $\frac{dy}{dx}$

**31.**  $y \cos x = x^2 + y^2$

*Solution*

$$\frac{dy}{dx} = -\frac{\frac{\partial F}{\partial x}}{\frac{\partial F}{\partial y}} = -\frac{F_x}{F_y}$$

Let  $F = y \cos x - x^2 - y^2$

$$F_x = -y \sin x - 2x$$

$$F_y = \cos x - 2y$$

$$\frac{dy}{dx} = -\frac{F_x}{F_y} = -\frac{(-y \sin x - 2x)}{\cos x - 2y} = \frac{2x + y \sin x}{\cos x - 2y}$$


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Use Equations 6 to find  $\frac{\partial z}{\partial x}$  and  $\frac{\partial z}{\partial y}$

**35.**  $x^2 + 2y^2 + 3z^2 = 1$

*Solution*

$$\frac{\partial z}{\partial x} = -\frac{F_x}{F_z} \quad \frac{\partial z}{\partial y} = -\frac{F_y}{F_z}$$

Let  $F = x^2 + 2y^2 + 3z^2 - 1$

$$F_x = 2x \quad F_y = 4y \quad F_z = 6z$$

$$\frac{\partial z}{\partial x} = -\frac{F_x}{F_z} = -\frac{2x}{6z} = -\frac{x}{3z}$$

$$\frac{\partial z}{\partial y} = -\frac{F_y}{F_z} = -\frac{4y}{6z} = -\frac{2y}{3z}$$


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## Section 6: Directional Derivatives and the Gradient Vector

**5, 7**

Find the directional derivative of  $f$  at the given point in the direction indicated by the angle  $\theta$ .

5.  $f(x, y) = y \cos(xy)$ ,  $(0, 1)$ ,  $\theta = \pi/4$

*Solution*

$$D_u f(x, y) = f_x(x, y) \cos \theta + f_y(x, y) \sin \theta$$

$$D_u f(x, y) = [-y^2 \sin(xy)] \cos \frac{\pi}{4} + [\cos(xy) - xy \sin(xy)] \sin \frac{\pi}{4}$$

$$D_u f(x, y) = \frac{\sqrt{2}}{2} [-y^2 \sin(xy) + \cos(xy) - xy \sin(xy)]$$

$$D_u f(0, 1) = \frac{\sqrt{2}}{2} [0 + 1 - 0]$$

$$\boxed{D_u f(0, 1) = \frac{\sqrt{2}}{2}}$$

7.  $f(x, y) = \arctan(xy)$ ,  $(2, -3)$ ,  $\theta = 3\pi/4$

*Solution*

$$D_u f(x, y) = f_x(x, y) \cos \theta + f_y(x, y) \sin \theta$$

$$D_u f(x, y) = \left[ \frac{y}{1 + (xy)^2} \right] \cos \frac{3\pi}{4} + \left[ \frac{x}{1 + (xy)^2} \right] \sin \frac{3\pi}{4}$$

$$D_u f(x, y) = \frac{\sqrt{2}}{2} \left[ \frac{x}{1 + (xy)^2} - \frac{y}{1 + (xy)^2} \right]$$

$$D_u f(2, -3) = \frac{\sqrt{2}}{2} \left[ \frac{2}{1 + (2(-3))^2} - \frac{-3}{1 + (2(-3))^2} \right]$$

$$D_u f(2, -3) = \frac{\sqrt{2}}{2} \left[ \frac{5}{37} \right]$$

$$\boxed{D_u f(2, -3) = \frac{5\sqrt{2}}{74}}$$



**9**

$$f(x, y) = x/y, \quad P(2, 1), \quad \vec{u} = \frac{3}{5} \hat{\mathbf{i}} + \frac{4}{5} \hat{\mathbf{j}}$$

- (a) Find the gradient of  $f$   
(b) Evaluate the gradient at the point  $P$   
(c) Find the rate of change of  $f$  at  $P$  in the direction of the vector  $\vec{u}$

*Solution*

(a)

$$\nabla f(x, y) = \langle f_x(x, y), f_y(x, y) \rangle \quad \text{or} \quad \frac{\partial f}{\partial x} \hat{\mathbf{i}} + \frac{\partial f}{\partial y} \hat{\mathbf{j}}$$

$$\boxed{\nabla f(x, y) = \left\langle \frac{1}{y}, -\frac{x}{y^2} \right\rangle}$$

(b)

$$\boxed{\nabla f(2, 1) = \left\langle \frac{1}{1}, -\frac{2}{1^2} \right\rangle = \langle 1, -2 \rangle}$$

(c)

$$D_u f(x, y) = \nabla f(x, y) \cdot \vec{u}$$

$$D_u f(2, 1) = \nabla f(2, 1) \cdot \vec{u}$$

$$D_u f(2, 1) = \langle 1, -2 \rangle \cdot \left\langle \frac{3}{5}, \frac{4}{5} \right\rangle$$

$$D_u f(2, 1) = \frac{3}{5} - \frac{8}{5}$$

$$\boxed{D_u f(2, 1) = -1}$$

**13, 15**

Find the directional derivative of the function at the given point in the direction of the vector  $\vec{v}$ .

**13.**  $f(x, y) = e^x \sin y, \quad (0, \pi/3), \quad \vec{v} = \langle -6, 8 \rangle$

*Solution*

$$\vec{u} = \frac{\vec{v}}{\|\vec{v}\|} = \frac{-6\hat{\mathbf{i}} + 8\hat{\mathbf{j}}}{\sqrt{(6)^2 + (8)^2}}$$

$$\vec{u} = -\frac{3}{5}\hat{\mathbf{i}} + \frac{4}{5}\hat{\mathbf{j}}$$

$$D_u f(x, y) = \nabla f(x, y) \cdot \vec{u}$$

$$D_u f(x, y) = (e^x \sin y \hat{\mathbf{i}} + e^x \cos y \hat{\mathbf{j}}) \cdot \left(-\frac{3}{5}\hat{\mathbf{i}} + \frac{4}{5}\hat{\mathbf{j}}\right)$$

$$D_u f(x, y) = -\frac{3e^x \sin y}{5} + \frac{4e^x \cos y}{5}$$

$$D_u f(0, \frac{\pi}{3}) = -\frac{3(\frac{\sqrt{3}}{2})}{5} + \frac{4(\frac{1}{2})}{5}$$

$$\boxed{D_u f(0, \frac{\pi}{3}) = \frac{4 - 3\sqrt{3}}{10}}$$

**15.**  $g(s, t) = s\sqrt{t}, \quad (2, 4), \quad \vec{v} = 2\hat{\mathbf{i}} - \hat{\mathbf{j}}$

*Solution*

$$\vec{u} = \frac{\vec{v}}{\|\vec{v}\|} = \frac{2\hat{\mathbf{i}} - \hat{\mathbf{j}}}{\sqrt{(2)^2 + (-1)^2}}$$

$$\vec{u} = \frac{2}{\sqrt{5}}\hat{\mathbf{i}} - \frac{1}{\sqrt{5}}\hat{\mathbf{j}}$$

$$D_u g(s, t) = \nabla g(s, t) \cdot \vec{u}$$

$$D_u g(s, t) = \left(\sqrt{t}\hat{\mathbf{i}} + \frac{s}{2\sqrt{t}}\hat{\mathbf{j}}\right) \cdot \left(\frac{2}{\sqrt{5}}\hat{\mathbf{i}} - \frac{1}{\sqrt{5}}\hat{\mathbf{j}}\right)$$

$$D_u g(s, t) = \frac{2\sqrt{t}}{\sqrt{5}} - \frac{s}{2\sqrt{t}\sqrt{5}}$$

$$D_u g(s, t) = \frac{1}{\sqrt{5}} \left(2\sqrt{t} - \frac{s}{2\sqrt{t}}\right)$$

$$D_u g(2, 4) = \frac{1}{\sqrt{5}} \left(2\sqrt{4} - \frac{2}{2\sqrt{4}}\right) = \frac{1}{\sqrt{5}} \left(4 - \frac{1}{2}\right)$$

$$\boxed{D_u g(2, 4) = \frac{1}{\sqrt{5}} \left(\frac{8-1}{2}\right) = \frac{7}{2\sqrt{5}}}$$

**21, 23**

Find the directional derivative of the function at the point  $P$  in the direction of the point  $Q$ .

**21.**  $f(x, y) = x^2y^2 - y^3$ ,  $P(1, 2)$ ,  $Q(-3, 5)$

*Solution*

$$\vec{v} = \vec{PQ} = \langle -3 - 1, 5 - 2 \rangle = \langle -4, 3 \rangle$$

$$\vec{u} = \frac{\vec{v}}{\|\vec{v}\|} = \frac{\langle -4, 3 \rangle}{\sqrt{16 + 9}}$$

$$\vec{u} = \left\langle -\frac{4}{5}, \frac{3}{5} \right\rangle$$

$$D_u f(x, y) = \nabla f(x, y) \cdot \vec{u}$$

$$D_u f(x, y) = \langle 2xy^2, 2x^2y - 3y^2 \rangle \cdot \left\langle -\frac{4}{5}, \frac{3}{5} \right\rangle$$

$$D_u f(x, y) = -\frac{8xy^2}{5} + \frac{3(2x^2y - 3y^2)}{5} = \frac{1}{5}(-8xy^2 + 6x^2y - 9y^2)$$

$$D_u f(1, 2) = \frac{1}{5}[-8(1)(4) + 6(1)(2) - 9(4)] = \frac{1}{5}[-32 + 12 - 36]$$

$$\boxed{D_u f(1, 2) = -\frac{56}{5}}$$

**23.**  $f(x, y) = \sqrt{xy}$ ,  $P(2, 8)$ ,  $Q(5, 4)$

*Solution*

$$\vec{v} = \vec{PQ} = (5 - 2)\hat{\mathbf{i}} + (4 - 8)\hat{\mathbf{j}} = 3\hat{\mathbf{i}} - 4\hat{\mathbf{j}}$$

$$\vec{u} = \frac{\vec{v}}{\|\vec{v}\|} = \frac{3\hat{\mathbf{i}} - 4\hat{\mathbf{j}}}{\sqrt{9 + 16}}$$

$$\vec{u} = \frac{3}{5}\hat{\mathbf{i}} - \frac{4}{5}\hat{\mathbf{j}}$$

$$D_u f(x, y) = \nabla f(x, y) \cdot \vec{u}$$

$$D_u f(x, y) = \left( \frac{y}{2\sqrt{xy}}\hat{\mathbf{i}} + \frac{x}{2\sqrt{xy}}\hat{\mathbf{j}} \right) \cdot \left( \frac{3}{5}\hat{\mathbf{i}} - \frac{4}{5}\hat{\mathbf{j}} \right)$$

$$D_u f(x, y) = \frac{3y}{10\sqrt{xy}} - \frac{4x}{10\sqrt{xy}} = \frac{3y - 4x}{10\sqrt{xy}}$$

$$D_u f(2, 8) = \frac{3(8) - 4(2)}{10\sqrt{2(8)}} = \frac{24 - 8}{10\sqrt{16}} = \frac{16}{40}$$

$$\boxed{D_u f(x, y) = \frac{2}{5}}$$

**27, 29**

Find the maximum rate of change of  $f$  at the given point and the direction in which it occurs.

**27.**  $f(x, y) = 5xy^2, \quad (3, -2)$

*Solution*

The maximum rate of change of  $f$  and its direction is given by the gradient vector

$$\begin{aligned}\nabla f(x, y) &= \langle f_x, f_y \rangle = \langle 5y^2, 10xy \rangle \\ \nabla f(3, -2) &= \langle 5(-2)^2, 10(3)(-2) \rangle\end{aligned}$$

Direction of the maximum rate of change,

$$\boxed{\nabla f(3, -2) = \langle 20, -60 \rangle = 20\langle 1, -3 \rangle}$$

Maximum rate of change,

$$\boxed{\|\nabla f(3, -2)\| = 20\sqrt{1+9} = 20\sqrt{10}}$$

**29.**  $f(x, y) = \sin(xy), \quad (1, 0)$

*Solution*

The maximum rate of change of  $f$  and its direction is given by the gradient vector

$$\begin{aligned}\nabla f(x, y) &= \frac{\partial f}{\partial x} \hat{\mathbf{i}} + \frac{\partial f}{\partial y} \hat{\mathbf{j}} = y \cos(xy) \hat{\mathbf{i}} + x \cos(xy) \hat{\mathbf{j}} \\ \nabla f(1, 0) &= 0 + \hat{\mathbf{j}}\end{aligned}$$

Direction of the maximum rate of change,

$$\boxed{\nabla f(1, 0) = \hat{\mathbf{j}}}$$

Maximum rate of change,

$$\boxed{\|\nabla f(1, 0)\| = \sqrt{1} = 1}$$

## 37

The temperature  $T$  in a metal ball is inversely proportional to the distance from the center of the ball, which we take to be the origin. The temperature at the point  $(1, 2, 2)$  is  $120^\circ$

- (a) Find the rate of change of  $T$  at  $(1, 2, 2)$  in the direction toward the point  $(2, 1, 3)$ .
- (b) Show that at any point in the ball the direction of greatest increase in temperature is given by a vector that points toward the origin

*Solution*

Since  $T \propto \frac{1}{d}$ ,  $T(x, y, z) = \frac{c}{\sqrt{x^2 + y^2 + z^2}}$ , for some constant  $c$ , and Euclidean distance to describe the distance from the origin.

If  $120 = T(1, 2, 2) = \frac{c}{\sqrt{1^2 + 2^2 + 2^2}} = \frac{c}{3}$ , then  $c = 360$

$\therefore$  Our function for temperature is,

$$T(x, y, z) = \frac{360}{\sqrt{x^2 + y^2 + z^2}}$$

(a)

$$\vec{v} = \langle 2 - 1, 1 - 2, 3 - 2 \rangle = \langle 1, -1, 1 \rangle$$

$$\vec{u} = \frac{\vec{v}}{\|\vec{v}\|} = \frac{\langle 1, -1, 1 \rangle}{\sqrt{1 + 1 + 1}}$$

$$\vec{u} = \left\langle \frac{1}{\sqrt{3}}, -\frac{1}{\sqrt{3}}, \frac{1}{\sqrt{3}} \right\rangle$$

Getting our gradient vector,

$$\nabla T(x, y, z) = \langle T_x, T_y, T_z \rangle$$

$$\nabla T(x, y, z) = \langle -180 \cdot 2x(x^2 + y^2 + z^2)^{-3/2}, -180 \cdot 2y(x^2 + y^2 + z^2)^{-3/2}, -180 \cdot 2z(x^2 + y^2 + z^2)^{-3/2} \rangle$$

$$\nabla T(x, y, z) = \frac{360}{(x^2 + y^2 + z^2)^{3/2}} \langle -x, -y, -z \rangle$$

so, our rate of change is

$$D_u T(1, 2, 2) = \nabla T(1, 2, 2) \cdot \vec{u}$$

$$D_u T(1, 2, 2) = \frac{360}{(1 + 4 + 4)^{3/2}} \langle -1, -2, -2 \rangle \cdot \left\langle \frac{1}{\sqrt{3}}, -\frac{1}{\sqrt{3}}, \frac{1}{\sqrt{3}} \right\rangle$$

$$D_u T(1, 2, 2) = \frac{360}{27} \left( -\frac{1}{\sqrt{3}} + \frac{2}{\sqrt{3}} - \frac{2}{\sqrt{3}} \right) = \frac{360}{27} \left( -\frac{1}{\sqrt{3}} \right)$$

$$\boxed{D_u T(1, 2, 2) = \frac{40}{3} \left( -\frac{1}{\sqrt{3}} \right) = -\frac{40}{3\sqrt{3}}}$$

(b) The direction of greatest increase at any point is the direction of  $\nabla T$  at that point. In part (a) we saw that  $\nabla T(x, y, z)$  and  $\langle -x, -y, -z \rangle$  have the same direction and the vector  $\langle -x, -y, -z \rangle$  points towards the origin.

**47-51 (odd)**

Find equations of (a) the tangent plane and (b) the normal line to the given surface at the specified point.

**47.**  $2(x-2)^2 + (y-1)^2 + (z-3)^2 = 10, \quad (3, 3, 5)$

*Solution*

(a)

$$F(x, y, z) = 2(x-2)^2 + (y-1)^2 + (z-3)^2 - 10$$

$$F_x(3, 3, 5) = 4(x-2) = 4(1) = 4$$

$$F_y(3, 3, 5) = 2(y-1) = 2(2) = 4$$

$$F_z(3, 3, 5) = 2(z-3) = 2(2) = 4$$

The equation of the tangent plane is given by,

$$F_x(x_0, y_0, z_0)(x - x_0) + F_y(x_0, y_0, z_0)(y - y_0) + F_z(x_0, y_0, z_0)(z - z_0)$$

$$4(x-3) + 4(y-3) + 4(z-5) = 0$$

$$x-3 + y-3 + z-5 = 0$$

$$\boxed{x + y + z = 11}$$

(b) The equation of the normal line is given by,

$$\frac{x - x_0}{F_x(x_0, y_0, z_0)} = \frac{y - y_0}{F_y(x_0, y_0, z_0)} = \frac{z - z_0}{F_z(x_0, y_0, z_0)}$$

$$\frac{x-3}{4} = \frac{y-3}{4} = \frac{z-5}{4}$$

$$\boxed{x-3 = y-3 = z-5}$$

**49.**  $xy^2z^3 = 8, \quad (2, 2, 1)$

*Solution*

(a)

$$F(x, y, z) = xy^2z^3 - 8$$

$$F_x(2, 2, 1) = y^2z^3 = (4)(1) = 4$$

$$F_y(2, 2, 1) = 2xy^2z^3 = 2(2)(2)(1) = 8$$

$$F_z(2, 2, 1) = 3xy^2z^2 = 3(2)(4)(1) = 24$$

The equation of the tangent plane is given by,

$$F_x(x_0, y_0, z_0)(x - x_0) + F_y(x_0, y_0, z_0)(y - y_0) + F_z(x_0, y_0, z_0)(z - z_0)$$

$$4(x-2) + 8(y-2) + 24(z-1) = 0$$

$$x-2 + 2(y-2) + 6(z-1) = 0$$

$$x-2 + 2y-4 + 6z-6 = 0$$

$$\boxed{x + 2y + 6z = 12}$$

(b) The equation of the normal line is given by,

$$\frac{x - x_0}{F_x(x_0, y_0, z_0)} = \frac{y - y_0}{F_y(x_0, y_0, z_0)} = \frac{z - z_0}{F_z(x_0, y_0, z_0)}$$

$$\frac{x - 2}{4} = \frac{y - 2}{8} = \frac{z - 1}{24}$$

$$\boxed{x - 2 = \frac{y - 2}{2} = \frac{z - 1}{6}}$$

**51.**  $x + y + z = e^{xyz}, \quad (0, 0, 1)$

*Solution*

(a)

$$F(x, y, z) = x + y + z - e^{xyz}$$

$$F_x(0, 0, 1) = 1 - yze^{xyz} = 1 - 0 = 1$$

$$F_y(0, 0, 1) = 1 - xze^{xyz} = 1 - 0 = 1$$

$$F_z(0, 0, 1) = 1 - xye^{xyz} = 1 - 0 = 1$$

The equation of the tangent plane is given by,

$$F_x(x_0, y_0, z_0)(x - x_0) + F_y(x_0, y_0, z_0)(y - y_0) + F_z(x_0, y_0, z_0)(z - z_0)$$

$$1(x - 0) + 1(y - 0) + 1(z - 1) = 0$$

$$\boxed{x + y + z = 1}$$

(b) The equation of the normal line is given by,

$$\frac{x - x_0}{F_x(x_0, y_0, z_0)} = \frac{y - y_0}{F_y(x_0, y_0, z_0)} = \frac{z - z_0}{F_z(x_0, y_0, z_0)}$$

$$\frac{x - 0}{1} = \frac{y - 0}{1} = \frac{z - 1}{1}$$

$$\boxed{x = y = z - 1}$$

## Section 7: Maximum and Minimum Values

### *5-21 (odd)*

Find the local maximum and minimum values and saddle point(s) of the function. You are encouraged to use a calculator or computer to graph the function with a domain and viewpoint that reveals all the important aspects of the function.

5.  $f(x, y) = x^2 + xy + y^2 + y$

7.  $f(x, y) = 2x^2 - 8xy + y^4 - 4y^3$

9.  $f(x, y) = (x - y)(1 - xy)$

11.  $f(x, y) = y\sqrt{x} - y^2 - 2x + 7y$

13.  $f(x, y) = x^3 - 3x + 3xy^2$

15.  $f(x, y) = x^4 - 2x^2 + y^3 - 3y$

17.  $f(x, y) = xy - x^2y - xy^2$

19.  $f(x, y) = e^x \cos y$

21.  $f(x, y) = y^2 - 2y \cos x, \quad -1 \leq x \leq 7$

### *33-39 (odd)*

Find the absolute maximum and minimum values of  $f$  on the set  $D$ .

33.  $f(x, y) = x^2 + y^2 - 2x,$

$D$  is the closed triangular region with vertices  $(2, 0)$ ,  $(0, 2)$ , and  $(0, -2)$

35.  $f(x, y) = x^2 + y^2 + x^2y + 4,$

$D = \{(x, y) \mid |x| \leq 1, |y| \leq 1\}$

37.  $f(x, y) = x^2 + 2y^2 - 2x - 4y + 1,$

$D = \{(x, y) \mid 0 \leq x \leq 2, 0 \leq y \leq 3\}$

39.  $f(x, y) = 2x^3 + y^4,$

$D = \{(x, y) \mid x^2 + y^2 \leq 1\}$

### *43*

Find the shortest distance from the point  $(2, 0, -3)$  to the plane  $x + y + z = 1$ .

### *45*

Find the points on the cone  $z^2 = x^2 + y^2$  that are closest to the point  $(4, 2, 0)$ .



**47**

Find three positive numbers whose sum is 100 and whose product is a maximum.

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**55**

A cardboard box without a lid is to have a volume of  $32,000 \text{ cm}^3$ . Find the dimensions that minimize the amount of cardboard used.

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